The optimal operating range of VAV supply units

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SUMMARY

Air diffusers equipped with variable air volume control function (VAV) regulate the air flow rate to meet the rising and falling heat gains within the thermal zone served. The VAV unit is basically a calibrated air damper with an automatic actuator.

When the air is supplied parralel to the ceiling surface negative pressure occurs between the air jet and the ceiling, causing the jet to attract to the ceiling (Coanda effect). This effect is of great importance, particularly when supplying cooling air.

Several types of diffusers were tested to determine the influence of the shape and constructional features of diffusers on the air distribution pattern within a premises. The tests were performed at Lindab Comfort aerodynamics laboratory in specially designed test chamber which represented a single office room. Thus we traced the path of air distribution pattern within the operating range to demonstrate the air distribution pattern on each tested diffuser. Acquired data are applicable in VAV systems.

KEYWORDS

Thermal comfort, Measurements, Perceived air quality, Acoustics.

1 INTRODUCTION

VAV systems are designed to supply only the volume of conditioned air to a space that is needed to satisfy the load. Fan energy is saved when the volume of air handled by the fan is reduced. Air volume control is accomplished by installing modulating dampers, or in some cases, an air valve, in the supply duct to each zone. As the room temperature demand becomes satisfied, the thermostat signals the damper to move the supply air zone valve toward the closed position.

When zone valves are throttled, the static pressure in the supply ducts changes. A static pressure sensor located in the supply duct senses the static pressure change and either increases or decreases the airflow from the source, using variable speed control or dampers on the main air supply fan.

A key component in the VAV system is the air valve. It is commonly installed inside an insulated sheet metal box suspended in a ceiling plenum. The air valve has a damper that regulates the air flow in response to the room's thermostat. A multi-port pressure sensing ring provides both accurate airflow sensing and control in response to duct static pressure.

There are two primary advantages to VAV systems. The fan capacity control, especially with modern electronic variable-speed drives, reduces the energy consumed by fans, which can be a substantial part of the total cooling energy requirements of a building. Dehumidification is greater with VAV systems than it is with constant-volume systems, which modulate the discharge air temperature to attain part load cooling capacity.

The air blower's flow rate is variable. For a single VAV air handler that serves multiple thermal zones, the flow rate to each zone must be varied as well.

A VAV terminal unit, often called a VAV box, is the zone-level flow control device. It is basically a quality, calibrated air damper with an automatic actuator. The VAV terminal unit is connected to either a local or a central control system.

2 MATERIALS/METHODS

The tests were performed in a specially designed test chamber which represented a single office room. 24 probes were installed at 3 levels: feet, waist and head area of a standing occupant in accordance with ASHRAE Standard 55-2004. The point of reference for the disposition of the probes was the vertical axis of the diffuser installation plane. The probes were attached to support bars so that horizontal distance between each probe was 0.2m. At each of 24 points air temperature and velocity were measured. The test chamber was isolated so that isothermal conditions were maintained and all measurements were carried out at 8°K (14.4°F) temperature difference between supply air temperature and ambient air temperature inside the chamber. Supply air temperature was maintained by cooling coil installed in the air duct system prior to the plenum box. Room temperature was maintained by four oil filled electric radiators with overall thermal capacity 400 W (figure 1). The air temperature and air movement velocity data were registered every 20 seconds so that any fluctuations or deviations were excluded.

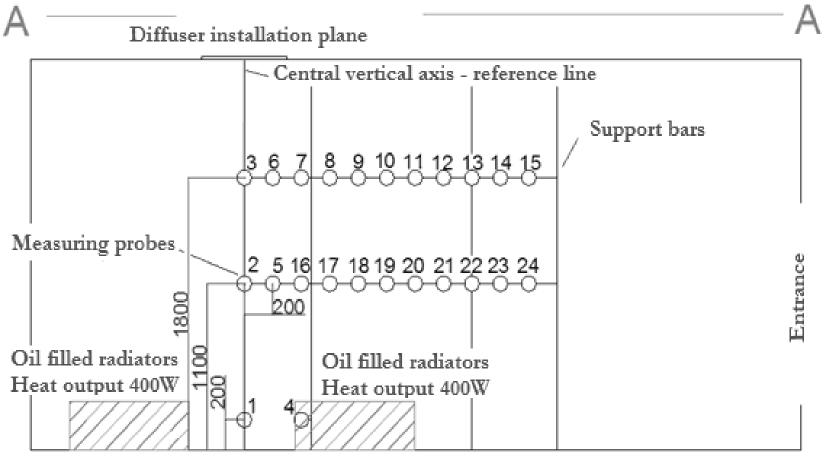

Figure 1: The cross section view of the test chamber

Two air flow values are of great importance to establish the operating range of air supply diffusers: the lowest threshold point at which Coanda effect appears resulting in horizontal air distribution pattern and the highest threshold point at which noise level of 35 dB is exceeded according to the CR 1752:1988 for small office room for B cathegory. Noise level data for each diffuser were gained from technical specifications.

The general value which characterizes the human comfort level is draught rate (DR). It is calculated by following equation:

$$DR = ((34 - t_A) \cdot (v - 0.05)^{0.62}) \cdot (0.37 \cdot v \cdot T_U + 3.14) \quad (1)$$

Where *DR* is the predicted percentage of people dissatisfied due to draft (%), t_A is the local air temperature (°C), *v* is the local average air speed (m/s), t_U is the local turbulence intensity (%).

The model of draught rating is based on studies comprising 150 subjects exposed to air temperatures of 20°C to 26°C, mean air velocities of 0,05 m/s to 0,4 m/s and turbulence intensities of 0% to 70%. The model applies to people at light, mainly sedentary activity with a thermal sensation for the whole body close to neutral. The sensation of draught is lower at activities higher than sedentary and for people feeling warmer than neutral.

ASHRAE stipulates in Standard 55-2004 that DR must be <20%.

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment. Dissatisfaction may be caused by warm or cool discomfort of the body. Thermal dissatisfaction may also be caused by an unwanted cooling (or heating) of one particular part of the body. Local discomfort may also be caused by an abnormally high vertical temperature difference between head and ankles, by too warm or cool a floor or by too high a radiant temperature asymmetry. Discomfort may also be caused by too high a metabolic rate, or by heavy clothing.
Due to individual differences, it is impossible to specify a thermal environment that will satisfy everybody. There will always be a percentage of dissatisfied occupants. But it is possible to specify environments predicted to be acceptable by a certain percentage of occupants.
The aim of testing the diffusers equipped with VAV was to determine the optimal operating range of certain diffusers in terms of occupants' sense of comfort. The comfort sense roughly consists of three components: thermal conditions, air freshness and acoustic environment. Basically the task was to determine the threshold for each diffuser at which the Coanda effect appears because it is high risk of draught when cooled air is supplied at low flow rate.

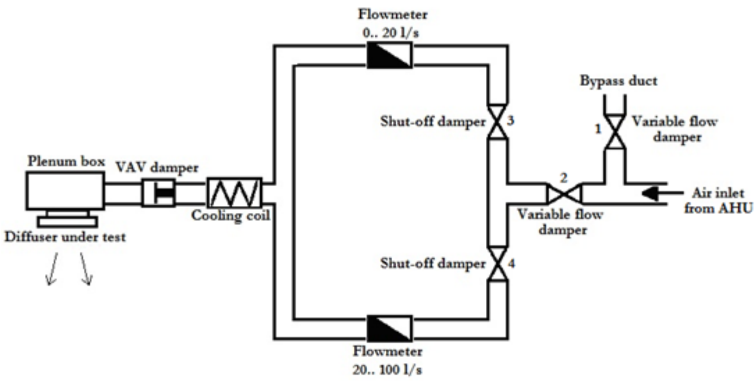

Figure 2: The layout of the VAV supply system

The system used the inlet air supplied from the outside and filtered prior to the fan. Fan forced the air to the test chamber at constant flow rate (l/s) and pressure (Pa). After passing the fan certain air volume flowed to the system but some volume continued its way to the bypass duct. The bypass duct provided a constant inlet air temperature to the room when VAV damper was slightly opened, i.e., at low flow rate. It was due to the fact that air mass flowing through the ductwork system warmed up resulting in too low temperature difference when reaching the test chamber. Heat gains from the oil filled radiators (1600 W in total) provided a stable room air temperature at approximately 22°C to 25°C level. Supply air temperature was kept at 14°C to 18°C level thanks to cooling coil. Since the capacity of cooling coil was limited the optimal solution to keep the supply air and room air temperature difference at required level (8 K) was to equip the system with the bypass duct (figure 2). When measurements were taken at low flow rate the variable flow damper (2) was slightly opened, the variable flow damper on the bypass duct (1) was fully opened. By raising the flow rate to the test chamber this relation changed - as variable flow damper (2) blade moved to more opened position variable flow damper (1) blade moved to less opened position. And so on. Although the plenum box usually contains an integrated flow damper at the current system VAV damper was installed prior to the plenum box and connected to the regulating devices. After passing the variable flow damper (2) ducts were split in two branches for making measurements at different airflows. When the flow rate was less than 20 liters per second (l/s) the shut-off damper (3) was in fully opened position whereas shut-off damper (4) was fully closed. And conversely when flow rate was equal or more than 20 l/s.

3 RESULTS

By implementing above mentioned methods we traced the path of air distribution pattern within the operating range, made the calculations on turbulence intensity, draft rate and eventually built the diagrams to demonstrate the results on each type and size of diffuser. The interaction between the construction of diffuser and optimal operating range showed the following regularities: In diffusers with plain face plate Coanda effect establishes earlier and remains steady allowing them to be used at wider flowrate range and bigger temperature difference; the duration of transition phase from vertical to horizontal air distribution pattern is longer at bigger connection sizes; in perforated diffusers stable Coanda effect was detected at very short range.

Diagram 1 shows the air movement pattern using diffuser with plain face plate (LCA-160+MBB-125-160-S). Initially there is a transition phase between vertical and horizontal air distribution pattern (figure 3- Coanda 1 and 2). At 20 l/s a stable Coanda effect establishes and remains steady so that thermal comfort level is not compromised. As the air flow increases the air jet orients horizontally and moves along the ceiling surface. Eventually air velocity and thus draft rate in the occupancy zone slightly decreases. Fluctuations in a trend line are due to the turbulence created by upwards oriented heat loads from radiators.

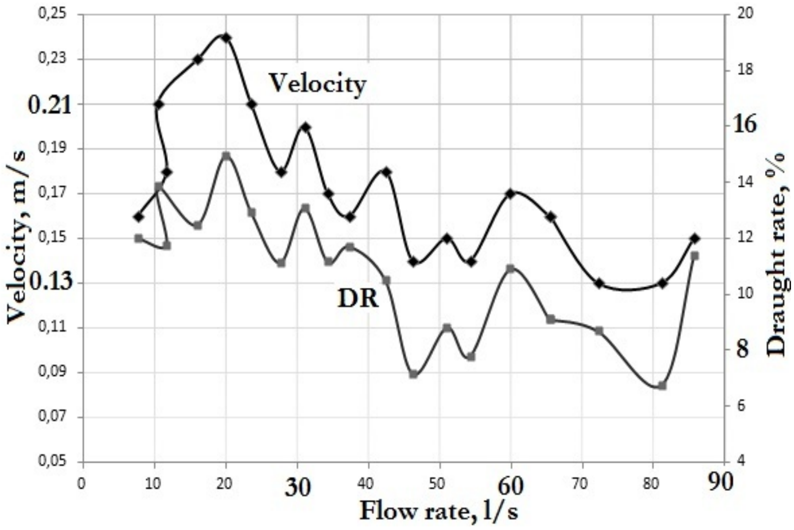

Diagram 1: Test results using diffuser with plain face plate at ΔT = 8 K.

Unlike plain diffusers most of perforated diffusers showed an opposite relationship. The higher air flow resulted in higher draft rate level in the occupancy zone. The air distributed downwards exceeded acceptable draft rate value. See diagram 2 for PCA-250+MBB-200-250-S. It is worth to mention that this air distribution pattern ensures good mixing at warm supply air conditions. As flow rate increases the air velocity and draught rate in occupancy zone increases. This relation showed

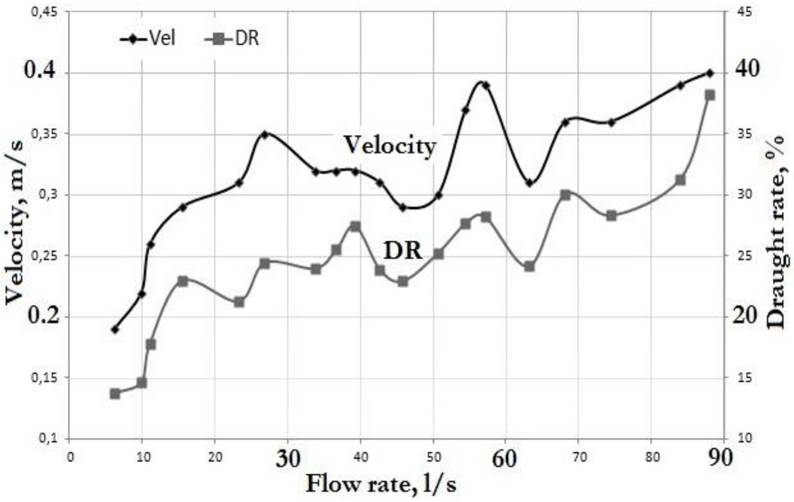

Diagram 2: Test results using diffuser with perforated face plate at ΔT = 8 K.

that perforated diffusers are not applicable for supplying a cooling air due to the increased risk of discomfort and annoyance.

4 DISCUSSION

This comparison showed the overall concept of plain and perforated diffusers. Diffuser of the same type had a different performance when the size changed. Therefore all diffusers were tested with all available standard connection sizes resulting in more than 80 tests in total.

The general theory on Coanda effect states that full development occurs through two prior stages. Figure 3 shows 3 stages of the development of Coanda effect.

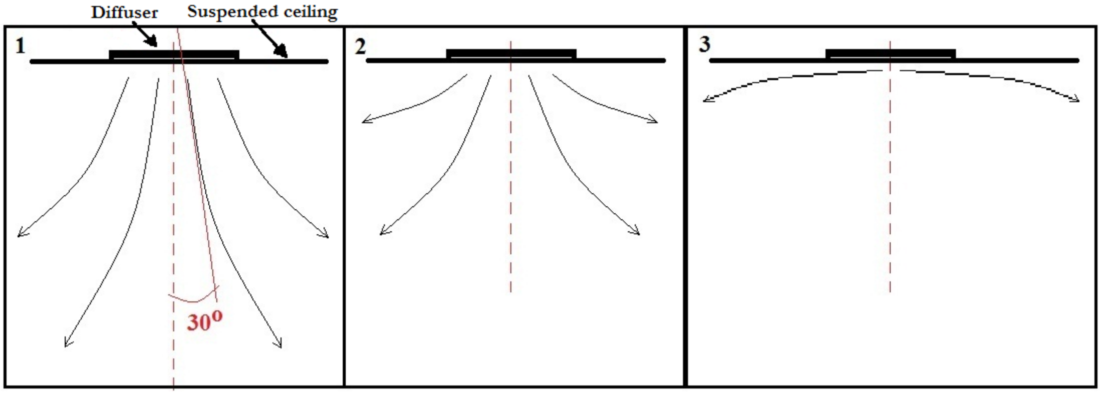

Figure 3: The development of Coanda effect (stages 1, 2, 3)

Stage 1 – initial phase, where we can observe how the air jet seeks to rise up. Basically it is assumed that first phase is characterized by the angle between the central vertical axis or the reference line (figure 1) and the air jet. When the angle is geting wider than 30^{o} it is first feature of Coanda effect. There is no doubt that it is pure theoretical assumption since the angle cannot be measured precisely. Stage 2 – transition phase at which air jet struggles to form a horizontal pattern. However, at this stage the air jet pattern is oriented diagonally down. It is worth to mention that at this stage slight wind blow can change the pattern to vertical, i.e., back to stage 1 or even to cause the jet to stick to the ceiling thus forwarding the air distribution pattern to stage 3 at which Coanda effect is fully established. At that stage the air jet pattern is horizontal and the air is distributed across the ceiling and drops down slightly whether along the sidewalls or by being mixed with room air through convectional flow. Coanda effect is stable and continuous.

To show the overall picture of optimal operating range for different diffusers we built a table which contains data on 4 different diffusers being measured at the same conditions and having the same connection size (table 1). Thus it is easy to observe the difference among those diffusers and their applicability at specific indoor environment. At the column it is stated whether at particular flow rate range (l/s) the specific diffuser creates draught or whether it creates Coanda effect (stage 1, 2, 3). At flow rates above which noise level (dB) is exceeded in accordance to CR 1752:1988 related columns are filled with the warning even though Coanda effect excludes the risk of draught or thermal discomfort. As mentioned above the room comfort also depends on acoustic environment.

Table 1. Comparison of operating range for different diffusers (connection size 160 mm)

No.	*Flow rate range (l/s)*	*Plain diffuser LCA-160+MBB-125-160-S*	*Perforated diffuser PCA-160+MBB-125-160-S*	*Nozzle diffuser NCA-160+MBB-125-160-S*	*Swirl diffuser RC15-160+MBB-125-160-S*
1	*0.. 5*	-	-	-	-
2	*5.. 10*	*Draught*	*Draught*	*Draught*	*Draught*
3	*10.. 15*	*Coanda (1,2)*	*Draught*	*Coanda (1,2)*	*Draught*
4	*15.. 20*	*Coanda (2)*	*Draught*	*Coanda (3)*	*Coanda (1)*
5	*20.. 25*	*Coanda (3)*	*Draught*	*Coanda (3)*	*Coanda (2,3)*
6	*25.. 30*	*Coanda (3)*	*Draught*	*Coanda (3)*	*Coanda (3)*
7	*30.. 35*	*Coanda (3)*	*Coanda (1)*	*Coanda (3)*	*Coanda (3)*
8	*35.. 40*	*Coanda (3)*	*Coanda (2)*	*Coanda (3)*	*Coanda (3)*
9	*40.. 45*	*Coanda (3)*	*Noise (>35 dB)*	*Coanda (3)*	*Coanda (3)*
10	*45.. 50*	*Noise (>35 dB)*	*Noise (>35 dB)*	*Noise (>35 dB)*	*Noise (>35 dB)*
11	*50.. 55*	*Noise (>35 dB)*	*Noise (>35 dB)*	*Noise (>35 dB)*	*Noise (>35 dB)*
12	*55.. 60*	*Noise (>35 dB)*	*Noise (>35 dB)*	*Noise (>35 dB)*	*Noise (>35 dB)*
13	*>60*	*Noise (>35 dB)*	*Noise (>35 dB)*	*Noise (>35 dB)*	*Noise (>35 dB)*

The diffusers are applicable to be used at the values where the third stage of Coanda effect is established. According to this it is obvious that a perforated diffuser (PCA-160+MBB-125-160-S) should not be used when supply air is used to cool the room air, whereas other types of diffusers are applicable at certain flow range.

5 CONCLUSIONS

Several types of diffusers were tested to establish the optimal operating range when variable air volume is supplied. Diffusers with adjustable nozzles and swirl diffusers did not show constant trend therefore these types are extremely sensitive to any adjustments, specific ambient conditions and connection size. The most common are diffusers with plain and perforated face plates. At $\Delta T = 8$ K plain diffusers performed very good results with respect to human thermal comfort. The operating range varied depending on the connection size but the overall picture was quite the same for all sizes. At the very beginning draft rate is slightly increasing but as soon as it reaches the transition threshold it starts to decrease continuously. This allows to use plain diffusers at supply air temperature significantly lower then room air temperature and at wide flowrate range. Diffusers with perforated face plate are recommended when warmer air is supplied or at low-impulse supply conditions when contaminated air needs to be displaced by clean air e.g. in laboratories, hospitals.

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