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Part Two

Fan-Powered VAV Terminal Units

Application and Modeling Implications From Past and Current Research

BY GUS FARIS, LIFE MEMBER ASHRAE; DAN INT-HOUT, FELLOW/LIFE MEMBER ASHRAE; DENNIS O'NEAL, PH.D., FELLOW/LIFE MEMBER ASHRAE; PENG "SOLOMON" YIN, PH.D., ASSOCIATE MEMBER ASHRAE

Series fan-powered VAV terminal units have been in use for commercial buildings since they first appeared in 1974. Upgraded components, current control systems and building design improvements helped to increase the use of fan-powered VAV terminal units. Specifying engineers as well as standard writers and building owners still have questions concerning the whole building system energy use with these products.

This is the second in a series summarizing the results and implications from a series of ASHRAE, Air Conditioning, Heating and Refrigeration Institute (AHRI), and industry-funded research projects conducted over the past 14 years on fan-powered terminal units (FPTUs). The major findings from these research projects are contained in technical reports and over 28 papers published in *ASHRAE Transactions*. Several observations regarding the performance of FPTUs are described here, including the effect of parallel FPTU backdraft damper leakage, and the use of electronically commutated motors (ECMs) to both enhance performance opportunities and reduce energy consumption.

Leakage in Parallel FPTUs

When comparing system energy use between series- and parallel-type fan terminals in several different climates, it was found that the leakage of the backdraft damper in parallel FPTUs (required when the fan shuts

off to prevent back flow) was a major determinant in the difference in energy use between the two types of devices.

Primary air leakage from the casing of a parallel FPTU is extremely hard to measure because it happens at different places under different circumstances, and it is impossible to predict the relative value for each location since they vary over the entire operating sequence of the FPTU. During the course of the FPTU research projects,¹ a total of 12 different FPTUs with permanent split capacitor (PSC) motors and ECMs from three manufacturers were tested.^{2,3} Six units had ECMs, and six had permanent split capacitor (PSC) motors. All of the parallel FPTUs had air leakage. Sources included the backdraft damper, seams, and penetrations in the housings. Some seams and penetrations could be sealed in the field. Penetrations at the electric heater, the tube penetrations in the water coil and damper shaft penetrations cannot be fully sealed. These leakage points will be active

Gus Faris is vice president, engineering at Nailor Industries in Kingwood, Texas. He is a former chair of TC 5.3, Room Air Distribution. Dan Int-Hout is chief engineer at Krueger in Richardson, Texas. He is a former chair of SSPC 55 and a consultant to SSPC 62.1. Dennis O'Neal, Ph.D., is dean of the School of Engineering and Computer Science at Baylor University in Waco, Texas. He is a former chair of the Handbook committee. Peng "Solomon" Yin, Ph.D., is assistant professor, Department of Mechanical Engineering, at the University of Louisiana in Lafayette, La.

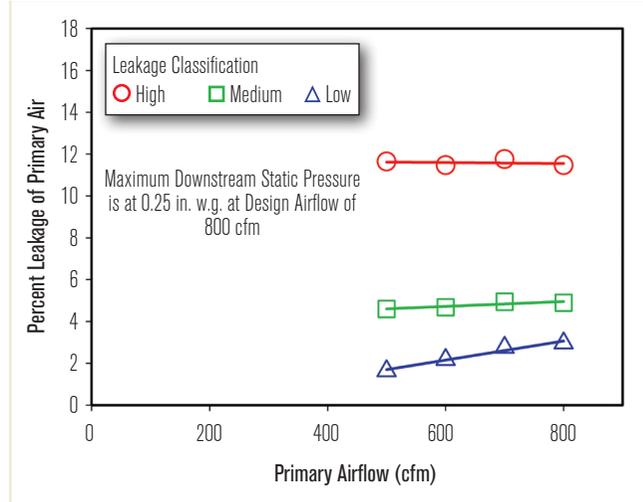
in both the heating and cooling modes. The backdraft damper will always be a source of leakage in the cooling mode.

Figure 1 shows a sample of data from tests on some of the ECM FPTUs with an 8 in. (203 mm) primary air inlet.⁴ In the cooling mode, with the fan off, the high leakage unit averaged nearly 12% leakage of primary airflow while the smallest varied from 1% to 3%. The low end leakage was measured at very low airflows. Recognizing that there are no 0% leakage parallel FPTUs and that 12% is probably not the highest leakage found in the field (Figure 2), the backdraft dampers in the parallel FPTUs have to be lightweight to prevent interference with the airflow upstream of the heating device; therefore, they are usually made from light gauge aluminum sheet or very light gauge steel sheet. Flanges along the edges have to be kept to a minimum to ensure minimal air deflection. Consequently, the dampers are somewhat fragile and can easily be bent or deformed from shipping or handling damage, and this can cause them not to seal as designed or to become stuck and partially open. The backdraft dampers in the tested FPTUs all seemed to be functioning as designed, so these measurements may be even lower compared to real world conditions.

What's the impact of the leakage through the backdraft damper? First, leakage directly impacts cooling and fan energy use. During cooling operations, the casing is positively pressurized by the primary fan and the backdraft damper is designed to prevent leakage of air into the plenum space. Every cfm of air that leaks into the plenum space is a cfm that has been cooled and dehumidified by the primary coil. This air does not reach the conditioned zone and the primary fan must work harder to provide an extra amount of primary air to the FPTU to offset the loss through the backdraft damper. If the FPTU is a high leakage unit like that in Figure 1, then the primary fan must provide 12% or more air to the FPTU to provide the same cooling to the zone as a FPTU that has no leakage. Thus, there is additional fan energy and cooling energy use with leakage.

Second, an indirect impact of leakage is increased heating energy use for those FPTUs sharing the same plenum as those FPTUs leaking primary air. As cold air spills into the plenum from the induction port, the air temperature in the shared plenum space decreases. In a typical application during winter and parts of spring and fall, some of the FPTUs are in cooling and some in

FIGURE 1 Percentage leakage of primary air from the 8 in. (203 mm) primary air parallel fan-powered FPTUs.



heating mode simultaneously. Those in heating mode will be recirculating secondary air from the plenum space that is colder than it would otherwise be if there were no leakage. Because this air in the FPTU has to be heated, those in heating mode will have a higher heating energy use than if there were no leakage.

As a part of the AHRI research project,⁵ some measurements were made in the field. Figure 2 shows an example of leakage through a backdraft damper found in a parallel FPTU in a research building. Thermal image measurements were made on a parallel FPTU that had air leakage from its induction port. Normally, one would expect the temperature of the filter to be near the surrounding air temperature of the plenum. However, air leaking through the backdraft damper cooled the filter down to 61.3°F (16.3°C) while the surrounding ducts and supports are at about 72°F (22.2°C).⁵ This back draft damper is obviously leaking a significant amount of primary air into the plenum. This leakage is classified as casing leakage and within the industry has been calculated to be \$1.84 per cfm per year (\$3.90 per L/s per year).

ECM Application in Series FPTUs

The application of electronically commutated motors (ECMs) into series FPTUs has made it possible for engineers to specify FPTUs that can provide significant energy savings over fixed airflow PSC FPTUs. ASHRAE research paper, “Energy Use Comparison for Series vs. Parallel Fan Powered Terminal Units in a Single Duct Variable Air Volume System,”⁶ demonstrated

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that building energy consumption with series and parallel FPTUs using PSC motors and operating at constant speeds were competitive at certain leakage rates. ASHRAE Research paper, “Reflections on ARI/ASHRAE Research Project RP-1292, Comparison of the Total Energy Consumption of Series Versus Parallel Fan Powered VAV Terminal Units,”⁷ tabulated the comparison based on leakage. When the parallel FPTU leakage exceeded 10%, the energy consumption difference was minimal and the units were competitive. Using the ECM in the series FPTU decreased the motor energy consumption by more than 60%. Modulating the series FPTU with the ECM reduced the plenum air recirculation and significantly reduced the total energy use. ECMs can be used in either fixed airflow or variable airflow applications.

Figure 3 shows the part-load performance of an ECM FPTU at different airflows and static pressures. As the ECM reduces the airflow of the fan, there is a corresponding decrease in the W/cfm. At 0.25 in. w.g. (62.3 Pa), at maximum speed, the ECM-powered fan consumes about 0.33 W/cfm (0.70 W/L·s), which is comparable to that of many PSC fan/motor combinations. If the ECM in a series FPTU is programmed to follow the load in the zone, then it can adjust airflow to just satisfy the load. For example, if the load dropped by 35%, then the ECM would drop the airflow from a maximum of 1,000 cfm (472 L/s) down to 650 cfm (307 L/s). The downstream static pressure would be expected to vary with the square of the airflow in a system. Thus, the downstream static pressure would be expected to drop from 0.25 in. w.g. (62.3 Pa) at 1,000 cfm (472 L/s) down to about 0.1 in w.g. at 650 cfm (307 L/s).

In this case the variable airflow ECM would consume 0.13 W/cfm (0.28 W/L·s), which is a 61% reduction compared to the 0.33 W/cfm (0.70 W/L·s) at full airflow. Because in many applications, much of the hours of operation are at a small fraction of the design load in a

FIGURE 2 Plenum and induction port thermal images for a parallel FPTU at a building on the Texas A&M University campus.⁵

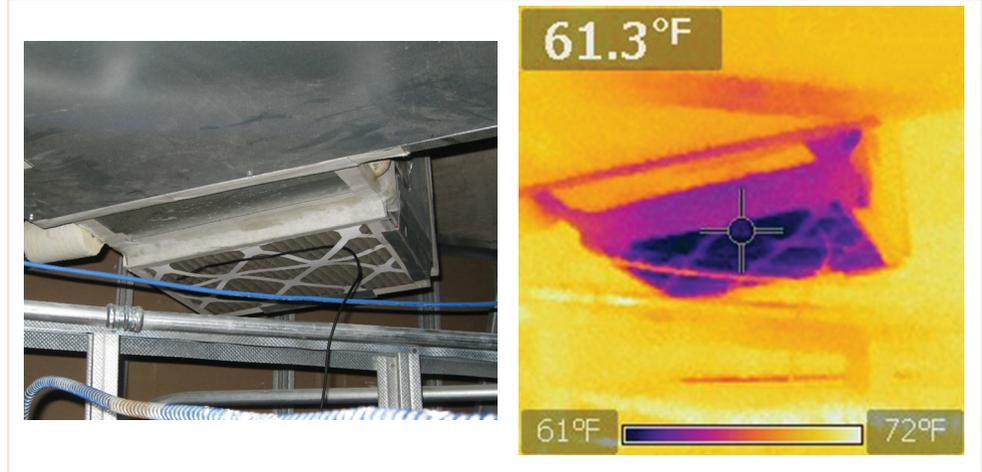
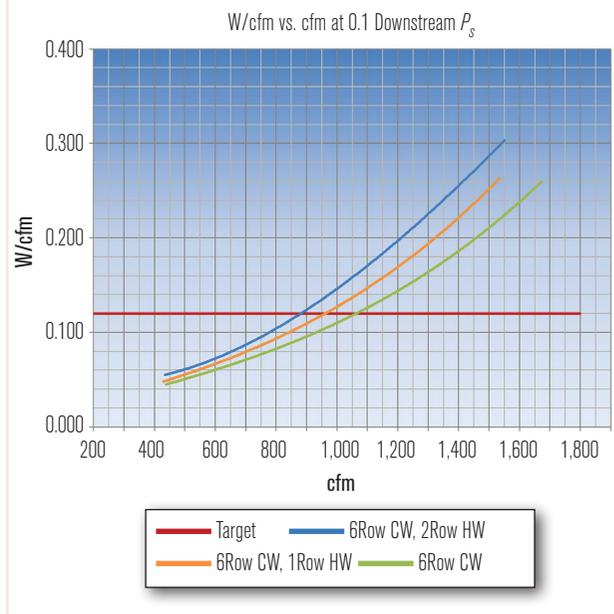


FIGURE 3 Sample of power/airflow for an ECM FPTU at two downstream static pressures.



space, the variable airflow series would operate much of the time below 500 cfm (236 L/s) and provide substantial savings over a fixed airflow FPTUs.

Building codes have evolved over the years, and many now require ECM motors in both series and parallel FPTUs. The state of Washington has introduced a new energy code that imposes limits on the energy use of fan boxes in terms of W/cfm. From the code:

C403.6.2 Heating/cooling system fan controls.

Heating and cooling equipment fans, heating and cooling circulation pumps, and terminal unit fans shall cycle off and terminal unit primary cooling air

shall be shut off when there is no call for heating or cooling in the zone.

Exception: Fans used for heating and cooling using less than 0.12 watts per cfm may operate when space temperatures are within the set-point deadband (Section C403.2.4.1.2) to provide destratification and air mixing in the space.

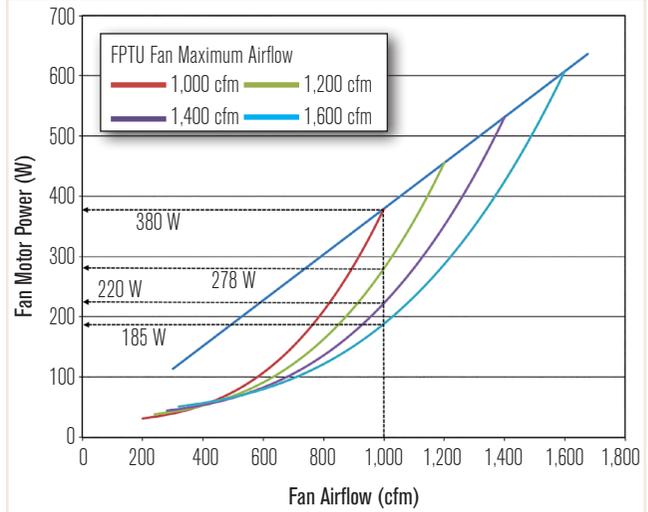
C403.6.3 Impracticality. Where the code official determines full compliance with all of the requirements of Section C403.6.1 and C403.6.2 would be impractical, it is permissible to provide an approved alternate means of compliance that achieves a comparable level of energy efficiency.

The ECM can meet these requirements, even with a sensible cooling coil on the induction port, as shown here. The terminal unit fan operation in the deadband can provide better air mixing and prevent temperature stratification, and therefore, better thermal comfort. At low flows, the downstream pressure is likely to be even lower than the 0.1 curve shown, but data at these lower external pressures was not taken in the past. Likely, to meet the Washington code, data will be gathered at even lower pressures in the future.

Even if an ECM is applied in a fixed airflow FPTU application, there is the potential for significant savings over a fixed airflow PSC FPTU. *Figure 4* shows how an engineer can take advantage of the ECM characteristics to provide a fixed airflow ECM FPTU with reduced power over a PSC FPTU.⁸ If there was an application where the design airflow requirement for a zone is 1,000 cfm (472 L/s), an ECM FPTU with maximum airflow of 1,000 cfm (472 L/s) could be installed. In this case the maximum airflow would just match the design airflow of the zone. For this unit, the power consumption would be 380 W.

Because a series FPTU's fan is on whenever the system is on, the FPTU fan would operate at 380 W. However, if a FPTU with a maximum airflow of 1,200 cfm (566 L/s) were installed, its airflow could be reduced to match the 1,000 cfm (472 L/s) requirement. In this case, the FPTU would consume 278 W. Likewise, a FPTU with 1,400 cfm (661 L/s) capacity could be installed, resulting in only 220 W consumed. While there may be more first costs with the larger capacity FPTUs, it is clear from *Figure 4*, they can provide significant fan energy savings. If the

FIGURE 4 Sample plot showing how sizing ECM FPTUs affect fan power.



FPTU was operating primarily in cooling mode, then not only would there be a reduction in fan power, there would also a reduction in cooling needed since the fan motor is putting less energy into the airstream.

The increased unit size described above actually happens automatically in practice. The mechanical equipment selected for commercial buildings is selected at maximum design conditions. However, commercial buildings do not operate at design conditions for much of the year. In fact, sometimes not at all. It is normal for a commercial building to operate at or below 50% of the design cooling mode for as much as 80% of the year, and at or below 35% of the design heating mode for as much as 95% of the year. ASHRAE research project 1515⁹ conducted at the Yahoo campus in California (and other buildings) showed that internal loads may be as low as 25% of the typical 1 cfm/ft² (5 L/s·m²) design typical today. Consequently, the savings described above happen automatically with significant savings over design.

Estimated Energy Use Impact of Leakage and ECMs

The impact on annual HVAC energy use of leakage in parallel FPTUs and ECM applications in series FPTUs were modeled in the research projects for a small five-zone office building with different local climates.^{5,10-12} Estimated savings can be expected to vary by the size of the building, climate, operations and other variables.

Table 1 shows the annual energy percentage savings in Houston, Phoenix, and Chicago. In this table, the HVAC energy use included the air conditioning, heating, and fans. In the comparison, the results for a PSC

series FPTU was used as the baseline, and results from other configurations, namely a fixed airflow ECM, a variable airflow ECM, and a fixed airflow parallel ECM FPTU with 0%, 5%, and 10% leakage were compared with this baseline.⁵ All of the ECMs in the table were sized so their maximum airflow capacities in each zone were 25% above the design capacities. Although both fixed and variable airflow series ECM FPTUs provide savings over the baseline; the energy savings provided by variable airflow series FPTUs is significantly higher.

The parallel ECM FPTU with zero leakage showed the largest savings over the baseline. However, results from the laboratory tests showed that all of the parallel units tested had leakage.⁴ Thus, we would not expect to find a 0% leakage parallel FPTU in the field. The 0% leakage estimates provide a reference point for an ideal parallel unit. The leakage results shown in *Table 1* were from O’Neal, et al.⁵ Davis¹⁰ and Davis, et al.,^{11,12} also estimated effect of

TABLE 1 Estimated annual HVAC energy savings for different fan powered terminal unit options in a small office application in three cities in a small five zone office building.⁵

| OPTION | PERCENTAGE ANNUAL HVAC ENERGY SAVINGS | | |
|-----------------------------|---------------------------------------|---------|---------|
| | HOUSTON | PHOENIX | CHICAGO |
| PSC Series Baseline | — | | |
| Fixed Airflow ECM Series | 2.2% | 2.6% | 1.8% |
| Variable Airflow ECM Series | 8.6% | 10.1% | 6.0% |
| ECM Parallel – No Leakage | 9.9% | 10.8% | 9.2% |
| ECM Parallel – 5% Leakage | 4.7% | 5.6% | 6.0% |
| ECM Parallel – 10% Leakage | -1.0% | -0.2% | 2.4% |

leakage on a small office building. A small amount of leakage can dramatically degrade the performance of parallel FPTUs. With 5% leakage, the performance of variable airflow series FPTUs outperformed the parallel FPTU shown in *Table 1*. While his calculated energy impacts due to leakage were less than those shown in *Table 1*, Davis¹⁰ showed a parallel unit with 5% leakage used slightly less energy than a fixed airflow ECM series unit in Houston and Phoenix and slightly more than one in Chicago. At 10% leakage, the benefit of using ECM parallel FPTUs become

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marginal. In the case of Houston, the ECM parallel FPTU with 10% leakage performed no better than the PSC series baseline FPTU. Davis¹⁰ found that with 10% leakage, the performance of all of the parallel units in the three cities fell between the PSC and ECM fixed airflow series units. Considering the leakage in parallel FPTUs found in previous field studies and laboratory testing, the use of variable airflow ECM series FPTUs should be considered for greater energy savings.

Benefits Other than Energy

There are other benefits besides just energy to the variable volume flow. The reduced airflow rates come with lower noise levels in the space. Room NC can be reduced as much as 10 NC in low volume operation, and that can represent a large portion of occupied hours. Series FPTUs induce some plenum air at all airflows and can improve ventilation by providing unvitiated air from the plenum space. Using demand-controlled ventilation controls can reduce total outdoor air required. As the room demand decreases, the amount of plenum air

induced into the terminal unit increases and the discharge air temperatures increase. This provides warmer room air as the load decreases avoiding overcooling and drafts in the occupied space.

The RP-1515 study showed that people can be comfortable at low airflow rates, as well as that the interior loads in buildings may well be close to minimum ventilation rates. Couple that with the studies that show diffusers can deliver very cold air at low flows without creating uncomfortable spaces, conditions for which chilled beams, water source heat pumps and VRF devices may experience difficulty. Current modifications to the Series FPTUs also offer an excellent choice when paired with dedicated outdoor air systems. Combining the RP-1515 findings with current ceiling diffuser performance is almost a prescription for a fan-powered chilled water terminal unit; one that provides variable volume outdoor air control, air side economizers, sensible indoor cooling and all the benefits of the traditional VAV system.

All the research done to date suggests that series ECM fan powered VAV terminal units may be an excellent

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choice for commercial buildings. These products provide very high efficiency, low noise, flexible designs, easy maintenance and allow designers to use superior and familiar components in the building.

The last needed component is correct and dependable modeling. That will be covered in the third article of this series.

References

1. Faris, G., D. Int-Hout, D.L. O'Neal, P. Yin. 2017. "Fan-powered VAV terminal units, application and modeling implications from past and current research." *ASHRAE Journal* (10):18–24.
2. Furr, J., D. O'Neal, M.A. Davis, J.A. Bryant, A. Cramlet. 2008. "Performance of VAV parallel fan powered terminal units: experimental results and models." *ASHRAE Transactions* 114(1).
3. Edmondson, J., D.L. O'Neal, J.A. Bryant, M.A. Davis. 2011. "Performance of parallel fan powered terminal units with electronically commutated motors." *ASHRAE Transactions* 117(2).
4. O'Neal, D.L., J. Edmondson. 2016. "Characterizing air leakage in parallel fan-powered terminal units." *ASHRAE Transactions* 122(1):343–353.
5. O'Neal, D.L., C. Reid, D. Ingram, D. Lu, J.A. Bryant, S. Gupta, B. Kanan, S. Bryant, P. Yin. 2016. "Developing Fan Power Terminal Unit Performance Data and Models Compatible with EnergyPlus." Report No. 8012. Air-Conditioning, Heating, and Refrigeration Institute.
6. Bryant, J.A., M.A. Davis, D.L. O'Neal. 2010. "Energy use comparison for series vs. parallel fan powered terminal units in a single duct variable air volume system." *ASHRAE Transactions* 116(2).
7. Faris, G. 2009. "Reflections on ARI/ASHRAE Research Project RP-1292, Comparison of the Total Energy Consumption of Series Versus Parallel Fan Powered VAV Terminal Units." *ASHRAE Transactions* 115(1).
8. O'Neal, D.L., D. Ingram, C.L. Reid. 2015. "A simplified model of the fan/motor performance of fan-powered terminal units that use electronically commutated motors." *ASHRAE Transactions* 121(2):306–320.
9. Zhang, H., T. Hoyt, S. Kaam, J. Goins, F. Bauman, Y. Zhai, T. Webster, B. West, G. Paliaga, J. Stein, R. Seidl, B. Tullym, J. Rimmer, J. Torftum. 2014. "Thermal and Air Quality Acceptability in Buildings that Reduce Energy by Reducing Minimum Airflow from Overhead Diffusers." ASHRAE Research Project RP-1515. Final Report.
10. Davis, M.A. 2010. "Development of a Laboratory Verified Single-Duct VAV System Model with Fan Powered Terminal Units Optimized Using Computational Fluid Dynamics." Ph.D. Thesis, Texas A&M University.
11. Davis, M.A., J.A. Bryant, D.L. O'Neal. 2012. "Modeling the performance of ECM and SCR series fan powered terminal units in single-duct VAV systems." *ASHRAE Transactions* 118(1).
12. Davis, M.A., J.A. Bryant, D.L. O'Neal. 2012. "Modeling the Performance of ECM and SCR parallel fan powered terminal units in single-duct VAV systems." *ASHRAE Transactions* 118(1). ■

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