Characterization of Open Plenum Air Return Operation Based on Field Data

Sabato N. Leo[1], Sarah R. Haines[2], Helen Stopps[1]
[1]Toronto Metropolitan University, Toronto, Canada
[2]University of Toronto, Toronto, Canada

Abstract

Open plenum air return systems are prevalent in many commercial and institutional buildings. Despite their widespread use, there is limited information on how well open-plenum systems perform in real-world conditions, and potential operational challenges remain poorly understood. This paper presents a two-week field study conducted in a 17-storey office building constructed in the 1990s in Hamilton, Ontario. During the study, data on the differential pressure between the ceiling plenum and conditioned space as well as between the mechanical room and air handler filters, were collected from two test floors. This data was analysed to explore variations in return airflow and how external weather factors affect indoor differential pressure. It was determined that there is a measurable difference between the 4th and 15th floors' zone-to-plenum differential pressure under varying conditions. The air handling unit operation, however, was observed to have a minimal impact on zone-to-plenum differential pressures on each floor.

Introduction

Open plenum air return systems in commercial and institutional buildings serve as a practical alternative to traditional ducted return air systems. Traditionally, ducted systems are difficult to integrate seamlessly into spaces with other utilities such as sprinklers, beams, sanitary services, and telecommunications. Open plenum air returns allow for the return of conditioned air from occupied spaces to HVAC equipment via a depressurised plenum space either above the ceiling or below the floor. The benefits of these systems include reduced installation costs of about $32 to $54 per square metre, easy maintenance access, space-saving characteristics, and adaptability to changing room layouts (Taylor, 2015). However, open plenum air returns have potential disadvantages. To prevent return air from re-entering the conditioned zone and/or amplifying air leakage, the system must maintain a low-pressure drop to ensure proper performance and allow for a return air path to the air handler. (Taylor, 2015)

A white paper published by ASHRAE Technical Committee 5.2 (Duct Design) further highlights the potential drawbacks associated with open plenum return systems. These include challenges with the control of air distribution and airflow patterns (spent air could re-enter the conditioned spaces), increased risk of uncontrolled infiltration of untreated, unconditioned outdoor air due to the negatively pressurised plenum spaces (amplifying air leakage through the building envelope) and limiting the ability of technicians to balance return air flows. (Constantinide et al., 2021).

Though open-plenum air return systems are commonly used, limited information is available on the in-situ operation of open-plenum air returns in large commercial buildings. The aim of this paper is to characterise the operation of an open plenum air return system in a case study building and identify which attributes will impact open plenum air return performance.

Methods

A 1990s, 17-storey office building with an open plenum air return system was selected for this study. The building is located in Hamilton, Ontario, Canada, within the downtown business district. Testing was conducted on the 4th and 15th floors of the building for a 15-day period between October 18th, 2023, to November 2nd, 2023. Supplementary measurements were taken on the 15th floor between December 2nd, 2023, to December 15th, 2023.

The HVAC system is operated on a schedule, with the ability for human intervention. The running cycle is set to operate when the building is most likely occupied. The automated running time is set from 5:30 AM to 6:00 PM, Monday to Friday, barring human intervention. During the period from Monday to Friday, 6:01 PM to 5:29 AM, and weekends Saturday and Sunday, the air handler is not running.

Veris PX Series Pressure Sensors, connected to Onset HOBO UX120-006 M Data Logger, were used to collect differential pressure data. The measurement range on the Veris sensor was set to ±100Pa, with a listed accuracy of ±1% F.S. of the selected range (Veris Pressure Sensors 2012). The sampling frequency was set to every 30 seconds. The resulting data was then aggregated into 15 intervals for analysis, with the differential pressure mean, maximum, minimum, 90th quartile, and 10th quartile calculated for each 15-minute period.

Differential pressure measurements across the plenum were taken in mirrored locations on the 4th and 15th floors

of the test building, as both floors have identical floor plans with the same spatial volume. Readings are reported as zone-to-plenum differential pressures, such that a positive zone-to-plenum pressure represents the condition in which the zone air pressure is higher than the air pressure within the plenum space. The differential pressure sensors were located within the office spaces (Location A) Figure 1, measuring the zone-to-plenum differential pressure, and the sensors within the mechanical rooms (Location B) Figure 1, measuring the pressure drop across the air handler filters. Data was collected from both locations on the 4th floor and Location A of the 15th floor from October 18th, 2023, to November 2nd, 2023. Data was collected in Location B on the 15th floor between December 2nd, 2023, and December 15th, 2023.

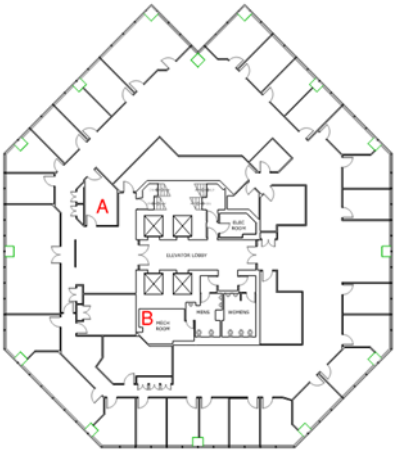

Figure 1: Veris PX Series Pressure Sensors location layout for the 4th and 15th floors. Both floors have identical floor plans with the same spatial volume.

Outdoor environmental data was gathered from a nearby Environment Canada weather station (climate.weather.gc.ca, 2024). These data include the wind direction, wind speed, temperature, relative humidity, and barometric pressure, each reported at one-hour intervals. Using this data, outdoor air density was calculated using the MetPy package in Python (May et al., 2022). Equation 1 shows the calculation used in the package:

$$\rho = (\epsilon p(1+\omega))/(R_d T(\omega+\epsilon)) \quad (1)$$

where ρ is the density of the air in Pa, ϵ is the molecular weight ratio (assumed to be 0.622), ω is the mixing ratio (dimensionless), R_d is the gas constant for one kilogram of dry air, and T is the outdoor air temperature (in K). The mixing ratio is a function of ϵ, the partial pressure of water vapour (calculated using outdoor temperature and relative humidity measurements), and the total air pressure.

The outdoor environmental data and the calculated outdoor air density were used in conjunction with the differential pressure data from the Veris PX Series Pressure Sensors to analyse the conditions that may affect the open air plenum return system of the 4th and 15th floors of the test building. Figure 2 shows the primary wind direction and magnitude over the main study period of October 18th, 2023, to November 2nd, 2023. The wind comes directly from North-Northeast for 80% of the study period from October 18th, 2023, to November 2nd, 2023. This makes sense as Hamilton Harbor is located directly northeast of the building, which results in the wind coming off the harbour into the downtown core.

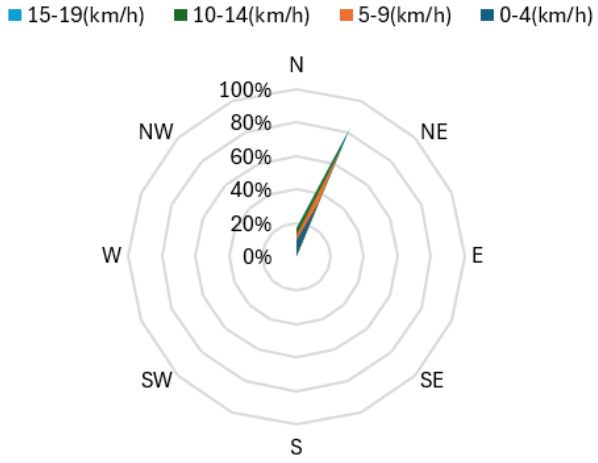

Figure 2: Wind rose for October 18th, 2023, to November 2nd, 2023.

Table 1 shows wind speed, outdoor air density, and outdoor temperature characteristics during the primary study period. Over the study period, there was a relatively low wind speed, with a mean speed of 5 km/h. The air density was as expected with the calculated mean air density of 1.23 kg/m^3. The outdoor temperature was moderate, with an interquartile range between 5.4°C and 15.3°C.

Table 1: Quartiles of the wind speed, air density, and outdoor temperature.

	Quartile 1	Mean	Quartile 3
Wind Speed	3 km/h	5 km/h	8 km/h
Outdoor Temperature	5.4 °C	10.1 °C	15.3 °C
Air Density	1.20 kg/m^3	1.23 kg/m^3	1.25 kg/m^3

Results

The operation of the open plenum return system was considered based on several factors. Specifically, this includes (1) zone-to-plenum differential pressure trends over the study period, (2) variation in zone-to-plenum differential pressure with air handler operation, and (3) variation in differential pressure with outdoor environmental conditions.

System Operation and Differential Pressures

Figure 3 shows the test period from October 18th, 2023, to November 2nd, 2023. As depicted in Figure 3, the air handler operating cycle and the differential pressure across the plenum and conditioned space can be clearly seen.

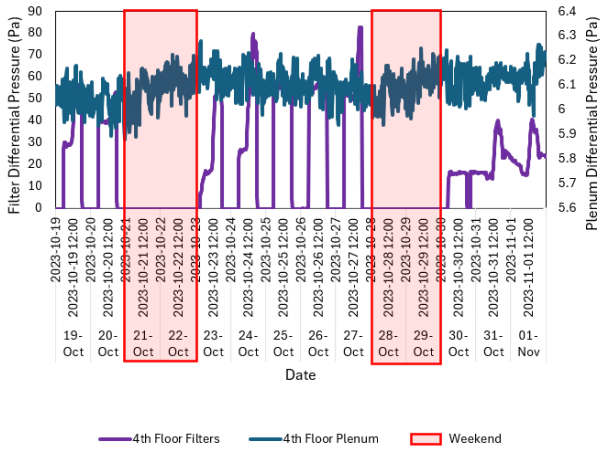

Figure 3: Fourth-floor air handler filter pressure (Location B) and office space zone-to-plenum (Location A) differential pressures over the study period of October 18th, 2023, to November 2nd, 2023. The red highlighted time periods are weekend days.

Figure 4 outlines the plenum testing period from October 18th, 2023, to November 2nd, 2023. The air handler filter pressure for this period was extrapolated based on the filter pressure measurements taken on the 15th floor from December 2nd, 2023, to December 15th, 2023. Weekday and weekend data from this period were separated, and the average filter pressure drop was calculated for each hourly period for each day type, respectively.

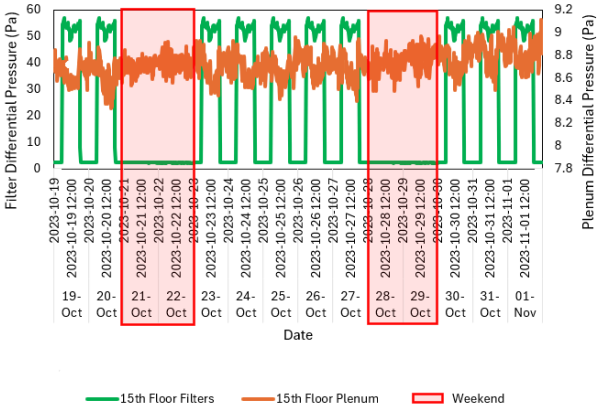

Figure 4: Fifteenth-floor air handler filter pressure (Location B) and office space zone-to-plenum (Location A) differential pressure with extrapolated filter pressure drop data for the study period of October 18th, 2023, to November 2nd, 2023. The red highlighted time periods are weekend days.

Over the testing period, a lower overall zone-to-plenum differential pressure was observed on the 4th floor compared to the 15th floor. The average difference between the 4th and 15th floors was calculated to be 2.62 Pa for the testing period. Figure 5 shows a box plot of the zone-to-plenum differential pressure for when the air handler was running and not running for both the 4th and 15th floors. Little variation in the zone-to-plenum differential pressures between the two operating conditions regimes was observed on both floors, with the 15th floor exhibiting a larger difference between the two operating conditions.

Notably, no positive pressure events were observed in the plenum throughout the testing period. The occurrence of positive pressure in the plenum relative to the conditioned zone would mean stale air was moving from the plenum back into the conditioned space.

On each floor, the variation in zone-to-plenum differential pressure was small. On the 4th floor, the observed pressures had a standard deviation of 0.063 Pa for periods when the air handler was running and 0.062 Pa for periods when the air handler was not running. For the 15th floor, the standard deviation in differential pressures was 0.12 Pa when the air handler was running and 0.10 Pa when the air handler was not running, respectively.

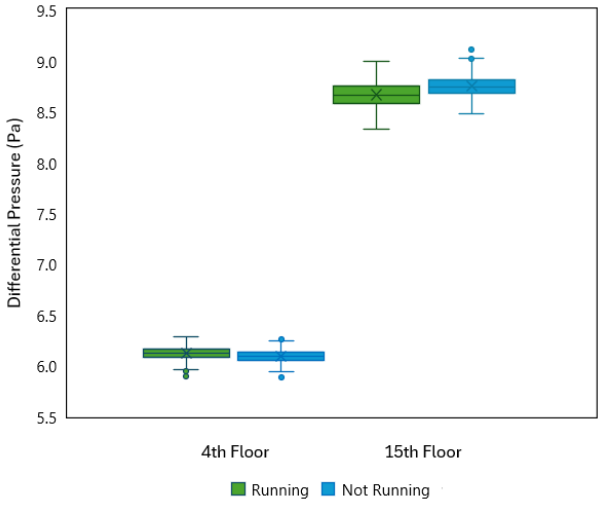

Figure 5: Box and whisker plot of the differential pressure between the plenum and the conditioned space for when the air handler is running and not running for the 4th and 15th floors.

A t-test was done for the 4th and 15th floor plenum to determine if there is a statistical difference in the zone-to-plenum differential pressures on each floor when the air handler is/is not running. The tests indicated a statistical difference between the differential pressures measured during each operating condition on both of the floors. Cohen's d for the 4th floor was calculated to be 0.5 ("moderate effect"), and the 15th floor's Cohen's d value was calculated to be 0.8 ("large effect"). However, given the small standard deviation of the differential pressures within each operating regime, the actual magnitude of this effect is very small in both cases (~0.03 Pa for the 4th floor

and ~ 0.09 Pa for the 15th floor). This means that even though there is a statistical significance between the differential pressures measured during each operating regime, there is little practical significance. Practically, air handler operation does not materially affect the differential pressures between the conditioned space and the plenum and, as such, will have minimal (if any) impact on return airflow. This is interesting as air handler operation is expected to impact zone-to-plenum air flow characteristics significantly; however, other conditions influencing differential pressures appear to overpower this influence. Further measurements are needed to investigate key contributing factors.

External Factors

The relationships between the zone-to-plenum differential pressure, outdoor wind speed, and outdoor air density for the testing period were analysed using the collected weather data.

Figures 6 and 7 show the zone-to-plenum differential pressures versus wind speed for the 4th and 15th floors. Visual analysis of the 4th floor shows that there may be a small positive correlation between wind speed and zone-to-plenum differential pressure (Figure 6). The Pearson correlation coefficient and the p-value for the 4th floor were computed to assess the statistical significance of the relationship between the two variables. The Pearson correlation coefficient for the 4th floor is 0.07 (weak, positive correlation), which is not statistically significant based on the calculated p-value (0.19).

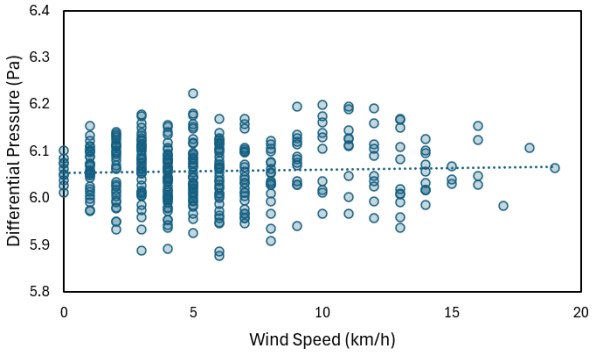

Figure 6: Wind speed relative to the differential pressure mean of the 4th-floor plenum to conditioned space.

Likewise, on the 15th floor, visual analysis shows a negative relationship between wind speed and the zone-to-plenum differential pressure (Figure 7). Like the 4th floor, the Pearson correlation coefficient indicated a weak, positive correlation (0.06), and the calculated p-value (0.27) indicated that this relationship is not statistically significant. This is not unexpected, as previous research has shown that estimating ventilation system performance based on simultaneous measurement of differential pressures and weather conditions has limitations as an analysis technique due to difficulty isolating the effects of different factors (Lozinsky et al., 2023.).

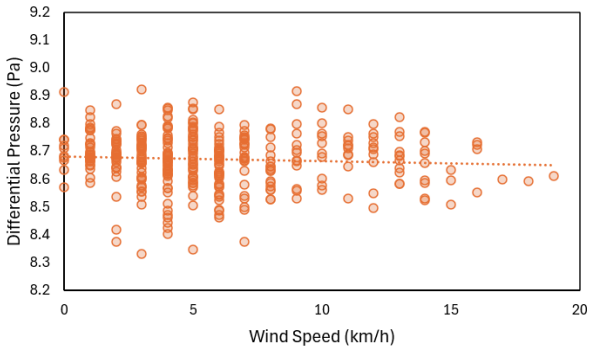

Figure 7: Wind speed relative to the differential pressure mean of the 15th-floor plenum to conditioned space.

To further understand if there is a correlation between the wind speed and the zone-to-plenum differential pressure, the zone-to-plenum differential pressure was separated into two categories: 1) when the air handler was running and 2) when the air handler was not running. The Pearson correlation coefficient and the p-value for the 4th and 15th floors were computed to assess the statistical significance of the relationship between the wind speed and running and not running zone-to-plenum differential pressure.

The Pearson correlation coefficient for the 4th floor when the air handler was running was calculated as 0.16, while the 4th floor not running was calculated as 0.04. The p-value for the 4th floor when the air handling unit was running was 0.05, indicating that the correlation may be statistically significant. However, the p-value for the 4th floor air handling unit was not running was 0.6, indicating that the correlation is not statistically significant.

The Pearson correlation coefficient for the 15th floor running was -0.01, indicating a weak negative correlation, with the 15th floor not running at 0.09, indicating a positive yet weak correlation. The p-value for the 15th floor when the air handling unit was running was 0.89 while the value for when the air handling unit was not running was 0.17 indicating that this relationship is not statistically significant.

Figure 8 shows the zone-to-plenum differential pressures versus wind speed for the 4th and 15th floors. The wind speeds are divided into the bottom 25%, middle 50% and top 25% of wind speeds. The bottom 25% of the wind speeds range from 0-4 km/h, the middle 50% range from 4-9 km/h, and the top 25% range from 9-19 km/h. Figure 8 shows that the range of differential pressures observed for varying wind speeds is smaller in Location A on the 4th floor than in Location A on the 15th floor. This is not unexpected, as local wind speeds vary with respect to height above ground and are likely to be higher (and, as such, have a larger impact on pressure) on the 15th floor.

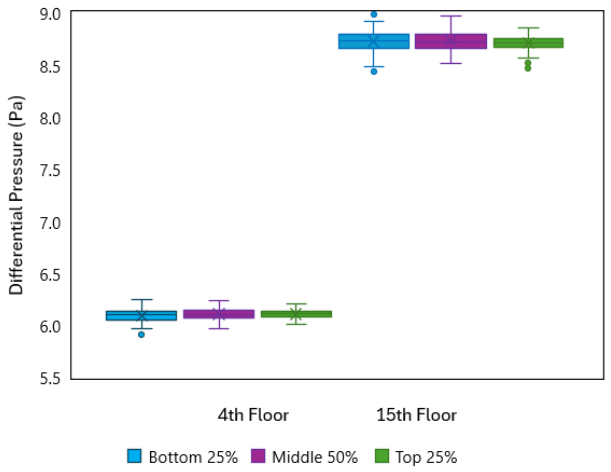

Figure 8: Box and whisker plot of 4th and 15th floor Location A zone-to-plenum differential pressures versus wind speed.

Figures 9 and 10 show the zone-to-plenum differential pressures versus air density for the 4th and 15th floors. Visual analysis shows a positive relationship between air density and zone-to-plenum differential pressure on the 4th and 15th floors.

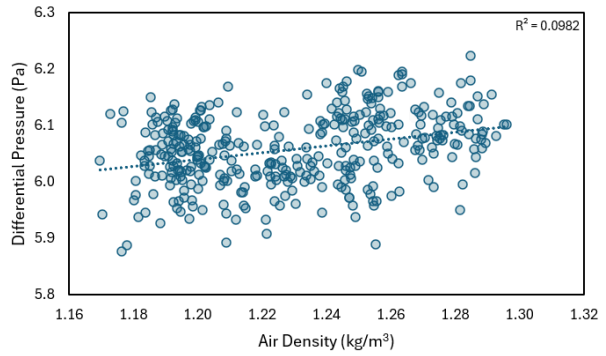

Figure 9: Plot of the air density relative to the zone-to-plenum differential pressure on the 4th floor.

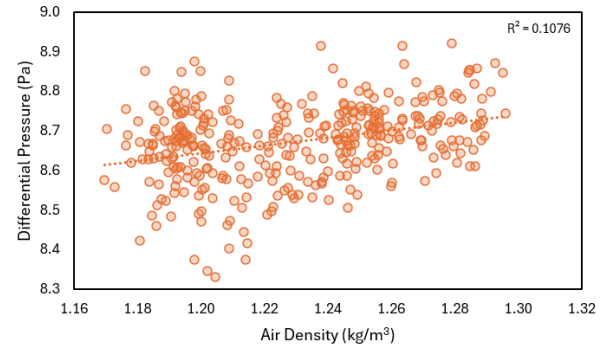

Figure 10: Plot of the air density relative to the zone-to-plenum differential pressure on the 15th floor.

Table 2: p-values of the zone-to-plenum differential pressures versus air density for the *4th and 15th floors.*

	4th-floor p-value	15th-floor p-value
Total air handler	0.54	0.05
Air handler running	0.07	0.17
Air handler not running	0.55	0.11

The Pearson correlation coefficient and the p-value (Table 2) were calculated for the 4th and 15th floors to determine if there is a statistical significance between the zone-to-plenum differential pressures versus air density. The 4th floor Pearson correlation coefficient is 0.031, indicating a positive yet weak correlation. Calculation of the p-value for this relationship (0.54) indicated that this relationship on the 4th floor is not statistically significant. On the 15th floor, the Pearson correlation coefficient equals 0.102, which is larger than the 4th floor, but there is still a weak correlation. The calculated p-value for the 15th floor is equal to 0.05, which indicates that there may be a statistically significant relationship between the zone-to-plenum differential pressures versus air density for this floor.

The coefficient of determination, R-squared, was calculated for both the 4th and 15th floors. The 4th floor has an R-squared value of 9.9%, with the 15th floor having a value R-squared of 10.8%, indicating that the influence of air density on zone-to-plenum differential pressure accounts for approximately one-tenth of the total variation and only limited variation in the data that is explained by this relationship.

To further understand if there is a correlation between the air density and the zone-to-plenum differential pressure, the zone-to-plenum differential pressure was separated into when the air handler is running and when the air handler is not running. The Pearson correlation coefficient and the p-value (Table 2) for the 4th and 15th floors were computed to assess the statistical significance of the relationship between the air density and running and not running zone-to-plenum differential pressure.

The Pearson correlation coefficient for the 4th floor for when the air handling unit was running is 0.15, indicating a positive yet weak correlation. However, the 4th floor value for when the air handling unit was not running is-0.04, indicating a weak negative correlation. Ap-value of 0.07 was calculated for when the 4th floor air handling unit was running. A p-value of 0.55 was calculated for the 4th floor for when the air handling unit is not running. This indicates that this relationship is not statistically significant.

The Pearson correlation coefficient for when the 15th floor air handling unit is running was 0.11, with the value for the 15th floor when the air handling unit is not running being 0.11, indicating a positive yet weak correlation. The

p-value of 0.17 for the 15th floor was calculated for when the air handling unit is running. A p-value of 0.11 was calculated for the 15th floor for when the air handling unit is not running. This indicates that this relationship is not statistically significant.

Limitations and Future Work

The test contains limitations, including two testing dates, weather data accuracy and resolution, and sensor locations. The need for two testing dates to retrieve data for the 15th-floor differential pressure across the air handler filter limits the ability to have the exact air handler running cycle for the 15th floor zone-to-plenum differential pressure. This further limits the ability to compare the 4th and 15th floor data for a testing period.

The weather data used for analysis was retrieved from an Environmental Canada weather station rather than a weather station located at the building site. This limits the ability to know if a microclimate can affect the building systems. Further, weather data was only available at a resolution of 1 hour (which is larger than the resolution of the collected differential pressure data), which limits the extent of analysis to average conditions and prevents consideration of the impacts of transient weather conditions (e.g., wind gusts).

Future work should expand on the measurements taken through this field study to measure the impacts of more variables on zone-to-plenum differential pressures (e.g., measurement of stack-induced pressure differentials across the building envelope at each floor). Further, collecting data from other floors in the building would enable a more robust analysis.

Conclusion

The collected data demonstrates the operational complexities of open plenum air return systems. Air handler operation was observed to have minimal impact on zone-to-plenum differential pressures – indicating that mechanical system-induced pressure differences may be overwhelmed by other drivers of pressure differences. This may limit the system's operational performance and raises concerns surrounding the consistency of return airflow and the potential for plenum pressurisation events. External environmental conditions appear to impact building operations; however, it is challenging to establish the nature of these relationships based on the interactive effects of different factors. The results from this study will help identify how these systems operate in real-world conditions and inform further decisions.

Acknowledgement

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