Title

Results from Lab Testing: Rethinking VAV Hot Water Terminal Unit Design

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Rethinking VAV Hot Water Terminal Unit Design: Results from Lab Testing

This article summarizes the results of a recent research project[i] that studied operational issues with variable air volume (VAV) reheat terminal units caused by temperature stratification at the discharge of the heating coil, and reduced capacity and higher flow rates required for increasingly popular low temperature hot water systems.

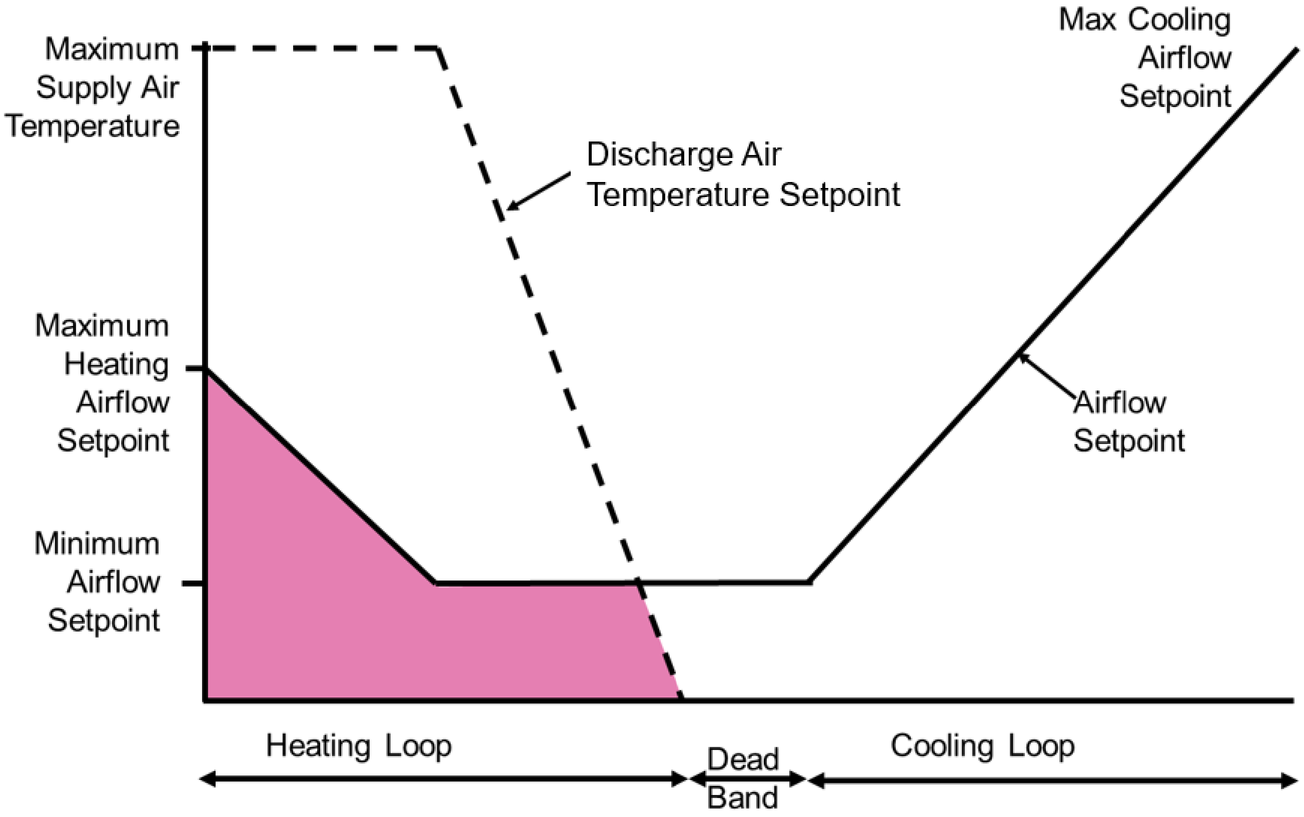
Background

The scope of this research project was driven by the following issues associated with recent design trends:

Discharge Duct Temperature Stratification with Dual Max Control Logic

Modern VAV reheat systems use what is known as "dual maximum" control logic[ii] depicted schematically in Figure 1. This logic requires a discharge air temperature (DAT) sensor be installed at the reheat coil outlet; the hot water control valve is then controlled to maintain DAT at a setpoint that is reset by the room temperature heating control loop. The intent of using cascading control loops is to limit space temperature stratification for systems that supply air from the ceiling, and to ensure compliance with ASHRAE Standard 90.1[iii] which limits DAT to no more than 20°F (11°C) above the space temperature setpoint. But in practice, users of dual maximum logic have found that DAT measurement can be inaccurate due to stratification of discharge air off the reheat coil. This can lead to underheated zones should the DAT sensor read a higher temperature than the average DAT, and to increased space temperature stratification when the DAT sensor reads lower than the average. This research aimed to determine the nature of DAT stratification and how the location and type of DAT sensor can improve DAT measurement.

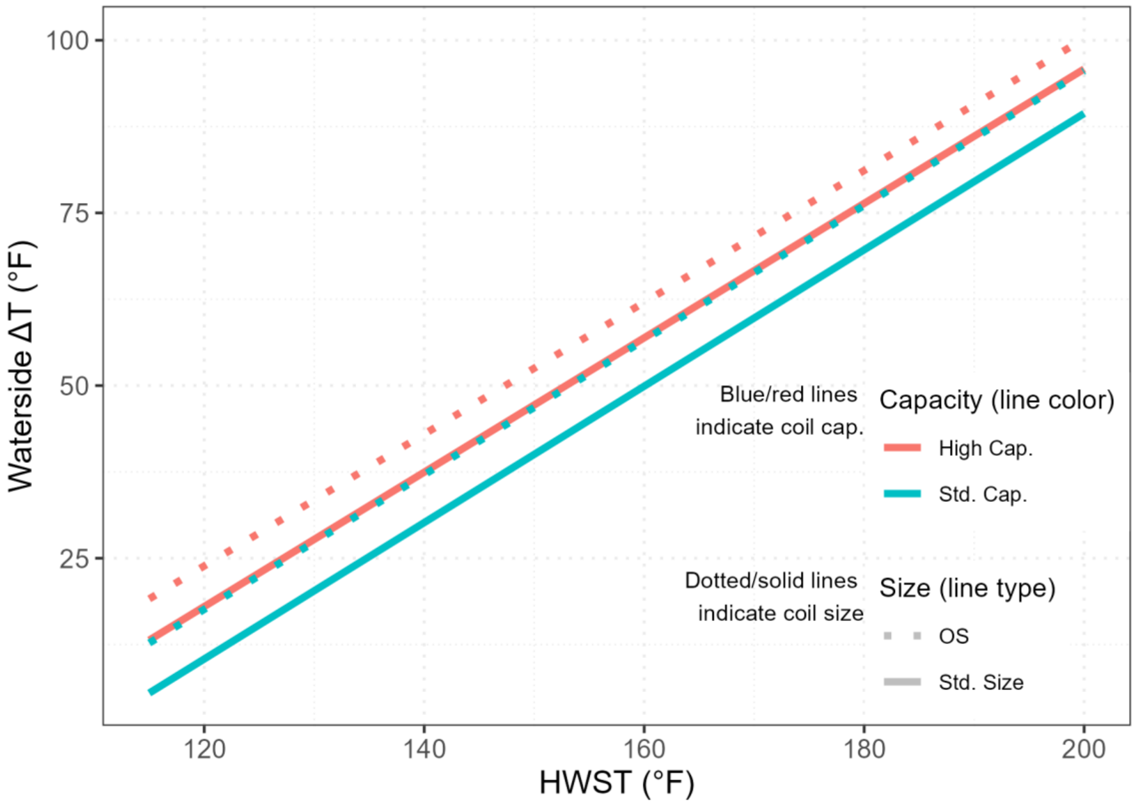
Figure 1. Dual Maximum VAV Reheat Control Diagram



Reduced Coil ΔT in Low Temperature Hot Water Systems

Conventional hot water boilers can readily produce hot water supply temperatures (HWST) in the 160°F to 180°F (70°C to 82°C) range. But modern HW systems are being designed for lower HWS temperatures. For instance, design HWST is commonly in the 140°F to 160°F (60°C to 70°C) range for condensing boilers so that return HW temperatures are low enough to result in condensing of flue gases, and in the 120ºF to 130F (50ºC to 55ºC) range due to the limitations of electric heat pumps, which are increasing in popularity to meet electrification goals. Reheat coils designed for traditionally high HWSTs are typically 1- or 2-rows with circuiting that provides a 40°F to 60°F (22°C to 33°C) temperature difference (ΔT), although engineers tend to conservatively design HW distribution systems for 30°F to 40°F (16°C to 22°C) ΔT. But these same coils when supplied with 120°F (50°C) HWST will generate a 10°F to 15°F (5°C to 8°C) ΔT which can triple or quadruple HW flow rates. This can be seen in Figure 2 which compares four variants of one manufacturer's 2-row reheat coils: standard capacity (10 fpi) vs. high capacity (12 fpi), and standard coil size vs. oversized (OS, which are one size larger by face area than standard coils – see Taylor 2015[iv]). For new construction, low ΔT substantially increases piping and pump sizes and costs. For retrofits, low ΔT may require the full replacement of existing HW piping that otherwise could be reused. Hence, our study aimed to determine optimal coil circuiting to maximize ΔT.

Figure 2. Typical Reheat Coil HWST vs. ΔT
(8” Inlet, 2 row coil, 285 cfm, 55°F EAT, 90°F DAT)



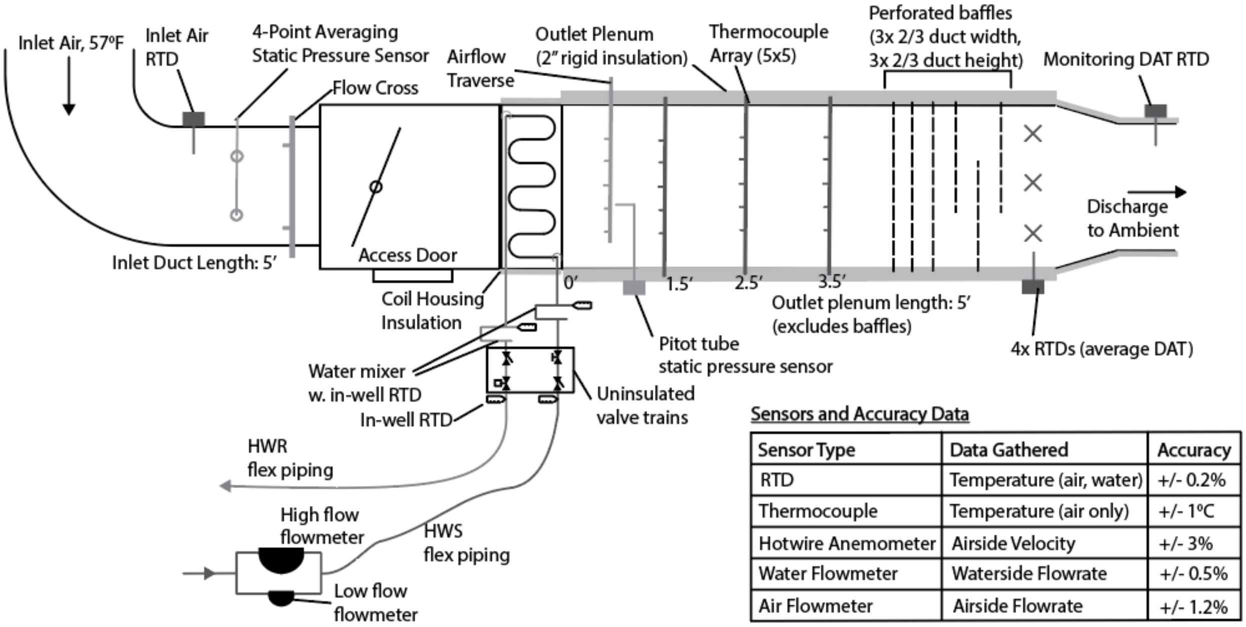
Description of Experiment

We conducted an experiment to explore the performance of coils operating under real-world conditions with these specific objectives:

1. **Determine the impact of damper position** on heating capacity.
2. **Determine the extent of discharge air temperature stratification** downstream of the reheat coil and the impact on DAT sensor location.
3. **Examine alternative coil circuiting designs to increase capacity and ΔT**, particularly for low HWST designs.

We conducted the experiment using the apparatus shown in Figure 3. We operated the system at design heating conditions and varied coil characteristics, damper positions, and HWST.

Figure 3. Testing Apparatus Diagram



Sensors and Accuracy Data

Sensor Type	Data Gathered	Accuracy
RTD	Temperature (air, water)	+/- 0.2%
Thermocouple	Temperature (air only)	+/- 1ºC
Hotwire Anemometer	Airside Velocity	+/- 3%
Water Flowmeter	Waterside Flowrate	+/- 0.5%
Air Flowmeter	Airside Flowrate	+/- 1.2%

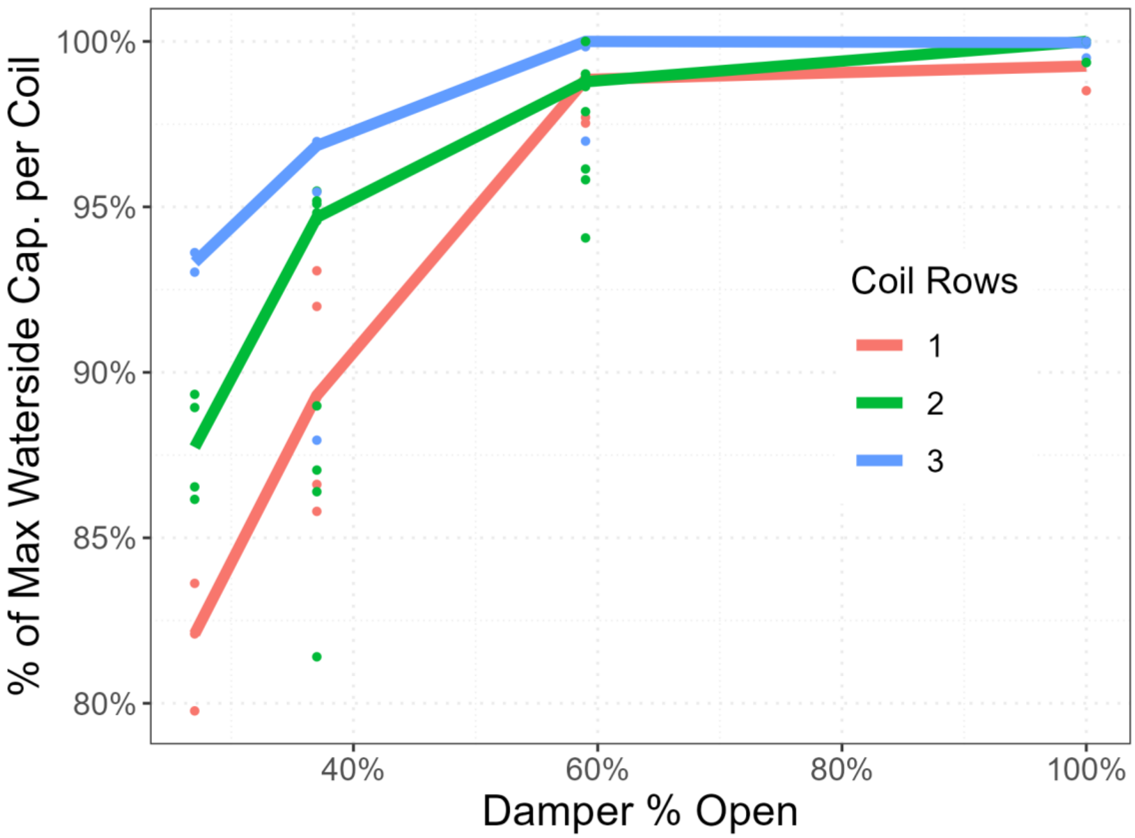
Results

Impact of Damper Position

We measured waterside capacity as damper position varied from 27% to 100% open with airflow and water flow held constant at design rates. We found that coil capacity decreases as the damper closes despite constant airflow – see

Figure 4 where each point shows the coil's capacity expressed as a percentage of the maximum capacity recorded in the same test run. Each line shows the median of all points for 1, 2, and 3 row coils.

Figure 4. Damper Position vs. Coil Capacity with Constant Airflow Rate



This finding highlights the potential for VAV reheat boxes operating at high static pressures and partially closed dampers to have up to 20% less heating capacity than design. Large VAV reheat systems typically operate with many zones having partially closed dampers during heating due to their proximity to the air handler or due to high duct static pressure setpoints. This can be mitigated by implementing duct static pressure setpoint reset according to ASHRAE Guideline 36[v]. Since normal variation in duct pressures in VAV systems will always result in some heating zones having partially closed dampers, higher HW flow will be required to compensate. This is almost always possible in 2-way variable flow systems if flow at each coil is not limited to design flow using, for instance, automatic flow limiting devices (see Taylor 2017[vi] for other reasons not to use these devices).

Temperature and Velocity Stratification

We measured temperature stratification in the discharge plenum with three 5x5 thermocouple arrays placed at different lengths within the plenum: 1.5 feet, 2.5 feet, and 3.5 feet from the coil. We also measured velocity stratification by taking a 5x5-point velocity measurement near the most upstream thermocouple grid at each damper position.

The velocity data showed that at more-closed damper positions, velocity was higher at the top of the duct and lower at the bottom of the duct, compared to the overall average. We saw a similar trend associated with the temperature data, in which temperatures were cooler at the top and warmer at the bottom, compared to the average, with the effect intensifying as the damper closed. Since reheat coils are typically piped with the hottest water entering at the bottom of the coil, there will always be a baseline level of DAT stratification. However, the fact that stratification intensifies as the damper closes suggests that this effect is at least in part a result of higher velocity air being directed toward the top of the coil by the damper blade as the damper closes as shown in Figure 5.

Figure 5. Schematic of Velocity Profile caused by Damper Blade Deflection

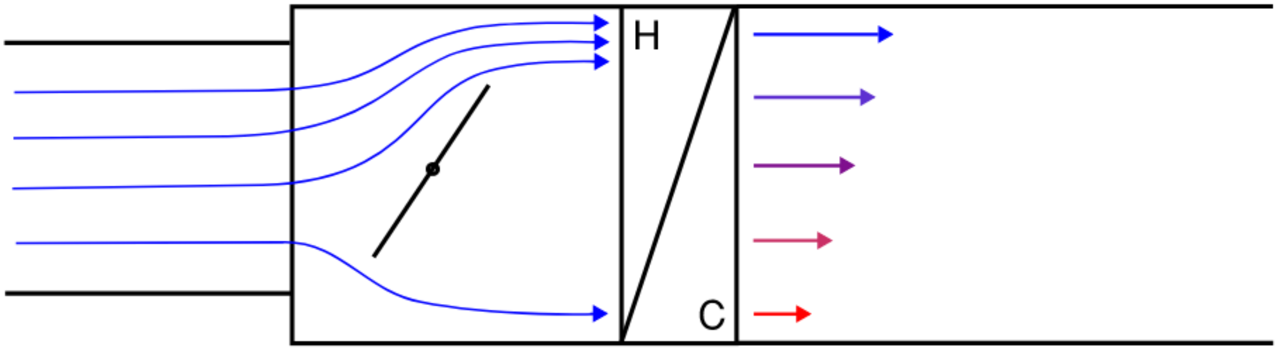
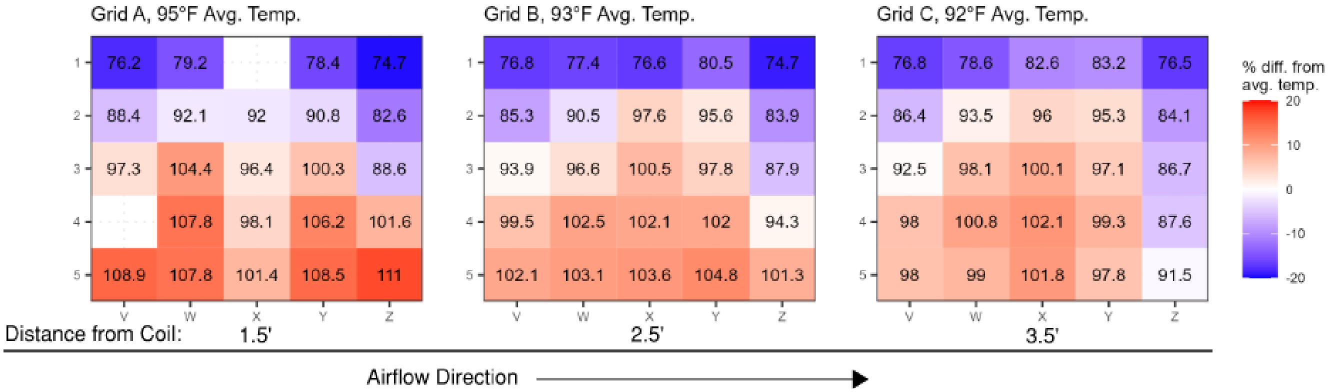


Figure 6 shows three heatmaps representing the difference between each thermocouple's measured temperature and the average temperature at each measurement plane for one representative test (12" box, 2-row coil, 160°F HWST, 37% open damper). The heatmaps show how stratification becomes less severe further downstream, as expected.

Figure 6. Heatmaps for temperature stratification through the length of the plenum


Grid A, 95°F Avg. Temp.

	V	W	X	Y	Z
1	76.2	79.2		78.4	74.7
2	88.4	92.1	92	90.8	82.6
3	97.3	104.4	96.4	100.3	88.6
4		107.8	98.1	106.2	101.6
5	108.9	107.8	101.4	108.5	111

Grid B, 93°F Avg. Temp.

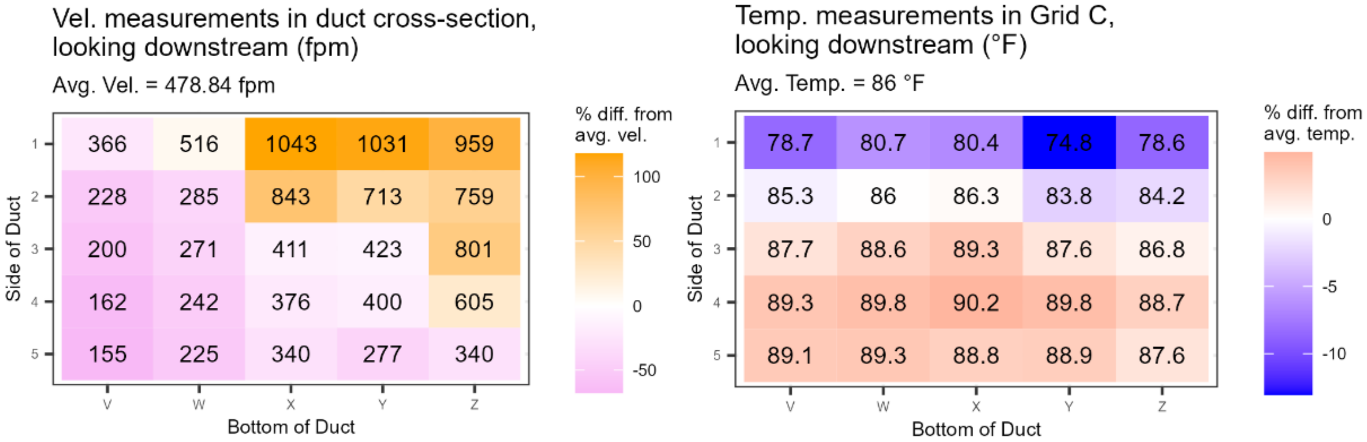
	V	W	X	Y	Z
1	76.8	77.4	76.6	80.5	74.7
2	85.3	90.5	97.6	95.6	83.9
3	93.9	96.6	100.5	97.8	87.9
4	99.5	102.5	102.1	102	94.3
5	102.1	103.1	103.6	104.8	101.3

Grid C, 92°F Avg. Temp.

	V	W	X	Y	Z
1	76.8	78.6	82.6	83.2	76.5
2	86.4	93.5	96	95.3	84.1
3	92.5	98.1	100.1	97.1	86.7
4	98	100.8	102.1	99.3	87.6
5	98	99	101.8	97.8	91.5

Figure 7 illustrates stratification in two heatmaps representing the velocity and temperature measurements for a representative test (8″ box, 1-row coil, 160°F HWST, 27% open damper, 90°F DAT setpoint) using the DAT measurement array that was 3.5 feet from the coil.

Figure 7. Heatmaps for Velocity (left) and Temperature (right) Stratification



Comparing the two heatmaps, it is evident that temperature stratification in the outlet plenum follows the velocity stratification. The left-to-right stratification shown in Figure 7 was unexpected and did not occur consistently on any one side of the plenum; we can offer no explanation for this result.

With this degree of temperature stratification in the outlet plenum, the accuracy of DAT readings clearly depends on the location of the temperature sensor. One solution is to use flexible averaging temperature sensors instead of single-point sensors, but they are more expensive and difficult to install. Figure 7suggests that the accuracy of single point sensors can be improved by locating the sensor tip as close as possible to the center of the duct, both horizontally and vertically. This requires that sensor probe length vary with coil/plenum width. Table 1 shows suggested single point DAT sensor probe lengths for typical coil widths. Also shown are typical VAV box inlet duct sizes that are associated with these coil widths both for standard and oversized coils.

Table 1: Single Point DAT Probe Length vs. Coil Width

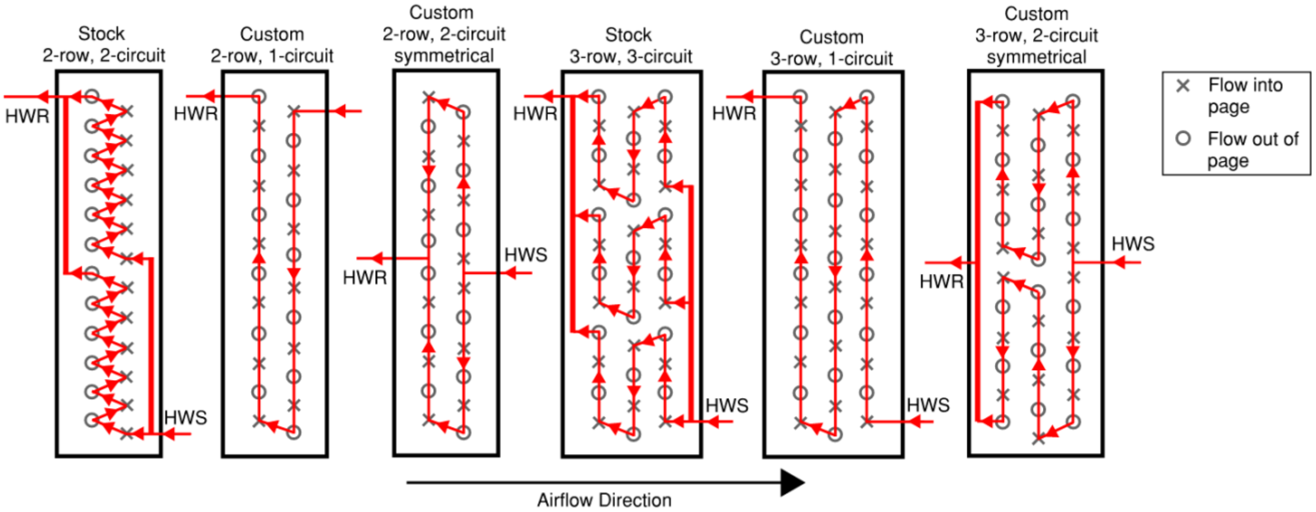
Typical Box Inlet Size		HW Coil Width	DAT Probe length
Standard HW Coil	Oversized HW Coil		
<12″	<10″	<16″	6″ or 8″
12″ to 14″	10″ to 12″	16-20″	8″
>14″	>12″	>20″	12″

Installation specification should require that the DAT sensor probe be mounted as close as possible to the center of the duct, both vertically and horizontally, and as far from the coil as possible but upstream of the last diffuser tap and at least 3 feet downstream of the coil.

Impact of Coil Circuiting

We designed and tested four coils with custom circuiting, shown in Figure 8along with the manufacturer’s stock 2- and 3-row coils. The custom designs were intended to 1) enable more symmetrical heat distribution to decrease stratification; and 2) enable higher waterside temperature differences (ΔT).

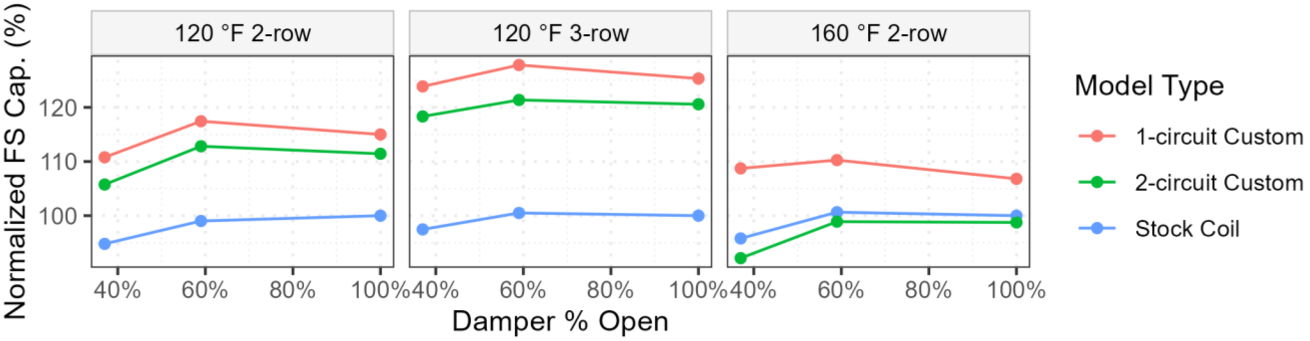
Figure 8. Circuiting diagrams



Our results showed that as the damper closed with constant air and water flow, the custom coils lost capacity at similar rates to stock coils (

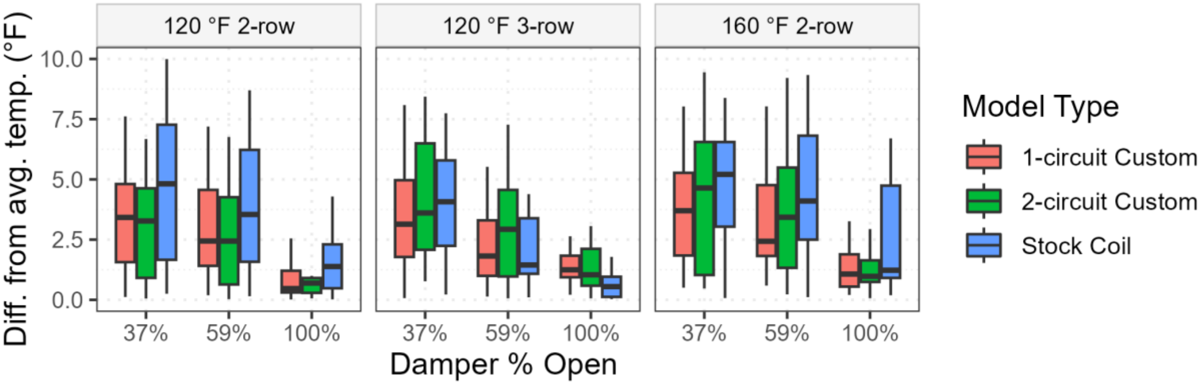
Figure 4). However, the total capacity (and ΔT, which is proportional to capacity) of the custom coils was higher than that of stock coils, particularly at 120°F (49°C) HWST (Figure 9).

Figure 9. Coil capacity normalized to stock coil capacity at 100% damper position vs. damper position



We also found the 2-row custom coils have consistently less DAT stratification than the stock coil across all damper positions. For the custom 2-circuit coils with symmetrical circuiting, we expected improved stratification over the 1-circuit coils. However, this was not the case, with stratification even slightly increasing for some tests (Figure 10). The results also show, once again, that stratification tends to increase with more closed damper positions.

Figure 10. DAT stratification stock vs. custom coils



Note that improvements in coil capacity (ΔT) and temperature stratification can be attained with a simple change in circuiting alone. This performance benefit will allow buildings designed for lower HWSTs to avoid costly pipe size increases otherwise needed for stock coils.

It is notable that the single circuit coils improved coil capacity without requiring additional copper – these could be manufactured for the same or even lower cost given the avoided headers. At our suggestion, one manufacturer developed a single circuit coil and found that it provides consistently higher ΔTs than their stock two circuit coils, consistent with the results of our testing. Other available options to increase coil ΔT result in higher costs (e.g., more coil rows, oversized coils, increased fin density) and sometimes higher supply air fan energy while simply improving coil circuiting increases ΔT at no or negative added costs.

Conclusions

Our results reveal that damper position significantly impacts discharge air temperature stratification and coil capacity in VAV reheat boxes. This can be mitigated by effective static pressure setpoint reset such as that implemented in ASHRAE Guideline 36. Stratification, in turn, can negatively impact the accuracy of DAT temperature readings used by modern "dual maximum" control logic, negatively impacting comfort control. This can be mitigated by selecting and mounting DAT sensors as close as possible to the center of the coil discharge plenum. Our experiment additionally revealed that alternative circuiting design can substantially increase low-HWST coil capacities and ΔT at similar or lower coil costs.

Acknowledgements

The California Energy Commission (Gas Research and Development Program, agreement number: PIR-19-013) and the Center for the Built Environment funded this work. The report submitted under the referenced grant further details the background, methods, and findings of the experiment (Wendler 2023[i]). Additional findings from this report not covered in the current article include results for coil piping methods when using a left-handed coil in the right-handed orientation; difference in performance when the damper actuator rotation is reversed; and the impact of losses from uninsulated piping, valve train, and coil housing and tube bends.

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