Displacement Ventilation for an Auditorium in a Hot Climate

BY MOHAMAD YEHIA ITANI, MEMBER ASHRAE; HASSAN CHEHADE, MEMBER ASHRAE; ADNAN AKHDAR

Mechanical ventilation systems conventionally have been used in hot climates to continually replace the air supply inside a building and maintain indoor air quality (IAQ) in densely occupied spaces such as an auditorium. However, while various traditional and novel ventilation strategies exist, displacement ventilation has become more widespread in nonindustrial spaces, especially those with high ceilings where the natural rising motion of thermal plumes is promoted and where contaminant levels are low and system energy efficiency is a priority. This article presents a case study on the implementation of the displacement ventilation system in the Riad Salameh Auditorium, which was built in 2017 and that is part of the Middle East Airlines (MEA) Training and Conference Center in Beirut, Lebanon.

People are always trying to make their lives more comfortable, and the indoor climate is a very significant component of our lives. Klepeis, et al,[1] reported that people are spending an average of 87% of their time in enclosed buildings and about 6% of their time in enclosed vehicles. Many existing halls have used displacement ventilation systems with different classifications such as passive thermal displacement systems, systems with unidirectional flow, systems with special nozzles, low-impulse systems and systems with the supply air ducts laid under the floor as is in our case.

Chen, et al,,[2] showed that a displacement ventilation system can provide a thermally comfortable indoor environment at a high cooling load through careful design. In previous and similar cases of auditoriums and lecture halls where the displacement system was

Mohamad Yehia Itani is the operations and technical manager at Climacond Middle East SAL in Beirut, Lebanon. Hassan Chehade is a senior mechanical engineer at Khatib and Alami in Beirut, Lebanon. Adnan Akhdar is the head of the CFD unit at Dar Al-Handasah in Beirut, Lebanon.

FIGURE 1 Night view of the Middle East Airlines (MEA) Training Center as seen from Airport Street. The large obtruding dome structure in the middle is the Riad Salameh Auditorium.

FIGURE 2 Internal view of the Riad Salameh Auditorium showing the seating area and stage. The projection room can be seen in the upper left side of the picture.

implemented, it is worth highlighting that the supply-return air outlets are predominantly configured with each supply floor diffuser connected directly to the main duct and with the return air outlets located at a high level above the occupied zone (above 6.5 ft [2 m] and below 13 ft [4 m]).

In the current study, a different configuration for the displacement ventilation system (which is currently operational) was designed following ANSI/ASHRAE Standard 62.1-2022, *Ventilation and Acceptable Indoor Air Quality*,[3] which assigns a zone air distribution effectiveness value (E_z) of 1.0 for conventional mixed air systems and 1.2 for fully stratified systems and is validated using computational fluid dynamics (CFD) simulations. The advantage of designing for a fully stratified system is the potential to achieve the same level of ventilation compared to the best mixed air systems with 20% increased efficiency and 16.7% reduction in air volume. This reduces the amount of outdoor air necessary to meet ventilation requirements. Better ventilation efficiency means, in addition to energy savings through a reduction in air volume, improved indoor air quality in the occupied zone is attainable.

The current work will present all relevant challenges faced during the construction phase from the design review to the on-site close coordination with architects and structural engineers to manage thermal decay and control humidity. It will also highlight the followed methodology to modify the ventilation design on-site in light of additional client requirements and interior design constraints, including revising the air outlets distribution using a CFD analysis that helped define their exact location. This work will also show that, despite the nonconventional supply/return configuration, we were able to achieve excellent results with regard to energy efficiency and thermal comfort according to ANSI/ASHRAE Standard 55-2023, *Thermal Environmental Conditions for Human Occupancy*,[4] and Standard 62.1-2022.

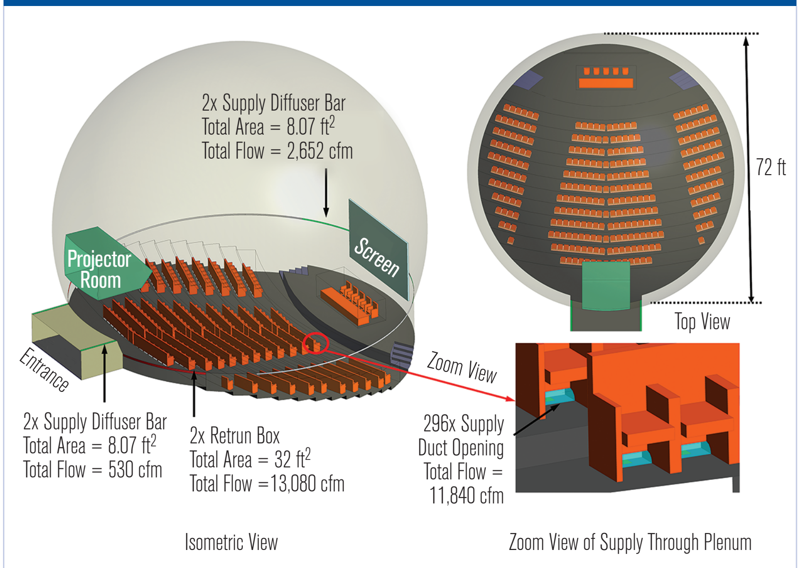
Project Overview

In 2012, Middle East Airlines (MEA) decided to build in Beirut its own aviation training academy with a built-up area of 474,000 ft^2 [44,000 m^2]. This flight training center is composed of three basements for parking, mechanical, electrical, plumbing (MEP) rooms and services. The total basement area is 300,000 ft^2 [28,000 m^2], including a total of 500 indoor parking spaces. The simulator areas are distributed on the lower ground, upper ground and first floors with a total area of 65,000 ft^2 [6000 m^2]. They contain four cockpit flight simulators, one cabin crew simulator and one hostess simulator in addition to many Airbus pilot transition trainer (APT) and computer based training (CBT) simulators.

Extending over an area of 5,100 ft^2 (474 m^2) with a maximum height of 62 ft [19 m], the Riad Salameh hall functions as an auditorium with a capacity of 300 people in the audience. The auditorium is circular with a concrete structural dome with skin encrusted by mirror cladding (*Figure 1*). Chairs are located on different stair levels. A wooden internal finish with strip LED lights covers the internal skin (*Figure 2*). A technical floor below the auditorium is designated for HVAC equipment serving the auditorium where a central air-handling unit (AHU) is installed.

The chilled water plant consists of four 300 ton

FIGURE 3 Figure 3 (a) Isometric view of the auditorium showing the location of the supply and return air outlets (b) Zoom view of the supply air diffusers showing below the seat.



(1054 kW) air-cooled water chillers, providing a total of 1,200 tons (4220 kW), of cooling. The chilled water plant delivers chilled water to the AHUs, fan coil units and blower coil units that serve the building at a temperature of 42.5°F [6°C], through four primary constant flow and four secondary chilled water pumps with variable frequency drives.

A centralized building automation system (BAS) is incorporated to control the building HVAC, lighting and other systems through a building management system (BMS). The objectives of the BAS are improved occupant comfort, efficient operation of the building systems, reduction in energy consumption and operating costs and improved life-cycle costs of utilities.

Construction Challenge

The construction of the auditorium posed a great challenge to the design and construction team, as no structure of this magnitude and shape had previously been constructed in Beirut, Lebanon; moreover, no other facility of this scale had previously implemented displacement ventilation as a main ventilation principle. This was far from traditional auditorium ventilation, which uses supply ducts and grilles located on the upper part of the auditorium and uses dilution principles. Other challenges emerged during the construction phase, which were due to the ongoing modifications imposed by the architect in light of the seemingly endless improvement needed for this iconic structure, all while working to achieve comfortable conditions in compliance with ASHRAE Standard 55-2023.

Computer simulation with the aid of CFD and full-scale test model allowed optimizing the location of the air outlets, specifically maintaining one diffusion grille beneath every seat, all while maintaining acceptable terminal velocities and noise levels. Close coordination with architects and structural engineers was required to create openings in the precast concrete slab for air supply beneath each seat, making it entirely integrated and invisible. Another challenge that emerged as a consequence of low air speeds and higher supply temperatures associated with displacement ventilation was how to efficiently cool the main stage area without affecting the displacement ventilation design. The design team proposed installing two supply diffuser bars above the main stage area (*Figure 3*).

Supply Air Connections

Displacement ventilation diffusers are usually supplied by ductwork, and they can be supplied from either above or below. In our case, supply displacement ventilation diffusers are connected to a pressurized concrete plenum under seats (airtight concrete chamber) where the pressures and airflow rate are equal. This was made possible by installing constant flow balancing dampers in each sub-branch serving the plenum. The selection of step diffuser was based on a supply air velocity of 39 fpm (0.2 m/s).

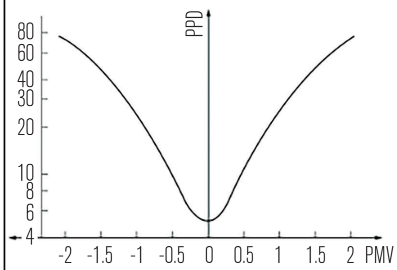
Location of Returns

Returns are usually located as high as possible in the space to remove as much of the stratified zone as possible, typically at ceiling height. If the return is located lower than 7 ft (2 m), some polluted/hot air may remain within the occupied zone. Despite the fact that in our case the return air grilles are lower than 7 ft (2 m), the introduction of a substantial quantity of fresh air helped avoid the contamination of the occupied space with polluted/hot air. The return air grilles are evenly and symmetrically distributed at the entrance in the back side of the auditorium at a level 3.3 ft (1 m) above the entrance floor level and 10 ft (3 m) above

FIGURE 4 Recommended thermal comfort range for typical applications.

PMV	
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

PPD



PMV Predicted Mean Vote
PPD Predicted Percentage Dissatisfied %

the stage floor level (*Figure 3*). The air is returned to the AHU through an opening located at the back side of the auditorium and sized based on a velocity of 390 fpm (2 m/s) and at a height of 10 ft (3 m) above the highest floor level.

Auditorium Air-Handling Unit

The AHU supplying treated air to the auditorium has a flow capacity of 18,800 cfm (8873 L/s) and 91 tons (320 kW) of cooling capacity. It is capable of supplying treated air at 64.4°F (18°C) and 45% relative humidity and has enough static pressure to supply the treated air to the auditorium via step diffusers located below each seat. To accomplish this the auditorium is served with a central station double-deck AHU with a cross flow heat exchanger located in the technical area below the auditorium. A high degree of care was taken during the selection of the AHU, and many adjustment features were integrated within the unit such as two supply and two return plug fans with variable frequency drives (VFD) in addition to balancing dampers and pressure independent flow control valves, which allowed balancing and adjustment of the system once in operation.

IAQ and Thermal Comfort

To investigate the acceptable thermal comfort range in the occupied regions, the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) comfort indices defined by Standard 55-2023 are computed. These indices combine the temperature, air speed, clothing insulation, metabolic rate and humidity values to define the comfort level of occupants.

- PMV is an index that predicts the mean value of the thermal sensation votes of a large group of persons on a sensation scale ranging between -3 and +3.
- PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV.

The acceptable thermal environment for general comfort as per *Figure 4* extracted from Standard 55-2023 is defined as such that the PPD should be lower than 10 and PMV values ranging between -0.5 and 0.5.

Contaminant Distribution

Displacement ventilation can be a very effective strategy for removing contaminants from zone air, because fully stratified systems take advantage of the fact that airborne pollutants are generally lighter than air. The natural buoyancy of human respiration allows these pollutants to rise above the breathing zone in plumes to the upper zone that forms below the ceiling. This upward migration of pollutants effectively increases concentrations in the unoccupied upper zone while reducing concentrations in the breathing zone. Contaminant distribution is influenced by several factors such as supply air method, contaminant source type, location within the space, heat sources and space height.

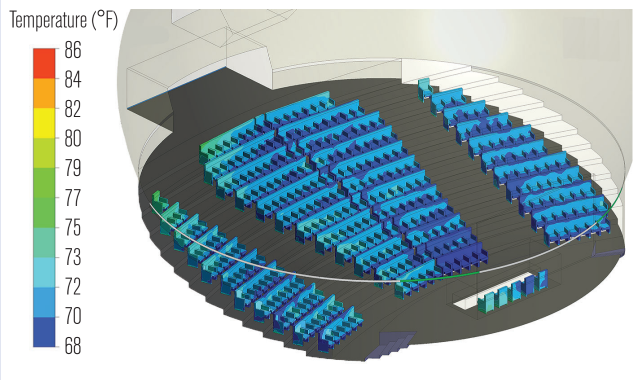
Temperature Distribution

Controlling stratification in the occupied zone is critical to maintaining occupant comfort. Standard 55-2023 requires the temperature difference between the head and foot level not exceed 5.4°F (3°C) for a standing person and 3.6°F (2°C) for a seated person. ASHRAE has determined a method for calculating the head-to-foot temperature stratification of a displacement system based on supply air volume and load distribution. This relationship was used to develop the design procedure for the displacement ventilation systems. Using this design procedure, an acceptable room temperature stratification level was achieved. For commercial displacement ventilation systems, supply air temperatures ranging from 63°F–68°F (17°C–20°C) can be expected. As well, the temperature difference between return and supply in a stratified system will generally be between 13°F–20°F (7°C–10°C).

Acoustical Performance

Like any mechanically conditioned space, those

FIGURE 5 Temperature contours at chairs.



supplied by displacement ventilation create an acoustical environment with contributions from air handlers, terminal units, diffusers and structure-borne sound. In the case of the Riad Salameh Auditorium, the main differences between a more typical supply-exhaust system and a displacement ventilation system are the type of diffusers and the duct network system, which is laid in a technical floor under the auditorium and that is sized at the minimum required air velocity. Supply air flows to a large concrete chamber (concrete plenum) under the seats, and air terminal devices are connected to this chamber.

A very important part of a displacement ventilation system is the supply diffusers. Diffusers are used for uniform distribution of airflows in the space. The catalog sound performance rating of a displacement diffuser is usually expressed in terms of a noise criteria (NC) level based upon a typical space with room absorption of 10 dB in each octave band per ASHRAE Standard 70-2006 (Appendix D). Properly sized and selected displacement ventilation diffusers are rarely the cause of noise complaints because they operate at low pressure and low velocity and therefore do not generate audible noise.

CFD Analysis

To determine the actual heat loads (external and internal) affecting the auditorium space throughout the year, a thermal cooling load simulation was carried out. Moreover, a CFD model was simulated at steady state and for peak load conditions considering the presence of nearly 300 occupants as listed below for reference:

- The sensible and latent loads released by 300 persons seated at rest were 78,000 Btu/h (23 000 W) and 41,000 Btu/h (12 000 W), respectively. No additional latent load other than the one released by the occupants was included.
- An additional sensible load of 41,000 Btu/h (12 000 W) of heat load was added to the occupied space as a result of overhead and task lighting as well as electric equipment.

From inspecting the simulation results, especially *Figure 5*, it can be deduced that a uniform thermal field is established at occupant level with no drafts. Indeed, temperatures at the stair level are observed to range between 70°F–72°F (21°C–22°C), while air speeds remain below 40 fpm (0.2 m/s), except near the auditorium's entrance where temperatures reach 75°F to 77°F (24°C to 25°C) as a result of the positioning of the return outlet. In fact, the vertical throw air velocity from the floor supply of cool air and ceiling return is less than or equal to 50 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor. As the area near the entrance is only a transitory space before the occupants reach their seats, the higher temperatures reported there are not detrimental to the performance of the system. In fact, the higher temperatures could be preferable as they correspond to a reduction in cooling capacity since no cooling is actually required at this area.

Of special note is the fact that there is no loss of cooling capacity in the volume of air above the occupant zone as a result of the optimized supply and return configuration, which promoted the establishment of a clearly visible stratification (*Figure 6*).

The above observations for the thermal distribution are further substantiated by inspecting *Figure 7a* and *Figure 7b* depicting contours of PMV and PPD at 4 ft (1.2 m) above the finished floor level, respectively. Indeed, both PPD and PMV fall in the comfort range (PMV range between 0.1 and 0.4 while PPD is below 10) as a result of the laminar rise of the supply airflow, which helped minimize any detrimental mixing.

Conclusion

The system and method that were fulfilled in the Riad Salameh Auditorium were a successful implementation of displacement ventilation. Construction and commissioning of the auditorium were completed on schedule, and the auditorium was opened in November 2017. Based on the study findings, it can be concluded that the displacement ventilation system is well suited for an auditorium with a high ceiling, as occupants were reported to be satisfied with the temperatures and humidity levels within the occupied space. Moreover, a comfortable microclimate was established without any drafts in compliance with ASHRAE Standard 55-2023. In addition, it can be concluded that the displacement ventilation system is well suited for an auditorium with high ceilings, as occupants were reported to have a proper amount of fresh air right under their seats and a comfortable microclimate is established without any drafts in compliance with Standard 55-2023.

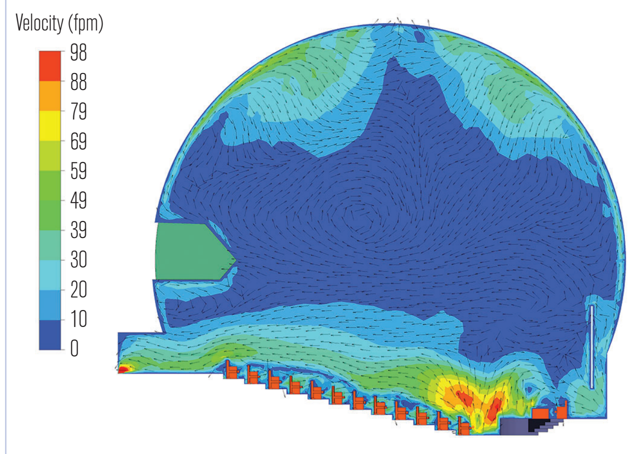
Displacement ventilation systems need to be carefully designed with regard to air outlet distribution to ensure a comfortable environment and energy reduction and proper selection of heat recovery exchanger in the central AC unit that will ensure proper and efficient operation of the system and occupant satisfaction.

Final Thoughts

CFD analysis is becoming an integral part of the HVAC design and construction process not only for cleanrooms, laboratories and operating rooms but more frequently for other spaces with large volumes. The results highlighted in this article demonstrate that CFD analysis, if performed with adequate expertise, can help optimize the HVAC layout and strategic placement of air outlets to increase thermal comfort in occupied spaces with an emphasis on occupant comfort changing from a distribution system that provides zone level conditioning to one that focuses on conditioning for each occupant.

Finally, and although not clearly stated in this article, with close coordination between the owner and design team, along with the contractor, we were able to break through the old design and construction standard and enter into a challenging process called integrated design. Architecture and

FIGURE 6 Air speed contours in a central longitudinal section through the auditorium.



engineering teams should be encouraged to promote an integrated design process that provides a suitable platform for the open exchange of information between the parties and an overall streamlining of the entire project leading to an environment with improved thermal, visual and acoustical comfort, high indoor air quality and energy efficiency within a defined construction framework.

References

1. Klepeis, N., W. Nelson, W. Ott, et al. 2001. "The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants." *J Expo Sci Environ Epidemiol* 11:231–252.

2. Chen, Q., L.R. Glicksman. 2003. *System Performance Evaluation and Design Guidelines for Displacement Ventilation*. Atlanta: ASHRAE.

3. ANSI/ASHRAE Standard 62.1-2022, *Ventilation and Acceptable Indoor Air Quality*.

4. ASHRAE. 2010. ANSI/ASHRAE Standard 55-2023, *Thermal Environmental Conditions for Human Occupancy*. ■

FIGURE 7 (a) PMV contours central in a longitudinal section through the auditorium (b) PPD contours central in longitudinal section through the auditorium.