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Air-Handling System Modeling in EnergyPlus: A Strategic Plan for Enhancements to Meet Stakeholder Needs

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Air-Handling System Modeling in EnergyPlus: Recommendations for Meeting Stakeholder Needs

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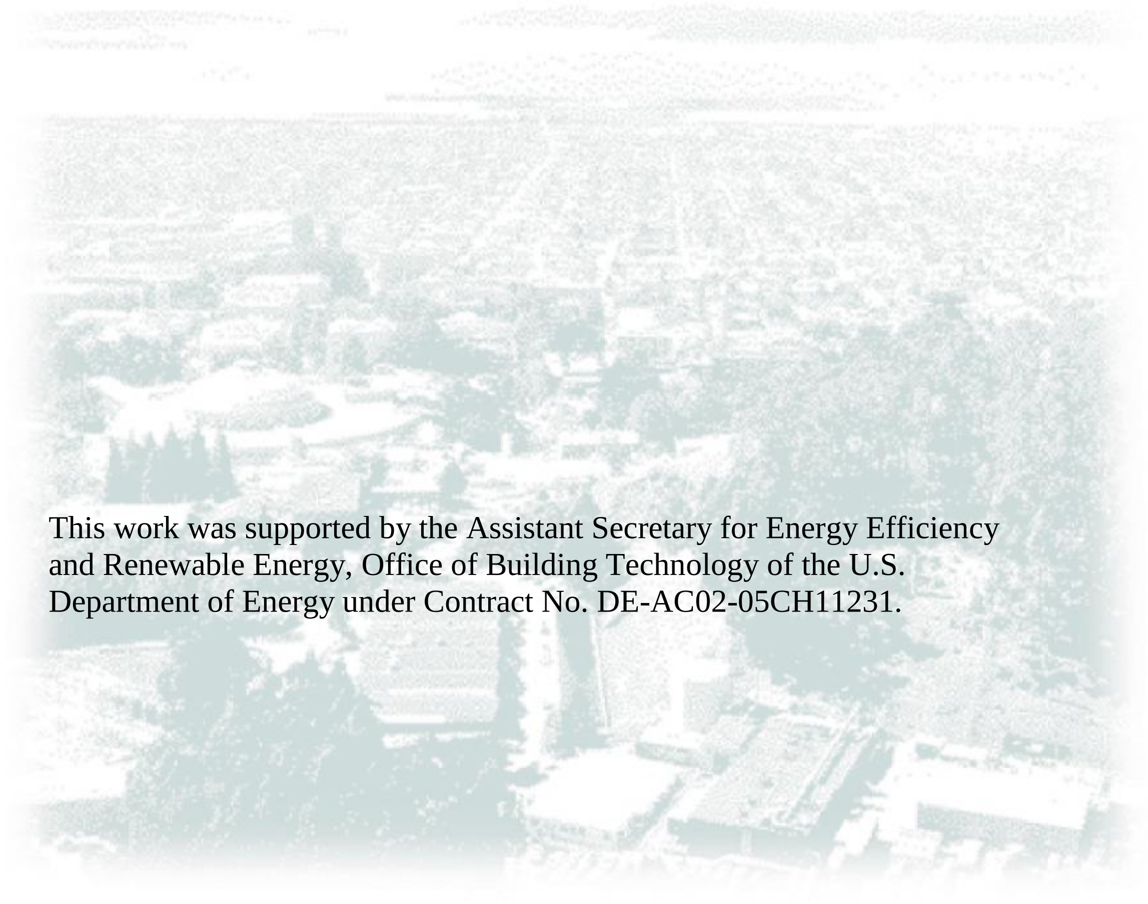

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DISCLAIMER

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Introduction

Proven air-handling technologies exist that, individually, can save 10 to 50% of air-handling system energy (Weale et al. 2001, Diamond et al. 2003, Wray and Matson 2003, AIRxpert Systems 2008, CEC 2009, Wray and Sherman 2010), while maintaining or improving indoor environmental quality (IEQ). These include sealing system air leakage to reduce system flows and short-circuiting, optimizing duct layout and sizing to reduce system pressure drops, converting constant-air-volume systems to variable-air-volume, and adding duct-static-pressure reset and demand-controlled ventilation.

The energy, comfort, and air quality consequences of a using a particular air-handling system technology depend not only on the characteristics of the technology, but also on how it interacts with other technologies and with the rest of the building. A capable prediction tool can help to determine how to integrate these technologies and the building, and how to commission the resulting systems. It can guide optimization for both the design and operation of the building, and it can be used for fault detection and diagnosis (FDD). Stakeholders such as Better Buildings Alliance (BBA) partners and Energy Service Companies (ESCOs) also need these tools to show compliance with codes and standards (e.g., DOE's planned fan efficiency regulations, or ASHRAE Standard 90.1, which is currently moving to a systems approach), to support building rating and labeling programs, and to participate in incentive programs.

EnergyPlus already has models to predict energy use by air-handling systems. However, simplifying assumptions built into the code can lead to inaccuracies, especially when the program is used to simulate integrated component retrofits or innovative systems. Inaccuracies also can result when making design decisions for new buildings, where the model will include relatively uncertain inputs, as well when making decisions about retrofits of existing buildings, where the model may have insufficient data available for calibration. Furthermore, EnergyPlus currently has no intrinsic capability to optimize system type, layout, or component sizing, for example to reduce system pressure losses and related fan energy, or to predict related impacts on indoor air quality.

This document presents a plan to enhance EnergyPlus for modeling air-handling systems in commercial buildings. The study aims to identify and prioritize industry needs in support of the design, operation, maintenance, retrofit, and commissioning of air-handling system components and whole systems. This includes policy-related needs, such as assessing potential impacts of technology and policy changes, developing codes and standards, and demonstrating compliance.

Scope

In this report, the air-handling system comprises all mechanical components directly involved in moving and conditioning air for space heating, cooling, and ventilation throughout the building. This includes fans, motors, drives, filters, coils, ducts, terminal boxes, dampers, and grilles and diffusers.

Although the air-handling system interacts with other building technologies, for example the chilled-water loop, this document focuses on recommendations for modeling air-handling system technologies.

This report focuses on the existing EnergyPlus code. Although this document was prepared at the same time as ongoing planning for the next-generation “Son of EnergyPlus” (SoEP), we do not attempt to dictate technology choices for that program. Rather, we hope that the discussion here, in particular the long-term goals, may guide the design and solver choices for SoEP.

Outline

This document draws on diverse sources, including the current EnergyPlus documentation, the ASHRAE Multidisciplinary Task Group on High Performance Air-Handling Systems for Buildings Except Low-Rise Residential Buildings (MTG.EAS), a literature review, and the EnergyPlus user forum. We also solicited use cases from various industry stakeholders, though with limited success.

The following section provides preliminary background information on multizone network theory. Subsequent sections describe our information-gathering efforts related to each source, and the resulting recommendations. A final, concluding, section summarizes these efforts and our recommendations.

Background – Airflow Network Theory

In order to describe and critique the air-handling system related simulation capabilities built into EnergyPlus, we adopt the language of airflow network theory. In particular, we focus on multizone airflow networks. Multizone models represent the current state of the art for estimating whole-building airflows, including those due to air-handling system operation. This section provides the necessary background to understand this common approach to whole-building airflow modeling. We reserve our critique of multizone models for the literature review.

An airflow network models a building as a collection of nodes, linked by flow paths. The nodes represent either inhabitable spaces (zones), discrete connection points between flow paths such as between duct segments in an air-handling system, or large uninhabited spaces such as a ceiling return plenum. Flow paths include fans, ducts, doors, windows, adventitious leaks, and any other path that can carry air between nodes. The solution to the resulting airflow network satisfies the state equations of all the nodes and flow paths.

In the standard multizone formulation, airflows result from pressure differences between nodes. These pressure differences arise due to three driving forces: (1) mechanical component operation, such as fans; (2) wind; and (3) temperature differences between nodes, which result in pressure differences due to the hydrostatic or “stack” effect (i.e., the decrease in static pressure with height).

The airflow solver seeks the pressures and flows that simultaneously satisfy the defining equations of all the network components. In the multizone formulation:

1. The mass flow and pressure drop through a flow path satisfy its pressure-flow relationship, which depends on the flow path type and parameterization;
2. The nodes enforce mass conservation (within a defined tolerance); and
3. The pressures in the zones and flow paths vary with height, according to the hydrostatic pressure relation, with the density calculated according to the ideal gas law.

For the following discussion of EnergyPlus airflow modeling, then, we identify the following salient characteristics of a “network airflow model”:

1. It treats the entire building as a network of interacting nodes and flow paths;
2. It models the flow paths as relating the pressure drop in the flow direction to the flow through the path; and
3. It solves the network to ensure mass conservation at each node (again, within a defined tolerance), and hence for the entire building.

The remainder of this section provides additional background information that may be helpful for understanding airflow network models. Axley (1989a) and Lorenzetti (2002) provide further detail about the theory of airflow networks.

In common airflow network modeling practice, the airflow network represents a steady-state system. That is, at any given time there is no net accumulation of air in a zone, so that the mass flows in and out of every node sum to zero. Furthermore there are no inertial or capacity effects in flow paths (i.e., the path pressure-flow relations do not depend on the time history of the pressures or flows). Any time variation in the airflows results from changes, from one time step to the next, in the boundary conditions (e.g., the node temperatures, wind pressures, and fan speeds). Note that, since air density is a function of air temperature (and, in the case of non-trace contaminants, concentration), this may require iterating until the algebraic equations that define the steady-state airflow system are satisfied at each step.

While a multizone simulation tool represents the building airflow network as a collection of interacting nodes and flow paths, the user can define the network using higher-level building blocks. For example, the CONTAM multizone program (Walton 2010) allows users to specify a “Simple Air-Handling System” which represents, using only a few parameters, all the associated supply and return airflow paths. Internally, CONTAM simulates all these high-level inputs within the same computational framework as that used to represent all the other airflow network components. In particular, this means that the airflows specified for the “Simple Air-Handling System” are still part of the air mass balance, and still affect the node pressures. Therefore changing a parameter in the high-level model can translate to a change in the calculated airflows throughout the building.

When creating a network model, the analyst identifies zones based mainly on the detail needed from the model predictions. Hence, a zone in the model may be smaller than an air-handling system zone: for example, the zone might represent an individual room or supply closet. A zone in the model may also be larger than an air-handling system zone (although this is less common in modeling practice). Nodes in the air-handling system are identified by the connections between discrete flow elements, for example, the connection of a fan to a duct.

Much of the literature on multizone models refers to zones as well-mixed. Note, however, that this assumption relates to the contaminant transport model, not to the airflow model. In fact, neither the airflow theory nor the transport theory requires the well-mixed assumption. Therefore, we do not insist on that assumption here.

In analogy with electric circuits, airflow paths correspond to discrete components, such as resistors and batteries, while nodes correspond to junctions where two or more electrical components connect. Air pressure corresponds to voltage, while airflow corresponds to electric current. As this analogy implies, the majority of the model complexity is associated with the flow paths, rather than with the nodes. In fact, while modern airflow simulation tools use a single basic zone type, they provide a wide range of path types, whose pressure-flow relations range from a simple engineering orifice equation to a Darcy-Colebrook duct friction model. Note that, compared to a typical electrical resistance model, in which voltage drop is directly proportional to current, the majority of the pressure-flow relations are nonlinear. Therefore, the computational cost of solving for the airflows typically is higher than for an electrical circuit with an equivalent topology.

Use Cases

To identify expectations that users of a whole-building energy simulation tool might have regarding its ability to simulate air-handling systems, we developed and solicited use-cases. These use-cases indicate the scope of applications that need to be considered, and in part justify our interest in achieving mass balance of air throughout the building.

We developed the first three use-cases ourselves to serve as examples for others to follow.

1. Duct-static-pressure reset control analysis (Appendix A). Design of a static pressure reset control system for a new commercial building. The fan speed will be controlled to maintain a target static pressure in the duct. To minimize duct pressures, the target static pressure will be continuously adjusted based on the demand at the terminal boxes.
2. Demand-controlled ventilation analysis (Appendix B). Evaluation of a CO_2-based demand-controlled ventilation system. The energy and IAQ implications of code and standard requirements will be examined.
3. Integrated building and air-handling system airflow and infiltration analysis (Appendix C). Estimation of airflow rates. Weather, system operation, and building characteristics such as envelope airtightness and building height will be considered. Infiltration and internal airflows will be predicted, to improve energy estimates.

We then solicited use-cases from members of the ASHRAE Technical Committee on Energy Calculations (TC 4.7) and the ASHRAE Multidisciplinary Task Group on High-Performance Air-Handling Systems for Buildings Except Low-Rise Residential Buildings (MTG.EAS). Unfortunately, neither committee provided use-cases. However, the MTG did provide a substantial list of research, standards, information transfer, and training needs related to air-handling systems (see Appendix D).

The following 12 use-cases were extracted from the MTG list of ideas (a later section examines the MTG list of ideas in greater detail):

1. Optimize fan selection for variable fan duty applications to minimize energy consumption.
2. Fan arrays. In applications that run multiple fans in parallel, develop control schemes to choose fan speeds for minimum energy consumption.
3. Determine the energy savings potential from using best available motor technology.
4. Develop validation tests for modeling a constant-volume terminal reheat air system serving multiple zones.
5. Evaluate energy implications of different methods of delivering energy (e.g., air vs. water vs. refrigerant).
6. Analyze interactions between fans and downstream fittings (“system effects”).
7. Optimize the efficiency of an air-handling system.
8. Determine the most efficient combination of supply air temperature and duct static pressure reset strategies.

9. Predict the energy consequences of a fan entering stall.
10. Find overall efficiency of a fan//belt/motor/variable-speed-drive combination.
11. Estimate the energy impacts of leaks in system components (e.g., in the air handler casing, ducts, VAV boxes, access doors)
12. Estimate heat loss and gain from ducts due to convection and radiation to unconditioned spaces.

The following five additional use-cases were derived from other literature surveyed in the course of this project:

1. Support development of DOE fan efficiency regulations, as well as other codes and standards such as ASHRAE 90.1 and California Title 24.
2. Support BBA partner and ESCO air-handling design/retrofit analyses (e.g., low-flow and low-pressure drop system design; intersystem comparisons to select optimal system type; component right-sizing and staging optimization; characterize savings from combined system sealing, duct static pressure reduction, demand-controlled ventilation, wireless conversion of CAV systems to VAV).
3. Support component manufacturer data transfer and energy savings claims (e.g., provide database of component leakage and fan, belt, motor, and VFD performance characteristics).
4. Develop control strategies for hybrid low-energy mechanical and natural ventilation systems.
5. Incorporate uncertainty analysis techniques to optimize a system design against probabilistic distributions of as-installed parameters that define other system components.

EnergyPlus already can support many of these use-cases for conceptual design to detailed design stages, without architectural changes. For example, it already provides a model for constant-volume systems with reheat. As another example, EnergyPlus already contains a detailed fan and system curve model, for use when more detail is needed that the simple polynomial part-load power versus part-load flow model can provide. The detailed model accounts for component characteristics such as the fan, belt, motor and variable-frequency drive efficiencies, and the fan pressure rise.

However, more advanced capabilities, such as estimating the impacts of system air leakage on fan pressure rise for constant volume systems, and on IEQ, or the effects of duct heat exchange (i.e., convection and radiation) with unconditioned spaces on energy use, requires more than simple component-level changes. Modeling these and, more broadly, novel air distribution and control systems requires features similar to those identified above for multizone airflow simulations: (1) the ability to express models at the component level; and (2) the ability to solve each component’s defining relations *simultaneously*, as part of a whole-building network, rather than in isolation. Note that simultaneous solution may imply other specific requirements, depending on the problem formulation and solver. For example, embedding the airflow system in a dynamic thermal system may require the solver to explicitly identify when the airflow in a path changes direction.

The first feature, modeling at the component level, is required to allow modeling novel systems, and to allow the user freedom in designing the system (Crawley 2008). In the system leakage example, the user may want to evaluate the impact of different system designs on the system efficiency. Because the duct system location (e.g., in a return plenum versus in an unconditioned space) affects its energy losses or gains via leakage, convection, and radiation, it also affects the overall transport of energy through the air-handling system. Therefore, the simulation tool should provide the ability to reposition the ducts in relation to other model components.

As another example, it should be possible to simulate a dual-duct system as two independent but interacting duct systems. While a monolithic “dual-duct system” model may satisfy the majority of modeling needs, a user who, for example, wants to test a new controller for establishing the economizer mix in each deck, or wants to change the assumptions about energy transfers between the decks, may need to break the rules embodied by a monolithic system model. Again, this would require the ability to implement the dual-duct system at the component level.

Recommendation: Any changes to the airflow modeling capabilities of EnergyPlus should preserve or enhance its ability to model individual airflow distribution components.

The second feature, integration into a whole-building network, is required to allow local changes to propagate through the rest of the model. In the system leakage example, because the location of leaks affects where the system exchanges energy and pollutant mass with the rest of the building, it also affects the overall transport of energy throughout the building. Crucially, the network model should allow for the simultaneous solution of the governing equations, because the leakage rate from the air distribution system to the spaces it passes through depends on the pressure drops between the duct system and the surrounding zones, which in turn depends on the response of the airflow network in all the connected spaces.

As another example, changing the assumed infiltration rate of a perimeter zone should affect the exfiltration rate, the air-handling system supply and recirculation rates, and the rate at which the perimeter zone exchanges air with other zones. Again, modeling this interconnectivity demands that the whole building be treated as an airflow network, rather than as a collection of non-interacting zones. That is, since a change in the infiltration rate might affect all of these, the building’s response cannot be isolated to a few assumptions made in the zone model. Local changes have to be allowed to propagate globally, throughout the model. This in turn requires a whole-building network.

Recommendation: It should be possible to treat all airflow components as part of a single, whole-building airflow network.

We stress that requiring the ability to express models at the component level, and to allow those components to interact as part of a global network, does not preclude high-level models such as, say, a dual-duct system model. The only requirement is that it must be possible to express the high-level model (i.e., the model presented to the user of the simulation tool) using the same analysis framework as the component models. Only then can the tool guarantee a globally-consistent solution.

Current EnergyPlus Capabilities

This section summarizes the current airflow network and air-handling system simulation capabilities of EnergyPlus. We focus on the high-level modeling approaches, mentioning subsystem models mainly to provide concrete examples. For example, we discuss the design intent of the primary air loop object AirLoopHVAC, but do not discuss subsystem models such as AirLoopHVAC:OutdoorAirSystem or AirLoopHVAC:UnitaryHeatPump:AirToAir.

At the highest level, EnergyPlus divides airflow components between those in the “primary air system” and those representing “zone equipment” (Engineering Reference 2013, Zhou 2013). Primary system components are central “supply side” equipment, including supply and return fans, heating and cooling coils, economizers, and the like. Zone equipment components are local “demand side” items, such as terminals, fan coils, window units, and so on. Note that this architecture reflects a pragmatic, historical solution to the problem of limited computer resources, rather than a deeper theoretical or physical distinction between air distribution systems and zones (Taylor 1990). By contrast, airflow network models make no corresponding distinction between different types of airflow paths, but instead treat all flow components as part of a single, coherent airflow system.

The two airflow subsystems are solved independently. To couple them, the heating or cooling that a zone requires from the supply system is calculated under the assumption that the zone controller succeeds in maintaining its temperature at set point (provisions are made for undersized systems; see “Summary of Predictor-Corrector Procedure” in the Engineering Reference). This calculation yields the heating or cooling requirements that the primary system must deliver to each zone. In case of a mismatch between the assumed solutions, the EnergyPlus “Integrated Solution Manager” solves the supply (primary) and demand (zone) sides iteratively, using a Gauss-Seidel method of successive substitution.

Following this solution scheme, we begin with the zone equipment models. Table 1 lists the models that determine airflow rates in the zones (Engineering Reference 2013). Of the models listed in Table 1, only the AirflowNetwork model has the potential to treat the entire building as a network of interacting components. The other models simply specify local airflow rates. More importantly, the other zone equipment models base their calculations on boundary conditions (e.g., temperature differences and wind speed) at the individual zone to which the model is applied. Thus, their airflow estimates do not respond to changes elsewhere in the building.

Of these zone models, we note the following:

- The ZoneInfiltration:DesignFlowRate model fixes the infiltration rate, without regard to other airflows in the zone. In fact, according to the Engineering Reference, “exfiltration (the leakage of zone air to the outside) is generally handled better as zone exhaust air in the zone equipment description.” Thus, there is no direct connection between the calculated infiltration and exfiltration rates, so that increasing the infiltration rate has no effect on the exfiltration rate. An airflow network, on the other hand, would enforce a connection, for example by predicting a higher zone pressure in response to an increased infiltration rate, which in turn would yield greater outflows through the remaining paths.

Table 1. Summary of airflow models for zones, as described in the EnergyPlus Engineering Reference.

Model	Capability
ZoneInfiltration:DesignFlowRate ZoneVentilation:DesignFlowRate	Infiltration and ventilation. Environmental conditions modify a design flow rate.
ZoneInfiltration:EffectiveLeakageArea	Infiltration. ASHRAE’s “basic” infiltration model, accounting for wind and stack effects. Based on Sherman and Grimsrud (1980).
ZoneInfiltration:FlowCoefficient	Infiltration. ASHRAE’s “enhanced” infiltration model, accounting for wind and stack effects. Based on Walker and Wilson (1998).
ZoneVentilation:WindandStackOpenArea	Infiltration. A neutral pressure level model that accounts for wind and stack effect.
ZoneAirBalance:OutdoorAir	Sums air exchange due to “balanced” and “unbalanced” flows.
ZoneMixing ZoneCrossMixing ZoneRefrigerationMixing	Air exchange between zones. The differences between models relate to assumptions about how airflow affects energy transport.
AirflowNetwork	Infiltration and ventilation. A standard pressure-based multizone airflow network.

- Similarly, none of the infiltration models account for the air entering a zone via the air-handling system, or from other parts of the building. Increasing the net rate at which air enters a zone from other parts of the building should decrease the infiltration rate. An airflow network model would predict this effect by predicting an increased zone pressure, which in turn would allow less infiltration through the building envelope. However, the infiltration models do not respond to such changes in the rest of the building. Similarly, the flows through the air-handling system do not change as a result of pressure changes in the zones.
- Both the Sherman and Grimsrud model (used by ZoneInfiltration:EffectiveLeakageArea) and the Walker and Wilson model (used by ZoneInfiltration:FlowCoefficient) are residential infiltration models, designed to estimate the whole-building air exchange rate (i.e., both infiltration and exfiltration). They do not predict zonal pressures nor do they account for flow changes through the air-handling system as a result of zonal pressure changes
- The documentation for ZoneVentilation:WindandStackOpenArea states that this model “can be used alone or in combination with ZoneVentilation:DesignFlowRate objects.” The fact that the model can be used alone shows that its predictions do not affect any larger whole-building mass balance.
- The ZoneAirBalance:OutdoorAir model assumes that volume flow rates due to infiltration, air-handling system leakage, and certain DesignFlowRate flows, add in

quadrature. In other words, this model does not even balance the volumetric airflow rates, let alone the mass flow rates.

- The models for air exchange between zones use airflow rates fixed by the user. Again, they do not adjust their predictions to reflect the flows estimated for other paths connecting the zone to the rest of the building.

In short, with the exception of the AirflowNetwork model, none of the zone equipment models adjust their airflow estimates in response to other airflows in or out of the zone. Even the current implementation of this model treats air-handling system flows in each time step as fixed values (driven by thermal loads) that cannot respond to zone pressure changes. Ultimately, this reflects the fact that these models were designed primarily to estimate the energy consequences of airflows, rather than airflows per se.

These criticisms of the individual zone airflow models do not, of course, mean that EnergyPlus could never respect air mass balance when users employ these models. Broadly, there are two ways to obtain mass conservation in a zone that uses one of these models: (1) incorporate the airflow predicted by the zone infiltration or air exchange models into a larger airflow network model; or (2) impose the required net flow rate, via the supply and return paths (assuming that air-handling system flows do not change with zone pressure).

Consider the first approach, i.e., incorporating the existing zone infiltration and air exchange models into the AirflowNetwork model. To ground the discussion in a specific case, suppose that a zone’s infiltration rate is specified using the ZoneInfiltration:DesignFlowRate model. Then the calculated infiltration rate could simply be imposed on the zone, in the same way as a constant-volume fan flow is treated under airflow network theory. The only requirement is that the zone has at least one “relief” flow path, connecting it to the outdoors or to some other zone. In multizone network theory, the flow in such a relief flow path varies with the pressure drop (Lorenzetti 2002). Informally, the relief paths allow a zone to respond to an increase in airflows from other paths, by letting air escape to some other location (conversely, they also allow a zone to respond to a decrease in airflows from other paths, by drawing air from some other location). A node that is missing such a variable-flow path cannot guarantee mass balance in a steady-state airflow model.

Now consider the second approach, i.e., imposing the required net flow rate via the supply and return paths. Absent an AirflowNetwork model, when EnergyPlus balances airflows, this is the method it uses. Recall that, after the zone equipment components are simulated, the primary air system is simulated. If the infiltration, exfiltration, and zone-to-zone exchange rates are fixed, then the only way for the simulation to achieve mass conservation of air is to adjust the supply and return flow rates accordingly. In cases with a constant-volume system (via the Fan:ConstantVolume component), this is clearly not possible, and air mass conservation cannot be respected. However, in cases with a variable-air-volume system (Fan:VariableVolume or Fan:ComponentModel), mass conservation is, in principle, possible.

Under the existing architecture, achieving mass conservation of air with a variable-air-volume supply system would require the zone equipment components to communicate their estimated airflows to the primary air system model. Unfortunately, the Engineering Reference does not specify whether this, in fact, happens. The coupling scheme described in the section “Basis for the Zone and Air System Integration” explicitly promises that the thermal energy estimates are communicated, but says nothing about the airflow estimates. For example, the thermal load due to interzone mixing is calculated as $m_i*C_p*\Delta T$, where m_i is the mass flow, C_p is the air specific heat, and ΔT is the temperature difference. The thermal load itself appears in the coupling equations, but no mention is made of whether m_i is explicitly considered when determining the airflow rates in the primary air system.

Indeed, the Engineering Reference states that in most cases, the primary system flows do not respect the mass balance of air. According to the subsection "Determination of Air Mass Flow Rates" (p.355):

> "In most cases the air mass flow rate of the central air system is set by zone equipment downstream of the primary air system. The air terminal unit components with their built in dampers and controllers respond to the zone heating and cooling loads by setting air flow rates at their inlet nodes. These flow rates are passed back upstream to the primary air system, establishing the flow rates in the primary air system branches."

We conclude that the majority of simulations do not respect air mass conservation in the zones. Indeed, users are generally expected to specify "balanced" airflows on a zone-by-zone basis (Nigusse 2014).

As described above, an iterative, Gauss-Seidel-like successive substitution procedure does couple the primary and zone equipment loops. To avoid any confusion regarding this updating procedure, we clarify that the iterations are used to match the thermal models. As described above, the airflow to each zone is set by its thermal load, which depends in part on the assumed zone temperature. For the first iteration, the zone temperatures are estimated based on the primary system airflows from the end of the previous time step. After the primary system airflows are updated for the new time step, the zone temperature estimates, and hence their thermal loads, may change. However, since the zone infiltration and exchange airflow rates determined by the EnergyPlus models for the most part do not depend on the zone temperatures or supply system airflows, the iterative solution for the most part cannot affect the airflow estimates for the zone equipment (the zone temperatures do, of course, affect the energy transport consequences of those airflows).

To summarize, we have identified several problems with the zone airflow estimates made in most EnergyPlus simulations (i.e., those that do not use the AirflowNetwork model):

1. The airflows estimated for flow paths to the outdoors, and to other zones, do not depend on the flows estimated in other flow paths. Thus there are no feedback paths so that, for example, high infiltration on the upwind side of a building could translate into high outflow from the perimeter zone to an interior zone.
2. The airflows estimated for the primary (supply) system do not necessarily respect the airflow estimates made for the other zone flow paths.

Before turning to solutions, we somewhat widen the scope of our comments. So far, we have described the problems with the current coupling strategy purely in terms of air mass balance. In general, we expect that achieving air mass balance is necessary for any simulation study whose conclusions rest on fundamental physical principles, for example, designing a novel control system, optimizing the design of a new building, extracting "rule of thumb" guidelines from prototypical buildings, and so on. There are, however, other implications we would like to make explicit, that further illustrate the problems:

1. With inconsistent airflow solutions, the pressure differences between system components may not be estimated correctly. Specifically, individual component models

estimate pressures as needed, with no mechanism to ensure consistency between components. Thus, any quantity that depends on pressure differences through the system, including fan power and air leakage, may be based on incorrect assumptions.

2. Incorrect airflow estimates affect the simulated transport of energy through the building. If the airflow solution does not correctly couple the airflows between zones (so that, for example, increasing the airflow from zone A to zone B forces more air to escape from zone B to zone C), then the tool cannot properly estimate the transport of energy from A to C via B.
3. Similarly, simulating a demand-controlled ventilation strategy depends on using realistic models for the generation, transport, and removal of species such as CO_2, other bioeffluents, and volatile organic compounds (VOCs) throughout the building. Without a consistent airflow solution, the predicted contaminant concentrations will be incorrect.
4. To first order, the existing coupling approach assumes that the air-handling system meets its load requirements. This makes it difficult to study control systems in the context of fault detection and diagnosis.

Solving these problems will require an airflow network model that: (1) respects mass conservation in each node; and (2) solves every airflow node in the building, from air-handling system nodes to zones, simultaneously, e.g., so that increasing the assumed rate of air supplied to a zone can result in less infiltration, or so that increasing the wind pressure on a zone's exterior can result in increased airflow from the perimeter to interior zones. Therefore we recommend re-implementing the existing airflow models within some airflow network formalism.

Since the AirflowNetwork model already provides such a formalism (Gu 2007), we recommend extending its implementation to subsume the other models as input methods. For example, if a user specifies an infiltration rate using the ZoneInfiltration:EffectiveLeakageArea model, those inputs should map to a forced flow component (akin to a fan) in a larger AirflowNetwork model of the whole building. This will ensure that users can "mix-and-match" infiltration and ventilation models, while still finding globally consistent airflows. (Of course, in the long run inappropriate infiltration models should be deprecated; however, our goal in this recommendation is to provide a transition path to more modern practice.)

This proposal affects both zone equipment components and primary air system components.

Recommendation: All existing "zone equipment" (infiltration and zone-to-zone air exchange) sub-models should be re-implemented within the framework provided by the AirflowNetwork model.

Recommendation: All existing "primary air system" (central supply and return loop) sub-models should be re-implemented within the framework provided by the AirflowNetwork model, thus removing the iterative updating between the supply and demand side calculations.

Unfortunately, such a transition would not be seamless. For many existing input files, fitting the legacy airflow models into a mass-balancing framework will result in ill-formed systems of equations. Ill-formed systems would result if any zone failed to connect to a zone of known pressure, such as the outdoors, through a series of passive “relief” flow paths. As described above, these relief flow paths allow airflow nodes to respond to changes in the assumed airflow through one path, by changing the airflow in other paths. Without such paths, mass balance cannot be guaranteed in a steady-state airflow network.

Fortunately, detecting an ill-formed system of equations can be done during the initialization stage, by directly querying the graph that represents the airflow network. Thus, it is not necessary to wait for the airflow solver to find a singular matrix, before signaling a problem. Furthermore, it is possible to identify the source of the problem explicitly, rather than making the user guess where the problem originates. Nevertheless, fixing such problems will likely require direct user intervention, since the places where relief paths should be inserted depends on the modeling intention, rather than on any mathematical analysis.

Unifying the treatment of all airflow models within an airflow network would have computational impacts as well. The entire airflow network, including all zone equipment and primary air system models, would have to be solved simultaneously. This would add to the computational cost of running any EnergyPlus model that did not already invoke the AirflowNetwork model explicitly.

At this time, it is impossible to know what the run-time consequences would be. However, based on our experience with CONTAM, we do not expect the cost of solving the airflow system to be large compared to that of solving the energy transport system. CONTAM addresses a similar problem to that of EnergyPlus, except that the calculated airflows transport contaminants, rather than energy, through the building. As with EnergyPlus, the resulting transport problem is modeled by coupled differential equations. However, the energy transport system is more complicated than contaminant transport, because energy, in addition to movement by airflows, has significant radiation and conduction transport components as well. Therefore, we begin by assuming that the computational cost of solving the airflow system can be no worse for EnergyPlus (say, as a fraction of the overall computational budget) than it is for CONTAM.

That said, in CONTAM, the computational cost of finding airflows generally is smaller than that of finding the resulting pollutant transport. This holds true even for the most recent version of CONTAM, which exploits multiple techniques in order to reduce the cost of solving the pollutant transport system (Lorenzetti 2013). Therefore, we expect that solving the airflow network should not be significant compared to solving the energy transport system in EnergyPlus.

Recommendation: To diagnose any potential problems with the EnergyPlus implementation, the relative time taken by the AirflowNetwork solver should be benchmarked against both the cost of solving the energy transport system in EnergyPlus, and the cost of solving a similar airflow system in CONTAM.

If the AirflowNetwork solver is found to constitute a significant fraction of the overall run time of EnergyPlus, then techniques similar to those recently implemented in the CONTAM pollutant transport solver – in particular, the aggressive caching of matrix results – can be brought to bear on the airflow network in EnergyPlus as well.

Recommendation: If solution times with AirflowNetwork models become prohibitively expensive, the implementation should avoid re-calculating airflow matrices whenever possible, by caching factored matrices for re-use.

In the short term, the airflow-related sub-models could have better documentation. As noted above, the Engineering Reference does not specify how the various models interact, or indeed whether they interact at all. For example, as noted above the documentation for ZoneVentilation:WindandStackOpenArea states that this model “can be used alone or in combination with ZoneVentilation:DesignFlowRate objects.” This statement seems to imply that some airflow models are not compatible. The Engineering Reference, however, does not specify which models can be used with each other, and, if they are, what effect each may have on the other, if any.

Recommendation: The Engineering Reference should describe the interactions and compatibility between the airflow models.

ASHRAE MTG.EAS

ASHRAE’s Multidisciplinary Task Group on High Performance Air-Handling Systems for Buildings Except Low-Rise Residential Buildings (MTG.EAS) coordinates work on air-handling systems among related ASHRAE technical and standards committees, as well as with external organizations (e.g., AMCA, DOE, SPIDA). Its scope includes the design, operation, and retrofit of high performance air-handling systems. The current MTG roster includes 42 industry experts from a wide range of disciplines.

As mentioned earlier in the Use-Case section, the MTG.EAS generated, as part of its internal discussions, a list of ideas in support of its strategic planning activities. Appendix D summarizes the analytical elements of the ideas, while Appendix E gives the complete list.

In general, the group focused more on applications, such as developing test methods or design guides, than on modeling per se. However, many of the applications of interest include a modeling component, or could be supplemented by simulation.

From the perspective of improving the modeling of air distribution systems, two main themes emerge from the list of MTG.EAS ideas: fans and leakage. Strategic suggestions related to fans range from design (e.g., aerodynamic improvement of blades) to selection (sizing and system effects) to prediction (in particular, pressure-flow relations and efficiency at part-load) to control. As noted above, related modeling issues can largely be accommodated within the modeling framework already provided by the EnergyPlus AirflowNetwork capability.

Within the MTG.EAS, strategic ideas related to leakage largely involve testing a built system, and modeling in support of design. The focus on testing over modeling makes sense, given that the goals of the task group orient around improving system efficiency. Nevertheless, a realistic simulation should include leaks, for example when: (1) routing and sizing duct systems; (2) sizing fans and heating and cooling coils; (3) estimating energy use; or (4) studying the tradeoffs between different efficiency measures. As an example of this last point, consider that realistic leakage models would enable a designer to include system-sealing technologies when comparing options for a new design or retrofit under a budget-constrained project.

Another theme that emerges from the MTG.EAS list is the tendency to use "system curves" as a modeling convenience. A system curve, of course, is an emergent property of the combination of air-handling system hardware and control algorithms (i.e., it does not directly represent a real physical component, but instead represents what the fan sees of the system). Furthermore, a system curve does not reflect the system geometry in sufficient detail to, for example, localize leaks. Therefore, the modeling approach is not, in itself, a sufficiently complete basis for specifying an air-handling system, particularly a novel one. Nevertheless, the fact that its use is so natural to professionals in the field suggests that EnergyPlus should make system curves a first-class modeling input. This means that, in addition to supporting a literal system curve input form, the wider EnergyPlus ecosystem also could provide tools for converting outside models of air distribution systems into the input data required to represent those systems. For example, one such tool could convert historical data into the inputs required by a system curve component. As another example, tools could be developed to convert the output from a duct system optimization program such as Ductsize (Elite Software 2001). Of course, in terms of computation the underlying model should be implemented within the same framework that supports the other models, again in order to ensure a consistent global airflow solution.

User Forum

In order to better understand how day-to-day EnergyPlus users of the tool interact with its air-handling system models, we reviewed comments and questions posted to the EnergyPlus user discussion group (https://groups.yahoo.com/neo/groups/EnergyPlus_Support/info). This review was informal, and consisted of reading the discussion threads over the course of about a year.

No particular issues related to air-handling system models emerged. Rather, questions about such modeling fell into the same broad classes as questions related to other capabilities of the program. In particular, we noted a number of questions related to auto-sizing, and a number of questions related to how the different sub-models interact. Because these are generic issues, we do not explore them further.

That said, the issue of auto-sizing may have some implications for a projected version of EnergyPlus that supports all airflow models within the framework of a single global network. When a subsystem model does not represent the air-handling system at the component level, auto-sizing relates to choosing high-level descriptive parameters, such as the maximum flow rates needed to meet heating and cooling requirements. If, on the other hand, an airflow system is represented in terms of discrete physical components, then auto-sizing must mean selecting physical parameters that directly affect the low-level representation of the airflow system. For example, auto-sizing a cooling coil may have implications for its airflow resistance characteristics, while auto-sizing a fan has direct bearing on its pressure-flow characteristic. Then there are related questions of scope, for example, whether optimizing duct sizes in an EnergyPlus model should be done from within the program itself, or by an external tool that changes parameters and makes multiple forward runs of the model. Similarly, in a component-based air distribution model, system parameters such as the gains of a PID controller may or may not be subject to auto-sizing.

Recommendation: The scope and capabilities of auto-sizing and other design aids should be reconsidered in the context of component-based modeling of air distribution systems.

Literature Search – Network Airflow Models

To make specific modeling recommendations, we performed a literature search on airflow and coupled airflow-thermal modeling. We also summarized the available ASHRAE research reports on air-handling systems (Appendix F).

For clarity, this section reports only on work restricted to network airflow models, for which the zone temperatures are assumed known. The following section addresses coupled models, in which the airflow system is solved as part of a larger energy transport simulation.

The literature makes clear that the multizone approach, embodied by programs like CONTAM (Walton 2010) and COMIS (Feustel 1998), is the de facto "state of the art" for airflow network modeling. As described above, the multizone formulation treats the airflow through each flow path as a function of the pressure drop through the path. The only pressure variation associated with nodes is the hydrostatic effect, where pressure decreases with height according to the temperature-dependent air density.

The implication for EnergyPlus is that no decision has to be taken regarding competing airflow network model formulations. The multizone approach commands the majority of research and validation effort for whole-building airflow models. Since the existing AirflowNetwork model in EnergyPlus already embodies the multizone approach, no major changes have to be taken in order to begin implementing the recommendations made elsewhere in this report.

Recommendation: Alternatives to the standard multizone formulation should be considered for modeling airflow networks in EnergyPlus. However, these alternatives should be regarded as research projects. In the meantime, any re-implementation of existing functionality (and, to the extent possible, any new functionality) should be treated as a straightforward software development effort, employing the framework laid down by the existing AirflowNetwork model.

Nevertheless, multizone models are not without their faults, and some variations have been explored.

The following limitations to the classic multizone formulation have been identified:

- The models ignore momentum. In particular, they have difficulty predicting wind-driven flows in naturally-ventilated buildings, especially in cases where cross-flow is important (Lorenzetti 2001, Wang 2008, Johnson 2012).
- The programs do not adequately model duct T-junctions, whose pressure-flow relations involve three flows and two pressure differences. In short, because the energy dissipated in each leg of the T-junction depends on the flow in the other leg, the T-junction does not fit the standard multizone formalism that the flow through a path depends only on the pressure drop through the path (Lorenzetti 2002).

- Realistic fan models do not meet a formal requirement of multizone models, specifically, that the flow be a unique function of pressure change through the flow path (Lorenzetti 2002). In particular, many fan curves have an infinite derivative at some point in the pressure-flow curve, possibly causing numerical difficulty. In addition, allowing the same flow at multiple pressure changes destroys the uniqueness of solutions. In practice, the problem is handled by restricting the inputs to the fan model, and by linearizing the fan pressure-flow relation outside its expected range of operation. However, this work-around means that the models do not predict conditions such as fan surge.
- In practice, multizone codes do not solve the mechanical energy balance together with the flow path equations. This means that, even with known node temperatures, the density of air in the path may not be consistent with the assumed flow direction (Lorenzetti 2001). This causes an incorrect hydrostatic prediction in vertical ducts. Note that this is an implementation issue, rather than an inherent defect with the network approach; see for example (Wetter 2006).
- Models for buoyancy-induced flows, for example to predict two-way flows in large horizontal apertures such as stairwells, do not necessarily meet all the formal requirements of multizone pressure-flow models (Lorenzetti 2001, Johnson 2012).
- Multizone models have difficulty modeling single-sided ventilation, especially due to turbulence. Single-sided ventilation models, while possible, do not by themselves meet the multizone requirement for a passive relief airflow path. Turbulence-driven flows do not fit the steady-state airflow model well. (Johnson 2012, Freire 2013).
- Multizone models require continuous pressure-flow relations, and therefore cannot properly handle the transition between the laminar and turbulent flow regimes, e.g., in a Darcy-Weisbach duct model (Lorenzetti 2002). In practice, the flow regime shift is handled by artificially smoothing the model between the regimes.
- Steady-state airflow models do not include transient effects due to, e.g., momentum effects in ducts (Lorenzetti 2001). Only quasi-steady effects, for example by stepping a fan through a series of speed changes, or slowly changing the position of a damper, can represent dynamic airflow effects.
- The steady-state airflow model does not lend itself to pumping flows, e.g., due to the operation of elevators, or due to doors opening and closing.
- The standard approach to forming and solving the airflow system assumes symmetry in the matrix representation. This in turn requires that the flow in each path depends only on the pressure drop through the path, and that changes in density with respect to pressure be ignored in the linearized matrix (Lorenzetti 2002).
- In practice, multizone models are more amenable to adding flow path models than to adding zone models (Lorenzetti 2001). For example, the lack of thermal stratification in zones, while handled in COMIS, was long considered a weakness of CONTAM.
- In practice, some multizone model implementations allow non-repeatable flow calculations, in which “memory” in the flow path data structures makes the flow results vary from call to call of the path routine (Lorenzetti 2001).

In addition to these documented complaints, we include a novel one. One problem with the multizone model implementation used in CONTAM is its overly-faithful adherence to the “element assembly” formalism introduced by Axley and Grot (1989). Axley (1989) provides a more complete description of the element assembly formalism, in the context of modeling contaminant transport. While we have not inspected the code for the AirFlowNetwork model in EnergyPlus, we assume that it shares the element-assembly approach, since that code was based on AIRNET, the precursor to CONTAM (Gu 2007).

In brief, the element assembly formalism provides a mathematical basis for expressing how the flow paths contribute to the airflow network equations. This approach writes the pressure-flow relations that describe the flow paths in a linearized form, i.e., as a matrix equation $w = Ap$, where w is a vector of air mass flow rates, p is a vector of pressure differences, and A is a matrix of coefficients that result from linearizing the pressure-flow equations about the current operating point.

Writing the airflow system in linearized form allows the authors to exploit matrix theory for proving the existence and uniqueness of solutions to the airflow equations. However, it does not make for an especially effective computational framework, since, in a naïve implementation, it leads to the calculation of a new coefficient matrix A at every iteration of the nonlinear flow system solver. Unfortunately, CONTAM embodies such a naïve implementation.

By contrast, modern practice for solving systems of nonlinear equations is to find w directly from the nonlinear pressure-flow relations, and to calculate or estimate A only as required by the nonlinear equation solver. This avoids potentially large performance penalties related to forming a matrix that need not be formed. These penalties include: (1) the cost of physically having to write the elements of A as well as the elements of w; (2) the cost of increased cache misses associated with the large number of nonzero elements of A, compared to the size of w and p; and (3) in the case of CONTAM, requiring that A be refactored at every iteration of the nonlinear solver.

Recommendation: The AirflowNetwork implementation of EnergyPlus should be inspected to determine whether it is needlessly faithful to the element assembly formalism. If so, consideration should be given to rewriting the solver to reduce needless computation.

In order to overcome some of the problems outlined above, a number of variations on the multizone modeling approach have been proposed. Three of them, in particular, are of interest here: (1) coupled CFD; (2) port-plane analysis; and (3) dynamic airflow formulations.

Many attempts to couple computational fluid dynamics (CFD) models to a multizone model have been explored. Of these, perhaps the most high-profile is Wang and Chen's work, since it has been incorporated into CONTAM (Wang 2007). The coupled CFD approach aims: (1) to estimate momentum effects in zones, for example in order to simulate cross-flows that make the hydrostatic assumption alone an untenable model for intra-zone pressures and flows; and (2) to estimate the thermal and contaminant profiles in the zone, in order to provide more realistic estimates of hydrostatic and transport effects when the well-mixed assumption breaks down.

Unfortunately, CFD is computationally expensive, to the point that, for problems involving even moderately complex buildings and time scales, whole-building CFD is out of reach even for most high-performance computing facilities (let alone design professionals with desktop machines). Furthermore, for predicting airflows in air-handling systems, with their fans, dampers, junctions, and bends, CFD has yet to prove itself as successful as in its application to rooms.

For these reasons, coupling a CFD model of a single room to a multizone building model, as is done in CONTAM, remains the norm. In practice, the multizone model provides boundary conditions for a detailed CFD model of a room, for example in order to study room-scale issues such as mixing in a large space, or short-circuiting of ventilation systems. While some work has been done to push the practical limits of CFD, for example using extremely coarse grids (Mora 2003), we do not anticipate integrated CFD analyses being of use to the majority of EnergyPlus users in the near term.

Recommendation: Coupling CFD airflow models to EnergyPlus may be useful for studying large individual zones, such as auditoria or atria, where stratification is likely to be important, or for naturally-ventilated perimeter zones, where momentum due to wind may significantly affect airflows. However, whole-building CFD is not likely to be practical without significant advances in solution methods.

The second variation on multizone models, port-plane analysis, considers the kinetic energy as well as the static pressure when driving the flow path models (Axley 2007). This allows the system equations to express conservation of mechanical energy as well as mass, at the cost of one additional state variable (the mass flow) for every flow path. This approach addresses the objection that multizone models do not properly couple the thermal energy balance in flow paths, even in cases when the zone temperatures are specified. Furthermore, it has the potential to avoid the restriction that prevents proper modeling of T-junctions. However, the approach does not overcome the greatest objections to multizone models, i.e., the lack of momentum effects.

The third variation on multizone models, introducing transient airflows, accounts for momentum effects in ducts but not zones (Federspiel et al. 2002). The approach models nodes using the same algebraic mass-continuity equations as conventional multizone models. However, it also includes the momentum of air in ducts, allowing for transient airflows modeled by differential equations. The resulting system of differential-algebraic equations (DAEs) typically is more difficult to solve than the purely algebraic equations of multizone airflow models, or the purely differential equations associated with transport modeling in multizone systems. The system can be converted to a differential system, either: (1) by differentiating the node equations, the approach taken by Federspiel; or (2) by including the dynamics associated with accumulation of air in the zones, and including momentum in flow paths other than ducts. Solving for the dynamics of accumulation in zones also will pave the way for more realistic simulation of smoke control systems than current models allow. For an example of including accumulation in zones, see Qin (2011). Note that the differential systems that result from either technique are likely to be stiff, requiring better numerical solvers than currently found in EnergyPlus.

Moving to a dynamic airflow model could, like Axley's port-plane approach, conserve mechanical energy. As with the port-plane approach, it could be made to model T-junctions properly. In addition, it would overcome the most pressing objections to realistic fan models in the multizone formulation, and would provide a path for simulating pumping flows, laminar-turbulent transitions, and, perhaps, turbulence-induced flows. In fact, the only major objection to multizone models not addressed by dynamic airflow modeling is the lack of momentum effects in zones. However, the method is not well-developed, and its numerical properties are not well characterized.

Recommendation: Dynamic airflow models, with a particular emphasis on solution methods, should be investigated for ultimate inclusion in EnergyPlus.

Literature Search – Coupled Airflow-Thermal Models

The ultimate aim of coupling the airflow and thermal systems is to make the airflows and temperatures consistent at any given point in simulation time. Most of the literature we found on coupled airflow-thermal modeling relates to specific techniques for integrating airflows into energy models. Central to this work is Hensen's "ping-pong versus onion" paradigm (Hensen 1995). The paper examines two methods for taking a single time step, from t_n to t_{n+1}, in the coupled thermal-airflow model.

A "ping-pong" solution projects the airflows at t_n forward over the step. Specifically: (1) find airflows consistent with the temperatures at t_n; (2) use these airflows to find the temperatures at t_{n+1}; then (3) advance to the next time step. The hallmark of the ping-pong solution is that the airflows used to estimate the building's thermal response over a time step are not consistent with the energy state at the end of the step.

An "onion" solution alternates between the thermal and airflow models until the airflow solution used to estimate the building's thermal response over a time step are consistent with the energy state at the end of the step. Note this means the airflows are no longer consistent with the energy state at the beginning of the step. However, by analogy with the backward Euler method of integrating ordinary differential equations, onion solutions are likely more stable, numerically, than forward-projecting ping-pong solutions. However, we do not know of research that examines this supposition.

Hensen concludes that, for a given time step, ping-pong coupling is less accurate than onion coupling. However, because onion coupling is computationally more demanding, Hensen finds that running ping-pong integration for shorter time steps compensates for its lower accuracy, without taking any more runtime. Note that a rigorous assessment of the relative stability of ping-pong versus onion solutions might shed light on their relative accuracy. The theory of numerical solution of differential equations shows that applying certain stable methods to a stable problem can yield good accuracy, even when taking steps much longer than the accuracy guarantees of the solution method would indicate; the property of interest is called "stiff decay" (Ascher 1998) or "L-stability" (LeVeque 2007). Again, we do not know of research that examines the stability of ping-pong versus onion coupling.

EnergyPlus effectively uses onion-style coupling, since the individual subsystems get iterated until convergence, via a "Gauss-Seidel philosophy of continuous updating" (Zhou 2013).

Most papers investigating the coupled thermal-airflow problem describe specific integration studies, rather than new theoretical developments. Many of these frame their work in terms of this "ping-pong versus onion" paradigm. Most conclude that onion coupling is best, or else use onion coupling without exploring ping-pong coupling in any depth. These works are too numerous to cite at length (and few provide any additional insight into the problem). We note that onion coupling is used to run CONTAM-based airflow models in TRNSYS (McDowell 2002). Hensen also has a follow-up study reaching similar conclusions to the original paper (Hensen 1999).

Hensen does acknowledge a third class of coupling methods, dubbed “full integration.” In full integration, the airflow and energy equations are solved simultaneously, as part of a larger, single system. However, Hensen dismisses this approach out of hand, as computationally too expensive. Computational advantages to partitioning the problem into separate thermal and airflow subsystems include: (1) reducing the size of the subsystems, hence reducing the cost of solving the linearized matrix equations (which generally varies as the cube of the problem size); and (2) allowing the use of solvers that exploit the particular structure of the subsystems (for example, applying specialized matrix solution techniques).

Nevertheless, other authors have considered full integration. For example, Axley and Grot (1989a) describe not only ping-pong and onion-style methods, but also a scheme in which the airflow and energy equations are solved simultaneously. Their analysis is tied to a single-step method, with a configuration parameter to choose between forward Euler, backward Euler, and a trapezoidal-method-like mix of the two. In principle, solving the coupled system using full integration with a backward Euler discretization should match an onion-style solution using backward Euler (although this is not explored in the literature).

Full integration also makes sense in the context of more advanced differential equation solvers. With a simple first-order solver like backward Euler, which specifies the derivatives at the end of a time step, “full integration” means that the airflows are consistent with the zone temperatures at the end of the step. Similarly, with a discretization scheme that evaluates the derivatives at multiple points, “full integration” means that the airflows should be consistent with the zone temperatures at each point where the derivatives are evaluated. This includes multi-step integrators, which allow stable high-order solutions, e.g. to solve stiff differential systems (Ascher 1998).

Some researchers have explored full integration using general-purpose differential-algebraic equation (DAE) solvers, for example using Equa (Sahlin 2003), Dymola (Wetter 2009), or Matlab (Qin 2011). A general DAE solver ensures that the entire system of equations is satisfied at every significant knot in simulation time. Possible advantages of using general-purpose solvers in EnergyPlus include: (1) moving to higher-order integration schemes, better adapted to handling stiff systems of equations; (2) “out-sourcing” the work of writing numerical solvers to professional numerical analysts, thus allowing building scientists to focus on their own domains of expertise; and (3) improving the rigor and clarity of the program documentation, by enforcing a clear distinction between the models and the solution methods.

Recommendation: Research opportunities for improving coupling among all subsystems in EnergyPlus – not just the airflow-thermal coupling – should explicitly encourage work that uses existing open-source general-purpose DAE solvers.

We note that, in the context of coupled airflow-thermal system modeling, full integration does not require a general-purpose DAE solver. In general, what makes solving DAE systems hard is when two or more state variables in the differential system also must satisfy an algebraic relationship. This is not the case under the current formulation of coupled airflow-thermal problems. To see this, consider the ordinary differential equations (ODEs) that represent energy transport between nodes. Suppose a differential equation solver proposes a particular distribution of thermal energy in the building. Under the steady-state airflow model, the proposed node temperatures have an associated unique airflow solution. In turn, those airflows influence the rates of transport of energy around the building. Note that this formulation of the problem exactly matches the requirements of modern general-purpose ODE solvers that, when the solver proposes a particular set of values for the state variables, the ODE system should define the resulting rates of change of those state variables. In short, the algebraic flow equations do not directly constrain the relations between the state variables in the thermal system. Therefore, they do not require a general-purpose DAE solver.

The resulting “partitioned full integration” scheme differs from onion coupling because it solves the airflow system for every proposed thermal state. Under onion coupling, the airflow solution is fixed for each invocation of the ODE solver over each time step. The ODE solver might propose many possible thermal states, but the assumed airflows never change until the ODE solver accepts a final state for the end of the time step. Then, under onion coupling, a new airflow solution would be calculated, and the ODE solver would be run again over the same time step. By contrast, under partitioned full integration, the airflow solver would be run every time the ODE solver proposed a new thermal state. Thus when the ODE solver accepts a final state for the end of the time step, the time step would be complete (i.e., no further iteration between the airflow and thermal problems would be required).

Because it would solve the airflow system separately from the thermal problem, such a partitioned full integration scheme would enjoy the advantages of full integration (maintaining consistency between the airflow and thermal models), without giving up the advantages of a partitioned solution (reduced matrix sizes, and the possibility of applying specialized solvers to each problem domain).

To our knowledge, this possibility has not been explored in the literature. This no doubt relates to the perceived relatively high cost of solving an airflow system. However, as noted above, it is possible to cache the matrix results associated an airflow solution, for application to the next airflow solution. Since successive airflow solutions will, in general, apply to “nearby” thermal states, it should be possible to amortize the cost of finding and factoring an airflow system matrix across many solutions (both internal iterations of the airflow solver, and between iterations of the thermal system solver).

Unfortunately, this approach has not even been implemented in CONTAM (which, while it has no thermal model, does allow time-stepping over changes in the thermal state). As suggested above, current implementations of airflow solvers suffer from a too-faithful adherence to the founding element-assembly literature, which appears to mandate forming a new system matrix at every iteration. Therefore, research would be needed to determine appropriate strategies for deciding when to re-calculate the airflow system matrix.

Recommendation: Research on coupling steady-state airflow systems to EnergyPlus should investigate a partitioned implementation of a full integration solution.

Note that one possible problem with a partitioned full integration scheme is that of finding system matrices for the ODE solver. If the airflows change with the thermal state, then the Jacobian matrix (of derivatives of the rate equations with respect to the thermal state) should include the effect of changes in the airflows. However, with the airflows partitioned into a separate system, this derivative information would not be easy to estimate analytically. Any research into this approach should investigate whether the effect of temperature changes on the airflows is small enough, compared to their other effects on the energy flows, to ignore this component of the Jacobian matrix.

Finally, we note that if EnergyPlus moved to dynamic airflow models, then coupling to the thermal problem would yield a system of ordinary differential equations. An effective implementation would require removing the architectural divisions between not only the primary (supply) and zone (demand) air loops, but also between the air loops and the system loops. The end result would yield stiff systems of equations (since the airflows would respond much faster than the temperatures). This, in turn, would require either a stiff solver, or, if the detailed dynamics of the airflow system were not of particular interest, a solver that has stiff decay (i.e., L-stability).

Recommendation: If dynamic airflow models are incorporated into EnergyPlus, they should be directly coupled to the thermal system.

Summary

For convenience, this section reiterates specific recommendations made throughout the discussion.

The following general recommendations are guidelines for evaluating future proposed work on airflow models in EnergyPlus:

- Any changes to the airflow modeling capabilities of EnergyPlus should preserve or enhance its ability to model individual airflow distribution components.
- Alternatives to the standard multizone formulation should be considered for modeling airflow networks in EnergyPlus. However, these alternatives should be regarded as research projects. In the meantime, any re-implementation of existing functionality (and, to the extent possible, any new functionality) should be treated as a straightforward software development effort, employing the framework laid down by the existing AirflowNetwork model.
- Research opportunities for improving coupling among all subsystems in EnergyPlus – not just the airflow-thermal coupling – should explicitly encourage work that uses existing open-source general-purpose DAE solvers.
- Coupling CFD airflow models to EnergyPlus may be useful for studying large individual zones, such as auditoria or atria, where stratification is likely to be important, or for naturally-ventilated perimeter zones, where momentum due to wind may significantly affect airflows. However, whole-building CFD is not likely to be practical without significant advances in solution methods.

In the short term, the following would benefit users of EnergyPlus:

- To diagnose any potential problems with the EnergyPlus implementation, the relative time taken by the AirflowNetwork solver should be benchmarked against both the cost of solving the energy transport system in EnergyPlus, and the cost of solving a similar airflow system in CONTAM.
- The Engineering Reference should describe the interactions and compatibility between the airflow models.

In the medium term, the program can be modified largely within the existing framework:

- All existing “zone equipment” (infiltration and zone-to-zone air exchange) sub-models should be re-implemented within the framework provided by the AirflowNetwork model.
- The AirflowNetwork implementation of EnergyPlus should be inspected to determine whether it is needlessly faithful to the element assembly formalism. If so, consideration should be given to rewriting the solver to reduce needless computation.
- Research on coupling steady-state airflow systems to EnergyPlus should investigate a partitioned implementation of a full integration solution.

In the long term:

- It should be possible to treat all airflow components as part of a single, whole-building airflow network.
- All existing “primary air system” (central supply and return loop) sub-models should be re-implemented within the framework provided by the AirflowNetwork model, thus removing the iterative updating between the supply and demand side calculations.
- If solution times with AirflowNetwork models become prohibitively expensive, the implementation should avoid re-calculating airflow matrices whenever possible, by caching factored matrices for re-use.
- The scope and capabilities of auto-sizing and other design aids should be reconsidered in the context of component-based modeling of air distribution systems.
- Dynamic airflow models, with a particular emphasis on solution methods, should be investigated for ultimate inclusion in EnergyPlus.
- If dynamic airflow models are incorporated into EnergyPlus, they should be directly coupled to the thermal system.

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APPENDIX A: Use Case 1

(1) Name

Static pressure reset.

(2) Analysis type

ENG = engineering/design (individual building).

(3) Purpose

A mechanical engineer wishes to design a static pressure reset control system for a new commercial building. The fan speed will be controlled to maintain a target static pressure in the duct. To minimize duct pressures, the target static pressure will be continuously adjusted based on the demand at the terminal boxes.

(4) Description

The mechanical engineer wants to use simulation to optimize the design of a static pressure reset control system.

For each candidate duct system design, outputs of interest include:

(a) The range of pressures found in the duct.
(b) The range of fan speeds, and in particular whether the fan goes below a minimum flow at which stability becomes an issue.
(c) The expected energy use over a design year.
(d) The expected sensitivity of these outputs to uncertainty in parameters such as the loss coefficient for each duct segment, or the fan and fan speed controller characteristics.
(e) Identify possible control issues, e.g., “seeking” in the target static pressure.

The simulation relates to the building air-handling system in the following design elements of interest:

(a) The layout and sizing of the ducts.
(b) The location and number of the static pressure sensors.
(c) The algorithm used to adjust the target duct static pressure (including which sensor to track, if multiple sensors are allowed).

(5) Analysis

The analysis calls for a mechanistic model of the duct system, because the system may change dynamically based on the current controller state. Furthermore the simulation must be able to estimate the pressure at any candidate location, in the ducts, for the static pressure sensor.

The analysis calls for a model of the fan that captures its true performance as fan speed changes. The analyst must be able to obtain reliable data for the fan’s performance (i.e., not simply estimated by the manufacturer using the “fan laws”). The analyst must be able to enter these data directly into the simulation tool, or else convert them into a format or representation that the tool provides (e.g., using an external program to estimate the input parameters of interest, given the data).

The analysis calls for a model of the energy losses through the fan speed controller and fan drive, as a function of speed.

A finely-detailed analysis might require transient models, particularly of the fan speed. A steady-state model of the airflow through the fan and duct system implicitly asserts that the system instantly adjusts to changes in the pressure set point, with no time needed to change the fan speed or to let the pressures equilibrate throughout the building. For modest changes in the set point, occurring on the order of five minutes apart or longer, a steady-state airflow model probably is adequate. However, if the control algorithm does not explicitly prevent high-frequency updates to the target static pressure, then a simulation using steady-state airflows may not detect control issues related to “hunting” on the part of the static pressure reset controller.

According to the EnergyPlus Engineering Reference, a Fan:ComponentModel object can model flow-dependent fan pressure rise, and includes detailed models for the fan, belt, motor, and drive efficiencies. The reference explicitly states that this object can be used for duct static pressure reset schemes.

The Fan:ComponentModel approach requires the user to describe the duct system in terms of a four-parameter fit of fan pressure rise to fan flow. For pressure-reset schemes, a linear curve relates the pressure set point to the fan flow. In other words, the model does not present a mechanistic view of the system components in the way that, say, a CONTAM duct system simulation does. However, in principle, all the coefficients can be related to mechanistic details. Therefore users could use a second-party duct design tool to model a proposed design, then extract fan model parameters for use in the EnergyPlus model.

This two-tool approach (simulate the system using a detailed duct system model, then extract parameters for use in the larger energy simulation) has several potential limitations. First is the potential difficulty of extracting the parameter fits, given that no dedicated tools apparently exist for doing so. Second, and more important, is that decoupling the duct system simulation from the energy system simulation threatens to lose important information about the actual ways in which the static pressure reset controller operates. For example, the energy system determines correlations between flows at the terminal boxes, while the combinations of flows at the terminal boxes determines the static pressure set point needed to maintain a given total flow through the fan. Thus in a branchy duct system, the desired static pressure set point may not be a simple linear fit to the total flow. As another example, in order for the system designer to experiment with rules for changing the duct static pressure set point, e.g., by responding to terminal box alarm conditions, the duct simulation tool must have knowledge of the actual loads in the served spaces.

Decoupling the analyses also reduces the opportunity for identifying poor system performance. If the duct system analysis uses flows extracted from an independent energy estimation, then the duct system model implicitly assumes that the flows are sufficient to meet the space loads and ventilation requirements. Therefore extracting a correlative model of the air handler system performance from the duct system model will implicitly produce a model that assumes every terminal box gets the flow it needs to meet the space loads and ventilation requirements. Hence, even if the actual system is able to meet the total flow requirement at a given static pressure, there is no guarantee it can meet the flow requirement at every terminal box. Furthermore, such a system may not be able to identify feedback control problems, since the decoupled approach probably has to rely on running the duct system analysis through a series of steady-states that, by definition, meet the control objectives.

(6) Recommendations

Ideally, EnergyPlus would give designers the option of simulating duct system and control elements at the component level, in order to couple the systems for analysis and optimization.

Alternately, an auxiliary tool could be provided, to automate the extraction of parameters for Fan:ComponentModel objects.

APPENDIX B: Use Case 2

(1) Name

Demand controlled ventilation

(2) Analysis type

ENG = engineering/design (individual building).

STD = develop standards/regulations.

(3) Purpose

The simulations of a carbon dioxide (CO_2) based demand-controlled ventilation (DCV) system would be performed either by a design engineer to evaluate the potential energy performance due to the design details for a particular building or performed for a set of buildings to develop application guidance and to evaluate the energy and indoor air quality (IAQ) implications of code and standard requirements.

(4) Description

CO_2-based DCV attempts to achieve acceptable indoor air quality (IAQ) at reduced energy cost by matching a ventilation system's outdoor airflow rate to the real-time occupancy as indicated by indoor CO_2 levels. The potential advantages of CO_2-based DCV are increased ventilation when occupancy is high, a feedback control mechanism to ensure acceptable IAQ and energy savings from decreased ventilation when occupancy is low. While the energy savings potential of this approach has been highlighted in several studies (Emmerich et al. 1994, Persily et al. 2003 and many others), there are still some important questions related to the implementation of CO_2-based DCV (Emmerich and Persily 2001). One of the most critical issues is that low CO_2 levels alone do not guarantee acceptable IAQ. For example, the concentrations of non-occupant generated pollutants may not be well controlled by such a system, or at least they can become elevated during periods of low occupancy due to decreased ventilation. Also, nonuniformities in air distribution and in building occupancy can present difficulties in locating sensors such that a representative CO_2 concentration is measured. One potential sensor location is a central location inside air distribution system return ductwork thus the conditions (including CO_2 concentration) inside the air-handling system are important.

(5) Analysis

Demand controlled ventilation is a technology which can support both reduced energy use and good IAQ and, as such, is an important technology for sustainable building design (Persily and Emmerich 2012). The use of DCV is currently required for some buildings by ASHRAE Standards 90.1 and 189.1 and by California's Title 24 and allowed with specific limitations by ASHRAE Standard 62.1. However, current energy simulation tools cannot properly simulate the energy impacts of DCV and cannot simulate the IAQ impacts at all due to the lack of a robust, fundamental airflow and contaminant transport modeling capability including airflow through a building envelope, through the HVAC ductwork and between buildings zones and contaminant entry from outside a building, generation by internal sources, and transport via the HVAC system.

As reported by Emmerich and Persily 2001, simulation case studies of DCV have indicated energy savings for DCV systems between 4% and over 50% compared to ASHRAE Standard 62 or other design ventilation rates. The energy savings varied widely depending on type of building, control algorithm, building location, assumed occupancy and other assumptions. No parametric or sensitivity analysis has been performed to determine which variables have the most influence on potential energy savings. A small number of the studies examined peak demand, economic impacts, humidity and concentrations of other pollutants. These studies verified the concern for increased concentrations of non-occupant generated pollutants, and one study examined potential solutions including scheduled purges. Shortcomings of most of the studies included inadequate treatment of infiltration and interzone airflows and control algorithms.

The primary reasons for the shortcomings of past simulation studies are the limitations of available simulation tools. Since the ventilation rates in a building with DCV are determined by the concentration of CO_2, the energy use of the building is fundamentally linked with the airflow moving through the building. Past simulation studies have used a variety of techniques to analyze the coupled thermal and airflow problem but typically either simulate the building airflow and contaminant transport in detail in combination with a simplified energy calculation or use a detailed building thermal model, such as EnergyPlus, with simplified assumptions for the building airflow and contaminant transport. In addition to affecting the accuracy of the overall analysis, these simplified approaches cannot be used to study the impact of non-ideal conditions (e.g., air-handling system leakage) that may impact results.

(6) Recommendations

Ideally, EnergyPlus would give modelers the capability of a robust building airflow and contaminant transport model with detailed air distribution system and control simulation, in order to properly analyze DCV systems including their energy and IAQ impacts.

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APPENDIX C: Use Case 3

(1) Name

Airflow and infiltration modeling

(2) Analysis type

ENG = engineering/design (individual building).

(3) Purpose

Currently, airflow rates between zones and infiltration rates through the building envelope are most commonly included in building energy models as scheduled, constant values that do not include the effects of weather or system operation. Since airflow rates are dependent on both weather and system operation, as well as individual building characteristics (e.g. envelope airtightness and building height), and can have a significant impact on energy use, it is important to account for airflow in a more physically-based fashion. As buildings are better insulated, internal loads are lowered, and equipment efficiencies increase, the energy impacts of airflow and infiltration will be a greater percentage of the totally building energy use. The improved infiltration and internal airflow modeling are capabilities are needed by design engineers evaluating the energy impacts of a particular level of airtightness requirement and to evaluate the energy implications of code and standard requirements.

(4) Description

A mechanical engineer wants to include more physically reasonable infiltration and internal airflow in the building energy model.

Inputs needed:
- (a) Weather data
- (b) Building envelope airtightness at a reference pressure
- (c) Building layout that includes zones necessary for airflow analyses
- (d) Design airflow rates at air handlers, diffusers, and vents
- (e) Building characteristics
- (f) Air-handling system leakage

Outputs of interest include:
- (a) Airflows and infiltration rates from CONTAM as inputs into EnergyPlus model and their impacts on building energy use

(5) Analysis

The development of this use-case would result in users of EnergyPlus being able to easily include more physically reasonable airflow and infiltration rates in their building energy models. This analysis is not normally performed by energy modelers because it either requires a separate airflow model (such as CONTAM) or requires the users to use the existing EnergyPlus capability, MultizoneAirflowNetwork. Neither of these approaches is particularly accessible, particularly for energy modelers who are not familiar with building airflow modeling, and therefore are seldom applied. The need to include more physically-based infiltration rates in a building energy model is not always appreciated by the energy modeling community, however, since airflow and infiltration can significantly impact energy use, it is important to more accurately account for airflow and infiltration as opposed to using a scheduled infiltration rate.

(6) Recommendations

EnergyPlus users would be able to easily and accurately access the full infiltration and interzonal airflow capabilities of CONTAM with graphic user interface and without needing to manually couple two separate simulation tools.

References

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APPENDIX D: ASHRAE MTG.EAS Ideas Summary

ASHRAE's Multidisciplinary Task Group on High Performance Air-Handling Systems for Buildings Except Low-Rise Residential Buildings (MTG.EAS) coordinates work on air-handling systems among related ASHRAE technical and standards committees. Its scope includes the design, operation, and retrofit of high performance air-handling systems in buildings except low-rise residential buildings.

The MTG.EAS was solicited for input on modeling needs. In addition, the task group generated, as part of its internal discussion, a list of ideas in support of its strategic plan (Appendix E). In general, the group focused more on applications than on modeling per se. However, many of the applications of interest include a modeling component, or could be supplemented by simulation. The table below lists the ideas generated by the group. In the table, the "objectives" and "modeling implications" are as taken from the group-generated document.

Title	Objective	Modeling implications
1. Determine optimum fan selection for variable fan duty based operating profile	Optimize fan selection for variable fan duty applications to minimize energy consumption.	Energy calculations must include the fan, motor, VFD, and losses in drive. Optimizing over more than a few operating points requires automation and statistical distributions.
2. VSD optimization	Determine if Variable Speed Drive can provide data to the BMS for energy optimization.	Determine what parameters should be used to optimize the VSD, motor, fan, and other drive components. Use models for real-time decision-making. Model interface to real-time data.
3. Balancing ASHRAE 62.1 and ASHRAE 90.1 requirements for energy, IAQ, health, and productivity	Eliminate variations in requirements between Standards 62.1 and 90.1. Develop CO_2 based Demand-Controlled Ventilation requirements and field verify. Investigate ASHRAE 62.1 field compliance and control strategies.	Verify system operating performance due to requirement perspective, contradictions, or weaknesses in standards. Need to re-evaluate ventilation system design, operation, and maintenance when changing building use, occupancy, or other changes inconsistent with system design assumptions.

Title	Objective	Modeling implications
4. Constant volume terminal reheat	Develop a standard method of test for air-side system simulation tools.	Test the ability to model a CV terminal reheat air system serving multiple zones. Ability to apply a variety of system models to address a CV reheat system.
5. Evaluate heating & cooling delivery systems	Design tool for engineers, for improving the overall efficiency in BTU delivery.	Evaluate alternate methods of delivering BTUs to a space. Consider space, energy, maintenance, building envelope, and geographic location. Include emerging technologies.
6. Fan system effects (similar to 17)	Establish minimum requirements for connecting the fan to the HVAC system to reduce the known, easily addressed causes of system effect.	
7. Improve energy efficiency of AHU systems	Reduce outside air requirements. Tighten ductwork. Control verification. Address impact of using dampers.	Design of system.
8. Determine diversity factors for hydronic systems	Identify potential energy savings.	
9. Method of test for determining air handling unit capacity	Identify impacts of measurement location on readings. Identify impacts of instrument accuracy. Identify required instrument accuracy.	

Title	Objective	Modeling implications
10. Optimizing the static efficiency of air handling systems	How to minimize system effects. Evaluate the impact of negative pressure in system analysis.	
11. Optimize air handlers		
12. Terminal unit published noise ratings	Replace lined duct in Table D18 of AHRI Standard 885 by unlined duct, provide dual ratings, or include a reasonably simple method for designers to convert without extensive acoustical training.	
13. VAV reset	Determine the most efficient method to control both temperature and terminal unit pressure in VAV systems.	Simulate VAV system control sequences and resultant energy cost, with selected ASHRAE 90.1 model building models and climate zones.
14. Harmonizing Standards 62.1 and 90.1 with Standard 189	A design tool for designers to implement Standard 62.1 and Standard 90.1 requirements to comply with Standard 189.1. Create a default value or table of values for minimum expected zone primary airflow at the ventilation design condition. Identify energy performance analysis programs that can incorporate all Std 62.1, Std 90.1 and Std 189.1 airside requirements. Conduct a comparative analysis to determine which of them does a reasonable job of modeling airside requirements.	Model coordinated airside controls, including fan pressure optimization, economizer control, building pressure control, energy recovery control, reheat restrictions on VAV box minimum settings, zone-level DCV and system-level ventilation optimization control and DCV.

Title	Objective	Modeling implications
15. Improve design of multi-nozzle chamber flow settling means for fan performance tests	Improve the design of flow settling means utilized in multi-nozzle chamber performance testing of fans.	
16. Establish accuracy of AMCA Standard 300 tests	Establish the accuracy of AMCA Standard 300 tests (Reverberant Room Method for Sound Testing of Fans).	
17. Fan outlet discharge effects (similar to 006)	Increase population of the ASHRAE Duct Fitting Database.	Research focus could be on the outlet velocity profile of different design fans. Once that is known, it should be possible to calculate or model (CFD) discharge effects.
18. Study of Air Curtains	Provide a standardized procedure to measure air curtain effectiveness (ability of the air curtain to reduce or eliminate undesired transfer of air, energy, moisture, and contaminants).	
19. Develop Method of Test for Large Circulating Fans	Prepare a MOT standard for large circulating fans.	
20. Investigate Fan Stall	Provide users better information about the effect of fan operation in stall, and how to make selections to avoid stall.	Provide HVAC industry with a design tool.
21. Fan Efficiency at Low Flow and Low Speed Operation	Improve fan laws over entire speed range.	Problem: Fan tests at low speed don’t agree with predictions based on higher speed data & fan laws.
22. Standardizing Leakage Tests of Operating Air-Handling Systems	Prepare a field Method of Test (MOT) leakage standard for operating HVAC systems.	
23. Overall Fan System Efficiency with VFD	Improve the energy efficiency of fan applications.	There are currently no tools available for determining the overall fan/motor/VFD system efficiency.

Title	Objective	Modeling implications
24. Fan Belt Drive Efficiency	Conduct research, including review of available information, to develop an ASHRAE special publication and possibly a MOT standard, on fan belt drive efficiency.	
25. Motor and Variable Speed Drive (VSD) Efficiency	Develop a method of test for determining the combined efficiency of motor and VSD systems for use in AMCA, ASHRAE, and AHRI standards.	
26. Energy Impacts from Air Handler Casing Leakage	Prepare an ASHRAE MOT (Method of Test) standard to determine leakage of air handling units at the factory and in the field after installation.	
27. Determine Air Leakage of Duct Transverse Joints and Associated Energy Costs	Identify common methods for assembling duct/equipment and typical methods used to seal joints. Quantify typical leakage for each type of transverse connection. Test duct assemblies in accordance with ASHRAE Standard 126. Associate measured leakage and energy cost with common pressure classes and seam length/size of transverse connection.	
28. Cost Effectiveness of HVAC System Air Leakage Tests During Operation	Conduct study to determine the costs and benefits associated with conducting system leakage tests during operation.	

Title	**Objective**	**Modeling implications**
29. Air Leakage of Duct-Mounted Equipment	Determine in the laboratory the air leakage of single duct VAV terminal units without an access door, hot water coil, or electric coil. Determine in the laboratory the leakage of the following equipment associated with terminal units: hot water coils and electric coils. Determine in the laboratory the air leakage of fan powered parallel flow terminal units without appurtenances.	
30. Air-Handling System Airflow and Pressure Diagnostics	Evaluate the applicability and reliability of air-handling system leakage diagnostics for use in new and existing buildings for common system configurations and for those that are gaining in popularity (e.g., under floor supply air distribution in larger buildings). Evaluate and develop where needed reliable, cost-effective ways to measure other air-handling system airflows and pressures (e.g., through and across fans, respectively). Assess the applicability and acceptance of tools and tests as training and quality control aids. Initiate standardization and commercialization of these tools and tests.	

Title	Objective	Modeling implications
31. Air-Handling System Performance Analysis Tools	Establish the purpose and scope of modeling commercial building air-handling systems and the intended outcomes. Summarize what is known now and what gaps still exist in terms of modeling air-handling systems. Identify appropriate performance metrics for rating air-handling system "efficiency". Extend ASHRAE Standard 152 calculation methods to include commercial buildings and address air-handling system efficacy (i.e., thermal comfort) issues. Establish integrated energy and indoor environmental quality (IEQ) baselines for standards. Develop standardized procedures for verifying whether energy-efficiency and IEQ program targets are met.	Some key issues can lead to prediction inaccuracies in existing analysis tools and need to be resolved, such as: (1) Commonly used overly-simplistic system curves that ignore effects of fan shut-off pressure and linear-like effects of filters and coils can lead to substantial pressure rise (and thus power) errors at part-load. (2) Connecting tools such as EnergyPlus to existing duct design software would help to bring them into mainstream practitioner use. (3) Component efficiencies are not constant and peaks are not necessarily coincident. (4) System leakage is estimated to increase HVAC energy consumption by 20 to 30% in small buildings and 10 to 40% in large buildings. EnergyPlus already contains simple models for supply leakage from simple VAV systems, but still cannot address leakage from systems with fan powered boxes or from constant-air-volume (CAV) systems. (5) The lack of distribution system multi-mode heat gain/loss thermal models in tools such as EnergyPlus means that all space conditioning energy from coils is assumed to reach zones. (6) More work is needed to develop models that can be used to address airflows entering VAV boxes from ceiling return plenums, and to address leakage from CAV systems.

Title	**Objective**	**Modeling implications**
31. Air-Handling System Performance Analysis Tools (continued)		(7) A model is needed for heat transfer across the duct wall. (8) Outside the duct, combined natural and forced convection can occur. For simplicity in large commercial buildings, the duct surface model could ignore heat transfer effects due to radiation. Those effects are less important there than in smaller buildings with hot attics and large temperature differences between the building envelope and duct surfaces. The model could also ignore startup transients, because unlike HVAC systems in small buildings, the systems in large commercial buildings usually do not cycle on and off during their daily operating periods
32. Characterize Air-Handling Systems and Assess System Retrofit Performance	Collect field data about the physical characteristics of installed air-handling systems. Determine if performance gains resulting from system retrofits are achieved. Document findings in case studies, and disseminate to industry.	
33. Determine Most Efficient HVAC System based on Geographic and System Loads	Study to determine where geographically and under what building load conditions DOAS systems are applicable.	

Title	**Objective**	**Modeling implications**
34. Guidelines for Air-Handling System Retrofit and Commissioning	After appropriate field diagnostics are developed (Idea 031), data are collected about the physical characteristics of air-handling systems in existing buildings, and performance gains that are actually obtained by system retrofits are demonstrated (Idea 033), new information about diagnostics and performance needs to be integrated into guides for air-handling system retrofit and commissioning. This effort should focus on developing a series of guides containing prescriptive air-handling system retrofit recommendations that can be used by designers and contractors to substantially reduce the energy consumption and improve the indoor environmental quality (IEQ) for specific existing commercial building sectors.	
35. Advanced Technology Applications	Develop aerodynamic improvements to make fans and other system components less susceptible to loss of efficiency during part load operation. Develop new air-handling system technologies that allow life-cycle cost effective reduction in energy use while meeting indoor environmental quality and sustainability requirements for non-residential buildings. Examine the integration of air-handling, hydronic, and building systems. Build proof of concept prototypes.	

Title	Objective	Modeling implications
36. Air-Handling System Design Specifications	Develop design specifications to: Provide robust seals that are integral to all HVAC cabinet/enclosures that will provide an air tight seal. When filter racks are provided by the manufacturer, provide air tight seals and sturdy racks that will not allow air bypass around the seals. Include specifications for insulating duct to increase thermal resistance and decrease thermal conductivity between the different mediums. Provide sufficiently large equipment rooms so that duct connection transitions from the air moving equipment to the duct is straight or at modest angles to avoid system effect issues.	
37. Cost Effectiveness of HVAC System Air Leakage Tests During Construction (similar to 28)	Conduct study to determine the costs and benefits associated with conducting ductwork leakage tests during construction.	
38. Economics of Airtight Non-Fan-Powered Single-Duct Terminal Units	Conduct an economics study to determine if the payback will justify the cost to manufacture low-leakage terminal boxes (basic unit only). Study to be based on laboratory leakage tests of standard and low-leakage boxes.	

APPENDIX E: ASHRAE MTG.EAS Ideas

ASHRAE Multidisciplinary Task Group: High Performance Air-Handling Systems for Buildings Except Low-Rise Residential Buildings

List of Ideas Submitted to Ad Hoc Subcommittee on Strategic Planning

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Background

MTG Rationale

ASHRAE has goals of creating technologies and design approaches that enable the construction of net zero energy buildings at low incremental cost, and also of ensuring that the efficiency gains resulting from related R&D will result in substantial reduction in energy use for both new and existing buildings.

HVAC systems are the largest energy consumer in U.S. non-residential buildings, consuming about 40% of the non-residential sector source energy in Year 2003 or about $44 billion. Moving air to provide ventilation and space-conditioning may consume about a third to a half of this energy. Clearly, efficient air-handling systems that use as little energy as possible are needed for ASHRAE to achieve its goals.

Although the energy efficiency of many HVAC components in non-residential buildings has improved substantially over the past 20 years (e.g., chillers, air-handler drives), there is still a need to make other equally critical components more efficient (e.g., the air distribution system, which links heating and cooling equipment to occupied spaces). For example, field tests in hundreds of small non-residential buildings and a few large non-residential buildings suggest that system air leakage is widespread and large. It is often 25 to 35% of system airflow in smaller buildings, and can be as large as 10 to 25% in larger buildings. Based on field measurements and simulations by Lawrence Berkeley National Laboratory, it is estimated that system leakage alone can increase HVAC energy consumption by 20 to 30% in small buildings and 10 to 40% in large buildings. Ducts located in unconditioned spaces, excessive flow resistance at duct fittings, poorly configured and improperly sized air-handler fans, unnecessarily high duct-static-pressure set-points, leaky terminal boxes, and inefficient terminal unit fans further reduce system efficiency, and in turn increase HVAC energy consumption even more.

There is no single cause for system deficiencies. One cause is that the HVAC industry is generally unaware of the large performance degradations caused by deficiencies, and consequently the problems historically have received little attention. For example, a common myth is that supply air leaking from a variable-air-volume (VAV) duct system in a ceiling return plenum of a large non-residential building does not matter because the ducts are inside the building. In fact, however, the supply ducts are outside the conditioned space, the leakage short-circuits the air distribution system, supply fan airflow increases to compensate for the undelivered thermal energy, and power to operate the fan increases considerably (power scales with the flow raised to an exponent between two and three depending on system type).

Other causes of the deficiencies include a lack of suitable analytical tools for designers (e.g., VAV systems are common in large non-residential buildings, but most mainstream simulation tools cannot model air leakage from these systems), poor architectural and mechanical design decisions (e.g., ducts with numerous bends are used to serve many zones with incompatible occupancy types), poor installation quality (e.g., duct joints are poorly sealed downstream of terminal boxes and in exhaust systems), and the lack of reliable diagnostic tools and procedures for commissioning (e.g., industry-standard duct leakage test procedures cannot easily be used for ducts downstream of terminal boxes). The highly fragmented nature of the building industry means that progress toward solving these problems is unlikely without leadership from and collaboration within ASHRAE.

MTG Purpose, Scope, and Membership

MTG.EAS coordinates activities of related ASHRAE technical and standards committees to facilitate the development of packages of tools, technology, and guidelines related to the design, operation, and retrofit of high performance air-handling systems in new and existing buildings except low-rise residential buildings. The intent is that these products can be integrated with industry processes and can be used to ensure that ASHRAE energy saving targets are met, to carry out high-profile demonstrations of improved air-handling systems, and to identify further energy saving opportunities.

Within ASHRAE, the MTG also coordinates activities to update related parts of ASHRAE Handbooks and Standards (particularly 62.1, 90.1, and 189.1) and to develop related education programs for technology implementers. Outside of ASHRAE, the MTG monitors related activities and represents ASHRAE interests where permitted to provide a conduit for related information transfer to ASHRAE members.

The MTG is concerned with the interactions between non-residential air-handling system components, the building, and related activities, which include at least the activities of:

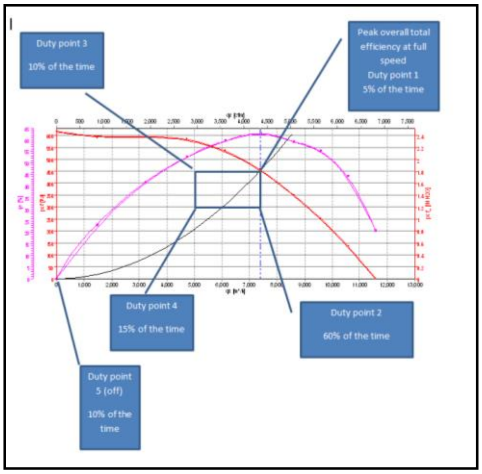
- TCs 1.4 (Control Theory and Application), 1.8 (Mechanical System Insulation), 1.11 (Electric Motors and Motor Control), 2.6 (Sound and Vibration Control), 4.3 (Ventilation Requirements and Infiltration), 4.7 (Energy Calculations), 5.1 (Fans), 5.2 (Duct Design), 5.3 (Room Air Distribution), 5.5 (Air-to-Air Energy Recovery), 6.3 (Central Forced Air Heating and Cooling Systems), 7.1 (Integrated Building Design), 7.2 (HVAC&R Contractors and Design Build Firms), 7.7 (Testing and Balancing), 7.9 (Building Commissioning), 8.10 (Mechanical Dehumidification Equipment and Heat Pipes), and 9.1 (Large Building Air-Conditioning Systems);
- SPCs 111 (Measurement, Testing, Adjusting and Balancing of Building HVAC Systems), SPC 200 (Methods of Testing Chilled Beams); and
- SSPCs 62.1 (Ventilation for Acceptable Indoor Air Quality), 90.1 (Energy Standard for Buildings except Low-Rise Residential Buildings), and 189.1 (Standard for the Design of High-Performance Green Buildings except Low-Rise Residential Buildings).

MTG membership currently includes representatives from all of the committees listed above (except TC 1.8), plus representatives of several external organizations, which include: AMCA International, the California Energy Commission (CEC), the U.S. Department of Energy (DOE), i4Energy, the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA), and the Spiral Duct Manufacturers Association (SPIDA).

001-10 Determine Optimum Fan Selection for Variable Fan Duty Based Operating Profile

Originating Group (Person): TC 1.11 (Armin Hauer)
Originating Date: 18 July 2013

State-of-the Art (Background): Fans are selected based on a single or maybe a few operating points, but can operate over a wide range.



Advancement to State-of-the-Art: Take into account the entire projected fan operating range and weigh the individual power consumption values with the projected duration. Objectives include:

- Optimize fan selection for variable fan duty applications to minimize energy consumption
- Energy to include fan, motor, VSD, and associate fan drive components
- Define design specification for variable fan duty applications
- Determine fan selection algorithms for variable fan duty applications

Type of Project: [Work Statement (Study) and/or Guideline]

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 1.11 (Electric Motors and Motor Controls)
- TC 5.1 (Fans)
- AMCA

MTG.EAS Action:

- Assigned to Armin Hauer (need an associate or a mentor on the action team)

Remarks:

On applications that require a variable fan duty, the design specification should include a load profile. In other words, how many hours will the fan operate at which duty point?

The fan duty might change over the years when the projected building use changes from an initial condition due to expansions or change of occupancy.

A selection for duty at the highest occurring fan output yields likely not the most efficient product for the majority of the hours of operation.

002-10 VSD Optimization

Originating Group (Person): TC 1.11 (Armin Hauer)
Originating Date: 24 August 2013

State-of-the Art (Background): Variable speed drives (VSD) are used to set the air performance of fans. The VSD output frequency is monitored on occasional projects. VSDs are commonly operated through BMS.

Advancement to State-of-the-Art: Modern fan motors and variable speed drives employ sophisticated electronics for their primary function. Many parameter measurements from these drive system are available as inputs to the BMS. Objectives include:

- Determine if VSD can provide data to the BMS for energy optimization.
- Determine what parameters should be considered to optimize the VSD, motor, fan, and other drive components for energy efficiency.

Type of Project: [Work Statement (Study)]

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 1.11 (Electric Motors and Motor Controls)
- TC 1.4 (Control Theory and Application)

MTG.EAS Action:

- Assigned to Armin Hauer (need an associate or a mentor on the action team)

Remarks:

1. Get metering information from the VSD back to the system controller: supply voltage level, motor load, motor control reserve, motor temperature, and motor run time. Then let the system controller decide what is more efficient: Running higher airflows during free cooling or running lower set points during DX operation?
2. VSDs can be set for optimum sound or for optimum energy consumption. Which VSD types have the ability to learn the characteristic of the load and self-optimize the output voltage-frequency ratio?
3. Energy implication from running induction motors at super-synchronous speed?
4. In applications that run multiple motors in parallel, how should one decide to switch off individual motors instead of speed-controlling all motors in parallel? Application example: Fan Arrays.
5. Which applications run long enough at strict line frequency so that installation and use of a bypass makes sense?
6. Which VSDs should be equipped with a control relay to disconnect the VSD and eliminate standby power?
7. Many fan motors are not regulated by EISA (Energy Independence and Security Act). What is the energy savings potential from using best available motor technology?
8. Produce technical white paper about AHRI 1210 as a follow-up to Rupal Choski's ASHRAE seminar presentation in June 2012.

003-10 Balancing ASHRAE 62.1 and ASHRAE 90.1 Requirements for Energy, IAQ, Health, and Productivity

Originating Group (Person): ASHRAE TC 1.4 / SSPC 62.1 (Len Damiano)
Originating Date: 12 December 2012

State-of-the Art (Background):

Advancement to State-of-the-Art: Eliminate variations in requirements between ASHRAE Standards 62.1 and 90.1. Objectives include:

- Develop CO_2 based Demand-Controlled Ventilation (DCV)* requirements and field verify
- Reconcile the requirements of ASHRAE 62.1 with ASHRAE 90.1
- Investigate ASHRAE 62.1 field compliance and control strategies

***Demand-Controlled Ventilation (DCV)**: any means by which the breathing zone outdoor airflow (V_{bz}) can be varied to the occupied space or spaces based on the actual or estimated number of occupants and/or ventilation requirements of the occupied space.

Type of Project: Work Statement (Study) and propose changes to both Standards 90.1 and 62.1.

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 1.4 (Control Theory and Application)
- SSPCs 62.1, 90.1, 189.1

MTG.EAS Action:

- Assigned to Len Damiano
- Other Possibilities: Jeff Boldt

Remarks:

1. System operating performance verification needed due to requirement perspective, contradictions, or weaknesses in standards.
   a. Standard 90.1 emphasis is on energy without much regard to other objectives that require more than minimal energy (e.g. IEQ, health and productivity)
   b. Standard 62.1 is openly discussed and referred to in publications as a ”design only” standard in contradiction to the published Scope [2.2 (see below)] and requirements for operational compliance [8.1.2 (see below)].

      2.2 This standard defines requirements for ventilation and air cleaning system design, installation, commissioning, and operation and maintenance.

      8.1.2 Building Alterations or Change-of-Use. Ventilation system design, operation, and maintenance shall be reevaluated when changes in building use or occupancy category, significant building alterations, significant changes in occupant density, or other changes inconsistent with system design assumptions are made.

   c. Standard 62.1 emphasizes minimum rates with “not less than” language, but no consideration to limit excess ventilation or any type of control performance requirements that directly impact energy. There is no language in the TPS to motivate the consideration of operational performance requirements and no requirement to verify compliance during operation. Excess ventilation has been shown to be the norm in buildings surveyed by NIST under BASE study.

d. Standards 62.1, 90.1 and 189.1 requirements involving CO_2-based DCV are weakly supported by field research and dominated by theoretical modeling that is heavily dependent upon assumptions. To counteract this tendency is particularly difficult since 62.1 is positioned best to identify potential control deficiencies, but has no mandate to require verifiable operational performance, better methods or alternatives.

2. Measurement and verification for controls operation and control function verification were recurring comments (Gaylon Richardson, Barry Bridges), but never addressed.

004-00 Constant Volume Terminal Reheat

Originating Group (Person): ASHRAE TC 4.7 (Jeff Haberl)
Originating Date: 5 December 2012

State-of-the Art (Background):

Advancement to State-of-the-Art: Develop a standard method of test for air-side system simulation tools

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]:

Primary ASHRAE TCs/PCs/Organizations Involved:

- SSPC 140
- SPC 130
- TC 4.7 (Energy Calculations)
- TC 5.1 (Fans)
- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)

MTG.EAS Action:

- Assigned to Jeff Haberl

Remarks:
Standard 140 has developed a working group to develop a SMOT for air-side systems. I suggest that MTG.EAS coordinate their efforts with this ongoing effort with Standard 140. Ron Judkoff or Joel Neymark would be the contacts for this effort.

[Note to SSPC 140: Sections 5.5.3 and 5.5.4 are all new material; tracked changes indicate revisions since the May 2012 simulation trial version. Tracked changes are not applied for items that have been re-ordered for editorial clarity; tracked changes are only applied to highlight revised language. Related Sec 3 definitions (and edits to them) are included at the end.]

5.5.3 Constant Volume (CV) Terminal Reheat System Cases (AET300 series)

The ability to model a CV terminal reheat air system serving multiple zones shall be tested as described in this section. If the software being tested is capable of applying a variety of system models to address a CV reheat system, the system model that is most similar to the system specified below shall be applied.

Informative Note: The user may test other possible modeling approaches (available system models) in this context, as appropriate to the software being tested.

Informative Note: The progression of these test cases follows the AET200 series (SZ system) tests. The CV reheat system serves two zones.

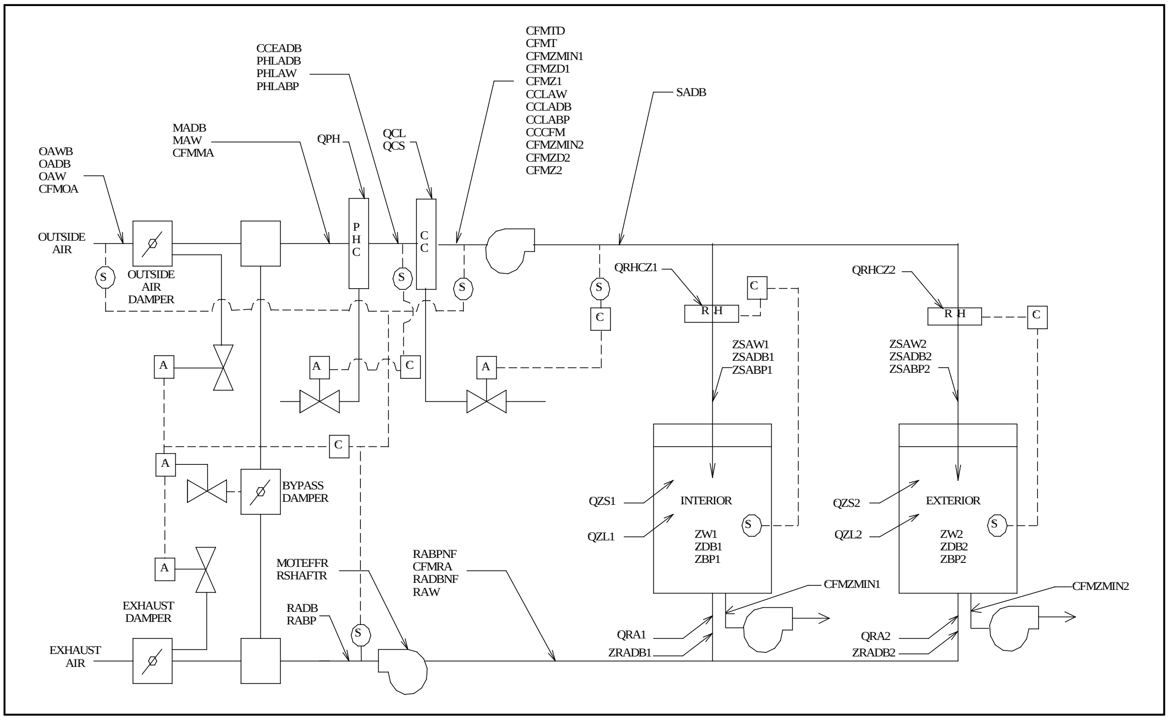
5.5.3.1 Case AET301: Base Case, High Heating 1

Case AET301 shall be modeled as described in this section and its subsections. The system configuration shall be modeled as presented in the schematic diagram in Figure 5.5-301.1. System input parameters shall be as described in the following sections.

***Informative Note, Objective*:** Test model treatment of a constant volume terminal-reheat system with high sensible heating load and cold outdoor air.

Informative Note, Method: A constant volume terminal reheat air system conditions two zones that have constant sensible and latent internal loads. The system consists of a constant volume air system with supply and return fans, pre-heat and cooling coils, and terminal reheat coils. The cooling coil provides cooling as needed to maintain the supply air temperature set point, and the reheat coils provide heating to maintain room temperature at its set point. The pre-heat coils will operate as needed to maintain a minimum supply air temperature. The model is run at specified constant outdoor and indoor conditions. Resulting coil loads are compared to verified external spreadsheet solutions and other example results.

Informative Note: In this base case, no economizer function is modeled; economizer function is tested in later cases.



005-10 Evaluate Heating & Cooling Delivery Systems

Originating Group (Person): ASHRAE TC 5.2 (Larry Smith)
Originating Date: 25 June 2013

State-of-the Art (Background):

Advancement to State-of-the-Art: Design tool for engineers. Objectives include:

- Evaluate alternate methods of delivering BTU's to a space and associated energy use.
- Space, energy, maintenance, as well as different building envelopes and geographic locations, are to be considered.
- Include emerging technologies as well as current practices.
- Compare systems using simulation tools, such as DOE's Energy Plus.

Type of Project: Work Statement (Study)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Diffusion)
- TC 6.1 (Hydronic and Steam Equipment and Systems)
- TC 6.5 (Radiant Heating and Cooling)
- TC 8.7 (Variable Refrigerant Flow)
- TC 8.11 (Unitary and Room Air Conditioners and Heat Pumps)
- TC 9.1 (Large Building Air-Conditioning Systems)

MTG.EAS Action:

- Assigned to Larry Smith (or he will find someone from appropriate TC to coordinate)

Remarks: Impact the reduction of the total energy consumption of HVAC systems by improving the overall efficiency in BTU delivery. Focus should:

1. evaluate delivery systems,
2. how comparison between systems,
3. include the impact of the building envelope and geographic location

Study not to be limited to current practices, technologies, and products

006-00 Fan System Effects (Similar to 017)

Originating Group (Person): ASHRAE TC 7.2 (Peyton Collie)
Originating Date: 18 June 2013

State-of-the Art (Background): System effect pressure losses are in addition to the calculated or measured HVAC system pressure losses. In some installed HVAC system designs, system effect totally offsets energy saving methods and equipment such as air leakage reduction or the use of high-efficiency fan motors. Design methods to mitigate system effects are well documented, but are not addressed in any building code. While the designer is responsible for analyzing the potential interactions of the fittings and fans for the potential consequences, system effect is often unanticipated by the designer and is only detected after the HVAC system is installed. Rather than incorporate complex calculations, a more effective approach is to establish minimum requirements that are easily enforceable by code officials to mitigate undesirable system effects.

Advancement to State-of-the-Art: Request that ASHRAE submit code proposals that establish minimum requirements for connecting the fan to the associated HVAC system to reduce the primary known, easily addressed cause of system effect. Objectives include:

- Determine the minimum requirements for connecting the fan to the associated system to ensure energy efficient fan performance

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]:

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 7.2 (HVAC&R Construction & Design Build Technologies)
- TC 5.1 (Fans)
- TC 5.2 (Duct Design)
- AMCA
- SMACNA

MTG.EAS Action:

- Assigned to Peyton Collie, Michael Ivanovich

Remarks:
Code Proposal Draft Text: A minimum length of straight duct equivalent to six diameters for round duct or six minor widths for rectangular duct must be provided from the outlet and inlet for any fan connected to an HVAC duct system in advance of any turns, bends, offsets, or duct-inserted accessories.

Peyton Collie: Fan efficiency is very important. But equally if not more important from and energy consumption standpoint is how the fan interacts with the system it serves. In HVAC duct systems "system effect" can totally negate all efficiency improvements designed into the fan. In roof mounted fan applications, the connection between the fan and the system it serves can create huge building air leaks -- some that will not be detected by building pressurization test.

Michael Ivanovich: Mr. Collie, you are absolutely correct that system design and installation defects can easily overrun efficiency gains from fans alone. AMCA has been educating the market on system effects for a long time, and we recently have been communicating more about issues such as system leakage and monitoring and control. But there really has been insufficient attention on fan sizing and selection and use of more efficient fan types, which codes, standards, and DOE regulations are only beginning to address.

007-00 Improve Energy Efficiency of AHU Systems

Originating Group (Person): ASHRAE TC 7.7 / SPC 111 (Gaylon Richardson)
Originating Date: 5 December 2012

State-of-the Art (Background):

Advancement to State-of-the-Art:

Objectives:
- Reduced outside air requirements
- Tighter ductwork
- Control verification
- Impact of using dampers

Primary ASHRAE TCs/PCs/Organizations Involved:
- TC 7.7 (Testing and Balancing)
- SPC 111

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]:

MTG.EAS Action:
- Insufficient information to act

Remarks: Suggestions to improve AHU systems: Reduced OA, tighter ductwork, sustainability of system, control verification, system design; discussed damper problems in installation and testing; building envelope; identification of components; ECM and direct drive fans (less than 2 HP)

008-00 Determine Diversity Factors for Hydronic Systems

Originating Group (Person): ASHRAE TC 7.7 / SPC 111 (Gaylon Richardson)
Originating Date: 5 December 2012

State-of-the Art (Background):

Advancement to State-of-the-Art:

Objectives:

- Identify potential energy savings

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]:

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 6.1 (Hydronic and Steam Equipment and Systems)
- TC 7.7 (Testing and Balancing)
- SPC 111

MTG.EAS Action:

- Insufficient information to act

Remarks: Hydronic systems designed with diversity need to identify the energy savings.

009-00 Method of Test (MOT) for Determining Air Handling Unit Capacity

Originating Group (Person): ASHRAE TC 7.7 / SPC 111 (Gaylon Richardson)
Originating Date: 5 December 2012

State-of-the Art (Background):

Advancement to State-of-the-Art:

Objectives:

- Identify impacts of measurement location on readings
- Identify impacts of instrument accuracy
- Identify required instrument accuracy

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]:

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 7.7 (Testing and Balancing)
- TC 1.2 (Instruments and Measurements)
- SPC 111

MTG.EAS Action:

- Insufficient information to act

Remarks: Capacity testing requires airflow, water flow, and temperature measurement with an accuracy of 5%; issues: instrument accuracy, measurement locations.

010-00 Optimizing the Static Efficiency of Air Handling Systems

Originating Group (Person): ASHRAE TC 7.7 / SPC 111 (Gaylon Richardson)
Originating Date: 5 December 2012

State-of-the Art (Background):

Advancement to State-of-the-Art:

Objectives:
- How to minimize system effects
- Evaluate the impact of negative pressure in system analysis

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]:

Primary ASHRAE TCs/PCs/Organizations Involved:
- TC 7.7 (Testing and Balancing)
- SPC 111

MTG.EAS Action:
- Insufficient information to act

Remarks: AHU efficiency is directly related to static efficiency of the system. Identify duct systems with minimum system effect; systems under negative pressure do not have the same losses across components as systems under a positive pressure.

011-00 Optimize Air Handlers

Originating Group (Person): TC 7.9 (J.R. Anderson)
Originating Date: August 2013

State-of-the Art (Background):

Advancement to State-of-the-Art:

Objectives:

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]:

Primary ASHRAE TCs/PCs/Organizations Involved:
- TC 7.9 (Building Commissioning)

MTG.EAS Action:
- Insufficient information to act

Remarks: Article from Energy Management, Buildings 12:12

012-10 Terminal Unit Published Noise Ratings

Originating Group (Person): SSPC 90.1 (Jeff Boldt)
Originating Date: 5 December 2012

State-of-the Art (Background):
The noise rating adjustments that are required by AHRI 885 cause room noise levels to be far above the published airborne noise levels for most VAV boxes (Exhibit 1: Item 2). This is because few systems today use lined ducts.

Advancement to State-of-the-Art:
Rating standards and published data will be more in line with HVAC system encountered by consulting engineers. Objectives include:

- Replace lined duct in Table D18 of AHRI Standard 885 by unlined duct, provide dual ratings, or include a reasonably simple method for designers to convert without extensive acoustical training.

Type of Project: Standard (Revision)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 2.6 (Sound and Vibration Control)
- TC 5.3 (Room Air Distribution)
- SSPC 90.1
- AHRI

MTG.EAS Action:

- Assigned to Jeff Boldt/Herman Behls. The MTG.EAS Chair to contact the chair of TC 5.3 (Ken Loudermilk, Trox ISA) and request an opportunity for Jeff Boldt to present his concern to the members of TC 5.3 at their NYC meeting. Hopefully, a TC 5.3/AHRI member will take-up the task to revise AHRI Standard 885.

Remarks: I believe that the rating adjustments that are required by AHRI 885 cause room noise levels to be far above the published airborne noise levels from all VAV boxes. This is because few systems today use lined ducts. I recommend asking to have the table (below) either modified, or that lined and unlined duct conversions be published.

Dan Int-Hout (12/26/13): As chair of AHRI 885, I would take issue with the basic assumption of section 012-10, Terminal Unit Published Noise Ratings. I'm sure we will have a chance to discuss, but I just wanted to put my two cents in early.

Exhibit 1

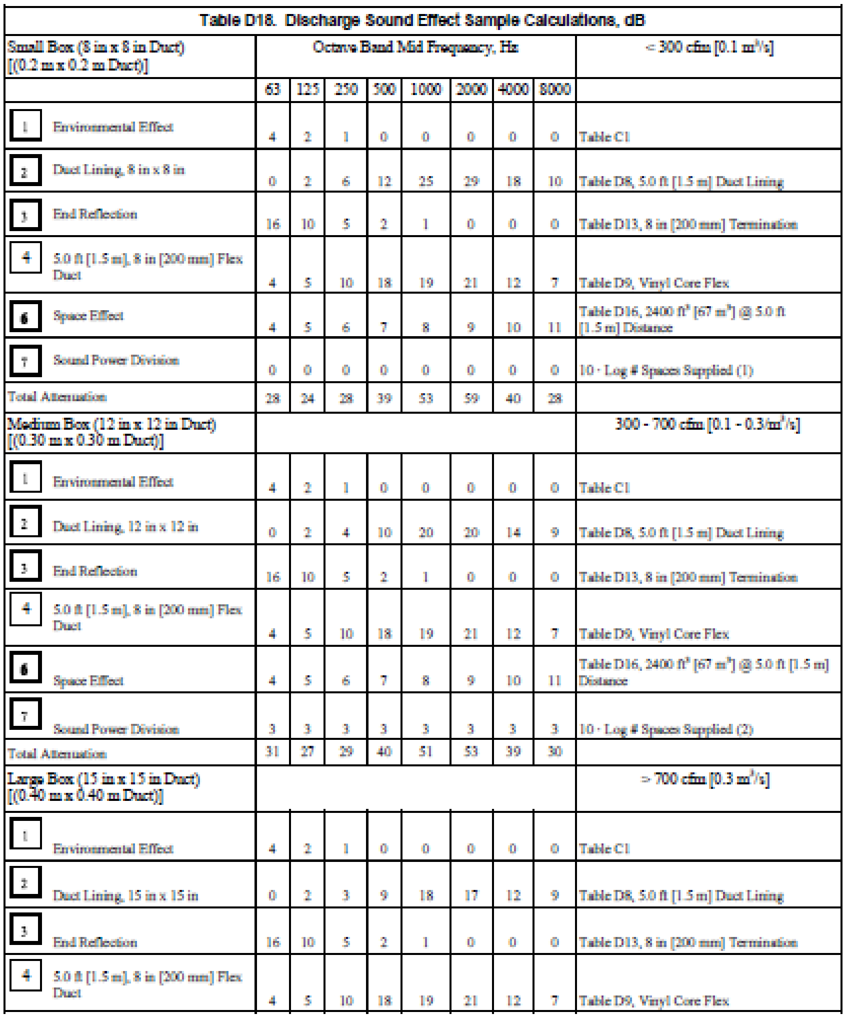


Table D18. Discharge Sound Effect Sample Calculations, dB

Small Box (8 in x 8 in Duct) [(0.2 m x 0.2 m Duct)]	Octave Band Mid Frequency, Hz								< 300 cfm [0.1 m^3/s]
	63	125	250	500	1000	2000	4000	8000	
1 Environmental Effect	4	2	1	0	0	0	0	0	Table C1
2 Duct Lining, 8 in x 8 in	0	2	6	12	25	29	18	10	Table D8, 5.0 ft [1.5 m] Duct Lining
3 End Reflection	16	10	5	2	1	0	0	0	Table D13, 8 in [200 mm] Termination
4 5.0 ft [1.5 m], 8 in [200 mm] Flex Duct	4	5	10	18	19	21	12	7	Table D9, Vinyl Core Flex
6 Space Effect	4	5	6	7	8	9	10	11	Table D16, 2400 ft^3 [67 m^3] @ 5.0 ft [1.5 m] Distance
7 Sound Power Division	0	0	0	0	0	0	0	0	10 · Log # Spaces Supplied (1)
Total Attenuation	28	24	28	39	53	59	40	28	
Medium Box (12 in x 12 in Duct) [(0.30 m x 0.30 m Duct)]									300 - 700 cfm [0.1 - 0.3/m^3/s]
1 Environmental Effect	4	2	1	0	0	0	0	0	Table C1
2 Duct Lining, 12 in x 12 in	0	2	4	10	20	20	14	9	Table D8, 5.0 ft [1.5 m] Duct Lining
3 End Reflection	16	10	5	2	1	0	0	0	Table D13, 8 in [200 mm] Termination
4 5.0 ft [1.5 m], 8 in [200 mm] Flex Duct	4	5	10	18	19	21	12	7	Table D9, Vinyl Core Flex
6 Space Effect	4	5	6	7	8	9	10	11	Table D16, 2400 ft^3 [67 m^3] @ 5.0 ft [1.5 m] Distance
7 Sound Power Division	3	3	3	3	3	3	3	3	10 · Log # Spaces Supplied (2)
Total Attenuation	31	27	29	40	51	53	39	30	
Large Box (15 in x 15 in Duct) [(0.40 m x 0.40 m Duct)]									> 700 cfm [0.3 m^3/s]
1 Environmental Effect	4	2	1	0	0	0	0	0	Table C1
2 Duct Lining, 15 in x 15 in	0	2	3	9	18	17	12	9	Table D8, 5.0 ft [1.5 m] Duct Lining
3 End Reflection	16	10	5	2	1	0	0	0	Table D13, 8 in [200 mm] Termination
4 5.0 ft [1.5 m], 8 in [200 mm] Flex Duct	4	5	10	18	19	21	12	7	Table D9, Vinyl Core Flex

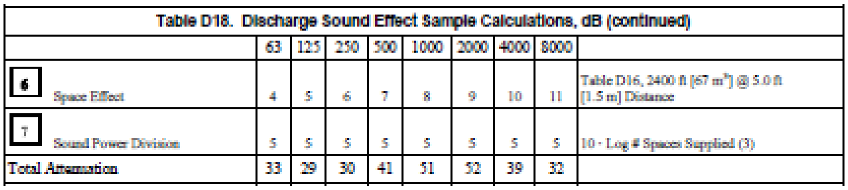


Table D18. Discharge Sound Effect Sample Calculations, dB (continued)

	63	125	250	500	1000	2000	4000	8000	
6 Space Effect	4	5	6	7	8	9	10	11	Table D16, 2400 ft [67 m^3] @ 5.0 ft [1.5 m] Distance
7 Sound Power Division	5	5	5	5	5	5	5	5	10 · Log # Spaces Supplied (3)
Total Attenuation	33	29	30	41	51	52	39	32	

The main problem is the noise of the air passing through the damper, and especially for the TABs that are near the fan and have higher inlet pressures. The Phoenix style air valves are somewhat quieter than the butterfly dampers, but also more expensive. It is even worse because AHRI 885 allows (actually requires) manufacturers to publish NC ratings based on the assumption that there is a lot of lined duct between the TAB and the diffuser (and flexible duct also). A TAB rated at NC25 will probably perform in unlined ductwork at NC40 or higher.

013-10 VAV Reset

Originating Group (Person): SSPC 90.1 (Jeff Boldt)
Originating Date: 29 April 2013

State-of-the Art (Background): Both temperature and pressure reset are required by Standard 90.1 for VAV systems (Section 6.5.3.4 and 6.5.3.2.2). Consulting Engineers are typically resetting temperature up to 5°F upward if no boxes are fully open, and once that threshold is reached doing pressure reset.

Advancement to State-of-the-Art: Determine the most efficient method to control both temperature and terminal unit pressure in VAV systems. This research may result in improved VAV system operation, including energy savings, without any significant economic impact. Objectives include:

- Simulate VAV system control sequences and resultant energy cost using EnergyPlus with selected ASHRAE 90.1 model building models and climate zones.

Type of Project: Work Statement (Study)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 1.4 (Control Theory and Application)
- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)
- TC 9.1 (Large Building Air-Conditioning Systems)
- SSPC 90.1

MTG.EAS Action:

- Assigned to Jeff Boldt
- Others: Herman Behls, Craig Wray

Remarks: none

014-10 Harmonizing Standards 62.1 and 90.1 with Standard 189

Originating Group (Person): SSPC 189.1 (Dennis Stanke)
Originating Date: 5 December 13

State-of-the Art (Background): No researcher or designer has attempted to determine a default value for Vpz-expected for VAV system ventilation-design purposes. However, at least one major energy performance simulation program can find Vpz for each of 8760 hours and determine which zone or zones will be critical and the Vpz value associated with each zone for each hour. At least one program could be used to help a researcher determine a table of default values for Vpz-expected.

Advancement to State-of-the-Art: A design tool for designers to implement Standard 62.1 and Standard 90.1 requirements to comply with Standard 189.1. At the present time, the requirements of Standard 189.1 cannot be met. Objectives include:

- Submit a Continuous Maintenance Proposal (CMP) to SSPC 62.1 to add a default value or table of values for minimum expected zone primary airflow at the ventilation design condition, taking the judgment and inconsistencies out of the VRP design procedure for VAV systems.
- A research project could analyze the 16 PNNL buildings in 16 or more climate zones, as analyzed for Std 90.1 determination, finding the critical zone Vpz-expected for each building in each zone. Analysis of the simulation results should lead to the publication of a Vpz-expected value, or a set of values as a function of building type, climate, or both (or perhaps some other parameter).

Type of Project: Research Project and Standards CMP

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 4.3
- SSPCs 62.1, 90.1, 189.1

MTG.EAS Action:

- Assigned to Dennis Stanke [Note: Dennis is not able to spend time on this project until February 2014].

Remarks: Designers need to be able to implement Std 62.1 and Std 90.1 requirements to comply with Std 189.1, one IECC compliance path, and LEED prerequisites. It must be possible to include the airside requirements found in all three standards, without conflict. It must be possible to design systems that can be modeled, constructed and operated to implement coordinated required airside controls, including fan pressure optimization, economizer control, building pressure control, energy recovery control, reheat restrictions on VAV box minimum settings, zone-level DCV and system-level ventilation optimization control and DCV. Research is currently underway to combine zone DCV with system ventilation optimization control (Lau). But in my view, very little software is available to model these controls and very little design and implementation information is available for designers.

Jeff Boldt mentioned doing away with the Std 62.1 VRP approach to multiple-zone systems; I don't think that's the right direction, because it's more accurate and saves energy compared with Title 24, and besides it's the basis for the model ventilation (and therefore model energy) codes, for energy labels, and for high performance building codes and rating systems. I think a better approach would be to coordinate a change to Std 62.1 which would allow designers to use a default value for design primary airflow; that would remove a lot of guesswork from VAV system OA intake flow at design. I also think that research needs to be done to identify energy performance analysis programs that can incorporate all Std 62.1, Std 90.1 and

Std 189.1 airside requirements, and then to conduct a comparative analysis of the programs (if they can be found) to determine which of them does a reasonable job of modeling airside requirements. And that’s probably just the start – systems must also be available to implement these airside requirements, and many disciplines need training.

The most important aspect of my suggestion is the CMP for SSPC 62.1 to add a default value or table of values for minimum expected zone primary airflow at the ventilation design condition. This value is used to calculate system outdoor air intake flow for the design of multiple-zone recirculating (VAV) systems. It is not an easy value for designers to determine, so they usually rely on judgment, repeated manual calculations, or in some cases, computer simulation programs that can check hourly zone primary airflow values to find those values that occur when required intake airflow is highest. To write this CMP, a research project is probably indicated to determine an appropriate default Vpz value(s), which probably differs for zones according to occupant density and climate zone.

015-10 Improve Design of Multi-Nozzle Chamber Flow Settling Means for Fan Performance Tests

Originating Group (Person): AMCA (Joe Brooks)
Originating Date: 30 October 2012

State-of-the Art (Background): AMCA 210 may not provide sufficient information to design and build a test chamber.

Advancement to State-of-the-Art: Improve accuracy of AMCA Standard 210/ASHRAE Standard 51 tests. Objectives include:

- Work Statement.
- Develop criteria for improving the design of flow settling means utilized in multi-nozzle chamber performance testing of fans defined in AMCA Standard 210/ASHRAE Standard 51.

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Fans)
- AMCA
- TC 1.2 (Instruments and Measurements)

MTG.EAS Action:

- Assigned to Joe Brooks
- Others: John Murphy and John Cermak

Remarks: See what happens in the next revision of AMCA 210. Then, decide what research might be needed.

016-10 Establish Accuracy of AMCA Standard 300 Tests

Originating Group (Person): AMCA (Joe Brooks)
Originating Date: 30 October 2012

State-of-the Art (Background):

Advancement to State-of-the-Art: Objectives include:

- Round robin test program to establish the accuracy of AMCA Standard 300 tests (Reverberant Room Method for Sound Testing of Fans).
- Establish a rationale for changing the tolerance.

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.1 (Fans)
- AMCA
- TC 2.6 (Sound and Vibration Control)

MTG.EAS Action:

- Assigned to Joe Brooks
- Others: John Murphy and John Cermak

Remarks:

- AMCA has a round robin underway. Expect testing to be done in 2013. John Murphy will review the results.
- Might remove from MTG.EAS list of ideas pending test conclusions from AMCA.

017-10 Fan Outlet Discharge Effects (Similar to 006)

Originating Group (Person): AMCA (Joe Brooks)
Originating Date: 30 October 2012

State-of-the Art (Background):

Advancement to State-of-the-Art: Increase population of the ASHRAE Duct Fitting Database. Objectives include:

- Work Statement
- Fan outlet system effects

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.1 (Fans)
- TC 5.2 (Duct Design)
- AMCA

MTG.EAS Action:

- Assigned to Joe Brooks
- Other: Rad Ganesh

Remarks:
Fan outlet discharge effects would be a logical step for research projects

- System effect is the outlet connection, not the fan itself.
- Depends on fan outlet velocity profile.
- Research focus could be on the outlet velocity profile of different design fans. Once that is known, it should be possible to calculate or model (CFD) discharge effects.
- Goal would be to help system designers and improve fan applications.

018-10 Study of Air Curtains

Originating Group (Person): AMCA (Joe Brooks)
Originating Date: 30 October 2012

State-of-the Art (Background): Air curtains are local ventilation devices that supply a high-velocity stream of air to reduce airflow through apertures in building shells. They are also used to localize gaseous and particulate emissions near their sources and to convey them toward local exhausts. AMCA has a MOT standard (ANSI/AMCA 220) for rating the performance of Air Curtain Units (it measures airflow, outlet air velocity uniformity, power consumption, and air velocity projection). However, AMCA 220 does not measure air curtain effectiveness. Effectiveness describes the ability of the air curtain to reduce or eliminate undesired transfer of air, energy, moisture, and contaminants from one space (or outside) to another space (or indoors).

Advancement to State-of-the-Art: A new MOT standard that would provide a cost-effective, standardized procedure to measure air curtain effectiveness, or a revision of AMCA 220 to correlate current test result metrics to an effectiveness metric. Data obtained using the new or revised standard procedures would improve the ability of engineers to specify and select effective air curtains.

Type of Project: A MOT standard supported by ASHRAE research.

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.1 (Fans)
- TC 5.3 (Room Air Distribution)
- AMCA

MTG.EAS Action:

- Assigned to Joe Brooks

Remarks:

- An effectiveness test could be added to AMCA 220, but it might be too costly to run the test for both rating and effectiveness comparison purposes.
- Joe Brooks will consult with the cognizant TC (TC 5.3 “Room Air Distribution” is updating the ASHRAE Handbook to address air curtains. TC 5.8 “Ventilation of the Industrial Environment” had related information in the Applications Handbook until 1999.).

Bibliography:

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019-10 Develop Method of Test (MOT) for Large Circulating Fans

Originating Group (Person): AMCA (Joe Brooks)
Originating Date: 30 October 2012

State-of-the Art (Background): No rating standard exists for large circulating fans greater than 6 ft in diameter.

Advancement to State-of-the-Art: Provide a rating system for large circulating fans. Objectives include:

- Prepare a MOT standard for large circulating fans.

Type of Project: Standard (MOT)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.1 (Fans)
- AMCA

MTG.EAS Action:

- Assigned to Joe Brooks
- Others: Mike Brendel

Remarks:
Develop method for testing/rating/comparing large circulating fans (e.g., Big Ass Fans)

- What is important to measure? Airflow or velocity? What is the purpose of the fan?
- AMCA 230 may be addressing the thrust & conversion to airflow. This metric was not well accepted.

020-10 Investigate Fan Stall

Originating Group (Person): AMCA (Joe Brooks)
Originating Date: 30 October 2012

State-of-the Art (Background):

Advancement to State-of-the-Art:
- Provide users better information about the effect of fan operation in stall, and how to make selections to avoid stall.
- Provide HVAC industry with a design tool.

Type of Project: Handbook update.

Primary ASHRAE TCs/PCs/Organizations Involved:
- TC 5.1 (Fans)
- TC 5.2 (Duct Design)
- AMCA

MTG.EAS Action:
- Assigned to Joe Brooks
- Others: Chuck Coward

Remarks: None

021-10 Fan Efficiency at Low Flow and Low Speed Operation

Originating Group (Person): AMCA (Joe Brooks)
Originating Date: 30 October 2012

State-of-the Art (Background):

Advancement to State-of-the-Art: Objectives include:
- Improve fan laws over entire speed range

Type of Project: Study and/or Guideline

Primary ASHRAE TCs/PCs/Organizations Involved:
- TC 5.1 (Fans)
- AMCA

MTG.EAS Action:
- Assigned to Joe Brooks
- Others: Chuck Coward, Bill Cory

Remarks:
- System oversizing causes fans to often run at low efficiency.
- Problem: Fan tests at low speed don’t agree with predictions based on higher speed data & fan laws.
- Question: Is the problem blade aerodynamics at low Re number?

022-10 Standardizing Leakage Tests of Operating Air-Handling Systems

Originating Group (Person): TC 5.2 (Erik Emblem)
Originating Date: 23 May 2013

State-of-the Art (Background): Leakage tests on ten HVAC operating systems showed that the system leakage ranged from 10 to 20% of design fan airflow (2012 ASHRAE Handbook, page 19.2).
The Duct Design chapter in the 2013 ASHRAE Handbook recommends that supply air (both upstream and downstream of the VAV box primary air inlet damper when used), return air, and exhaust air systems be tested for air leakage after construction at *operating* conditions to verify (1) good workmanship, and (2) the use of low-leakage components as required to achieve the design allowable system air leakage. To enable proper accounting of leakage related impacts on fan energy and space conditioning loads, the allowable system air leakage for each fan system should be established by the design engineer as a percentage of fan airflow at the maximum system operating conditions.

Advancement to State-of-the-Art: Reduce energy wasted by leaky HVAC air systems. Objectives include:

- Prepare a field Method of Test (MOT) leakage standard for operating HVAC systems.

Type of Project: Standard (MOT)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)
- TC 7.2 (HVAC&R Construction & Design Build)
- TC 7.7 (Testing and Balancing)
- CEC (California Energy Commission)
- SMACNA
- SSPC 90.1

MTG.EAS Recommended Action:

- Assigned to Craig Wray; Others: Julie Ferguson, Erik Emblem, Herman Behls

Remarks:
Emblem: I suggest the MTG.EAS consider developing "key knowledge areas" necessary for installers and verifiers of HVAC systems. It is very apparent that, as system design and emerging equipment/controls are implemented, trainers and certifiers are going to need to have access to this information.

I serve on the Mechanical Technical Committee at IAPMO and two years ago when this MTG was being discussed IAPMO Technical Committee members were informed that ASHRAE was developing a "whole system" testing protocol that would take into account all HVAC duct system components including the duct. Codes are moving towards requiring system testing prior to certificate of occupancy. Currently the Green Uniform Mechanical Code Supplement requires all ducts to be tested. The 2015 UMC update has begun and the Green UMC Supplement undergoes continuous maintenance. IAPMO's Technical Committees are patiently waiting for ASHRAE to develop a "whole system" testing protocol that can be referenced in the Mechanical Codes.

023-00 Overall Fan System Efficiency with VFD

Originating Group (Person): ListServ (Brian Reynolds)
Originating Date: 23 May 2013

State-of-the Art (Background): There are currently no tools available for determining the overall fan/motor/VFD system efficiency.

Advancement to State-of-the-Art: Improve the energy efficiency of fan applications.

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]:

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.1 (Fans)
- TC 1.11 (Electric Motors and Motor Controls)

MTG.EAS Action:

- Assigned to Brian Reynolds

Remarks: none

024-10 Fan Belt Drive Efficiency

Originating Group (Person): ListServ (Brian Reynolds)
Originating Date: 23 May 2013

State-of-the Art (Background): Accurate information on fan belt drive efficiency is lacking.

Advancement to State-of-the-Art: Improve the energy efficiency of fan applications. Objectives include:

- Conduct research, including review of available information, to develop an ASHRAE special publication and possibly a MOT standard.

Type of Project: Work Statement (Study, Lab Tests) and MOT Standard

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.1 (Fans)
- AMCA
- RMA (Rubber Manufacturers Association)

MTG.EAS Action:

- Assigned to Brian Reynolds (Brian would like to consult with the TC 5.1 Research Subcommittee in New York during Jan 2014 before deciding whether he or someone else from the committee would be willing to organize and coordinate a work statement effort on the proposed topic.)

Remarks: None

025-10 Motor and Variable Speed Drive (VSD) Efficiency

Originating Group (Person): ListServ (Brian Reynolds)
Originating Date: 23 May 2013

State-of-the Art (Background): Fans in air-handling systems typically include a VSD.

Advancement to State-of-the-Art: Industry tests standards for air-handling products currently do not include the motor and VSD efficiency. Objectives include:

- Develop a method of test for determining the combined efficiency of motor and VSD systems for use in AMCA, ASHRAE, and AHRI standards.

Type of Project: Standard (MOT)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.1 (Fans)
- TC 1.11 (Electric Motors and Motor Control)
- AHRI
- AMCA

MTG.EAS Action:

- Assigned to Brian Reynolds (Brian would like to consult with the research sub-committee in New York during Jan 2014 before deciding whether he or someone else from the committee would be willing to organize and coordinate a work statement effort on the proposed topic.)

Remarks: none

026-10 Energy Impacts from Air Handler Casing Leakage

Originating Group (Person): Self (Julie Ferguson)
Originating Date: 30 October 2012

State-of-the Art (Background): Commercial packaged air-handling units are leaky and as a result waste energy. Custom-built AHU are of airtight construction.

Advancement to State-of-the-Art: Limiting the leakage of packaged AHU to reasonable values (say 1% of fan flow) will result in significant energy savings because AHU leakage typically exceeds 10% of fan flow. Objectives include:

- Prepare an ASHRAE MOT (Method of Test) standard to determine leakage of air handling units at the factory and in the field after installation.

Type of Project: Work Statement (Study)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)

MTG.EAS Action:

- PMS Chair: Julie Ferguson
- PMS Members: Herman Behls, Gaylon Richardson, and others.

Remarks:
I was doing a Google search on commercial air handler air leakage and ran across a study Iain Walker in 2010. http://buildings.lbl.gov/sites/all/files/Walker%20LBNL-5553E_1.pdf

Are there any studies done for commercial air handling units? The reason I'm looking for this information is because I am representing a product manufacturer who builds to a tolerance of 1% air leakage at 15" and their calculations for some projects show significant energy savings. As an example: If you have a cabinet that has less than 1% air leakage at 15" at 30,000 cfm, the estimated annual energy savings over a standard air-handler or even a typical custom air handler can be between $11,000 and $22,000 a year and can have paybacks of 2 to 5 years. This is almost as much savings as adding good energy recovery, with 1 to 2 year paybacks common. Combine the two and we're really making a dent in energy consumption, peak demand use, and energy waste. So yes, cabinet air leakage has got my attention. I'm looking for outside data to support their calculations and claims so I can approach customers such as power companies and possibly hand this over to people in the code arena.

027-10 Determine Air Leakage of Duct Transverse Joints and Associated Energy Costs

Originating Group (Person): SPIDA (Bob Reid)
Originating Date: 14 June 2012

State-of-the Art (Background): Approximately 85 to 95% of duct leakage occurs at transverse connection joints --- both duct-to-duct and duct-to-equipment. Contractors use a variety of both proprietary products and generic methods when assembling and sealing duct joints. AMCA 511-10 (Rev. 8/12), Section 22 (Transverse Duct Connectors / Air Leakage Rating Requirements) offers a method for certifying leakage performance of proprietary transverse duct connectors. In Northern Europe, the Swedish Institute for Technical Approval in Construction (SITAC) offers leakage class certification for duct systems using tested and rated proprietary transverse duct connector systems.

Advancement to State-of-the-Art: Expand the data for transverse joint leakage beyond proprietary products to include all common generic methods. By associating duct leakage with energy costs, we can identify cost effective methods for reducing transverse joint duct leakage and identify products and methods that are most effective. Data will allow owners/designers/contractors to select duct construction types on a true cost-benefit basis. Objectives include:

- Identify common methods for assembling duct/equipment and typical methods used to seal joints.
- Quantify typical leakage for each type of transverse connection. Test duct assemblies in accordance with ASHRAE Standard 126. Associate measured leakage and energy cost with common pressure classes and seam length/size of transverse connection.

Type of Project: Work Statement (Study, Lab Tests)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)
- SPIDA
- AMCA
- SMACNA

MTG.EAS Action:

- Assigned to Bob Reid
- Other: Bill Stout

Remarks: Some studies identify duct leakage as the single greatest energy waste in commercial construction. Current specifications, codes, and standards --- like ASHRAE Standard 90.1 or the 2008 California Green Building Standards Code --- mandate duct leakage testing or an overall allowable system leakage as a way to reduce it. None of them identify specific methods or practices that may be effective. Current duct leakage classifications and test standards associate leakage volume with total duct surface area. That incorrectly implies that the path to reducing leakage is to reduce total duct surface area. In reality, we would expect true duct leakage reduction to come from changes in the amount and types of duct joints.

Duct system leakage performance usually comes down to a choice of assembly methods and "workmanship". Total duct system leakage is then a combination of assembly performance and the duct system layout/size/amount of transverse connections. Mandating a specific type of transverse connection, generic or proprietary, may result in leakage reduction but you wouldn’t know if it was truly cost effective. The results of this project would produce three tools for achieving measurable cost effective leakage reduction. First, the designer would be able to see predicted changes to duct system leakage from various projected system layouts. Second, the owner, designer and contractor could balance transverse connection cost versus anticipated leakage reduction to determine the most cost effective method for reaching leakage reduction targets. Third, the data will establish a baseline for each transverse connection type against which “workmanship” can be measured. When taken together, these three tools could produce alternatives to traditional duct leakage tests that could produce the desired goals without the penalties of cost and time. Also, any truly inappropriate transverse connections could be identified from their measured performance and their use eliminated from accepted practice.

028-10 Cost Effectiveness of HVAC System Air Leakage Tests During Operation

Originating Group (Person): SSPC 90.1 (Jeff Boldt)
Originating Date: June 2013

State-of-the Art (Background): Leakage tests on ten HVAC operating systems showed that the system leakage ranged from 10 to 20% of design fan airflow (2012 ASHRAE Handbook, page 19.2).
The Duct Design chapter in the 2013 ASHRAE Handbook recommends that supply air (both upstream and downstream of the VAV box primary air inlet damper when used), return air, and exhaust air systems be tested for air leakage after construction at operating conditions to verify (1) good workmanship, and (2) the use of low-leakage components as required to achieve the design allowable system air leakage. The recommended initial maximum system leakage is 5% of design airflow (2013 Handbook, page 21.16).

Advancement to State-of-the-Art: Reduce energy wasted by leaky HVAC air systems. Objectives include:

- Conduct study to determine the costs and benefits associated with conducting system leakage tests *during operation*. Study to be supported by ASHRAE research.

Type of Project: Work Statement (Study)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)
- TC 7.2 (HVAC&R Construction & Design Build)
- TC 7.7 (Testing and Balancing)
- CEC
- SMACNA
- SSPC 90.1

MTG.EAS Action:

- Assigned to TC 5.2

Recommended (Suggested) Action:

- PMS Chair: Jeff Boldt
- Proposed PMS: Herman Behls, Craig Wray

Remarks: none

029-10 Air Leakage of Duct-Mounted Equipment

Originating Group (Person): MTG.EAS Chair (Herman Behls)
Originating Date: June 2013

State-of-the Art (Background):

Advancement to State-of-the-Art: Leakage of duct-mounted equipment (terminal unit with electric or hot water coils, access doors, dampers) is needed to support leakage rates proposed for Standard 90.1, codes, and master specifications. Objectives include:

- Determine in the laboratory the air leakage of single duct VAV terminal units without an access door, hot water coil, or electric coil.
- Determine in the laboratory the leakage of the following equipment associated with terminal units: hot water coils and electric coils.
- Determine in the laboratory the air leakage of fan powered parallel flow terminal units without appurtenances.

Type of Project: Work Statement (Lab Tests)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)
- SSPC 90.1
- AMCA
- AHRI

MTG.EAS Action:

- Assigned to TC 5.2

Recommended (Suggested) Action:

- PMS Chair: Herman Behls
- Proposed PMS: Steve Idem, Craig Wray

Remarks: none

030-20 Air-Handling System Airflow and Pressure Diagnostics

Originating Group (Person): MTG.EAS Vice-Chair (Craig Wray)
Originating Date: December 2011

State-of-the Art (Background): Recent diagnostic tool developments have begun to address the reliability, usability, and cost problems associated with testing air-handling systems (Palmiter and Francisco 2000, Xu et al. 2000, ASTM 2003, NBI 2003, Walker and Wray 2003, Walker et al. 2004, EMI 2004, Wang 2005). However, their direct applicability and reliability for testing systems in small and large commercial buildings needs to be assessed.

Advancement to State-of-the-Art: Reliable, cost-effective, standardized system airflow and pressure diagnostics will enhance commissioning, test and balance, and M&V activities. Efforts should include:

- Evaluate the applicability and reliability of air-handling system leakage diagnostics for use in new and existing buildings for common system configurations and for those that are gaining in popularity (e.g., under floor supply air distribution in larger buildings).
- Evaluate and develop where needed reliable, cost-effective ways to measure other air-handling system airflows and pressures (e.g., through and across fans, respectively).
- Assess the applicability and acceptance of tools and tests as training and quality control aids.
- Initiate standardization and commercialization of these tools and tests.

Type of Project: Research (Field Tests, Analysis), Standards (MOT), Deployment

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)
- TC 5.1 (Fans)
- TC 1.2 (Instruments and Measurements)
- TC 7.7 (Testing and Balancing)
- TC 7.9 (Building Commissioning)
- SPC 111
- AMCA
- CEC (California Energy Commission)
- DOE
- SMACNA

MTG.EAS Action:

- Assigned to Craig Wray

Remarks: This effort will evaluate the applicability and reliability of current and new airflow and pressure diagnostics for commercial HVAC systems, with a focus on field testing. The tests should be carried out in multiple buildings to account for different system characteristics and different air leakage and thermal characteristics of unconditioned spaces where ducts are typically located.

Data collected should include air-handler airflow and pressure rise, supply and return pressure and leakage distributions, building envelope leakage, and ceiling space leakage. Sufficient data should be collected to characterize the thermal conditions surrounding ducts (e.g., insulation levels). If, during the tests, it becomes obvious that modifications can be made to the tests to enhance their usability and accuracy, modifications should also be tested while in the test buildings.

Air-handler airflows should be measured using industry standard practices such as cross-sectional traverses of coils, and, when appropriate in smaller buildings using the Energy Conservatory TrueFlow^{TM} orifice-plate device (Palmiter and Francisco 2000), using the "temperature split" method described by Conant et al. (2004), and using duct pressure matching described in California's Title 24 energy code and in ASHRAE Standard 152. Duct airflows should be measured using an accurate flow capture hood (i.e., measure the flow through the supply and return grilles using a powered flow hood). The CO_2 pulse-injection tracer gas method developed by LBNL can be used as a reference for these tests (Wang 2005).

In each building, tests should include determining leakage airflows using industry standard duct pressurization tests (AABC 2002, SMACNA 2012), blower-door-based zone pressurization methods that have been developed for residential applications (when appropriate), and the inlet versus outlet flow subtraction method that LBNL has developed for large commercial HVAC whole-system applications. Also where appropriate, duct and damper leakage tests should include ones, such as those described in a recent paper submitted to ASHRAE HVAC&R by Modera, Wray, and Dickerhoff. "Low Pressure Air-Handling System Leakage in Large Commercial Buildings: Diagnosis, Prevalence, and Energy Impacts".

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031-20 Air-Handling System Performance Analysis Tools

Originating Group (Person): MTG.EAS Vice-Chair (Craig Wray)
Originating Date: December 2011

State-of-the Art (Background): Separate, proven air-handling system technologies already exist that each can save 10 to 50% of HVAC system energy in new and existing commercial buildings while maintaining or improving indoor environmental quality (IEQ). The savings in each case depend on the issues addressed (e.g., remote sealing of system air leakage, optimizing duct layout and sizing, wireless conversion of constant-air-volume systems to variable-air-volume, adding duct static pressure reset and demand-controlled ventilation). When implemented together, these technologies interact so that the resulting savings are likely larger than those achieved by any single technology, but less than the sum of the individual savings.

Stakeholders such as DOE's Commercial Building Energy Alliance partners and energy service companies (ESCOs) need analysis tools to determine how these and other building technologies should be integrated to assure optimum energy performance and IEQ, and how to best commission these systems. Stakeholders also need these tools to develop and show compliance with new codes and standards (e.g., DOE's planned fan efficiency regulations, ASHRAE Standard 90.1) and to support building rating and labeling programs and various levels of incentive programs.

EnergyPlus and other simulation tools like it already contain rudimentary models to predict energy consumed by air-handling systems. However, embedded simplifying assumptions can lead to inaccuracies, especially when the programs are used to simulate the impacts of integrated component retrofits or new innovations. Furthermore, there is currently no intrinsic capability in such tools to optimize system type, layout, and component sizing to reduce system pressure losses and related fan energy and to predict related impacts on indoor air quality. The fragmented and simplistic nature of current analytical processes impedes exploiting the full potential of energy and IEQ performance improvements obtainable through integrated and regulated approaches.

ASHRAE Standard 152 provides a simplified analysis technique to perform energy loss calculations for residential thermal distribution systems. More recent work by LBNL and others has shown that small commercial buildings have thermal distribution systems that are similar to residential systems and share similar energy loss problems. However, the systems differ from those in houses in a few key areas, for example, they are often located in suspended ceilings that are neither inside or outside the conditioned space and ducts in such locations require modifications to the Standard 152 calculation procedure. More complex analysis tools (supported by field data) are needed to determine the necessary Standard 152 adaptations.

Advancement to State-of-the-Art: Identifying and then eventually providing new analytical capabilities so that existing and new technologies can be optimally combined represents a significant opportunity to enable improved energy performance in the existing and future building stock. Efforts should include:

- Establish the purpose and scope of modeling commercial building air-handling systems and the intended outcomes. Here, the air-handling system includes all mechanical components (e.g., fans, motors, drives, filters, coils, ducts, terminal boxes, dampers, grilles/diffusers) involved in moving and conditioning space heating, cooling, and ventilation air into, out of, and throughout the building. The preliminary purpose is to support technology integration as well as codes and standards development and compliance. Sample use cases to consider include:

    - Support development of DOE fan efficiency regulations, as well as other codes and standards such as ASHRAE Standard 90.1 and California Title 24.
    - Support CBEA partner and ESCO air-handling design/retrofit analyses (e.g., low-flow and low-pressure drop system design; intersystem comparisons to select optimal system type; component right-sizing and staging optimization; characterize savings from combined system sealing, duct static pressure reduction, demand controlled ventilation, wireless conversion of CAV systems to VAV).
    - Support component manufacturer data transfer and energy savings claims (e.g., provide database of fan, belt, motor, and VFD performance characteristics, based on a simulation standard methodology for calculating savings).
    - Determine optimal system configurations that maximize energy savings while still maintaining acceptable indoor air quality and thermal comfort (e.g., developing control strategies for hybrid low-energy mechanical and natural ventilation systems).
- Summarize what is known now and what gaps still exist in terms of modeling air-handling systems. Where possible, leverage review efforts already underway regarding ASHRAE Standards 90.1, 55, 62.1, and California Title 24, which seek to identify modeling needs and gaps in general. Include a review of multizone airflow and pollutant transport simulation tool (e.g., NIST's CONTAM) capabilities in terms of modeling air-handling system pressure and airflow networks, and a discussion of how current energy and IEQ programs could be combined to provide a state-of-the-art performance analysis capability.
- Identify appropriate performance metrics for rating air-handling system "efficiency" (e.g., wire to zone energy efficiency, efficacy in maintaining thermal comfort and IAQ). Address necessary input data, user interface issues, program validation, and standardization needs.
- Extend ASHRAE Standard 152 calculation methods to include commercial buildings and address air-handling system efficacy (i.e., thermal comfort) issues.
- Establish integrated energy and indoor environmental quality (IEQ) baselines for standards and technical targets that are technologically feasible and economically justified,
- Develop standardized procedures for verifying whether energy-efficiency and IEQ program targets are met.

Type of Project: Research (Analysis, Lab and Field Tests), Standard (MOT)

Primary ASHRAE TCs/PCs/Organizations Involved:
- TC 4.7 (Energy Calculations)
- TC 5.1 (Fans)
- TC 5.2 (Duct Design)
- TC 6.3 (Central Forced Air Heating and Cooling Systems)
- TC 9.1 (Large Building Air-Conditioning Systems)
- SSPCs 62.1, 90.1, 189.1
- CEC (California Energy Commission)
- DOE

MTG.EAS Action:
- Assigned to Craig Wray

Remarks: Some key issues can lead to prediction inaccuracies in existing analysis tools and need to be resolved, such as:
- Fan power use (e.g., brake horsepower) is in part a product of fan airflow and pressure rise. System curves represent the part-load fan pressure rise (system pressure drop) versus airflow

relationship. VAV systems (often used in new construction) rarely operate at full-load (design airflow) and instead may often operate at part-load ratios of about 30 to 70%. Commonly used overly-simplistic system curves that ignore effects of fan shut-off pressure and linear-like effects of filters and coils can lead to substantial pressure rise (and thus power) errors at part-load. For example, the actual pressure rise at 50% of full flow can be two times greater than commonly used estimates. The ability of commercially-available tools such as Elite Software's "Ductsize" program to provide system curve inputs for tools such as EnergyPlus needs to be examined, along with the potential to restart ASHRAE's abandoned efforts to develop a T-Method-based duct system life-cycle-cost optimization tool. Connecting tools such as EnergyPlus to existing duct design software would help to bring them into mainstream practitioner use.

- Air-handling system power is also a function of system efficiency, which is the product of component (i.e., fan, belt, motor, VFD if used) efficiencies. Component efficiencies are not constant and peaks are not necessarily coincident. Assuming constant, coincident peak efficiencies can lead to system efficiency overestimates on the order of a factor of 1.5 (e.g., 41% versus correct 30% at 50% flow), which also means similar errors in power estimates. Some of this error might be offset by embedded, unknown assumptions about efficiency variations in current polynomial fan power curves, but the offset has not been defined. Oversizing equipment (a common design approach to provide future flexibility and to account for analytical uncertainties) makes these errors worse, especially if the fan ends up operating in stall, where efficiency falls off much more rapidly than in the non-stall region.
- Most design analyses today assume that systems do not leak. However, field tests in hundreds of small non-residential buildings and a few large non-residential buildings suggest that system air leakage is widespread and large. It is often 25 to 35% of system airflow in small buildings, and can be as large as 10 to 25% in larger buildings. Based on field measurements and simulations by LBNL, system leakage alone is estimated to increase HVAC energy consumption by 20 to 30% in small buildings and 10 to 40% in large buildings. EnergyPlus already contains simple models for supply leakage from simple VAV systems (without fan powered boxes), but still cannot address leakage from systems with fan powered boxes or from constant-air-volume (CAV) systems (the predominant system type in existing buildings).
- The lack of distribution system multi-mode heat gain/loss thermal models in tools such as EnergyPlus means that all space conditioning energy from coils is assumed to reach zones (less the impacts of leakage when modeled). Gains/losses for systems passing through unconditioned attics (50% of buildings may have the primary thermal barrier at the ceiling rather than at the roof) or outdoors are not constant and can be substantial (including due to thermosiphoning of hot air through ducts into zones during off-cycles).

More work is needed to develop models that can be used to address airflows entering VAV boxes from ceiling return plenums (e.g., to model parallel fan-powered VAV boxes where the plenum air can mix with the supply air), to address leakage from CAV systems, and to deal with duct surface heat transfer effects. The new model for fan-powered VAV boxes will require an expansion of existing models for VAV boxes and for the ceiling return air plenum. Changes to the latter model are needed, because the induction effect of the fan-powered VAV boxes will affect the amount of zone return air that passes directly from the zones through the open ceiling plenum and then to the return air ducts (if used) and fan. Currently, energy balance calculations account for the effects of supply-duct air leakage, plenum "floor" (zone ceiling) and "ceiling" (zone floor) conduction, plenum exterior wall conduction, heat gain from ceiling-mounted lights, and zone return airflow. Also, a fan model for the VAV boxes is needed to account for the fan power used by the VAV box fans.

Heat transfer across duct surfaces is another mechanism for energy transfer to or from the air inside a duct, and in some cases can be as important as duct leakage in terms of affecting fan power. The surface heat transfer involves conduction through the duct wall and insulation, convection at the inner and outer surfaces, and depending on the environment surrounding the duct (e.g. the underside of a hot roof or direct solar gains outdoors), radiation between the duct and its surroundings. A model is needed for heat transfer across the duct wall (e.g., one that uses heat exchanger effectiveness methods). The model could assume that the heat exchanger effectiveness is an exponential relation that depends only on the overall heat transfer coefficient and heat capacity rate for air inside the duct (product of the air mass flow rate inside the duct and the air's specific heat). It could also assume that the heat capacity rate of the air surrounding the duct exterior is infinite (i.e., the temperature of the air surrounding the duct remains approximately constant along the length of the duct). In calculating the duct surface heat transfer, an iterative solution will need to be used to account for the interdependencies between the average temperature of the duct exterior surface, the heat transfer rate across the duct wall, and the overall heat transfer coefficient.

The overall heat transfer coefficient for the duct can be determined from the sum of the reciprocals of the resistances associated with the conduction and the convection layers. An empirical expression will be needed for the convection resistance of the internal flow, perhaps assuming that turbulent forced convection occurs inside the duct. The conduction resistance of the duct wall could be calculated as the sum of the duct wall resistance and the insulation resistance. The duct wall resistance itself depends on the duct construction material and the wall thickness. The insulation resistance could simply be specified.

Outside the duct, combined natural and forced convection can occur. Determining a generally applicable combined convection coefficient is difficult because of the wide variation in duct characteristics and environmental conditions that can be found in the commercial building stock. One possible approach is to use empirical correlations like the ones used for residential attics, which are somewhat like ceiling return air plenums. The forced convection coefficient could be expressed by an empirical correlation that has been linearized over the expected range of temperatures. The natural convection coefficient could be expressed by another empirical correlation, which uses the same length scale as the forced convection coefficient. A third empirical correlation could be used that makes the larger of the two coefficients most dominant and maintains a smooth transition from one to the other.

For simplicity in large commercial buildings, the duct surface model could ignore heat transfer effects due to radiation. Those effects are less important there than in smaller buildings with hot attics and large temperature differences between the building envelope and duct surfaces. The model could also ignore startup transients, because unlike HVAC systems in small buildings, the systems in large commercial buildings usually do not cycle on and off during their daily operating periods.

A new metric could be used to characterize distribution system performance: transport efficiency. This metric is the total energy used to transport the working fluid (air or water) per unit of thermal energy delivered ($kW_{transport}$ / $kW_{thermal\text{-}delivery}$) and per unit of supply air delivered ($kW_{transport}$ / $cfm_{air\text{-}delivered}$). Transport efficiency depends on fan and pump characteristics and on the resistance, leakage, and heat transfer characteristics of the distribution system network.

The new metric and ones like it could be used to synthesize performance data into a manageable number of descriptors that allow systems to be compared on a level playing field, and could help identify potential areas for improvement. For example, the metric could be used to compare impacts on fan and pump power use of technology options such as air versus hydronic systems, distributed heating and cooling equipment versus central systems, variable-air-volume (VAV) versus constant-air-volume (CAV) systems, and perfect versus improper installation. Using the results of simulations, one could calculate the thermal and ventilation transport energy metrics in each case. The metrics would in turn help establish baselines for standards and technical targets that are technologically feasible and economically justified over the life of the system, and that can be used in the future to verify that energy saving program targets are being achieved.

032-20 Characterize Air-Handling Systems and Assess System Retrofit Performance

Originating Group (Person): MTG.EAS Vice-Chair (Craig Wray)
Originating Date: December 2011

State-of-the Art (Background): Measurements over the past 15 years by Lawrence Berkeley National Laboratory (LBNL), Florida Solar Energy Center (FSEC), and others have begun to characterize air-handling systems in the U.S. commercial building stock (e.g., Withers et al. 1996; Delp 1997, 1998a, 1998b; Withers and Cummings 1998; Modera et al. 1999; Xu et al. 1999; Modera and Proctor 2002; NBI 2003; Jacobs 2004). Although the sample size of buildings and systems assessed is still small and is limited to the U.S., data collected indicate that system design is problematic and installation quality is often poor. Retrofit technologies to address deficiencies and achieve efficient air-handling systems already exist (e.g., remote sealing of system components, ad hoc duct static pressure reset schemes for systems with pneumatic control), but are not widely implemented in part because of the lack of knowledge about deficiencies and related performance improvement opportunities.

Advancement to State-of-the-Art:
More field data need to be collected about the physical characteristics of air-handling systems in existing buildings (especially for complex ones in larger buildings), both in the U.S. and elsewhere, and there is a need to demonstrate performance gains that are actually obtained by system improvements (both from an energy and an indoor environmental quality standpoint). Efforts should include:

- Collect field data about the physical characteristics of installed air-handling systems.
- Determine if performance gains resulting from system retrofits are achieved.
- Document findings in case studies, and disseminate to industry.

Type of Project: Research (Field Tests), Standards (Guidelines)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 1.4 (Control Theory and Application)
- TC 5.1 (Fans)
- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)
- TC 6.3 (Central Forced Air Heating and Cooling Systems)
- TC 7.7 (Testing and Balancing)
- TC 7.9 (Building Commissioning)
- TC 9.1 (Large Building Air-Conditioning Systems)
- SPC 111
- CEC (California Energy Commission)
- DOE

MTG.EAS Action:

- Assigned to Craig Wray

Remarks: none

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033-10 Determine Most Efficient HVAC System based on Geographic and System Loads

Originating Group (Person): MTG Section Head (Dan Int-Hout)
Originating Date: 28 December 2012

State-of-the Art (Background): The key to efficient air systems starts at the DOAS unit. Any system, no matter if it is VRV (VRF), WSHP, fan coil or chilled beam, needs a DOAS unit. In addition, the DOAS system needs to be pressure independent at the zone, as ventilation requirements at the zone level are seldom, if ever, constant. It sure starts to look like a typical VAV system. As interior loads continue to drop, one can question the need for any of the other expensive systems in addition to the mandatory, system independent, ventilation system. The default ventilation rate, 17 cfm per person, provides 350 Btu of cooling at 55°F, and coincidentally, a person generates 350 Btu/h of cooling demand. That airflow rate also handles the latent load if persons are the only source of latent load. At the low interior loads being seen, the only source of additional cooling demand is the perimeter load. Putting a return opening above all window allows the local heat to be drawn into the plenum, which in cooling mode, is almost all exhausted to counter the ventilation supply. The chiller never sees the perimeter heat gain.

Advancement to State-of-the-Art: A design tool for consulting engineers where the results would be a Special Publication and the results included in the Handbook - HVAC Systems and Equipment. Objectives include:

- Study to determine where geographically and under what building load conditions DOAS systems are applicable.

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 9.1 (Large Building Air-Conditioning Systems)
- TC 9.4 (Justice Facilities)
- TC 9.6 (Healthcare Facilities)
- TC 9.7 (Educational Facilities)
- SSPC 62.1

Type of Project: Work Statement (Study)

MTG.EAS Action: Assigned to TC 9.1

Recommended (Suggested) Action:

- PMS Chair:
- PMS Members: Herman Behls; Dan Int-Hout, and others solicited from the TCs/PCs listed above.

Remarks: Int-Hout: The key to efficient air systems starts at the rooftop DOAS unit. Any system, no matter if it is VRV (VRF), WSHP, Fan Coil, or Chilled Beam, needs an efficient DOAS unit.

Boldt: As long as 62.1 clings to the multiple spaces equation, only DOAS and 100% OA VAV can be shown with no doubt to comply; and DOAS is by far the more efficient solution. Unless we see a closed solution from 62.1 for multiple zone systems, my opinion is that the multiple spaces equation should be abandoned as impractical to solve on an 8760 basis (or even for one hour).

Int-Hout: In addition, I suspect we will discover that it needs to be pressure independent at the zone, as ventilation requirements at the zone level are seldom, if ever, constant. It sure starts to look like a typical VAV system doesn't it?

Boldt: We see this more and more. Our DOAS standard now is to discharge to the room with separate diffusers. We see too much variation in OA supplied if we go to the return side of heat pumps (or whatever), even more if we connect to the outlets (as Mumma recommends), and both fail the 15°F above space temperature 62.1 rule. Pressure independence, however, changes cheap balancing dampers to VAV boxes. Clients aren't accepting that cost today.

Int-Hout: As interior loads continue to drop, I question the need for any of the other expensive systems IN ADDITION to the mandatory, system independent, ventilation system. The default ventilation rate, 17 cfm per person, provides 350 Btu of cooling at 55°F, and coincidentally, a person generates 350 Btu/h of cooling demand. That airflow rate also handles the latent load, if persons are the only source of latent load. I wonder what the carbon footprints of live plants in the office are, since they must constantly be watered, and then evaporation adds to the chiller's latent load.

Boldt: True, if you are in cooling mode. In Wisconsin at 0°F, what temperature should the DOAS deliver? It is a quandary for us. Perimeter zones could get "free" reheat via a second wheel or other heat recovery device if air were delivered at space neutral; but interior zones would then need more cooling.

Int-Hout: At the low interior loads we are seeing, (We don't see them dropping much. Lighting is down a lot, but computers bring it back up. In buildings where employees use laptops, I agree entirely.) the only source of additional cooling demand is the perimeter load. Putting a return opening above all window allows the local heat to be drawn into the plenum, which in cooling mode, is almost all exhausted to counter the ventilation supply. The chiller never sees the perimeter heat gain!

Boldt: I disagree. Solar gain is mostly received at the floor or other surface where the sunlight strikes. Only the convective load is truly "at the glass" and that is very small.

034-20 Guidelines for Air-Handling System Retrofit and Commissioning

Originating Group (Person): MTG.EAS Vice-Chair (Craig Wray)
Originating Date: December 2011

State-of-the Art (Background): Design guidelines for new air-handling systems are available now (e.g., SMACNA 1990, ASHRAE 2004, Jacobs 2004) or are in preparation (ASHRAE 2013). Numerous publications about HVAC system testing and balancing are also available (SMACNA 1993, 2012; Gladstone and Bevirt 1997; AABC 2002a, 2002b; Conant et al. 2004; ASHRAE 2008). However, few of these documents comprehensively address practices (appropriate metrics, diagnostic tools, and procedural guidelines) that have been confirmed to be reliable for retrofitting and commissioning air-handling systems.

To avoid problems that occur in the current building stock, guidelines about retrofit design and installation practices need to be developed for use by building designers, owners, and HVAC contractors. Guidelines describing how to commission air-handling systems also need to be developed.

Advancement to State-of-the-Art: After appropriate field diagnostics are developed (Idea 031), data are collected about the physical characteristics of air-handling systems in existing buildings, and performance gains that are actually obtained by system retrofits are demonstrated (Idea 033), new information about diagnostics and performance needs to be integrated into guides for air-handling system retrofit and commissioning.

Type of Project: Standards (Guidelines)

Primary ASHRAE TCs/PCs/Organizations Involved:
- TC 1.4 (Control Theory and Application)
- TC 1.8 (Mechanical System Insulation)
- TC 1.11 (Electric Motors and Motor Control)
- TC 2.6 (Sound and Vibration Control)
- TC 4.3 (Ventilation Requirements and Infiltration)
- TC 5.1 (Fans)
- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)
- TC 5.5 (Air-to-Air Energy Recovery)
- TC 6.3 (Central Forced Air Heating and Cooling Systems)
- TC 7.1 (Integrated Building Design)
- TC 7.2 (HVAC&R Contractors and Design Build Firms)
- TC 7.7 (Testing and Balancing)
- TC 7.9 (Building Commissioning)
- TC 9.1 (Large Building Air-Conditioning Systems)
- SPC 111
- SSPCs 62.1, 90.1, 189.1
- CEC (California Energy Commission)
- DOE
- SMACNA

MTG.EAS Action:

- Assigned to Craig Wray

Remarks: This effort should focus on developing a series of guides containing prescriptive air-handling system retrofit recommendations that can be used by designers and contractors to substantially reduce the energy consumption and improve the indoor environmental quality (IEQ) for specific existing commercial building sectors. These guides would also provide a basis to develop training materials for workers who will retrofit these buildings.

More specifically, the guides should integrate and synthesize existing relevant guidance for retrofitting commercial buildings (e.g., from ASHRAE, DOE, FEMP) with new information from other MTG.EAS projects to develop a series of retrofit guides that each target a specific type of existing commercial building. The initial series of guides would target 30% savings relative to existing code requirements or existing performance (whichever is greater for the building being retrofitted). Subsequent guides would address more ambitious 50% savings and net-zero energy goals.

This effort should also consider providing technical support for nationwide demonstration projects with energy and IEQ measurement and verification (M&V) to provide case studies that show the impact and value of using these guides and to establish a retrofit impact/value and performance benchmark database.

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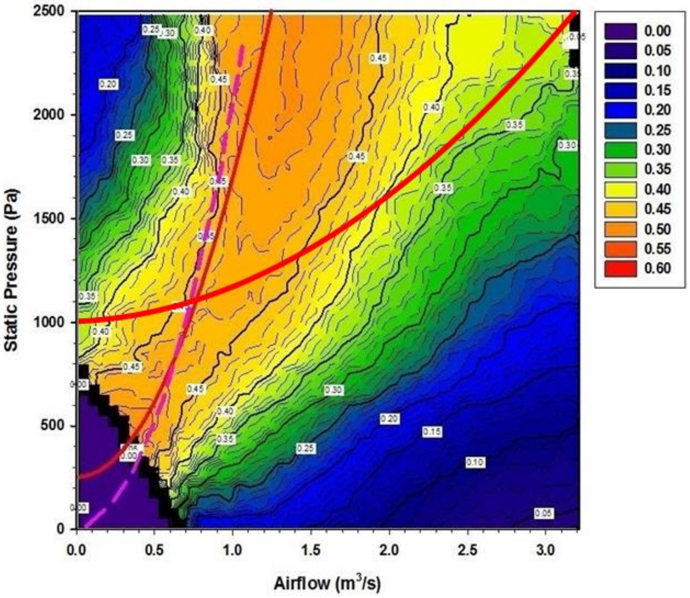
035-20 Advanced Technology Applications

Originating Group (Person): MTG.EAS Vice-Chair (Craig Wray)
Originating Date: December 2011

State-of-the Art (Background): Fan electric power depends on fan air power (product of the airflow through and pressure rise across the fan), mechanical efficiencies (fan and belt), and electrical efficiencies (motor and drive). For air-handling systems with variable flows, none of these parameters is constant and all are interrelated. For example, as shown below, fan efficiency can vary significantly, depending on the "system curve" representing the system pressure drop versus flow relationship (solid red lines). Stall-related sharp drops in efficiency can occur if the fan operates to the left of the "do not select line" (pink dashed line). If the fan could be improved aerodynamically (e.g., so that air speed over the blades and/or angle of attack are maintained relatively constant), then fan efficiency variations could be minimized over the operating range, and the fan itself could be used for a broader range of systems while still maintaining near peak efficiency (e.g., within say 5 points or less of maximum efficiency). This capability is especially important in retrofit cases where one might change out the fan, but it is impractical to replace the duct network.



Separate, proven air-handling system technologies already exist that each can save 10 to 50% of HVAC system energy in new and existing commercial buildings while maintaining or improving indoor environmental quality (IEQ). The savings in each case depend on the issue addressed (e.g., remote sealing of system air leakage, optimizing duct layout and sizing, wireless conversion of constant-air-volume systems to variable-air-volume, adding duct static pressure reset and demand-controlled ventilation). When implemented together, these technologies interact so that the resulting savings are likely larger than those achieved by any single technology, but less than the sum of the individual savings. Little is known, however, to what extent these air-handling system technologies interact, let alone how they can be integrated with other HVAC system types (i.e., hydronic and radiant), envelope components, and advanced technologies (e.g., chilled beams). Optimal, cost effective system configurations that maximize energy savings while still maintaining acceptable indoor air quality and thermal comfort (e.g., developing control strategies for hybrid low-energy mechanical and natural ventilation systems) need to be developed and tested.

Advancement to State-of-the-Art:

- Develop aerodynamic improvements to make fans and other system components less susceptible to loss of efficiency during part load operation.
- Develop new air-handling system technologies that allow life-cycle cost effective reduction in energy use while meeting indoor environmental quality and sustainability requirements for non-residential buildings.
- Examine the integration of air-handling, hydronic, and building systems. As a result of this examination, build proof of concept prototypes in collaboration with equipment manufacturers, and then test in the laboratory and field to demonstrate performance improvements.
- Support the development of related new standards.

Type of Project: Research (Lab and Field Tests), Standards (MOT)

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 7.1 (Integrated Building Design)
- TC 5.1 (Fans)
- TC 5.2 (Duct Design)
- TC 4.3 (Ventilation Requirements and Infiltration)

MTG.EAS Action:

- Assigned to Craig Wray

Remarks: none

036-20 Air-Handling System Design Specifications

Originating Group (Person): SMACNA (Allison Fee)
Originating Date: May 2013

State-of-the Art (Background):

Advancement to State-of-the-Art: Develop design specifications to:
- Provide robust seals that are integral to all HVAC cabinet/enclosures that will provide an air tight seal. Seals on service panels need to be durable for a lifetime of repeated service removal and reinstall.
- When filter racks are provided by the manufacturer, provide air tight seals and sturdy racks that will not allow air bypass around the seals. Constructed filter racks should be specifically engineered by the designer to provide airtight seals and service panel seals that will durable.
- Include specifications for insulating duct to increase thermal resistance and decrease thermal conductivity between the different mediums.
- Provide sufficiently large equipment rooms so that duct connection transitions from the air moving equipment to the duct is straight or at modest angles to avoid system effect issues. HVAC air equipment has been increasing in size as efficiency minimums have increased so additional space should be added for future equipment upgrades.

Type of Project [Work Statement (Study, Lab Tests), Standard (MOT), Other]: not yet defined

Primary ASHRAE TCs/PCs/Organizations Involved:
- SMACNA
- TC 7.2 (HVAC&R Contractors and Design Build Firms)
- TC 5.2 (Duct Design)
- TC 5.1 (Fans)
- TC 1.8 (Mechanical System Insulation)

MTG.EAS Action:
- Assigned to: Allison Fee (left SMACNA in July 2013) – no new champion identified

Remarks: none

037-00 Cost Effectiveness of HVAC System Air Leakage Tests During Construction

Originating Group (Person): SSPC 90.1 (Jeff Boldt)
Originating Date: June 2013

State-of-the Art (Background): Leakage tests on ten HVAC operating systems showed that the system leakage ranged from 10 to 20% of design fan airflow (2012 ASHRAE Handbook, page 19.2).
The Duct Design chapter in the 2013 ASHRAE Handbook recommends that supply air (both upstream and downstream of the VAV box primary air inlet damper when used), return air, and exhaust air systems be tested for air leakage after construction at operating conditions to verify (1) good workmanship, and (2) the use of low-leakage components as required to achieve the design allowable system air leakage. This chapter also recommends that, to ensure that a system passes its air leakage test at operating conditions, sufficient ductwork sections should be leak tested *during construction*. An equation is provided to translate system fractional air leakage to test section leakage class for such tests.

Advancement to State-of-the-Art: Reduce energy wasted by leaky HVAC air systems. Objectives include:

- Conduct study to determine the costs and benefits associated with conducting ductwork leakage tests *during construction*.

Type of Project: Work Statement (Study). Study to be supported by ASHRAE research.

Primary ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)
- TC 7.2 (HVAC&R Construction & Design Build)
- TC 7.7 (Testing and Balancing)
- CEC (California Energy Commission)
- SMACNA
- SSPC 90.1

MTG.EAS Action:

- Assigned to TC 5.2

Recommended (Suggested) Action:

- PMS Chair: Jeff Boldt
- Proposed PMS: Herman Behls, Craig Wray

Remarks: none

038-10 Economics of Airtight Non-Fan-Powered Single-Duct Terminal Units

Originating Group/Person: SSPC 90.1 (Jeff Boldt)
Submittal Date: 2 February 2013

State-of-the Art (Background): Normally, standard terminal units are specified and installed. Some manufacturers' market low-leakage boxes and some users (e.g., the University of Texas and University of Chicago) require the installation of low-leakage boxes. Terminal unit manufacturers resist requiring that low-leakage boxes be installed in HVAC systems, in part because they are unsure whether the incremental cost increase between standard and low-leakage boxes is justified.

Advancement to State-of-the-Art: Limiting the leakage of ductwork and equipment will result in significant energy savings. Objectives include:

- Conduct an economics study to determine if the payback will justify the cost to manufacture low-leakage terminal boxes (basic unit only). Study to be based on laboratory leakage tests of standard and low-leakage boxes.

Type of Project: Work Statement (Study)

ASHRAE TCs/PCs/Organizations Involved:

- TC 5.2 (Duct Design)
- TC 5.3 (Room Air Distribution)

MTG.EAS Action:

- Assigned to TC 5.2

Recommended (Suggested) Action:

- PMS Chair: Herman Behls
- Proposed PMS: Jeff Boldt and others.

Remarks: none

APPENDIX F: Annotated List of Selected Available Air-Handling-System Related ASHRAE Research Reports

The following lists 41 available research reports related to modeling and performance data for air-handling system airflows and pressure distributions, with annotations principally based on abstracts provided on the ASHRAE website (https://www.ashrae.org/standards-research--technology/research), as of July 26, 2013. Hyperlinks are also provided to access the reports.

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Clark, M.S., T. Barnhart, F. Bubsey, and E. Neitzel. 1977. “The Effects of System Connections on Fan Performance”, AMCA-ASHRAE Research Report 139-RP. September. 72pp.

In recent years there has been increased emphasis placed upon the rating, cataloging, and testing of fans and systems to assure their proper operation and to minimize the consumption of energy. As a result, safety factors in system design have been reduced so that there is very little allowance for error either in the calculated system resistance or the fan performance. It is, therefore, essential that those items which can affect fan performance and the magnitude of that, effect become an important part of our general knowledge.

It has been known for many years that a fan tested in the laboratory may not perform the same once it is installed in the field. Several articles have been written which describe these phenomena. This project was initiated to address the problem, in much greater detail, of variations between laboratory fan ratings and the actual performance obtained under field conditions. Field installation conditions, including the specific location and design of ductwork components, can affect a fan's performance. These elements influence not only the flow rate and fan static pressure, but also the fan brake horsepower.

Sponsor: TC 5.1, Fans; Conducted: August 1973 - October 1977

Free Download: Downloadable - RP139.pdf

Swim, W.B. and E.I. Griggs. 1986. “A Laboratory Study to Determine the Resistance to Flow in Galvanized Ducts”. ASHRAE Research Report 383-RP. June. 404pp.

The final report on work performed under ASHRAE 383-RP is being presented in three parts. This part, Part I, contains the final results. Part II constitutes a master's thesis completed as part of the study. Part III complements Part II in documenting the experimental program. Two experimental systems were used to complete the scope of tests required by ASHRAE 383-RP. Air flow with the smaller system was provided with a 25-hp centrifugal blower and flow rate was measured with a plenum nozzle arrangement. The larger system included a 125-hp axial-flow blower and air flow rate was measured using a pi tot-tube. The smaller system was used at the outset of the work since the larger system was still under development. All work described in Part II of this report was completed using the smaller system. Tests on round ducts having diameters of 18, 24, 30, and 36 inches were done using the larger system. All other tests were done on the smaller system. The experimental effort with the larger system in described in Part III. Work described in Part II was done in the early stages of the study; consequently, the data do not reflect a small calibration correction of measured flow rate which is included in the final results given in Part I. Part II discusses some of the theoretical background for the work. It describes in detail the smaller of two experimental systems, and it presents an error analysis pertinent to experiments with the smaller system. A small but apparent nozzle effect was noted in plotting friction factors, determined using different nozzle sets, on the Moody chart. This is discussed in Part II. Later in the investigation, the nozzles were checked against a TIMA flow calibration system. After this calibration, small corrections were applied to flow rates measured with the nozzles. This tended to remove the apparent nozzle effect shown by the plotted friction factors. But the small corrections did not change the conclusions about effective roughness. Consequently, the documentation in Part II was retained and is presented in its original form. The final results given here in Part I include the small correction. The calibration procedure, using the TIMA flow calibration system, is described in Part III.

Sponsor: TC 5.2, Duct Design; Conducted: September 1984 - June 1986

Free Download: Downloadable - RP383_(3_parts).pdf

Griggs, E.I. and W.B. Swim. 1985. “A Study to Determine the Proper Placement of Air Sensors Following Branch Duct Take-Offs”. ASHRAE Research Report 403-RP. December. 201pp.

The objective of ASHRAE 403-RP is to develop a method for predicting the velocity profiles of airflow downstream of common fittings used in HVAC duct systems. The work is subdivided into two phases. Phase I consists of a literature survey and a definition of test work for Phase II. A series of experimental tests are proposed for Phase II.

Sponsor: TC 9.7, Testing and Balancing Conducted: April 1985 - January 1989

Free Download: Downloadable - RP403_(2_phases).pdf

Swim, W. and E. Griggs. 1988. “Duct Leakage - Measurement, Analysis and Prediction Model”. ASHRAE Research Report 447-RP. June. 172pp.

The prediction of leakage rates for commercial sheet metal duct systems is most difficult. The leakage rates of specific components are largely unknown and only crude models have been advanced to estimate the leakage. ASHRAE Technical Committee 5.2, Duct Design and Construction, recognized the need for reliable methods of leakage prediction for sheet metal ducts and commissioned several studies aimed at resolving this design problem. The work reported herein is a part of TC 5.2's effort.

Sponsor: TC 5.2, Duct Design; Conducted: May 1985 - June 1988

Free Download: Downloadable - RP447.pdf

Swami, M. and S. Chandra. 1987. “Building Pressure Distribution for Natural Ventilation Calculations”. ASHRAE Research Report 448-RP. April. 131pp.

This is the final report of ASHRAE research project 448-RP "Building Pressure Distribution for Natural Ventilation" initiated in October 1985. The objective of the research was to review the worldwide data on building pressure coefficient and to assimilate the data for use in hourly calculation of natural ventilation airflow rates in buildings. This report is organized in two parts. Part 1 is written for the user who wants to use the information. Part 2 provides the background and research data analysis which was conducted to come up with the Part 1 information.

Sponsor: TC 4.7, Energy Calculations; Conducted: October 1985 - April 1987

Free Download: Downloadable - RP448.pdf

Tsal, R. 1988. “Calculation Techniques for Optimum Duct Design and Flow Simulation”. ASHRAE Research Report 516-RP. March. 905pp.

This report offers a comprehensive survey of numerical methods for duct and pipe network optimization.- Only tree networks are considered. Procedures reviewed, analyzed, and compared include Coordinate Descent, Penalty Function, Lagrange Multipliers, Reduced Gradient, and Dynamic Programming. In all cases, the objective function is the present worth of the total life-cycle cost. Constraints, such as standard pipe or nominal duct diameters, maximum velocities, pressure balancing, and other nonlinear or integer functions are applied to the problem. Recommendations for microcomputer programs to optimize pipe and duct networks are given.

Sponsor: TC 5.2, Duct Design; Conducted: September 1986 - March 1988

Free Download: Downloadable - RP516_(3_parts).pdf

Griggs, E.I. and F. Khodabakish-Sharifabad. 1990. “Flow Characteristics in Rectangular Duct”. ASHRAE Research Report 549-RP. June. 217pp.

Specific conclusions are: 1. Joint size and joint spacing affect the pressure drop for an air flow in a duct. 2. Beaded construction and cross breaks, both common with rectangular ducts, also contribute to the pressure drop for air flow in a rectangular duct, but, comparatively, these effects are not as strong as those due to the joints. 3. For the range of test covered in this work, no significant effect of aspect ratio was found when correlating the data for the "smooth" passages with the parameters of the Moody diagram using the hydraulic diameter.

Sponsor: TC 5.2, Duct Design; Conducted: June 1987 - June 1990.

Free Download: Downloadable - RP549.pdf

Brooks, P. 1991. “Laboratory Study to Determine Flow Resistance of HVAC Duct Fittings”. ASHRAE Research Report 551-RP. January. 282pp.

There has long been discussion about the credibility of the fitting loss coefficient data in the ASHRAE Fundamentals Handbook chapter on duct design. A forum was conducted 26 June 1983 at the Annual ASHRAE meeting in Washington, D.C. to discuss the source and accuracy of the data. A summary of the major comments made regarding the chapter included: (1) Some coefficient data was developed or investigated over 50 years ago. (2) The chapter has several inaccuracies and is incomplete. (3) Variations were as much as -42% to +54% for a 6-inch elbow from four different sources. Much of the loss coefficient data listed in the chapter originated from a translation of a Russian manuscript (Idel'chik, 1966). The main reason for this was the lack of other information for many of the fitting constructions. His handbook is a compilation of data checked satisfactorily by laboratory studies but also includes data obtained by crude experiments, data obtained theoretically, data obtained from approximate calculations, and other methods. Idel'chik felt that publishing all data available was justified since "the accuracy with which conduits and components are manufactured and installed under industrial conditions can differ considerably from installation to installation and also from the laboratory conditions under which most coefficients were obtained." Idel'chik warns in his FOREWORD, "it would have been better to delay the publication of this handbook until all coefficients could have been checked experimentally by some standard method..."

Sponsor: TC 5.2, Duct Design; Conducted: December 1987 - January 1991

Free Download: Downloadable - RP551.pdf

Sauer, H.J. and R.H. Howell. 1991. “Control of Outside Air and Building Pressurization in VAV Systems”. ASHRAE Research Report 590-RP. February. 242pp.

ASHRAE Research Project 590, Control of Outside Air and Building Pressurization in VAV Systems, was officially begun on September 1,1988, with the following stated objective: To develop a methodology, preferably adaptable to manual calculation and to personal computer calculations, by which to compare operating cost, ventilation air quantity and building pressurization resulting from various means of outside air and return air/relief air control in variable volume air conditioning systems, and to evaluate and compare typical representative systems. Because of the complexity of the problem, it was not possible to develop a totally manual method. However, a very versatile personal computer technique was successfully developed as detailed in this report. The PC program accurately models seven basic types of VAV control systems and is easily extended to many sub-types within each of these seven major configurations.

Sponsor: TC 9.1, Large Building Air Conditioning Systems; Conducted: September 1988 - December 1991

Free Download: Downloadable - RP590.pdf

Wray, C.P. 1992. “Evaluation of Algorithms for Analysis of Smoke Control Systems”. ASHRAE Research Report 618-RP. January. 257pp.

The objective of this project was to develop and verify an improved and extended algorithm for use in a smoke control program that simulates the flow of air in a multizone building. The algorithm requirements were that it: uses the best possible solution method chosen from a set of algorithms frequently used for solving pipe network problems; be programmed in FORTRAN; and includes models not available in ASCOS (fan and duct flow models). Four different network analysis algorithms were considered. These were: the sequential node method, the simultaneous node method, the simultaneous loop method, and the linear theory method, which is also a loop-based simultaneous method. A description of each of the simultaneous solution techniques was developed, after which these methods were implemented in separate computer programs. Each program was based on a single existing computer program, so that similar solution techniques and the same input data would be used. That program was reviewed by an external agency to ensure it had capabilities similar to those required for smoke control analysis. The sequential method had already been implemented in another existing program (ASCOS). The algorithms, as implemented in these programs, were then evaluated by comparing their performance on the basis of convergence reliability, accuracy, speed, memory requirements, ease of use, and flexibility. A data set supplied by ASHRAE, which consisted of 50 different cases involving various building and smoke control system types, was used in the evaluations.

On the basis of these evaluations, the simultaneous node method was selected as the best algorithm for smoke control analysis. A new computer program called SMOKESIM was developed in the final phase of this project. It implements the simultaneous node method, and includes all the capabilities required for the analysis of smoke control systems. SMOKESIM is a quasi-transient program that has the ability to model steady-state airflows and transient smoke concentrations. It takes into account all major driving forces present during a fire: stack effects, wind effects, thermal expansion, HVAC system operation (fans and ducts), pressure losses due to friction in vertical shafts, and the operation of windows and doors.

Predictions of airflow, pressure, and smoke concentration by SMOKESIM have been validated through comparisons with results obtained using hand-calculations for simple building and system configurations. Perfect agreement was obtained in every case. In addition, the airflow and pressure predictions of SMOKESIM were verified by an external agency against those of a separate smoke control analysis program using several cases for which measured data from full-scale fire tests are available. In each case, there was excellent agreement between the SMOKESIM predictions and those of the other program. The predictions of the other program have shown good agreement with the measured data.

Sponsor: TC 5.6, Control of Fire and Smoke; Conducted: September 1989 - January 1992

Free Download: Downloadable - RP618.pdf

Tsal, R.J. 1992. “Duct Design Using the T-Method With Duct Leakage Incorporated”. ASHRAE Research Report 641-RP. June. 201pp.

Studies show that HVAC air duct systems are one of the major energy consumers in industrial and commercial buildings. Inefficient design of a duct system means that either energy is being wasted and/or excessive ductwork material is being installed. Duct system optimization offers the opportunity to realize significant owning and energy savings. The new duct system optimization method, called T-Method. was developed as a result of cooperative research between ASHRAE and Fluor Daniel Corporation [ASHRAE 1988]. The purpose of this research activity was to develop a practical duct optimization procedure and conduct an economic analysis using the example in the ASHRAE 1985 Handbook as a reference. Life cycle cost is selected as the objective function. Constraints are pressure balancing, nominal duct sizes, preselected ducts, air velocity, and installation limitations. The T-Method duct design consists of three steps performed in series: system condensing, fan selection, and system expansion. The papers "T-Method Duct Design, Part I and Part II" present the theory of the method, step-by-step calculation procedures, economic analysis, and examples. A comprehensive explanation of each step with many examples confirm the practicality of the T-method.

Sponsor: TC 5.2, Duct Design; Conducted: December 1989 - June 1992

Free Download: Downloadable - RP641.pdf

Milke, J.A. and F.W. Mowrer. 1993. "Algorithm for Design Analysis of Atrium Smoke Management Systems". ASHRAE Research Report 658-RP. July. 216pp.

The principal purpose of this project is to develop a computer-based algorithm which can be used as a design aid for smoke management systems in atria. The developed algorithm, FMD, predicts the development of hazardous conditions in a tall space due to various fire conditions, either with or without an operating smoke management system. FMD is able to address the hybrid fires, transient conditions as well as the interaction between two types of smoke management systems. In addition to characterizing hazardous conditions in terms of smoke layer position and temperature as provided for in NFPA 92B, the algorithm can evaluate species concentration and light obscuration of a smoke layer. One important aspect of this report is the second chapter which describes the fundamentals of smoke management system design. This chapter provides two important contributions. This chapter provides two important contributions. First, the numerous algebraic equations provided throughout the chapter can be used as a design aid. Second, these equations are provided to permit designers to conduct analyses of one aspect of smoke management system or subsystem performance as a check to the computer-based calculations.

Sponsor: TC 5.6, Control of Fire and Smoke; Conducted: September 1990 - July 1993

Free Download: Downloadable - RP658.pdf

Wilson, A.G. 1993. "Field Verification and Simulation of Problems Caused by Stack Effect in Tall Buildings". ASHRAE Research Report 661-RP. June. 243pp.

Stack or buoyancy forces due to the difference in density between cold outdoor air and warm indoor air are known to be a source of problems in tall buildings in cold climates. The best known example is high pressure differences causing entrance and stairwell doors to require excessive force to open or close. Other problems are due to the airflow induced by stack forces through the building envelope and interior zones. A common example is excessive infiltration of cold air through the building envelope on lower floors, causing excessive heating load and discomfort to building occupants. Stack effect occurs in reverse in hot climates, where outdoor air is less dense than cool indoor air. However, the pressure difference is usually much smaller in hot climates because the temperature difference is smaller; thus the problems induced are not as noticeable. This study concentrates on the cold outdoor situation, which can produce peak stack forces twice as large as the hot outdoor situation.

Sponsor: TG/TB, Tall Buildings; Conducted: September 1991 - June 1993

Free Download: [Downloadable - RP661.pdf]

Rivers, R.D. and D.J. Murphy. 1999. “Determination of Air Filter Performance Under Variable-Air-Volume (VAV) Conditions”. ASHRAE Research Report 675-RP. January. 393pp.

The collection of data described in Part I of this Final Report describes the performance of 31 general-ventilation-type air filters, using the methods of ASHRAE Standard 52.1 on full-size filters. These data were gathered for fixed airflow, as specified in the standard, and under simulated VAV operating conditions (with airflow cycling between filter rated flow and half that flow). In addition, particle-size efficiency measurements were made, using ambient atmospheric dust as a test aerosol and a white-light scattering aerosol spectrometer. The loss of filter fibers was determined by passing HEPA-filtered air through the filters (in clean condition) while measuring the downstream aerosol spectra with the same aerosol spectrometer. The dislodgement of collected dust was measured in the same way, using dust-loaded filters. The 15 fibrous media used in 30 of the 31 filters tested were also evaluated as flat-sheet samples. (The 31st filter was an electrostatic air cleaner, which had no fibrous media). Media thickness and resistance were measured as a function of media velocity. A rough measure of media fiber diameter distributions was made using a visible-light microscope. The overall goal in this project was to develop an algorithm which would relate filter resistance and particle-size efficiency to be predicted as a function of operating time under a typical VAV operating sequence and typical dust conditions.

Sponsor: TC 2.4, Particulate Air Contaminants and Particulate Contaminant Removal Equipment; Conducted: April 1991 - January 1999

Free Download: Downloadable - ASHRAE-D-RP675-20070821.pdf

Idem, S., F. Khodabakhsh, and B. Townsend. 1994. “Laboratory Study to Determine the Flow Resistance of Oval Ducts and Fittings”. ASHRAE Research Report 690-RP. January. 208pp.

This report describes an experimental investigation of pressure losses in spiral flat oval ducts and related fittings. Accurate pressure drop predictions are required to design HVAC (heating, ventilating, and air conditioning) systems. Incomplete or inaccurate pressure loss data can contribute to errors in duct system sizing, fan selection, and system balancing, leading to penalties in terms of initial and operating costs.

Sponsor: TC 5.2, Duct Design; Conducted: September 1991 - January 1994

Free Download: Downloadable - RP690.pdf

Bourdouxhe, J.-P. and J. Lebrun. 1995. “Reference Guide for Dynamic Models of HVAC Equipment”. ASHRAE Research Report 738-RP. June. 245pp.

Dynamic HVAC equipment models are useful in energy management for studying optimal control strategies. These models may be used to minimize cyclic losses, to fix start/stop times and to get better control of electricity peak power requirements.

Quick dynamic models are required for closed loop control analyses. In HVAC, the quickest phenomena occur in air handling units. When simulating such subsystems, realistic dynamics have to be introduced in all the components involved (heat and mass exchangers, ducts and pipes, sensors and actuators).

Recently there has been interest in the development of ON LINE analyses to allow the user to test the control equipment of any component of the subsystem under realistic conditions. This could involve EMULATION, where actual and simulated components are interconnected. Better dynamic models will allow more sensitive fault detection diagnosis; they could also provide possibilities for predictive fault detection.

A few years ago, ASHRAE sponsored a project (530-RP) to produce a survey of primarily steady-state models that are useful for performing energy calculations. However, there is no consolidated source of information documenting the mathematical models necessary for analyzing the dynamic behavior of HVAC systems.

The objective of this project was to prepare a publication that identifies and describes the available dynamic models for HVAC related equipment. An additional objective was to identify the need for the development and validation of new dynamic models for equipment weakly covered in the literature.

Sponsor: TC 4.6, Building Operation Dynamics; Conducted: April 1992 - June 1995

Free Download: Downloadable - ASHRAE-D-RP-738-20100309.pdf

Carpenter, S. 1995. "An Evaluation of the Effect of CO_2 Based Demand-Controlled Ventilation Strategies on Energy Use and Occupant Source Contamination Concentrations". ASHRAE Research Report 740-RP. June. 65pp.

This study examines the effectiveness of using CO_2 -based demand-controlled ventilation (DCV) to provide adequate indoor air quality with minimum energy use. A detailed building energy analysis program (ENERPASS) was combined with a contaminant level prediction program (CONTAM) to perform the analysis. The combined program was used to evaluate the annual heating and cooling energy consumption and carbon dioxide and formaldehyde concentrations. The assessment was made on a mid-sized commercial building designed to comply with ASHRAE 90.1 for four climate zones (Chicago, Nashville, Phoenix and Miami). Three separate HVAC systems were studied: single zone (i.e., multiple roof-top units), multi-zone and variable air volume (VAV). The simulations were made for five ventilation control strategies: fixed ventilation, building return air controlled to 1000 ppm and 800 ppm, floor return air controlled to 1000 ppm and each zone controlled to 1000 ppm.

Sponsor: TC 1.4, Control Theory and Application; Conducted: April 1994 - June 1995

Free Download: Downloadable - RP740.pdf

Haves, P. 1997. "A Standard Simulation Testbed for the Evaluation of Control Algorithms and Strategies". ASHRAE Research Report 825-RP. January. 266pp.

The aim of 825-RP was to develop a set of tools and supporting data to allow the evaluation of HVAC control algorithms and strategies using computer simulation. Specific achievements of the project include: detailed documentation and modeling of the envelope, plant and controls of a mixed use, air-conditioned, building on the MIT campus; development and documentation of new models to allow the explicit simulation of air flow in fan/duct systems, including fan control; development of a library of control functions and skeleton code to facilitate the modeling of DDC controls; production of a documented library of component models of mechanical equipment and control strategies in the formats of both the HVACSIM+ and TRNSYS public domain component-based simulation programs; and demonstration of the ability of the models to simulate various aspects of the controlled performance of VAV HVAC systems.

A building on the MIT campus has been extensively documented and then used to test the capabilities of the models developed or enhanced in the project. The part of the building that was documented has a VAV HVAC system consisting of a single air handling unit and 34 terminal boxes. The sizes, thermal properties and other relevant characteristics of those elements of the building fabric and the mechanical equipment that affect the controlled performance have been recorded. These characteristics have been analyzed in order to derive parameter values for the models referred to above and system models for HVACSIM+ and TRNSYS developed. The 34 zones of the real building have been combined into six zones for simulation purposes. A duct system with similar characteristics to that of the real building has been designed to serve the six aggregated zones in the system model.

Simulation of local loop control performance requires information about load changes and other disturbances on shorter time-scales than the hourly intervals for which this information is normally available. Sources of meteorological data and information on internal gains suitable for control simulation have been investigated and are described in the report.

The results of the project should enable detailed simulation to be used to investigate a variety of issues in HVAC control, including issues regarding the dynamics of controlling outside air flow and room pressurization in VAV systems.

Sponsor: TC 1.4, Control Theory and Application; Conducted: April 1994 - January 1997

Free Download: Downloadable - ASHRAE-D-RP825-20070914.pdf

Sahlin, P., A. Bring, and E. Sowell. 1998. “The Neutral Model Format for Building Simulation”. ASHRAE Research Report 839-RP. February. 146pp.

To foster development of better models of building energy systems, ASHRAE has sponsored several recent projects to identify, catalog and standardize models of building components and subsystems. For example, 629-RP has produced a Secondary Systems Toolkit, and 665-RP will soon produce a Primary Systems Toolkit. These Toolkits are collections of HVAC component and subsystem models expressed as computer subroutines for selected target environments. The Neutral Model Format (NMF) has been proposed as a more appropriate means of expressing mathematical models such as represented in the ASHRAE Toolkits. With the Toolkit models re-expressed in NMF, appropriate translators can be used to automatically produce modules of common provenance for a diverse group of building simulators.

The idea of a completely general simulation environment, where a user can interconnect predefined sub-models freely into a tailored system model, is today a reality. In the field of building simulation, existing environments like TRNSYS and HVACSIM+ along with several new developments, allow fully coupled models of envelope, distribution systems and controls at an arbitrary level of detail. However, the ultimate usefulness of any of these tools hinges on the existence of a comprehensive library of component models and the development cost of such a library will easily exceed that of the environment itself. In this report a Neutral Model Format (NMF) is specified. NMF models can be automatically translated into the format of a number of environments. Based on NMF, independent libraries can be established, and inter-environment model exchange is likely to increase. Since the first NMF proposal in 1989, several prototype translators have been developed, model libraries have been written, and the concept has earned acceptance among experienced users. This report repeats the modelling principles underlying NMF and presents a brief reference manual. A formal syntax definition and some model examples are presented in appendices.

Sponsor: TC 4.7, Energy Calculations; Conducted: September 1994 - February 1998

Free Download: Downloadable - rp-839.pdf

Wiggert, D.C. and C.S. Martin. 2004. “Dynamic Response of Ductwork Serving Laboratory VAV Exhaust Systems”. ASHRAE Research Report 847-RP. December. 99pp.

This report details the development of a numerical model named DUCT, which analyzes unsteady flows in laboratory ductwork systems. The analysis is based on the method of characteristics, analogous to liquid piping systems. Damper opening and/or closing initiate time-variable boundary conditions at hood inlets. Minor losses and ductwork friction are included, as well as interaction with fans. Extensive data were obtained from three university laboratory systems for purposes of code verification: two sets at the Georgia Institute of Technology and one set at Michigan State University. Comparisons between experiments and simulations demonstrate the accuracy and versatility of DUCT. The report also demonstrates the significance of system inertia.

Sponsor: TC 9.10, Laboratory Systems; Conducted: April 1999 - December 2004

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Mumma, S. 1996. "Determination of Duct Fitting Resistance by Numerical Analysis". ASHRAE Research Report 854-RP. February. 67pp.

The one calendar year research project employed commercially available CFD code to generate flow coefficient data for 9 ductwork fittings. The DEC workstation by Digital Corp., the platform upon which the computational work was performed, was in almost constant use around the clock for the 12 month duration of the project The computer code was used to produce the total pressure drop data necessary to compute the flow coefficients, as well as to produce flow field plots and static pressure plots. The agreement between the published and representative computational results was considered good. The good agreement has led to the conclusion that computational techniques can be effectively utilized to verify and expand the ASHRAE Duct Fitting Database.

In the event that ASHRAE chooses to proceed with the computational approach, it will be critical that the contractor take great care in setting up the model and performing a sensitivity study tor each fitting to assure that all variable settings including grid size, turbulence intensity, and entrance/exit section length yield reliable results.

The time and skill level necessary to accurately utilize the commercially available CFD codes is not generally available within the vast majority of consulting engineering offices at this time. Therefore it is still important to the industry that ASHRAE continue to provide the design data for ductwork fittings as has been its long standing policy.

Sponsor: TC 5.2, Duct Design; Conducted: September 1994 - February 1996

Free Download: Downloadable - rp-854.pdf

Yuill, G.K. and J.S. Haberl. 2002. "Development Of Accuracy Tests For Mechanical System Simulations". ASHRAE Research Report 865-RP. July. 50pp.

This project is needed to develop a comprehensive reference set of analytical solutions that are well-documented, peer-reviewed, and stated appropriately for use in testing simulation software. This work will assist users of SPC 140 SMOT by expanding the range of mechanical systems for which reference solutions are available. This work will be published as a supplement or incorporated into a future revision to SPC 140 SMOT, which will widen its acceptance and applicability.

The objective of this research project is to develop and document a reference set of steady-state analytical solutions for secondary HVAC systems. These solutions will show step-by-step the calculation of airflows, air temperatures, and coil loads given specifications of system configuration, space loads, space temperatures, and outside air conditions. They will demonstrate the application of these solutions for testing of simulation software by developing DOE-2 and BLAST input files for each case and comparing the simulation results with the analytical solutions.

Sponsor: TC 4.7, Energy Calculations; Conducted: April 1996 - July 2002

Free Download: Downloadable - rp-865.pdf

Yuill, G.K. 2003. “A Validation Study of Multizone Airflow and Contaminant Migration Simulation Programs as Applied to Tall Buildings”. ASHRAE Research Report 903-RP. July. 264pp.

There are many computer simulation models designed to predict the air flow and contaminant migration patterns in buildings. The purpose of the research described here was to validate multizone airflow and contaminant migration simulation programs as they apply to the modeling of tall buildings. To do this, a number of tracer gas experiments were performed in a building on the Pennsylvania State University campus. For these tests, up to three non-toxic gases were injected into the building in different locations at a constant rate. The concentrations of these gases were then measured in up to twelve zones within the building over time. The measured tracer gas concentrations from these tests were compared to those predicted by a model of the building in an air flow and contaminant migration computer program. To produce an accurate model of the building, it was necessary to accurately determine the parameters used in the model, particularly the flow coefficients and exponents which describe the flow paths within the building and to the outside. The results of this study indicated that it is not practical to use computer air flow and contaminant migration programs to model a building precisely, due to the difficulty in providing accurate parameters for the model. Also, the lack of mixing models in most programs for contaminant distribution within individual zones makes such programs impractical for precise determination of concentrations within a building. Air flow and contaminant migration programs are useful, however, for examining general migration patterns of airflow and contaminants within tall buildings as long as their limitations are acknowledged.

Sponsor: TC 4.10, Indoor Environmental Modeling; Conducted: September 1996 - July 2003

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Mumma, S. 1997. “Impact of Close Coupled Ductwork Fitting Arrangement on System Pressure Drop Based on CFD Analysis and Field Measurement”. ASHRAE Research Report 916-RP. October. 29pp.

The impact of close coupled ductwork fittings on system pressure drop is the central thrust of this paper. The configuration selected for in-depth research was taken from the engineering mechanical plans and specifications for a college library building under construction. The mechanical room is small and the ductwork leaving the air handling unit consists of very close coupled ductwork fittings. Design engineers currently have very little in the way of industry standards or design tools to quantify the impact of such arrangements. In order to better understand the magnitude and direction of close coupling on overall system pressure loss, the following research tools were employed: computational fluid dynamic (CFD) analysis, scaled fitting and arrangement testing in the laboratory, and full-scale arrangement field testing. Overall, each of these different approaches supported one another. The research revealed that close coupling of fittings can be either complementary or detrimental, depending upon the specific circumstance. For the specific set of fittings investigated, close coupling resulted in an approximately 27% higher pressure loss than predicted using conventional procedures. This led the authors to conclude that further research and better design tools are needed.

Sponsor: TC 5.2, Duct Design; Conducted: September 1995 - October 1997

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Riffat, S.A., L. Shao, and S.J. Smith. 2000. “Laboratory Testing of Selected HVAC Duct Fittings to Determine Flow Resistance”. ASHRAE Research Report 963-RP. October. 86pp.

Energy use and the environment in mechanically-ventilated buildings are strongly influenced by the performance of heating, ventilation, and air-conditioning (HVAC) systems, which is in turn governed by accurate prediction of pressure loss. This report presents the results of an investigation of pressure loss and associated loss coefficient, k-factor, for selected HVAC duct fittings used with square, rectangular, oval and round cross section ducts. Various aspects of HVAC design have been investigated with the study of different hydraulic diameters, transition ratios, and angles of reduction and expansion. This paper reports experimental results obtained under the instruction of a detailed study of flow resistance by ASHRAE. The object of this investigation is to experimentally test selected duct fittings for flow resistance for a comparison with Computational Fluid Dynamics (CFD), and to test other duct fittings so that data can be used to update the 1994 ASHRAE HVAC Duct Fitting Database. The duct fitting construction in this investigation complies with the 1995 SMACNA HVAC Duct Construction Standards and the experimental tests comply with the 1995 version of ASHRAE Standard 120P.

Sponsor: TC 5.2, Duct Design; Conducted: April 1997 - October 2000

Free Download: Downloadable - rp-963.pdf

Swim, W.B. 2004. “Inlet Installation Effects, Air and Sound on Axial Fans”. ASHRAE Research Report 1010-RP. March. 142pp.

Noise and performance measurements were made on three 36 inch (914 mm) diameter variable pitch axial fans with nominal hub diameters of 14, 17 and 26 inch (360, 430 and 660 mm). Each of the three fans was tested at four blade angles providing "twelve" test fans. The twelve fans were tested using ten test-wall positions designed to simulate the effect of installing fans in close proximity to the walls of an inlet plenum. This test program was designed to meet the requirements of ASHRAE Research Project 1010, "Inlet Installation Effects, Air and Sound, on Vaneaxial Fans". The measurements were made at the Air Movement and Control Association International (AMCA) laboratories in Chicago.

The 120 tests of this project covered the fan flow-rate range from free delivery to near shutoff with data collected at 9 to 11 test points or determinations for each test. The 120 tests yielded 120 fan performance curves, 1200 fan noise measurements, 120 Reference Sound Source (RSS) measurements and 120 test room background (BKG) measurements. Figure 1 describes the test fans and the test wall positions. The test fan sizes are identified as 36x14, 36x17 and 36x26 and the wall positions are identified as WP1 through WP10 in this report. Space limitations in the original test coding required the use of a single digit for wall position so the "1" was dropped from position 10 and that position was listed as "0" in the test data and results tables.

Sponsor: TC 5.1, Fans; Conducted: January 1999 - March 2004

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Sauer, H.J., F. Finaish, and B. Van Becelaere. 2003. “Verifying Mixed Air Damper Temperature and Air Mixing Characteristics”. ASHRAE Research Report 1045-RP. March. 226pp.

Air mixing problems are encountered by engineers in many applications. Central air conditioning systems, HVAC modules in automobiles, pulverizer mill of power generating systems, engine combustion systems in vehicles, and ventilating ducts to mention are a few examples of such applications. A great deal of experimental and computational fluids dynamics (CFD) studies of airflow mixing have been conducted and reported in the open literature. Velocity and temperature measurements and flow visualization methods were applied to investigate mixing of airflows. Further, several CFD methods have been applied to simulate airflow mixing and developments in the mixing boxes. A literature survey pertaining to air mixing and associated systems was been conducted. The survey focused on five topics: (1) Simulation and measurement of airflow patterns in mixing boxes (2) Stratification problems in mixing boxes (3) Air damper control characteristics (4) Air mixing boxes (5) Methods for air mixing enhancement The researchers then developed a test plan consisting of the configuration tested, an experimental facility, instrumentation, and test procedures.

Sponsor: TC 1.4, Control Theory and Application; Conducted: January 1999 - March 2003

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Hanby, V., J. Wright, Y. Zhang, P. Angelov, and R. Buswell. 2006. "Building System Design Synthesis and Optimization". ASHRAE Research Report 1049-RP. February. 192pp.

Model based optimization can be used to reduce the capital cost or energy use of a building. The research described here addresses the application of model based optimization in the synthesis of novel heating, ventilating and air conditioning (HVAC) system designs (the design including the choice of system components, the topological connections between the components, and the size and operation of the components).

Sponsor: TC 4.7, Energy Calculations; Conducted: October 1999 - February 2006

Free Download: Downloadable - rp-1049.pdf

Milke, J., F.W. Mowrer, and J.L. Torero. 2006. “Investigation of the Application of Duct Smoke Detectors in Heating, Ventilating, and Air Conditioning Systems”. ASHRAE Research Report 1079-RP. February. 392pp.

The spread of smoke due to the redistribution of air by the heating, ventilating and air conditioning (HVAC) system is a significant concern. One of the principal purposes for a duct smoke detector is to sense smoke in the HVAC system and initiate shutdown of the HVAC system. Another purpose for duct smoke detectors is to sense smoke generated from a fire involving a filter.

While a significant amount of research has been conducted in the area of smoke detection, little research has been conducted on the mechanics of smoke flow in ducts or the performance of duct smoke detectors. As such, the technical basis for guidelines pertaining to the need for or placement of duct-mounted smoke detectors is very limited. The primary purpose of the research program is to ascertain the validity of the prescriptive requirements currently in NFPA 90A [1999] and NFPA 72 [1999] relating to the use of duct smoke detectors for the control of smoke spread in buildings. The secondary purposes of this research are to:

- develop engineering methods and tools to determine when and where duct smoke detection is necessary
- determine where duct smoke detectors should be installed
- describe how duct smoke detectors should be tested for listing purposes in a performance-based code environment.

Sponsor: TC 5.6, Control of Fire and Smoke; Conducted: January 1999 - February 2003

Free Download: Downloadable - RP1079.pdf

Idem, S. and S. Sahu. 2002. “Leakage Of Ducted Air Terminal Connections”. ASHRAE Research Report 1132-RP. August. 164pp.

The performance of duct systems suffer due to (1) air leakage at the duct/air terminal connections because of inadequate attention by designers, air terminal manufacturers, installers, sheet metal contractors, and TAB contractors, and (2) the disputed responsibility for effective connection of ducts to air terminals. If the leakage of unsealed, marginally sealed and effectively sealed connections were quantified and publicized, a reliable database would exist to prompt and possibly obligate manufacturers and designers to take appropriate action and leave little excuse for not properly sealing duct/air terminal connections. The objectives of this research project are: 1) fill voids in earlier investigations sponsored by ASHRAE, 2) provide information that is not available in manufacturer’s air terminal rating and installation literature, 3) enhance assessment of the accuracy of field (flow rate) TAB reports, and 4) supply data that will affect the energy consumption of HVAC systems, and the control of indoor air quality (room air motion and room ventilation effectiveness).

Sponsor: TC 5.2, Duct Design; Conducted: September 2000 - February 2003

Free Download: Downloadable - rp-1132.pdf

Becelaere, R. and H.J. Sauer. 2004. “Flow Resistance and Modulating Characteristics of Control Dampers”. ASHRAE Research Report 1157-RP. September. 128pp.

This report presents the experimental results of the performance of various types of HVAC system airflow control dampers over a wide range of types, installations, and operating conditions. 368 tests have been conducted with the data and results presented herein. The fundamental performance parameters are the loss coefficient and the percentage of maximum flow as functions of the degree of damper opening. Results should prove very useful for HVAC system designers in the proper selection of airflow modulating dampers.

Sponsor: TC 5.2, Duct Design; Conducted: September 2000 - September 2004

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Darvennes, S. Idem, and M.N. Young. 2009. “Inlet Installation Effects on Propeller Fans, Air and Sound”. ASHRAE Research Report 1223-RP. March. 155pp.

Fan performance data measured as installed may show lower performance than manufacturer ratings, primarily because of improper inlet or outlet connections. It was proposed to experimentally measure air and sound performance of propeller fans with systematic variation of inlet flow components, intended to simulate typical “in the field” installations of the fans.

Sponsor: TC 5.1, Fans; Conducted: December 2004 - March 2009

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Stevens, M. and J. Schubert. 2010. “Inlet Installation Effects on Forward Curved Centrifugal Fans, Air Performance and Sound”. ASHRAE Research Report 1272-RP. June. 38pp.

It has been known to the air moving industry for some time that duct fittings installed close to a fan’s inlet or outlet have adverse effects on the fan’s performance. The magnitude of these adverse effects is generally determined through laboratory testing, and the body of knowledge is relatively small compared to the possible number of combinations of fan types, duct and inlet configurations, and duct fittings.

The purpose of this research project was to determine the effect of a limited number of various inlet installations and product configurations on the air performance and sound of a typical forward curved centrifugal fan.

Sponsor: TC 5.1, Fans; Conducted: April 2007 - June 2010

Free Download: Downloadable - ASHRAE-D-RP-1272.pdf

Furr, J.C., D.L. O'Neal, M. Davis, J.A. Bryant, and A. Cramlet. 2007. "Comparison of the Total Energy Consumption of Series versus Parallel Fan Powered VAV Terminal Units, Phases I and II". ASHRAE Research Report 1292-RP. June. 309pp.

Research Project ASHRAE 1292-TRP had the objectives to: (1) quantify the energy use of parallel and series VAV terminal units as a function of a nominal space load and control strategy in the laboratory, and (2) extend the experimental data to evaluate annual energy use for VAV terminal units in a wide range of climates. The first phase of this project focused on developing empirical models of airflow output and power consumption for a sample of series and parallel fan powered variable air volume terminal units at typical design pressure conditions. The objective of the second phase was to develop system models of single duct, multi-zoned VAV systems based on series and parallel fan terminal units and to use the model to compare the performance of the systems. It was a project requirement that the system model be verified using controlled laboratory experiments before the model was used to compare the systems based on the two terminal unit types. The linked file (36 MB) contains the reports for Phase I, Phase II, and the Spreadsheet Tutorial (all three documents contained in one pdf); and an Excel spreadsheet of data.

Sponsors: TC 5.3, Room Air Distribution; TC 7.7, Testing and Balancing; Conducted: April 2006 - June 2007

Free Download: Downloadable - ASHRAE-DRP-1292-20070919.zip

Idem, S., D. Kulkarni, and S. Khaire. 2008. “Laboratory Testing of Duct Fittings to Determine Loss Coefficients”. ASHRAE Research Report 1319-RP. December. 78pp.

An experimental program was initiated to determine the friction factor in corrugated circular spiral ducts. Pressure loss coefficients were measured for three types of mitered elbows for various aspect ratios of flat oval ducts. The tests were performed in accordance with ANSI/ASHRAE Standard 120-1999. A regression analysis was performed on the loss coefficient data. A power law correlation was proposed to correlate the flat oval elbow loss coefficient data for each type of flat oval elbow. Error in the measurement of pressure loss coefficients and in the curve-fit data was calculated in order to estimate the quality of regression analysis.

Sponsor: TC 5.2, Duct Design; Conducted: December 2005 - December 2008

Free Download: Downloadable - ASHRAE-D-RP-1319-20090923.pdf

Kashef, A. and G.V. Hadjisophocleous. 2010. "Algorithm for Smoke Modeling in Large, Multi-Compartmented Buildings". ASHRAE Research Report 1328-RP. June. 144pp.

Smoke generated by fires in buildings frequently creates a greater threat for occupants than does the heat. Reduced visibility and eye irritation caused by smoke makes it difficult for an occupant in a building to locate escape routes and exits. Therefore, studies of predicting smoke movement inside a building during a fire has become very important. An approach to doing this is to develop a hybrid computer-based model to effectively predict the movement of smoke which combines the accuracy of a zone based model near the fire and the efficiency of a network based model sufficiently far away.

The objective of this research is to develop a hybrid of zone and network fire modeling which would be able to simulate the smoke movement from fires in multi-compartmented buildings.

Sponsors: TC 5.6 Control of Fire and Smoke, TC 9.12 Tall Buildings; National Council of Research of Canada; Conducted: April 2006 - July 2010

Free Download: Downloadable - ASHRAE-D-RP-1328-20100802.pdf

Culp, C. 2011. “HVAC Flexible Duct Pressure Loss Measurements”. ASHRAE Research Report 1333-RP. July. 67pp.

Flexible ducts were modeled and simulated under computational fluid dynamics (CFD) with the project starting in August 2005. The objective of the study was to determine the optimum flexible duct modeling geometry and CFD simulation method. A validated and verified CFD model has the capacity to eliminate the time and cost issues associated with laboratory tests. The verified model can then be used for design purposes and to understand the behavior of airflow inside ducts

A standard k-ε turbulence model was used to simulate maximum stretched, 4%, 15% and 30% compressed 6 in. and 8 in. flexible ducts. Standard and RNG k-ε models were used to simulate 10 in. 15% compressed flexible duct. Model domains (3 ft long for 6 in. and 8 in. ducts and 2 ft long for 10 in. duct) which are free of end effects were used in the pressure loss calculations. Simulations showed agreement for the maximum stretched and 30% compressed 6 in. and 8 in. ducts. However, considerable discrepancy existed for 4% and 15% compressed ducts. Similar discrepancy existed for the 15% compressed 10 in. duct. The RNG k-ε model which was also used by Taghavi et al. in 2007 presented closer agreement with the measured data. The second part of the study focused on explaining the discrepancy by creating more realistic wall geometries. Parametric studies on the 15% compressed 8 in. duct wall geometry showed that modeling helical geometries do not improve simulation results. Periodic geometry with triangular wall generated the closest agreement with the measured data. The reason is that triangular wall geometry with extra cusp better represents the irregular real-world character of the flexible ducts.

Sponsor: TC 5.2, Duct Design; Conducted: June 2005 - September 2011

Free Download: Downloadable - ASHRAE-D-RP-1333-20120307.pdf

Landsberger, B., Z. Poots, and D. Reynolds. 2011. “Effects of Typical Inlet Conditions on Air Outlet Performance”. ASHRAE Research Report 1335-RP. September. 175pp.

Building air distribution terminal system designers and system installers require accurate quantitative information on the performance of the installed system to achieve optimum efficiency and levels of human comfort. This requires field installation adjustment values from published ideal pressure loss, air distribution and sound generation installation performance. This study documents the air output performance of different installation configurations of six types of ceiling diffusers and compares the results to performance when installed according to ANSI/ASHRAE Standard 70-2006. A diffuser inlet supply plenum was designed for optimum flow and was used to acquire a baseline set of data covering the six types of diffusers at different inlet neck sizes and inlet airflow rates. Full scale laboratory testing of typical field installation variations was completed for the same diffuser types and airflow rates with variations in damper installation, duct approach angle, duct type, duct vertical height above the diffuser and close coupling duct installation. A set of look-up tables were developed that can be used to easily predict how the installation configuration would affect diffuser performance compared to published data.

The research objective was to develop quantitative guidelines that will relate manufacturers’ air outlet cataloged data that have been obtained using ASHRAE Standard 70 to field installed application conditions.

Sponsor: TC 5.3, Room Air Distribution; Conducted: April 2009 - September 2011

Free Download: Downloadable - ASHRAE-D-RP-1335-20120307.pdf

Wen, J., R. Liu, A. Regnier, X. Zhou, and C. Klaassen. 2012. “Stability and Accuracy of VAV Box Control at Low Flows”. ASHRAE Research Report 1353-RP. May. 163pp.

The objectives of this project are to:
1) Identify and obtain typical single duct VAV boxes and controllers from various representative manufacturers.
2) Systematically design and conduct controlled laboratory tests to evaluate the performance of various VAV boxes; VAV controllers and pressure transducers; and VAV terminal units (including both the VAV box and the controller) over a range of typical operating conditions.
3) Conduct field tests to evaluate the performance of at least three typical VAV terminal units in real commercial buildings considering VAV terminal units from different manufacturers.
4) Analyze the test data to identify a) the relationships between airflow sensor performance and other impacting factors; b) the relationships between controller performance and other factors; c) the relationships between overall VAV terminal unit performances.
5) Generate a) a methodology to determine the minimum airflow set point; b) recommendations for the development of a new Method of Test (MOT) for Rating Air Terminal Unit Controls (ASHRAE SPC 195P) c) other practical recommendations.
6) Document the product selection process, testing procedures, test data, analysis procedure, and analysis conclusions and recommendations through a final report and technical paper.

Sponsor: TC 1.4, Control Theory and Application; Conducted: September 2007 - August 2012

Free Download: Downloadable - ASHRAE-D-RP-1353-20120530.pdf

Idem, S., D. Gibbs, and D. Kulkarni. 2012. “Laboratory Testing of Flat Oval Tees and Laterals to Determine Loss Coefficients”. ASHRAE Research Report 1488-RP. February. 137pp.

Because of the dearth loss coefficient data for flat oval junctions, a test program sponsored by ASHRAE was undertaken to experimentally determine loss coefficients for tees and wyes. This report presents experimental main and branch fitting loss coefficient data on diverging and converging flow flat oval junction fittings. A further goal of RP-1488 was to incorporate measured main and branch loss coefficients into the ASHRAE Duct Fitting Database for use in the design of duct systems.

The initiative set forth by ASHRAE to improve building energy efficiency motivated the present work. Loss coefficient data for a variety of HVAC duct fittings have been reported in the literature. Publications by Townsend et al. (1996), Idem and Khodabakhsh (1999), and Idem (2003) have presented coefficient data for various flat oval elbows and transition fittings. The scope of the present work was to expand upon this previous work and make available a more extensive database of loss coefficient data. In order to enhance the utility of the computer database, loss coefficient data are presented in terms of curve-fit equations.

For converging flows, a logarithmic model was used to correlate branch and main loss coefficients as functions of branch-to-common and main-to-common flow rate ratio, respectively, and pertinent geometry characteristics of the fitting.

Sponsor: TC 5.2, Duct Design; Conducted: September 2008 - March 2012

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Sleiti, A. and Z. Zhai. 2011. "CFD Shootout Contest – Prediction of Duct Fitting Losses". ASHRAE Research Report 1493-RP. December. 30pp.

A shoot-out contest to determine loss coefficients using CFD modeling for two prescribed duct fittings has been sponsored by ASHRAE Technical Committee: TC 5.2, Duct Design under the project number of ASHRAE RP-1493. The CFD technical expertise was provided by two CFD experts. The tasks of the CFD experts include soliciting contestants, developing the evaluation criteria, judge the submitted CFD methods for their practicality, i.e., if loss coefficient predictions can be achieved using commercial CFD software, whether they require an excessive number of nodes or extensive run times, and if they can be applied to developing flows with high turbulence intensity levels, recirculation, and complex geometries, etc. The CFD models were also assessed for their ability to predict loss coefficients within 15% of laboratory test values without previous knowledge of experimental data.

The main findings of the research project showed that the trends of the pressure loss coefficients were predicted correctly, while the accuracy was limited. None of the contestants could predict the pressure loss coefficients within 15% of the experimental results. The prediction error varies between 20% in some cases to more than 80% in most cases. The reasons for this error may be attributed to several facts including: errors in the geometry, errors in the definitions of the duct fitting loss coefficients, C_s (main loss coefficient) and C_b (branch loss coefficient, choice of turbulence model, near wall treatment, errors in the inlet and outlet boundary conditions, inappropriate modeling of wall roughness, inappropriate grid conversion, not considering thermal effects considerations and other reasons yet to be explored.

Sponsor: TC 5.2, Duct Design; Conducted: September 2010 - June 2012

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