Performance of VAV Series Fan-Powered Terminal Units: Experimental Results and Models

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ABSTRACT

Empirical models of airflow output and power consumption were developed for series fan powered variable air volume terminal units at typical operating pressures. Terminal units with 8 in. (203 mm) and 12 in. (304 mm) primary air inlets from three different manufacturers were evaluated. Generalized models were developed from the experimental data with coefficients varying by size and manufacturer.

Fan power and airflow data were collected at downstream static pressures of 0.25 w.g. (63 Pa). Upstream static pressures ranged from 0.1 to 2.0 in w.g. (25 to 498 Pa). Data were collected at four different primary air damper positions and at four terminal unit fan speeds. Model variables included the RMS voltage entering the terminal unit fan, the inlet air differential sensor pressure, and the upstream static pressure.

In all but one of the VAV terminal units, the resulting models of airflow and power had $R^2$ values greater than 0.98. For the remaining unit, a faulty motor had been installed and shipped in the unit which prevented proper operation of the SCR. These models can be applied to HVAC simulation programs to model series fan powered VAV systems.

INTRODUCTION

Variable Air Volume (VAV) systems maintain comfort conditions by varying the volume of primary air that is delivered to a space. VAV terminal units that include a fan to improve circulation within a zone are called fan powered terminal units. These terminal units can draw in return air from the plenum space and mix it with primary air from the central Air Handling Unit (AHU).

When the fan is in the path of the primary airflow, the configuration is called a series terminal unit (Figure 1). During normal operations, the terminal unit fan usually remains on except during un-occupied times in the zone. The controller will modulate the terminal unit damper in response to the control signals from the thermostat and the inlet air differential sensor. The inlet air differential sensor within the primary airstream allows the controller to maintain a consistent volume of airflow to the zone depending on the temperature setpoint.

The fans on these terminal units output a constant amount of air that does not vary with load because the downstream pressure is constant (Alexander and Int-Hout 1998). As a result, when the primary air damper closes, more plenum air is induced and recirculated into the space. When the signal from the air velocity sensor indicates that the primary airflow has reached a predetermined minimum (because of ventilation requirements), the damper will not close any more. If the space is still too cold, electric or hot water supplemental heat can be used to meet the thermostat setpoint. To allow for various fan airflows, the units are typically equipped with a silicon controlled rectifier (SCR) fan speed controller.

There is a need to develop a better understanding of systems using parallel and series fan powered VAV terminal units. To model a system properly, it is important to be able to characterize the individual terminal units. To date, there has been little work in this area.

The primary goal for this research was the development of empirical models of power and airflow output for series fan powered terminal units at typical operating pressures. Three manufacturers (labeled A, B, and C) provided series terminal units for this work. An experimental setup was developed and used to test the fan powered terminal units. An experimental protocol was developed and used for all tests. Statistical analyses of experimental data were performed and used to develop

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generalized models that can be applied to the different manufacturers’ terminal units. The units included three 8 in. (203 mm) and three 12 in. (304 mm) units. Manufacturer’s A 8 in. unit had the designation S8A, manufacturer’s B 12 in. unit was S12B, etc.

This paper is the third of three papers that describe the development of experimentally based models of VAV fan powered terminal units. The first paper (Furr et al. 2008a) described the experimental setup and methodology used to measure the performance of parallel and series fan powered units. That paper also described the small differences between the terminal units that included the rated power of the terminal unit fan, the style of the primary airflow damper, and the style of the backdraft damper. In the second paper (Furr et al. 2008b), the performance of six parallel fan powered terminal units from three manufacturers was measured and characterized.

DATA ANALYSIS METHODOLOGY

One goal of this research was to determine if a single generalized model could be used for all the series terminal units tested for a given size. Because of design differences in the units, the performances of the same sized units varied dramatically. Thus, no single model could be used to describe a given size unit. The models had the same form, but used different coefficients for the different sizes and manufacturers.

Variables were first identified that were expected to be significant in explaining fan airflow and power. Models were then developed by determining the most statistically influential independent variables using the $F$ statistic. The variable with the largest $F$ statistic was added first. This method of adding terms to the model was continued until no other variables added were significant, defined as when the variables’ $F$ statistic was below 4.0. Between each step, models were compared against each other according to their adjusted coefficient of determination, $R^2_{adj}$ (Neter et al. 1996).

In developing the models for the series units, several variables were considered: the SCR voltage, inlet air differential pressure ($P_{iad}$), upstream pressure ($P_{up}$), and primary airflow ($Q_{primary}$). The models for all of the series terminal units were compared against each other. Any differences in terms included in the airflow or power models were investigated in an effort to create a single form model that would be applicable to all of the terminal units.

RESULTS AND MODELS

Fan Terminal Unit Airflow

The fans on the series units used centrifugal, forward-curved style fans. These fans were expected to follow typical fan curves and fan laws (ASHRAE 2001). The SCR voltage, upstream static pressure, and inlet air differential pressure were expected to be variables that could influence the capacity of the terminal unit fan.

SCR setting was a variable in the model that had to be quantified. Each SCR setting corresponded to a different fan speed. A simple experiment was conducted to determine the relationship between SCR setting and the speed of the fan. A tachometer was instrumented to an 8 in. (203 mm) parallel fan terminal unit from manufacturer A. Because the same motors and SCRs were used with the parallel and series terminal units, it was assumed that the relationship between SCR setting and fan speed would be the same for fans in both the series and parallel units. It would have been preferred to test the series units’ fans, to verify this assumption. However, given that the fan in a series unit is inside the terminal unit, it would have been difficult to ensure a constant pressure difference across the fan so that the relationship between fan speed and SCR setting could have measured.

At several different voltage settings, the RPM of the fan was measured. During this testing, the upstream and downstream static pressures were maintained constant to eliminate the effects of pressure on the fan speed. A quadratic equation was fit to the data (Figure 2) and had a $R^2$ value of 0.999.

This test was conducted on two other terminal units, parallel terminal units P12B and P8C, which resulted in $R^2$ values of 0.994 and 0.997, respectively. Because of the high $R^2$
values for the variety of groups and sizes, it was assumed that a general quadratic relationship would remain true for all of the terminal units.

According to the fan laws, there should be a linear relationship between airflow and fan speed (ASHRAE 2001). Because a quadratic equation had been used to show the relationship between SCR voltage and fan speed, it was assumed that an equation of the same form could be used for the relationship between SCR voltage and fan airflow.

After this relationship was established, the other factors that were considered in the modeling of the air output of the fan were the pressures immediately upstream and downstream of the fan. Because the downstream static pressure was maintained at the same value for all tests, it was not used explicitly as an explanatory variable for the model. Another pressure that could influence the airflow output of the unit fan would be the pressure inside the terminal unit, immediately upstream of the fan, $P_{\text{unit}}$ (Figure 3).

During normal operation, some air was always induced into the terminal unit. Thus, the static pressure within the series terminal unit was always sub-atmospheric but the pressure was not measured. In planning for the experiments, there did not appear to be a good way to instrument the terminal unit to measure this pressure accurately. After statistical analysis, it was determined that the pressure that the inlet air differential pressure, $P_{\text{iad}}$, was a suitable variable to include in the model to estimate the influence of the internal terminal unit static pressure. For example, when an airflow model using $V$, $V^2$, $P_{\text{iad}}$, and $P_{\text{up}}$ was regressed for the series terminal unit S8C, the resulting F statistics for $P_{\text{iad}}$ and $P_{\text{up}}$ were 160 and 15, respectively. Because both F values were greater than 4.0 both variables could have been used in the model. However, the model using only $V$, $V^2$, and $P_{\text{iad}}$ for the S8C terminal unit obtained an $R^2_{\text{adj}}$ value of 0.989. This model was deemed sufficient and in an attempt to maintain model simplicity, the variable $P_{\text{up}}$ was not included in the airflow models for the series units. The resulting model for predicting the airflow in series terminal units was a function of the SCR voltage and the inlet air differential pressure.

Five of the six series terminal units had very similar results for outlet airflow as a function of inlet air differential pressure. Two samples are shown in Figures 4 and 5 for terminal units S8A and S12C, respectively. The gentle slopes of the lines indicate that airflow was only slightly dependent on $P_{\text{iad}}$. These results support the premise, found in literature (Alexander and Int-Hout 1998), that variations of upstream duct pressure, primary airflow, and damper position have little

![Figure 2](image-url)

**Figure 2** Effect of SCR voltage on fan speed for parallel terminal unit P8A.

![Figure 3](image-url)

**Figure 3** Series VAV fan-powered terminal unit with pressure measurement locations.

![Figure 4](image-url)

**Figure 4** Fan airflow for series terminal unit S8A.

![Figure 5](image-url)

**Figure 5** Fan airflow for series terminal unit S12C.
effect on the pressure inside a series terminal unit, resulting in fairly constant airflow. After a series terminal unit has been balanced for airflow, the air output of the series terminal unit should be relatively constant despite changes in the upstream conditions.

The airflow results from series terminal unit S12B showed much more scatter than the results from the other terminal units (Figure 6). After trouble shooting the unit and discussions with the manufacturer of this unit, the disparity was due to an incorrect fan motor installed and shipped in the unit. This motor prevented the SCR from working correctly: the full range of SCR settings on this unit only resulted in a difference of 30 V as compared to differences of over 100 V in the other units. The result was that there was no discernable distinction in airflow output for different SCR settings.

Analysis of the data from unit S12B showed that the quadratic relationship between the SCR voltage and fan output was not evident. After initially developing models that included $V^2$ and $V$, the $F$ statistics were 0.04 and 0.22, respectivley. A model developed using only $V$ resulted in an $F$ statistic of 34. Inclusion of the squared term was never significant. This was probably due to the SCR/motor combination not behaving as the ones in the other terminal units that were tested.

The fan terminal unit output airflow model in series fan terminal units is shown in Equation 1. The coefficients for each unit are presented in Table 1.

$$Q_{out} = C_1 + C_2 \cdot V + C_3 \cdot V^2 + C_4 \cdot P_{iad}$$

Equation 2 is the model to characterize series terminal unit S12B, which was determined to have a faulty motor. In this model, $V$ captures the small effect that SCR setting has on the airflow output. $P_{up}$ and $P_{iad}$ were both included in this model, because their $F$ values in the model were 88 and 83. Table 2 provides the coefficients for the model of this terminal unit.

$$Q_{out} = C_5 + C_6 \cdot V + C_7 \cdot P_{up} + C_8 \cdot P_{iad}$$

### Table 1. Airflow Model Coefficients for Series Terminal Units

<table>
<thead>
<tr>
<th>Name</th>
<th>$C_1$, cfm</th>
<th>$C_2$, cfm/V</th>
<th>$C_3$, cfm/V²</th>
<th>$C_4$, cfm/in. w.g.</th>
<th>$R^2_{adj}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S8A</td>
<td>–1776</td>
<td>–0.0228</td>
<td>16.49</td>
<td>0.0036</td>
<td>0.989</td>
</tr>
<tr>
<td>S8B</td>
<td>–1705</td>
<td>–0.0254</td>
<td>18.15</td>
<td>–0.0448</td>
<td>0.994</td>
</tr>
<tr>
<td>S8C</td>
<td>–1310</td>
<td>–0.0183</td>
<td>13.94</td>
<td>0.0677</td>
<td>0.997</td>
</tr>
<tr>
<td>S12A</td>
<td>–778.5</td>
<td>0.0091</td>
<td>6.918</td>
<td>0.0394</td>
<td>0.993</td>
</tr>
<tr>
<td>S12C</td>
<td>–1903</td>
<td>–0.0105</td>
<td>16.78</td>
<td>0.0812</td>
<td>0.990</td>
</tr>
</tbody>
</table>

### Table 2. Airflow Model Coefficients for Series Terminal Unit S12B

<table>
<thead>
<tr>
<th>Name</th>
<th>$C_5$, cfm</th>
<th>$C_6$, cfm/V</th>
<th>$C_7$, cfm/V²</th>
<th>$C_8$, cfm/in. w.g.</th>
<th>$R^2_{adj}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S12B</td>
<td>–925.7</td>
<td>2.68</td>
<td>–55.8</td>
<td>–293.2</td>
<td>0.688</td>
</tr>
</tbody>
</table>
differential pressure. The coefficients for the various sizes and groups are presented in Table 3.

\[ \text{Power}_{\text{fan}} = C_1 + C_2 \cdot V^2 + C_3 \cdot V + C_4 \cdot P_{\text{iad}} \]  

(3)

Primary Airflow Model

As with the parallel terminal units, prediction of the primary airflow as a function of differential pressure across the units is needed to predict the upstream static pressure under a range of operating conditions for energy modeling purposes. The equations developed above allow prediction of the unit’s outlet airflow and power. These equations did not include any variables that would allow for direct estimation of the upstream static pressure for operation of the terminal unit either with or without the operation of the fan.

The performance of the series terminal units was similar to that of the parallel units. The primary airflow showed little dependence on SCR voltage, but did vary with damper setting, \( S \) (in degrees), and pressure differential (DP) across the terminal unit. Sample plots of primary airflow for terminal units S8B and S12C are shown in Figures 10 and 11, respectively.

![Figure 8](image1.png)

**Figure 8**  Fan power for series terminal unit S12C.

![Figure 9](image2.png)

**Figure 9**  Fan power for series terminal unit S12B.

![Table 3](image3.png)

**Table 3. Model Coefficients for Series Fan Power Model**

<table>
<thead>
<tr>
<th>Name</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
<th>( C_4 )</th>
<th>( R^2_{\text{adj}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>S8A</td>
<td>-732.7</td>
<td>-0.0114</td>
<td>7.13</td>
<td>-2.12</td>
<td>0.989</td>
</tr>
<tr>
<td>S8B</td>
<td>-595.7</td>
<td>-0.0111</td>
<td>6.96</td>
<td>-13.25</td>
<td>0.983</td>
</tr>
<tr>
<td>S8C</td>
<td>-455.5</td>
<td>-0.00817</td>
<td>5.32</td>
<td>1.91</td>
<td>0.994</td>
</tr>
<tr>
<td>S12A</td>
<td>-269.4</td>
<td>0.00854</td>
<td>1.80</td>
<td>19.05</td>
<td>0.997</td>
</tr>
<tr>
<td>S12B</td>
<td>125.9</td>
<td>0.00534</td>
<td>0.736</td>
<td>-16.36</td>
<td>0.870</td>
</tr>
<tr>
<td>S12C</td>
<td>-917.0</td>
<td>-0.0129</td>
<td>9.86</td>
<td>97.73</td>
<td>0.990</td>
</tr>
</tbody>
</table>

![Figure 10](image4.png)

**Figure 10**  Primary airflow as a function of inlet damper setting and pressure differential across the S8B terminal unit.

![Figure 11](image5.png)

**Figure 11**  Primary airflow as a function of inlet damper setting and pressure differential across the S12C terminal unit.

Both figures showed that the primary airflow varied with approximately the square root of the pressure differential across the terminal unit at a given damper setting.
For the series units, zero flow was at approximately –0.25 in. water (62 Pa). The data from the series terminal units were fit to a similar model to that of the parallel, except the pressure differential term (DP) had to be offset so the flow would be zero for negative DP. The offset that provided the best correlations was a value of 0.27 in. water (67 Pa). The equation that was fit to the primary airflow is shown in Equation 4. Table 4 provides the coefficients and R-Squared values for the six series terminal units. All units had R-Squared values above 0.9.

\[
Q_{primary} = C_1(1 + C_2^*S + C_3^*S^2)^{C_4^*}(DP + 0.27)^{0.5}
\]

SUMMARY AND CONCLUSIONS

Characterizing the performance of series terminal VAV units required developing models for the primary and output airflow and the fan power. Comparison of the statistics for the airflow model shows that it accounts for 99% of the variation in airflow for five of the six terminal units. The exception was series terminal unit S12B. In this case, it was not possible to develop a model that could adequately describe the response to the airflow variable. The model did not account for 31% of the variation in the data. This variation appeared to be the result of a faulty fan motor.

The power model had \( R_{adj}^2 \) statistics greater than 98% for five of the six terminal units. The lowest \( R_{adj}^2 \) value of 0.870 was for the series S12B terminal unit, which also had the lowest \( R_{adj}^2 \) for the airflow model. This is the same unit which had the lowest of the six \( R_{adj}^2 \) values in the airflow model, mentioned above.

These units were obtained from several manufacturers and in different sizes in an effort to get a “snapshot” of units typically installed in the field. Unfortunately, this sample of six terminal units had one unit (S12B) that would be expected to perform poorly in the field because of problems with its fan motor. The terminal unit models developed in this study should provide researchers with accurate models that can be incorporated into building energy simulation tools to model the energy use of VAV systems with multiple terminal units.

For all simulations, these voltages would remain the same. The to each terminal unit to set the fan airflow. For the calculations. For each step-iteration, most simulations calculate the primary airflow required to meet the space load. The inlet air differential pressure can be calculated using these primary airflow values and the Table A-1 in the appendix.

When using these models as a tool to predict performance, it is important to note that extrapolation of data points outside the range of experimentally determined values is not recommended. The response of the dependent variables, airflow and power, was only statistically determined within the ranges of independent variables.

ACKNOWLEDGMENTS

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REFERENCES


APPENDIX

For this study, the relationship between the inlet air differential pressure and the amount of primary air entering the terminal unit was assumed to be linear over the ranges measured. This linear approximation is presented in Equation A.1, with the coefficients for each terminal unit presented in Table A-1.

\[ P_{iad} = C_1 + C_2 \cdot Q_{primary} \]  
(A.1)

<table>
<thead>
<tr>
<th>Name</th>
<th>(C_1) [in. w.g.]</th>
<th>(C_2) [in. w.g./CFM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S8A</td>
<td>-0.204</td>
<td>0.00111</td>
</tr>
<tr>
<td>S8B</td>
<td>-0.140</td>
<td>0.000776</td>
</tr>
<tr>
<td>S8C</td>
<td>-0.183</td>
<td>0.000922</td>
</tr>
<tr>
<td>S12A</td>
<td>-0.162</td>
<td>0.000409</td>
</tr>
<tr>
<td>S12B</td>
<td>-0.129</td>
<td>0.000306</td>
</tr>
<tr>
<td>S12C</td>
<td>-0.158</td>
<td>0.000351</td>
</tr>
</tbody>
</table>