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IMPROVING THE PERFORMANCE OF AIR-CONDITIONING SYSTEMS IN AN ASEAN CLIMATE[*]

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ABSTRACT

This paper describes an analysis of air conditioning performance under hot and humid tropical climate conditions appropriate to the Association of South East Asian Nations (ASEAN) countries. This region, with over 280 million people, has one of the fastest economic and energy consumption growth rates in the world. The work reported here is aimed at estimating the conservation potential derived from good design and control of air conditioning systems in commercial buildings.

To test the performance of different air conditioning system types and control options, whole building energy performance was simulated using DOE-2. The 5,100 m^2 (50,000 ft^2) prototype office building module was previous used in earlier commercial building energy standards analysis for Malaysia and Singapore. In general, the weather pattern for ASEAN countries is uniform, with hot and humid air masses known as "monsoons" dictating the weather patterns. Since a concentration of cities occurs near the tip of the Malay peninsula, hourly temperature, humidity, and wind speed data for Kuala Lumpur was used for the analysis. Because of the absence of heating loads in ASEAN regions, we have limited air conditioning configurations to two pipe fan coil, constant volume, variable air volume, powered induction, and ceiling bypass configurations. Control strategies were varied to determine the conservation potential in both energy use and peak electric power demands. Sensitivities including fan control, pre-cooling and night ventilation, supply air temperature control, zone temperature set point, ventilation and infiltration, daylighting and internal gains, and system sizing were examined and compared with a base case which was a variable air volume system with no reheat or economizer. Comfort issues, such as over-cooling and space humidity, were also examined.

VAV systems clearly have the best performance minimizing energy use while maintaining comfort conditions. Excess outdoor air in this humid climate has a significant energy penalty. Two pipe fan coil units have the lowest energy consumption due to fan energy savings and low latent cooling capacity but perform poorly during morning pulldown periods. Large fan energy savings for all systems can be obtained by using supply air temperatures as low as 7 °C (45 °F). A combination of system conservation measures incorporated into one building saved 14% of annual energy and 16% on peak power. Other results of the analysis will be discussed.

INTRODUCTION

The countries of the Association of South East Asian Nations (ASEAN), Indonesia, Malaysia, the Philippines, Singapore, and Thailand, with over 280 million people, are among the fastest growing regions economically and in terms of energy use. With the elevated standard of living, there have been dramatic increases in the number of air conditioned commercial buildings. In this hot humid climate, more than 50% of the energy use of western-style buildings goes for air conditioning.

Besides increasing the overall energy intensity of commercial buildings, the installation of electric air-conditioning adds to the peak electrical demand of the country's power system for the life of the building. This can place a significant capital burden on the country to provide the additional generation capacity to meet this demand. Thus, measures that reduce peak cooling loads and electrical demands of new commercial buildings will reduce demands for capital and foreign-exchange for imported energy sources and provide greater opportunities for making effective use of limited indigenous resources. Therefore, energy conservation for air-conditioning in Southeast Asian commercial buildings has public planning and policy significance.

Energy conserving principles worked out in the developed world are not always relevant because of differences in climate and structure of economies. While a major concern in tropical building design for energy efficiency is the mitigation of cooling loads, either through the envelope or internally-generated, we concern ourselves here only with the performance of the mechanical systems that cope with the loads that do appear. We attempt to identify, through a parametric study, the impact of some air-conditioning operating strategies and equipment choices on energy-use and comfort levels in ASEAN climates.

This report describes issues surrounding air-conditioning use and develops preliminary solutions and guidelines for future work within the context of a larger collaborative research effort between the Lawrence Berkeley Laboratory and researchers, practitioners, and policy makers in the ASEAN countries. The project, which is funded by the U.S. Agency for International Development, seeks to develop workable conservation policies for commercial buildings energy use in the region. While policy options will not be directly addressed in this report, we are aware that the conditions for realizing the energy-saving potential of the measures suggested here are often lacking and will require skilled attention. For instance, lowest first cost is a powerful driving force for design of air conditioning systems, and thus the most efficient and cost-effective options (over the building's life-cycle) are often overlooked. Also, those with responsibility for operating and maintaining air conditioning equipment may not be rewarded for efficient operation.

What follows is an explanation of our approach and methodology for estimating the air-conditioning conservation potential, some results from an informal survey of installed systems in ASEAN and from our simulation work, and recommendations for further research.

METHODOLOGY

In order to test a number of air-conditioning system-types and wide variety of control options, we simulated building energy performance using a state-of-the-art computer model. We chose whole-building analysis over a system-only simulation to give a more comprehensive picture of the energy-savings potential. Our analysis consists of three elements: the DOE-2.1C computer model, a prototype office building module used in earlier studies of commercial building energy standards for Malaysia and Singapore, and measured hourly weather for Kuala Lumpur, each of which is described below. Our approach was to vary the important system configuration and control parameters in individual simulations to determine the conservation potential in energy use and peak power demands and then to compare the performance of these options. We also compared the performance of the different generic system types using comparable input assumptions. Comfort issues such as overcooling, and space humidity levels are also discussed. Because of the absence of heating loads in the ASEAN region, we have limited the types of air conditioning systems. For instance, four-pipe fan-coil units, heat pumps, or dual-duct systems are rarely used in the region and thus were ignored.

DOE-2

The DOE-2.1C program simulates the thermodynamic behavior of a building [Curtis 1984; DOE-2 1980]. It does this by (approximately) solving the mathematical relations describing the non-linear flows of heat through and among all the building's surfaces and enclosed volumes, driven by a variety of heat sources, both internal and external. Hour-by-hour calculations are performed in four sequential modules, LOADS, SYSTEMS, PLANT, and ECONOMICS. In the LOADS module, the instantaneous heating and cooling loads are calculated and then modified to incorporated dynamic effects of thermal mass through the use of weighting factors. These loads are calculated at a single space temperature setting. The SYSTEMS module calculates the heat extraction/addition of the coils while reconciling the varying temperature set points and humidity levels from actual system operation and schedules. Fuel requirements of the primary heating and cooling equipment and pumps are determined in PLANT, while annual operating energy and life-cycle building costs for are evaluated in ECONOMICS.

The program was employed here not only because of the variety of HVAC systems and control options available, but also because of the demonstrated accuracy of the code in numerous validation efforts and relative ease-of-use.

ASEAN Weather Data

In general, the weather pattern for ASEAN countries is quite uniform throughout the year compared to temperate climate zones with distinct summer and winter seasons. Hot and humid air masses known as "monsoons" dictate the weather patterns. The countries closer to the equator receive two different monsoon seasons originating from different compass directions, while those further away from the equator generally only experience one. Therefore, some distinctions can be made between climates in the region. The climate tends to be hot and humid all year long with monthly average wet-bulb temperature varying from 75.5 °F to 78.4 °F in Singapore and 74.1 °F to 76.9 °F in Kuala Lumpur (Malaysia). Other areas have more seasonal weather patterns that are humid during the wet season but have a cooler, drier season. In Chiang Mai (Thailand) the monthly average wet bulb temperature in the wet season ranges from 73.5 °F to 74.3 °F from April to September, but drops to 63.9 and 62.1 °F in December and January, respectively, and stays below 68 through March. The rest of the metropolitan area climates in the ASEAN region fall between these extremes. However, since a concentration of cities occurs near the tip of the Malay peninsula (principally Kuala Lumpur, Singapore, and Jakarta), we selected Kuala Lumpur as our representative site.

For the purposes of this study we used temperature, humidity and wind speed data from Kuala Lumpur to represent a typical hot humid climate. Solar gains play an important role in the building cooling loads, and obtaining good solar data is one of the objectives of research now underway in the ASEAN region. Earlier research demonstrated the inadequacy of using the DOE-2 cloud-cover model as a substitute for actual measured data in the ASEAN region [Busch 1987]. Within the region, the only city with reliable and verified solar data consistent with the requirements of DOE-2 is Singapore. Because of the close proximity of Kuala Lumpur to Singapore, Singapore solar data was used to simulate the solar loads.

Malaysia Building Module

Simulation of an office building was chosen to provide a basis for evaluation of different types of cooling systems. Office buildings are the most representative commercial building type in ASEAN using central systems, and so, we used a prototype office building, originally developed for analysis of standards in Singapore [Turiel 1985], but later adapted to Malaysia [Deringer 1987]. Features of the building will be summarized here, but the interested reader can find more detail on the building in the above references.

The building is a 10 floor office complex with a total of 55,000 ft^2 (5,150 m^2). A central chilled water VAV system is used with central fans sized for 70,000 cfm (32.7 m^3/s) with about 230 tons (825 kW of cooling) provided by a centrifugal chiller. Air is supplied to the zones at a minimum of 55 °F (12.8 °C) (the actual supply temperature being that which adequately cools the warmest zone at design flow rates) through VAV boxes with minimum stops at 50% of design flow. Temperatures are controlled by zone thermostats set at 75.2 °F (24 °C) during occupied hours and set-up to 99 °F (37 °C) otherwise. Fans are forward-curved centrifugal design, controlled by means of inlet vanes. No economizer cycle was used, because, unlike temperate climates, economizer cycle is not feasible in hot, humid ones.

These system options were varied, both for this and different system types. The systems with central fans include single zone constant volume multiple zone constant volume, variable air volume, ceiling bypass VAV, powered induction unit, and two-pipe powered induction, all without reheat. A two-pipe fan coil system with no central fan was also modeled.

System-Type General Descriptions

Here we describe the systems modeled, their typical operating strategies and control settings. More complete explanations are found in the DOE-2 Reference Manual [DOE2 1980], ASHRAE Systems Handbook [ASHRAE 1984], or McQuiston [1982]. We will identify and henceforth refer to the system types with the mnemonic codes used in DOE-2.

Single Zone Reheat (SZRH). This is a constant-volume system with a central fan and cooling coil that responds to meet the cooling load in a specified control zone. All other zones are sub-ordinate to the control zone in terms of the supply-air temperature with no reheat available. Though in the United States these systems are usually installed with reheat capability, which would undoubtedly enhance zone temperature control and comfort conditions in Southeast Asia, the energy and cost penalty is considered too high for wide application in ASEAN countries. When these systems are installed without reheat, then some overcooling typically occurs.

Reheat Fan System (RHFS). This system is also a constant-volume system with a central fan and cooling coil, but is a multi-zone system. That is, the supply-air temperature is set according the logic of one of several options, including responding to the warmest zone's needs, which will change throughout the day. Again, no reheat is simulated with this system.

Variable Air Volume System (VAVS). A variable-volume central fan and cooling coil provide supply air according to the particular cooling control strategy followed. Zone control is achieved via individually-controlled VAV terminal boxes in each space which control air-flow by throttling the primary supply air down to a specified minimum level.

Ceiling Bypass Variable Volume (CBVAV). This system is similar to the VAVS system except that the primary air is supplied at constant volume and the VAV terminal boxes behave somewhat differently. When throttling of the primary air is called for, the correct amount of air is injected into the space and the excess is rejected to the plenum.

Powered Induction Unit (PIU). The PIU system is yet another variation on the basic VAVS system. There are both parallel and series types, but here we consider only the latter. The terminal box is fitted with a small fan running at constant speed which draws air from two sources, the primary supply air stream and a secondary source. The secondary source is typically a core zone return air stream using standard VAV boxes. The proportion of air drawn from each source is dependent on the cooling demand. The function of this system is to provide warm air an interior zones (thus saving reheat energy) and to increase the air movement in zones normally served by VAV boxes. Obviously, with no reheat being used anyway, the benefits of this system come in increased comfort.

Two-Pipe Fan Coil (TPFC). This is an all-water terminal system consisting of coil and fan located in the zone. Temperature control is achieved by throttling the flow of water through the coil. The fan operates at constant speed across a low static head.

Fan coil units are commonly used in hotel rooms and other zone cooling applications. Typical fan coil installations include reheat to allow control of both the sensible and latent cooling load for the systems. When the reheat coils are omitted, either the zone temperature is controlled by raising the effective coil temperature decreasing cooling with lighter loads but losing dehumidification, or the coil is kept cold maintaining dehumidification but doing significant overcooling.

Two-Pipe Induction Unit (TPIU). This is a zonal air-water system whereby cooling is provided at both the system and zone levels. Primary supply air is cooled and dehumidified and delivered to an induction box located in each space. Room air is induced over a zone coil providing additional sensible cooling and mixed with the primary air. A key parameter is the ratio of induced room air-to-primary air simulated.

SYSTEMS TYPICAL TO THE ASEAN REGION

Efforts were made to identify the types of mechanical system that are commonly used in ASEAN countries. A limited number of questionnaires (~30) were sent to leading building energy professionals in each country requesting estimates of the types of systems and the configurations commonly used based on the engineering judgment of the respondent. Approximately 65% of the commercial buildings use systems with central fans and ducts and of these 35% have variable air volume (VAV), systems, and the rest have constant volume air distribution systems. Of the 35% of buildings with variable air volume systems, a little over half used inlet vane fan control, and there is some use of variable speed drives (~8%) with the rest using discharge dampers. Zone control is achieved by on/off controls (38%) and thermostats (62%). Typical thermostat settings are in the range of 75.2 °F (24 °C). Very few buildings use return fans.

Estimates indicate that 35% of the commercial buildings use systems with no central fan. Split-type systems are the most popular air-conditioners of this category where they are found in 38% of the these buildings, followed by window units (24%) and two-pipe fan-coil units (22%), the rest being rooftop units.

Most of the ventilation air is supplied through fixed outside-air dampers, with ventilation rates designed for 12 cfm/person (5.7 liter/s-person) on the average. Economizer cycles and reheat are simply not used.

Packaged air conditioners are commonly used in retail and small office buildings. Chilled water systems are used for larger buildings. In hotels, central fan systems are used for meeting and common areas and two pipe fan coil units are used in guest rooms. Older office buildings tend to have single zone constant volume systems, while newer construction utilizes VAV systems in large buildings and packaged units in 5 story and smaller office buildings.

Design trends in the ASEAN region, based on responses to the above questionnaire, are in the area of VAV systems, high efficiency chillers (centrifugal and screw-type), variable speed drives for pumps and fans, and more sophisticated controls.

SIMULATION RESULTS

We evaluated HVAC system performance under various assumptions to establish the sensitivity of annual energy consumption and comfort provision. These assumptions included: ventilation rate, increase in infiltration, economizer cycle, control strategy to determine supply-air temperature, zone thermostat set point, cooling coil control strategy, system over- and under-sizing, fan control strategy, internal gains and daylighting, precooling, night ventilation, and zoning. We combined several effective measures together to establish a high-performance case. The different system types were then run under various conditions and compared to the base case.

Base-Case System Performance

The base-case system against which other systems and alternative operating strategies are compared is a variable volume system (VAVS) with no economizer cycle or reheat, inlet vane fan control at a static pressure of 11 cm-H_2O (1080 Pa), a minimum fan volume ratio of 0.5, a supply air temperature of 55 °F (12.8 °C), a minimum outside air quantity of 10 cfm/person (4.7 liter/s-person), and thermostat set points of 75.2 °F (24 °C) daytime and 98.6 °F (37 °C) nighttime, and represents "typical" conditions based on questionnaire responses and engineering judgement.

The 376 MWh of chiller cooling energy constitutes over 40% of the total; lighting at 328 MWh uses 36%; fans at 136 MWh use 15%; and the rest is miscellaneous equipment. The building peak electrical demand of 354 kW occurs Monday February 25 at 3 PM (15:00). The control of space temperatures is good. With a zone thermostat setting of 24 °C and throttling range of 1.1 °C, the average zone temperature during system operating hours was 23.93 °C and only 4% of the time was the temperature beyond the throttling range in some zone. The ability of the VAVS system to handle the high humidity conditions is also quite good (see Table 3). More than 99% of the time the relative humidity of the return-air is within 41-50%. Plant loads were met 99.9% of the hours in the one-year simulation period.

Sensitivity Analysis of Base-Case System Performance

The following sensitivities on the assumptions in our base-case building are shown in Table 1.

Fan Control. The base case assume inlet vane control of supply fans. Fan control using discharge-dampers increases fan energy use by 38% and total energy usage more than 7% over inlet vane control. Consequently discharge dampers are seldom used in commercial building applications to control fan volume. Application of variable speed fan control save 13% of fan energy and 3% overall. The new variable frequency motor drive controllers provide opportunities to take advantage of these energy savings. Building peak power is unchanged for variable-speed fans but increases 2% with discharge-dampers.

Pre-cooling and night ventilation. Pre-cooling the building prior to occupancy one hour earlier than usual raises the total energy budget by 2%, but saves 2% of the peak power. Starting the pre-cooling 2 hours earlier increases total energy by 3% and lowers peak energy both by 3%, while 3 hours of pre-cooling results in a 5.3% energy penalty for a 4.5% peak savings.

An earlier study [Eto 1985] identified Mondays as the most likely day for a peak load to occur due to the "charging" of building thermal mass over the weekend when cooling systems are normally turned off. Therefore, under a scenario where one hour of pre-cooling was undertaken on Mondays only, peak power went down 2% with no significant increase in energy use. Lengthening the pre-cooling period on Mondays had little benefit in terms of reducing the building peak but increased total energy penalty.

Starting the fans *alone* prior to occupancy in an "optimal" fashion (that is, by specifying that they be turned on only when there is just enough time to cool the majority of the zones down to their day-time set-points and no sooner) has the identical end result as the one-hour pre-cooling scenario.

Due to the fact that during the fan-off hours, zone temperatures averaged 3.5 °C higher than outdoor temperatures, it seemed that night ventilation might be a viable strategy for reducing peak power due to morning "pull-down" under certain conditions (i.e. provided there was a net enthalpy loss). A control strategy, whereby the building was mechanically ventilated with the system fans when the indoor-outdoor temperature difference was at least 5 °F *and* some zone was above a threshold temperature setting, was simulated. With a threshold temperature of 75.2 °F (the base-case cooling set-point), the building peak lowers by 3.3% as does the chiller sizing by 3.6% and cooling energy use by 9%. However, fan energy use increases by 146% leading to 20% greater total energy than the base-case. Humidity conditions also increase to 11% of the time in the 51-60% RH range. If, however the threshold is raised to 85 °F, which is about the average zone temperature during fan-off hours for the base-case, peak savings of 3.3% still obtain but at a smaller total energy penalty of 9%.

Supply Air Temperature Control. The control-strategy used in the base-case sets the supply-air temperature at the level were the the *warmest* zone is adequately cooled at the design air-flow rate. The supply-air temperature was limited to a minimum 55 °F. When the supply-air temperature was controlled at a *constant* 55 °F, the resulting performance was identical to the base-case. Therefore, during every operating hour, some zone demanded at least 55 °F air in the base-case strategy. In either case, the temperature condition in other zones is maintained by air-flow modulation of each VAV box.

When the supply-air temperature is dictated by the outside-air temperature under *reset* control logic, it is difficult to maintain temperature conditions in the zones. However, out of the many combinations of supply- and outside-air temperatures examined, a few combinations do hold zone conditions within the throttling range *and* save 2% energy and 3% peak power.

Tamblyn [1987] describes the advantages of using low supply-air temperatures in hot and humid environments. Lowering the minimum supply air temperature set point to 50 °F and 45 °F under the control strategy whereby the the warmest zone determines the actual setting, resulted in total energy savings of 2.2% and 3.4%, respectively. At 45 °F the 28% savings in fan energy is offset by an increase in chiller usage to give an net 3.4% annual energy savings and there is an additional peak power reduction benefit of 5.7%. This is primarily due to reduction in the fan energy that offsets the additional chiller power required to produce the lower temperatures. Return air humidity is also reduced with over half of the hours in the 31-40% RH range. The latent coil capacity increases with lower supply-air temperatures, and since the latent load is relatively high in the ASEAN region, this strategy is promising for reducing humidity levels as well as saving energy. However, as Guntermann [1986] points out, this necessarily results in low air motion in spaces served by VAV systems, often leading to comfort complaints. Care must be exercised in balancing the factors that affect human comfort while pursuing energy conservation.

Alternatively, raising the minimum supply-air temperature to 60 °F increases total and peak 4% and 5%, respectively and leaves loads unmet 25% of the time. In addition, humidity control is lost, somewhat, with all hours registering return-air humidity of 51-60% RH.

Zone Thermostat Set-point. Increasing the zone-thermostat set-point for cooling from 75.2 °F to 77 °F saves 3% total energy and 4% peak power; from 75.2 °F to 79 °F saves 6% and 8%, respectively; and from 75.2 °F to 81 °F saves 8% and 12%.

Internal Gains and Daylighting. Cooling systems are designed with a particular split between latent and sensible cooling. In ASEAN climates, the latent loads are the primary concern. Internal gains typically make up a large portion of the sensible load in commercial buildings. As measures such as more efficient equipment and lighting are introduced, the sensible cooling load in the zones may be reduced significantly increasing the importance of latent loads. This may adversely affect the performance of certain system types.

For the case of efficient artificial lighting, for instance, lowering the lighting power density from 1 to 2 W/ft^2 saves 9% of the cooling energy, 23% of building total energy, and 20% building peak power. Likewise, an increase to 4 W/ft^2 consumes 18% more cooling energy, 47% more total energy, and a 38% higher building peak load. More than a third of the time, loads in some space go unmet.

Daylighting has been identified as a major option of reducing energy use in commercial buildings in tropical climates. When properly controlled, daylighting reduces the electric lighting power requirement, but may increase the sensible heat gain in the perimeter zones. Daylighting can be used to reduce the lighting loads. A continuous-dimming control scheme saves 19% of total energy.

Ventilation and Infiltration. The latent load in ASEAN buildings is very dependent on the rate of ventilation and infiltration. The various system types have different capabilities for dealing with latent loads. Ducted systems bring all ventilation air past the cooling coil where the supply air is dehumidified to near the dew point temperature of the coil. If the coil temperature is set upward (for instance under the supply-air control scheme responding to the warmest zone), there can be a loss of dehumidification. Fan coil systems, on the other hand, must do their dehumidification in the zones where ventilation and infiltration air mixes with the zone air. The this causes the humidity of the air entering the coil to be less, and consequently there is less dehumidification.

Simulation of the operation of an economizer cycle where outdoor air is used when its temperature or enthalpy is below the return air conditions demonstrated no benefit in the latter case and increased total energy by 5% in the former.

Increasing outside-air quantity during system operating hours from 10 to 30 cfm/person increases total energy by 16%, cooling energy by 37%, fan energy by 6%, chiller size-requirements by 38%, and building peak by 18%.

Infiltration introduces outdoor air directly into the perimeter zones. If infiltration is large, one would expect humidities and zone latent cooling loads to be greater in the perimeter zones. However, in our simulations infiltration occurs only during fan-off hours and actually shows a very small depression in energy usage when increasing the infiltration rate from 1 to 2 air changes per hour (ach).

Impact of System Sizing. Our base case sizing methodology uses endogenous DOE-2 routines which size fans and coils to meet maximum non-coincident zone loads and chillers to meet the peak load. It has been suggested that it is a grave design error to oversize air-conditioning systems in hot and humid conditions, because of the loss of latent cooling, and that in fact slight undersizing is preferable [ARMM 1980]. We tested the liability of oversizing the fans and chiller by 25%. A small (3%) energy penalty results, with little effect on return-air humidity impact. Undersizing the fans and chiller by 25% shows less than 1% savings and a significant loss of temperature control (i.e. over half of the time some zone's temperature is out of its throttling range).

Over-sizing of the air-handling unit (AHU) by *only* 25% has the effect of raising total energy consumption by 2% and shifting the humidity conditions upward such that 7% of the time it is above 50% RH, as opposed to virtually no hours above 50% RH for the base-case. Undersizing the AHU behaves similarly as above.

Sizing of the system equipment to meet the maximum coincident building demand (instead of the default assumption of sizing to meet each zone's maximum load regardless of when it occurs) increases consumption only slightly, but leaves loads unmet 10% of the time.

Sensitivity to Zoning. Separate variable temperature systems have greater flexibility than a single system. As the temperature is set upward, however, there is a loss of dehumidification. The sensitivity to zoning was tested by running simulations with separate systems serving zones with core, east, west, south, and north orientations. Total and building coincident peak energy use falls 5.6% and 7.1%, respectively, mostly due to the 28% reduction in fan power due to the lower static pressure accompanying shorter duct runs. Cooling energy savings were 3.5%. The humidity balance changed, though, with 11% of the operating hours showing return air RH greater than 50%.

High Performance Case. Combining several of the measures together in one high-performance case shows significant savings. It is usually necessary to run a separate simulation, because invariably the savings are less than the sum of the savings for each measure run individually. This is because of interaction among conservation measures. In this case we combined variable-speed fans with raised space thermostat-settings (81 °F) and supply-air temperature (45 °F) and one-hour of pre-cooling on Mondays. All other variables remained as in the base-case. Total energy consumption goes down 14% while the electrical peak is reduced 16%. The total energy savings are achieved through

13% and 58% cooling and fan energy reductions, respectively. Humidity levels are very low, however, with the majority of hours below 40% RH. Building occupants accustomed to high outdoor humidity levels may find these conditions unacceptable.

Comparisons Among System Types

In this section, we compare the performance of the base case VAV system with that of six other generic systems. Table 2 shows the annual energy breakdown and peak for the various systems modeled. For the more commonly installed systems in the ASEAN region, we also discuss sensitivities of the input assumptions, focussing on those instances where the results differed from those of the base case VAV system, or where a significant change in performance was exhibited.

Two-Pipe Fan Coil (TPFC). This systems uses 16% less cooling energy, 59% less fan power, and 15% less total energy than the VAVS. Because it is not necessary to move air through long ducts, the pressure drops are much smaller. Chillers are also sized smaller by 13% and building peak electrical load is 18% lower. However, this comes at the cost of a significant loss of humidity control. Only 6% of the time is the relative humidity below 50%; 29% of the time the relative humidity is above 60% The building electrical peak demand registered on June 10 at 4 PM (16:00) (again on a Monday) and was 291 kW, the lowest of all systems.

The pre-cooling strategy only makes the humidity matters worse. Raising the thermostat set-point only exacerbates the humidity situation. For instance, with a thermostat set-point of 81 °F there is a significant energy savings of nearly 10%, but the relative humidity is always above 50% and 70% of the time it is above 60% RH. Running the coils colder helps to alleviate the high humidity conditions somewhat by increasing dehumidification, though, with no energy penalty. With a 45 °F supply-air temperature, the RH is above 60% only 6% of the operating hours and RH 50% or below 71% of the time.

Single Zone Reheat (SZRH). This system responds only to one zone specified as the control zone (in this case an east-facing zone on a middle floor), and all other zones are conditioned as the control zone with no reheat capability. It uses 10% more energy than the VAVS system, mostly due to the 50% increase in fan power. Chiller energy use was higher by 4% and the chiller sizing greater by 6%. The peak day in terms of total electrical demand was June 10 at 4 PM (16:00) with 365 kW, though February 22 was a close second. Humidity control is almost as poor as with the TPFC system, with only 89% of the hours above 50% RH and 21% of the hours above 60%. Shifting the control zone to one with a different orientation has the effect of improving the performance of the system. For the case where the control zone was west-facing, a 2.4% overall savings occur with no change in the building peak, improved temperature control, and only a slight degradation in humidity control. When the control zone is shifted to a south-facing zone, a slightly more modest 1.8% savings accrue.

Reheat Fan System (RHFS). This system under the base control scheme reponds to the warmest zone, and all other zones are similarly supplied with cooling. As with the SZRH system, no reheat was made available. This is the highest energy user of all, 11% more total energy and 4% higher peak load than VAVS. However, zone temperature control is maintained at all times in the simulations and humidity control is improved over SZRH, though not as well as VAVS.

The strategy of under-sizing the system by 25% by reducing the design air-flow and chiller capacity has a positive impact on energy consumption *and* humidity control. Total energy goes down 6% and 78% of the time the humidity is below 50% RH (as compared to only 11% in the base RHFS strategy). The explanation is that the chiller operates at near capacity, where the efficiency is highest, for a much larger portion of the operating hours (in the 90-100% PLR instead of 70-80% PLR). A particular configuration of the RHFS system whereby multiple systems each serving zones of a particular compass orientation are run produces significant savings: total energy 10.4%, peak power 9%, fan energy 31%, and cooling 10%. Although the savings are great compared to the base RHFS, the energy use level is only slightly better than the base VAVS system. Humidity conditions were unfavorable too, with 82% of the time the return air over 50% RH, 23% of the time above 60% RH, and 7% of the time above 70%. Variations in other system operating parameters produce similar *savings* (in percentage terms) as the with VAVS system but always use more energy than other systems.

Powered Induction Unit (PIU). This system provides a constant volume of air to each zone, inducing plenum air when less cool primary air is needed to handle the load. This system is used in the perimeter zones with standard VAV boxes in the core zone. The PIU system uses 3% more total energy than the VAVS system, 6% more each in the chiller and fans. Peak power demand is 2.5% more as well. Humidity control is comparable to the VAVS system.

Ceiling Bypass Variable Volume (CBVAV). This system throttles zone air-flow when full cooling is not needed by diverting flow into the plenum space above the zone. The energy performance is identical to the RHFS, but with much superior humidity control.

Two-Pipe Induction Unit (TPIU). This system is a mixed air-hydronic zonal system providing some cooling and humidification at the system level. The constant volume of primary air is mixed with 2.5 times as much induced secondary air at the terminal unit. The energy performance is second only to the other zonal system considered here (e.g. TPFC). It uses 6.7% less total energy, 11.3% less peak power, 32% less fan power, and 4.8% less energy to run the chiller. The primary air supply maintains good dehumidification of the outdoor ventilation air, while the induction unit maintains good mixing of air in the zones and good zone temperature control. What distinguishes this system from the TPFC system is that the return-air relative humidity is virtually always in the 41-50% range.

Hourly Profiles

It is often helpful in interpreting the annual results to look at hourly profiles within the building. In Figures 1 through 6 we compare the SZRH, VAVS, and TPFC systems on two separate days. August 15 was chosen arbitrarily whereas February 22 is the peak day for the two central system-types. We are primarily interested in the space conditions and cooling loads. Four variables are plotted over the course of the day: air flow, dry-bulb temperature, humidity ratio, and cooling coil load. For the two central system-types the space conditions are actually ***return-air*** conditions and thus represent a weighted-average of individual-zone conditions across the building, whereas the fan coil results come from an arbitrarily chosen zone. So that systems can be directly compared, the air-flow and energy quantities are expressed on a per unit floor area basis and the ordinate range is the same for each day simulated.

Fan coil systems have trouble handling latent loads. As shown in Figure 4, during the morning humidity ratios reach almost 14 g moisture/kg dry air. As the coil responds to increasing sensible loads throughout the day, the humidity is eventually driven down to acceptable levels.

The SZRH system displays a curious transient response to the morning start-up load by first cooling at near-peak capacity in the first hour, then throttling way back in the second hour, and finally recovering in the third hour and beyond to a more stable climb in coil load response. The VAVS system behaves similarly but dampened considerably and with little impact on temperature or humidity. It is unclear whether real buildings with these systems would experience a similar phenomenon or whether this is simply a simulation artifact.

By maintaining lower coil temperatures and by modulating capacity by reducing the air flow through the cooling coils, the VAVS system shows superior moisture control, maintaining humidity ratio at or below 9 g/kg.

Temperature control is similar between the system types, although the SZRH system maintains somewhat lower levels. Again, since the central systems report return air conditions, individual zones will exhibit more variable behavior.

Load Shapes

The pattern of electric loads in buildings is of interest to both utilities who see rising electricity demand on the system and to building operators who pay must demand charges for electricity. One such representation is the load duration curve (LDC) which describes the number of hours total building electrical demand was at or above a given level. In Figure 7, we plot two curves, one is the base-case LDC and the other is the earlier mentioned high-performance case. Both buildings have a fairly "flat" load shape at the higher demand level dropping off precipitously at 30% to 35% time fraction. Beyond the 40% time fraction the building is unoccupied and operates at minimal demand. The high-performance case shows less opportunity for peak-shaving due to the flatter slope at high demand.

Cooling load can be similarly plotted and is shown in Figure 8. The cooling load never goes below 110 (387 kW) tons during the operating hours. However, only 5% of the time does the cooling load go above 210 tons (739 kW). If conservation measures or load shifting could preempt the need to meet those loads for only 5% of the operating hours, a 12% cooling-peak savings results.

The chronological daily electrical load pattern is helpful for knowing when demand occurs during the day. Figure 9 shows an *average day* profile for electrical demand. This is determined by summing the electricity consumption by hour of the day over the whole year and dividing by the total to get the demand frequency. It is curious that the peak demand frequency occurs at noon when the instantaneous peak actually occurs later in the afternoon. This is probably because the plot includes Saturday morning operation over the year. An interesting plot would be the demand profile over the *peak* day but is not shown here.

To be most meaningful to the utility analyst, the coincidence of building loads with the electric utility's system loads has to be established explicitly. This allows a determination of the value of any load reduction (or increase) to the the utility. Since our analysis is regionally based (and not focussed on a single utility service area), we have ignored this effect here.

CONCLUSIONS

- Variable air volume systems clearly have the best combination of low energy use and maintenance of comfortable zone temperature and humidity levels.
- Constant volume systems have significantly higher energy use than the other systems, and without reheat can give significant overcooling of the space as well as producing high space humidity conditions.
- Two pipe fan coil units have the lowest energy consumption primarily due to fan energy savings. The low latent cooling capacity adversely affects humidity control and these systems performed poorly during morning pull-down periods.
- Permitting excess outdoor air into the building either by the use of an economizer cycle or high ventilation rates carries a significant energy penalty.
- The power level for internal gains has a direct impact on both total, cooling, and fan electrical energy use.
- The easiest measure for generating savings is to increase the thermostat setting during the daytime. Savings in system equipment sizing, energy and peak power all accrue at no cost.
- Lower supply-air temperatures have significant benefits in reducing fan and building power requirements.
- Control strategies such as pre-cooling, for operating the system during unoccupied hours can save on peak power at the expense of higher energy costs. The structure of local electricity tariffs will determine whether the trade-off is worthwhile.
- A combination of system conservation measures incorporated into one building saved 14% of total energy and 16% on peak power. Clearly, proper air-conditioning system configuration and operation has comparable savings potential to the more frequently cited envelope and and internal gain conservation measures.
- The nature of the savings, be it energy, peak power or equipment sizes, are different for each measure. Depending on whether one is trying to economize on first cost, energy costs, or demand charges dictates the choice of technologies and control strategies.

FUTURE WORK

In view of the preliminary nature of this work it is fruitful to suggest areas of further research pursuit namely:

- A careful identification of *actual* air-conditioning practices in ASEAN buildings is needed. Energy audit and survey activities getting underway should help in accomplishing this. "Benchmarking" the performance of the stock air-conditioning systems clarifies the conservation potentials indicated here.
- Moisture conditions within the spaces are a large concern in the ASEAN region. The daily cycle of moisture adsorption/desorption is not well understood in buildings. Measurements indicate that the effect may be large [Martin 1986]. Part of the auditing effort in the ASEAN regions should attempt to characterize the success or failure in dealing with the high ambient humidity levels. Humidity also presents a significant modeling challenge. DOE-2, for instance, does not handle adsorption/desorption processes between room air and furnishings, and this may skew results. Handling the mass transfer processes rigorously entails a large

increase in the computational effort. MAD/TARP, developed at the Florida Solar Energy Center, is a model with these capabilities. Analysis of moisture impacts is a current area of research in the United States [FSEC 1987].

- Collection of cost data on system components (including labor costs), and electricity and fuel rates should be gathered in ASEAN countries to facilitate economic analysis. Because of the distribution of costs between capital and labor are different in ASEAN countries from the U.S., analysis based on U.S. values can be misleading.
- In this work we analyzed the load impacts of measures which are employed primarily for saving energy. There are situations, however, where it might be advantageous to undertake cooling strategies, such as thermal energy storage, that shift load to other time periods without saving any energy (or even at the expense of somewhat higher energy use). These situations usually entail either time-of-use electricity rates with significant price differentials between on- and off-peak, or high demand charges with ratcheting clauses. Thermal storage technologies under different operating strategies and tariff structures need to be analyzed.
- Other locations within the ASEAN region besides Malaysia need to be assessed for air-conditioning performance using local weather and building types.
- Comfort conditions were referenced in a general way in this paper by looking at binned temperature and humidity levels. A preferable approach is to link hourly DOE-2 zone conditions with a predictive comfort model such as the Fanger [1970] or Gagge [1972] models, which both explicitly account for air-flows, and occupant clothing and activity levels in addition to coincident temperature and humidity.

ACKNOWLEDGEMENTS

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Table 1.

Sensitivity results from base-case VAV system*

CASE	FAN SAVINGS		CHILLER SAVINGS		BLDG SAVINGS	
	Energy	Sizing	Energy	Sizing	Energy	Peak
Fan Control:						
Discharge Dampers	-38%	0	-4%	-1%	-7%	-2%
Inlet Vane (Base Case)	-	-	-	-	-	-
Variable Speed	+13%	0	1%	0	+3%	0
Precooling:						
Precool 1 hr	-4%	0	-3%	+2%	-2%	+2%
Precool 2 hrs	-8%	0	-5%	+4%	-3%	+3%
Precool Monday 1 hr	0	0	0	+2%	0%	+2%
Supply Air Temperature:						
Tset 60F	-28%	-30%	0	0	-4%	-5%
Tset 55F (Base Case)	-	-	-	-	-	-
Tset 50F	+17%	+17%	-1%	0	+2%	+4%
Tset 45F	+28%	+29%	-2%	0	+3%	+6%
Zone Temperature Setpoint:						
Tzone 75.2 (Base Case)	-	-	-	-	-	-
Tzone 77F	+9%	0	+4%	+3%	+3%	+4%
Tzone 79F	+15%	0	+9%	+8%	+6%	+8%
Tzone 81F	+19%	0	+13%	+12%	+8%	+12%
Lighting and Daylighting:						
2 W/ft2 (Base Case)	-	-	-	-	-	-
1 W/ft2	+11%	+6%	+9%	8%	+23%	+20%
4 W/ft2	-24%	-12%	-18%	-14%	-47%	-38%
Continuous Dimming	+10%	+8%	-	+7%	+19%	+19%
Ventilation:						
10cfm/per (Base Case)	-	-	-	-	-	-
30cfm/per	-6%	0	-37%	-38%	-16%	-18%
Night Ventilation:	-68%	0	+4%	+3%	-9%	+3%
High Performance:	+58%	+29%	+13%	+11%	+14%	+16%

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* Sign convention in Table 1: positive savings (+) means lower energy use and visa versa.

Table 2.
Comparison of System Performance: *Energy*

System	Chiller (MWh)	Fans (MWh)	Lights (MWh)	Equip. (MWh)	Total (MWh)	Peak (kW)
VAVS	376	136	328	72	912	354
SZRH	391	209	328	72	1000	365
RHFS	401	210	328	72	1011	368
PIU	398	145	328	72	943	363
TPFC	315	56	328	72	771	291
TPIU	358	93	328	72	851	314
CBVAV	401	209	328	72	1010	362

Table 3.
Comparison of System Performance: *Humidity*

	Return-Air Relative Humidity Hours						
System	81-100	71-80	61-70	51-60	41-50	31-40	0-30
VAVS	0	0	0	7	3077	0	0
SZRH	0	109	525	2126	324	0	0
RHFS	0	3	405	2346	330	0	0
PIU	0	0	0	0	3084	0	0
TPFC	0	180	716	2000	188	0	0
TPIU	0	0	0	22	3062	0	0
CBVAV	0	0	0	27	3057	0	0

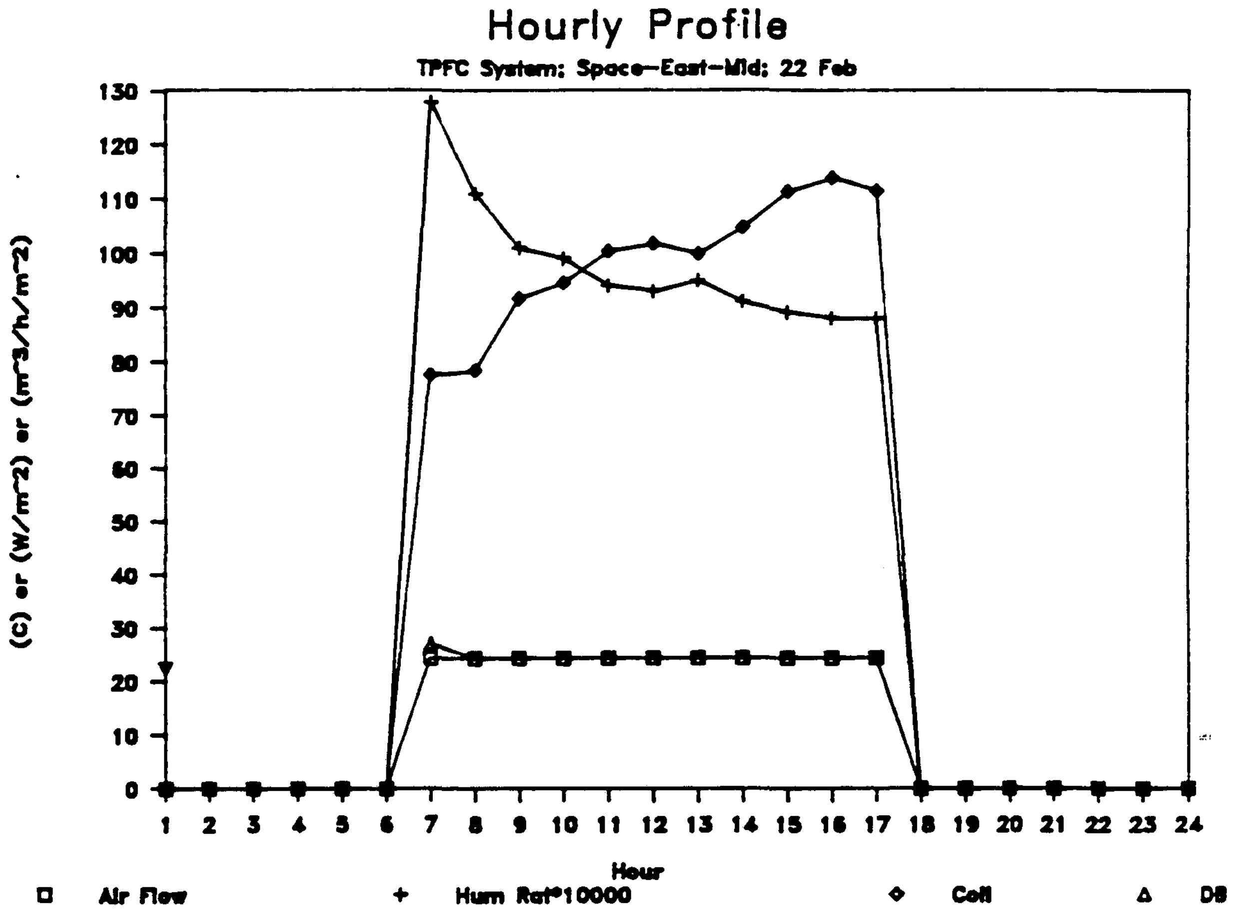

Figure 1. Hourly Profile for a Two Pipe Fan Coil (TPFC) System showing zone humidity ratio, temperature, coil air flow and cooling load on a typical day (22 February 1985).

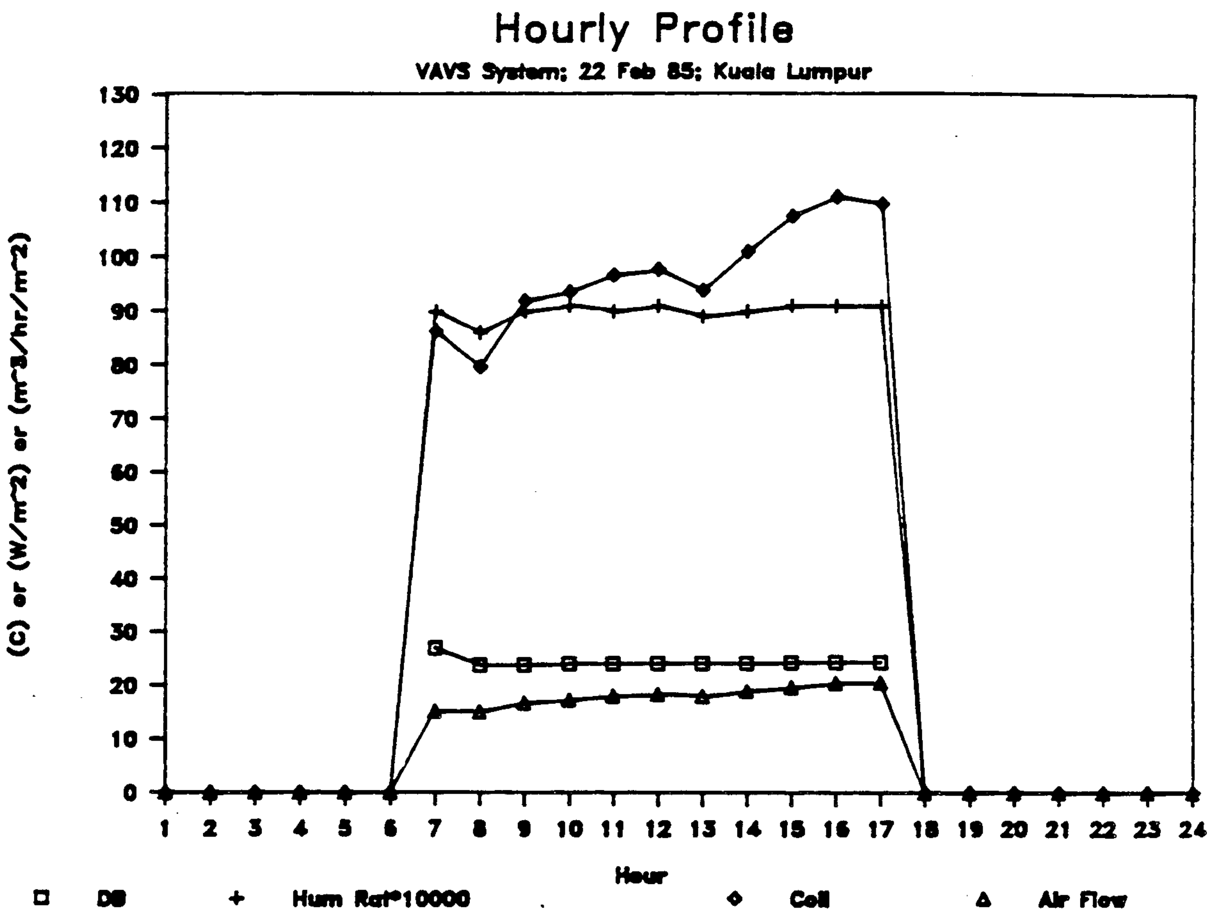

Figure 2. Hourly Profile for a Variable Air Volume (VAV) System showing return air humidity ratio and temperature and system air flow and cooling load on a typical day (22 February 1985).

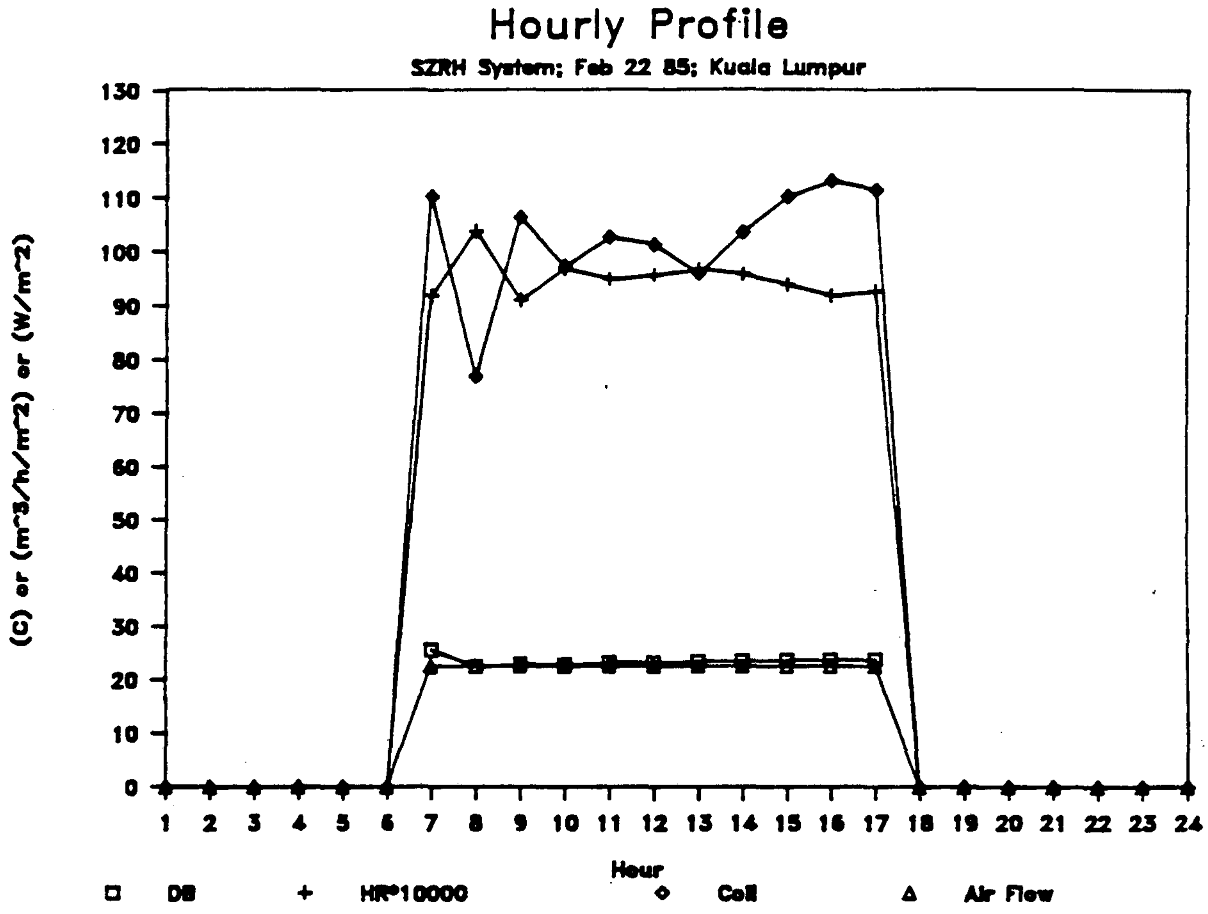

Figure 3. Hourly Profile for a Single Zone Reheat (SZRH) System showing return air humidity ratio and temperature and system air flow and cooling load on a typical day (22 February 1985).

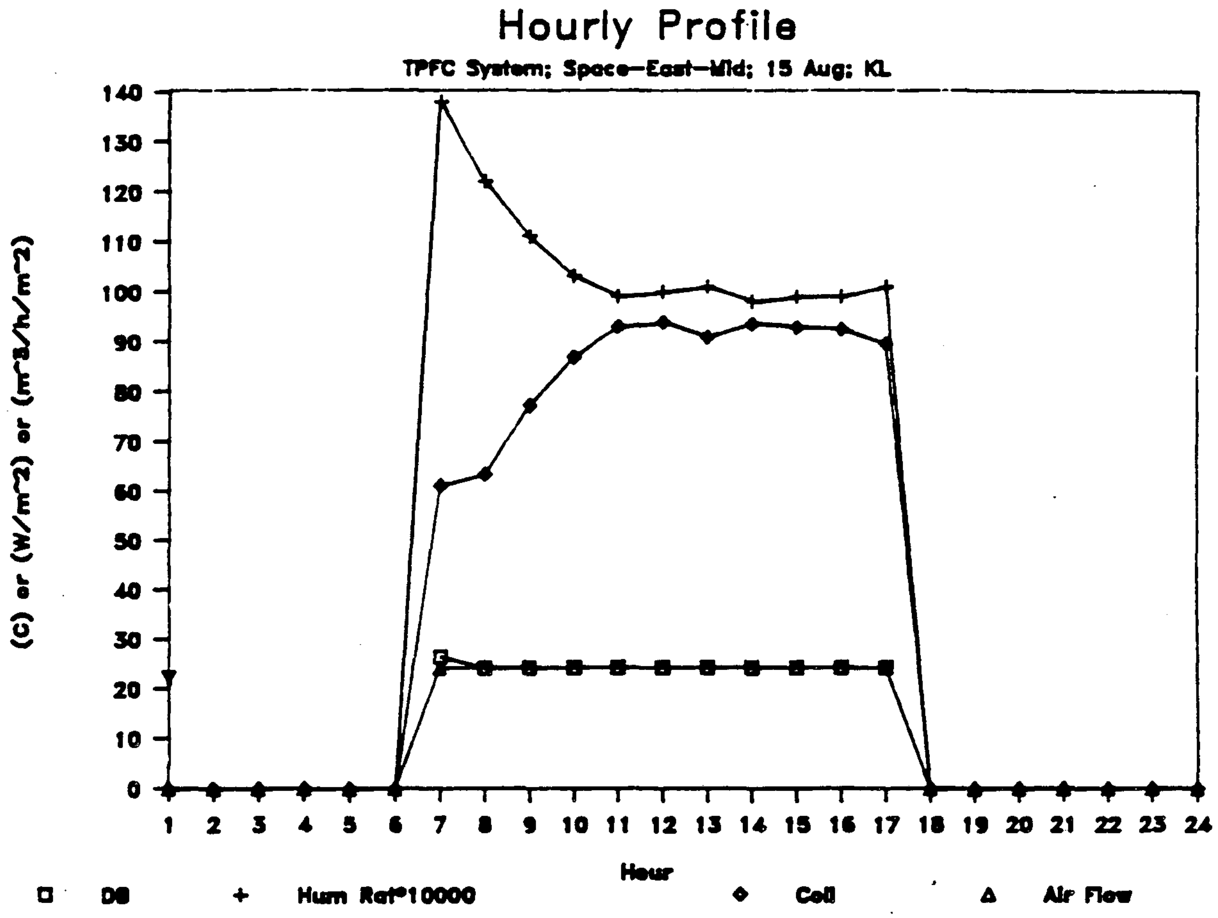

Figure 4. Hourly Profile for a Two Pipe Fan Coil (TPFC) System showing zone humidity ratio, temperature, coil air flow and cooling load on a peak day (15 August 1985).

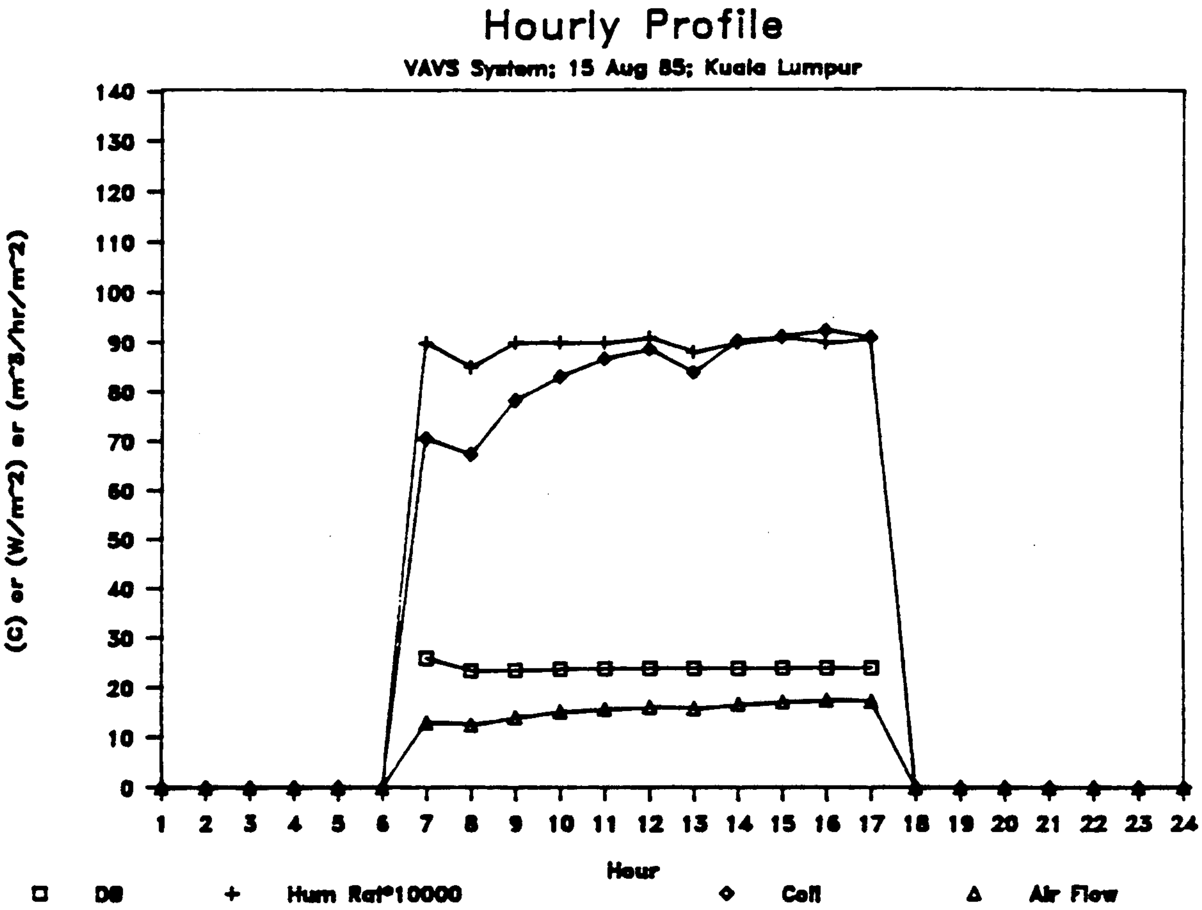

Figure 5. Hourly Profile for a Variable Air Volume (VAV) System showing return air humidity ratio and temperature and system air flow and cooling load on a peak day (15 August 1985).

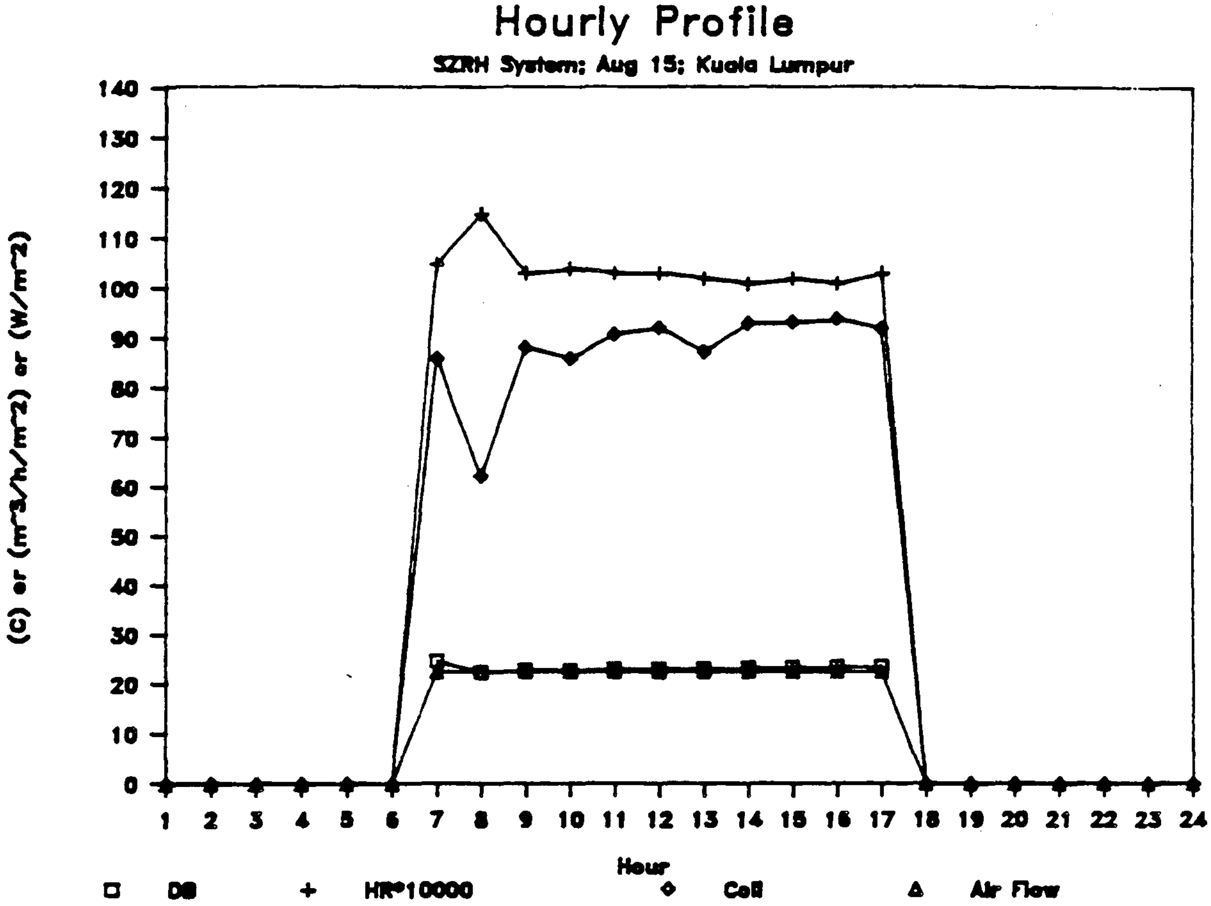

Figure 6. Hourly Profile for a Single Zone Reheat (SZRH) System showing return air humidity ratio and temperature and system air flow and cooling load on a peak day (15 August 1985).

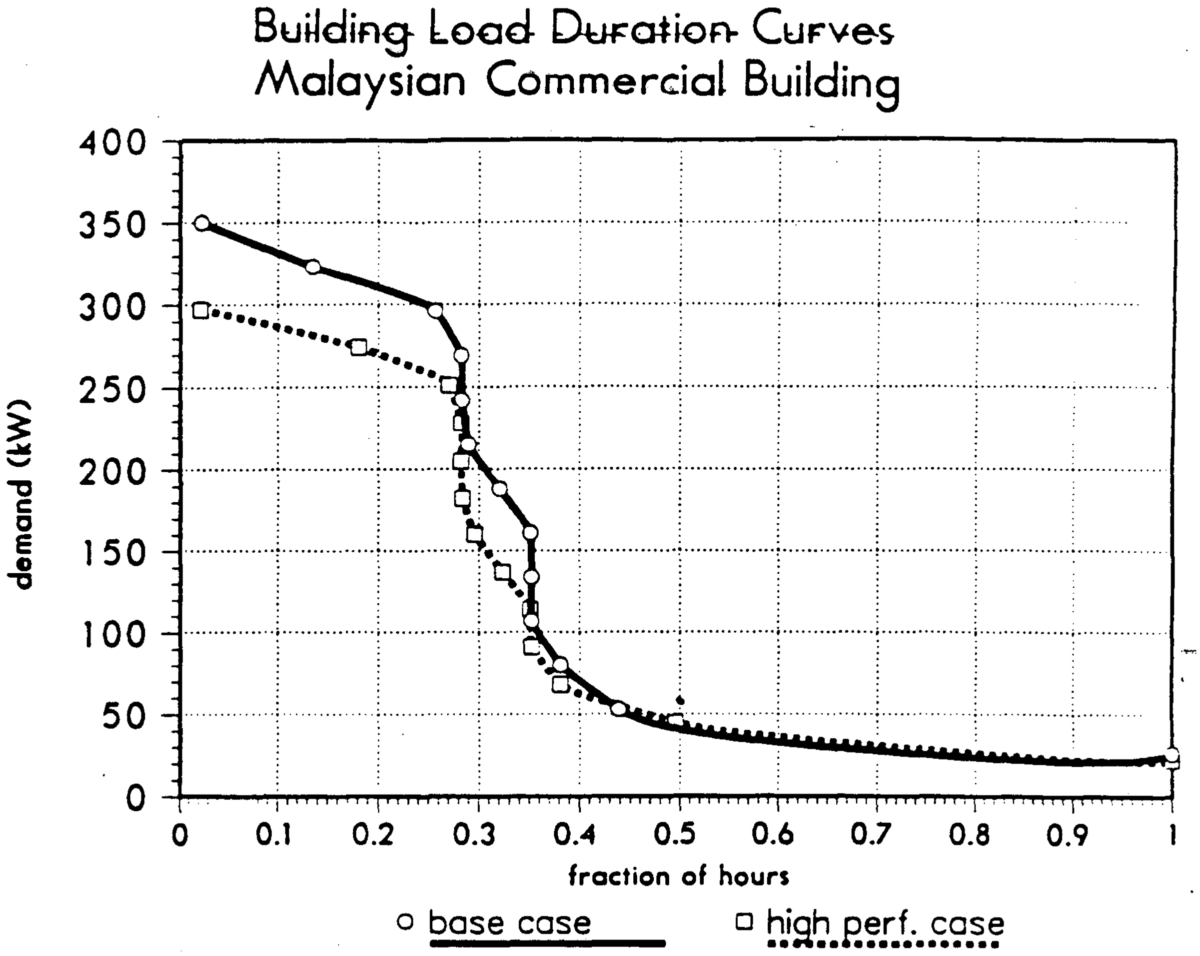

Figure 7. Load Duration Curves for Malaysian Commercial Building showing total electricity demand (kW) as a function of the fraction of annual hours for the base and high performance cases.

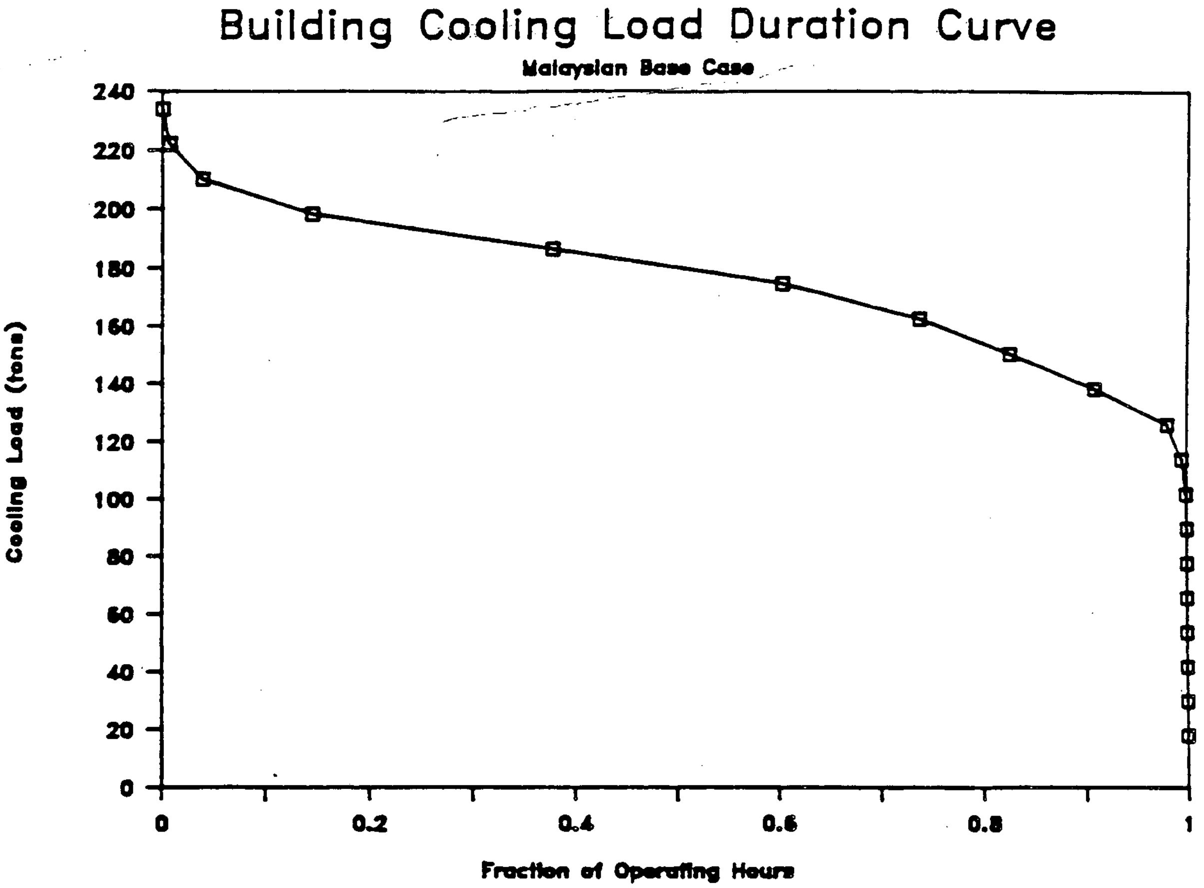

Figure 8. Cooling Duration Curves for Malaysian Commercial Building showing chiller cooling load (tons) as a function of the fraction of operating hours for the base case.

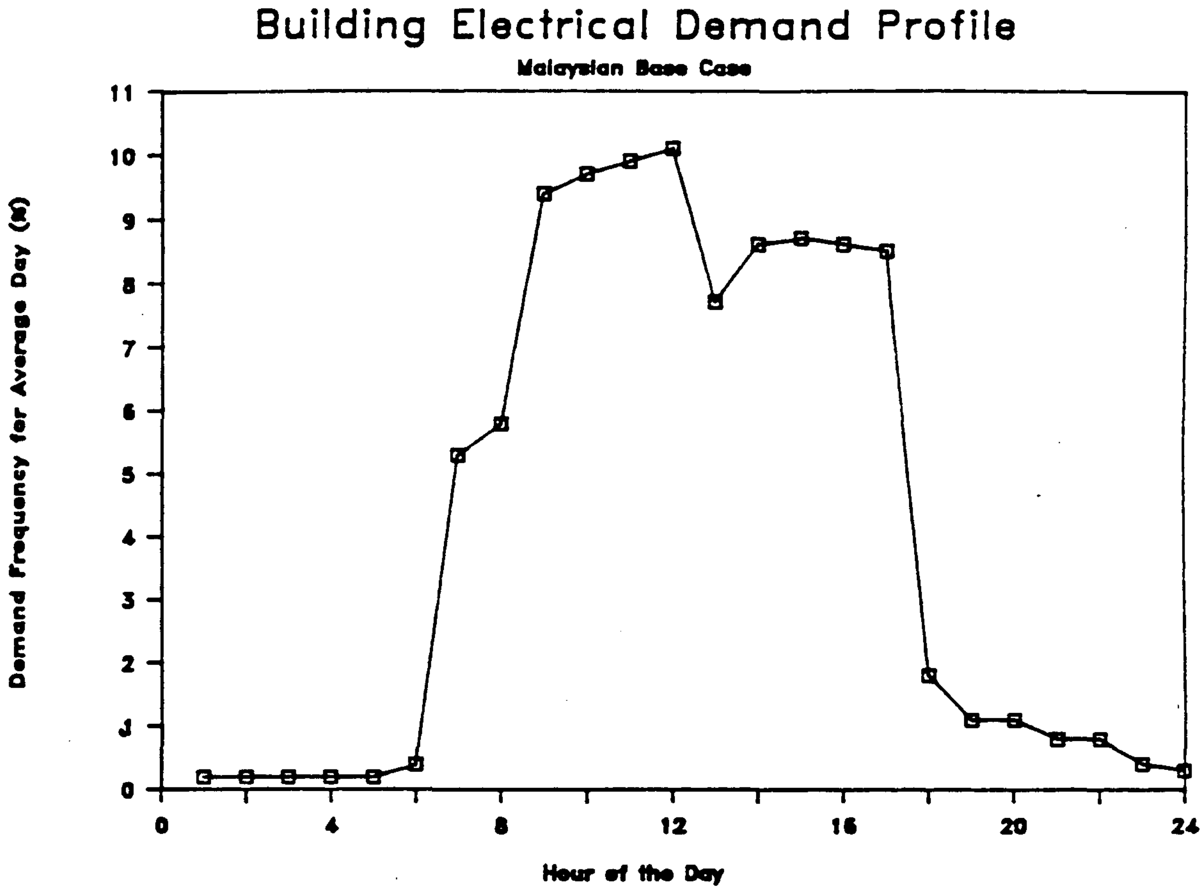

Figure 9. Average Annual Building Electrical Demand Profile showing demand frequency for the average day (%) as a function of the hour of the day for the Malaysian base case commercial building.

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