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Performance Analysis of Displacement Ventilation in a Baggage Reclaim Area under Hot-Arid Conditions: A Case Study

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ABSTRACT

This study assesses the performance of a displacement ventilation (DV) system in the baggage reclaim area of an airport under hot, arid conditions, utilising computational fluid dynamics (CFD). The analysis focuses on thermal comfort, guided by the ISO 7730 and ASHRAE 55-2023 standards. Results show that the DV system effectively supplies cold air throughout the area, with an average temperature of 20.7°C at 1.1 m above the floor, achieving comfort class B and satisfying over 90% of occupants. Localised discomfort was observed near outlets due to high draughts, particularly at floor level and in regions close to multiple diffusers, where air velocities exceeded recommended thresholds. Vertical temperature gradients were maintained within 3 K/m, meeting comfort class B requirements. These findings offer valuable insights into the operational performance of DV systems, highlighting areas for improvement, such as diffuser placement and design, to enhance occupant comfort in similar large-scale spaces.

1. Introduction and Literature Review

The baggage reclaim area is an integral part of airport operations, designed to facilitate the efficient return of checked luggage to arriving passengers. It is located within the terminal's secure zone and is a transitional space connecting arrival gates, immigration and customs. At Kuwait International Airport, the baggage reclaim area is thoughtfully designed to accommodate large passengers while ensuring smooth operations. It features multiple baggage carousels, escalators and open spaces to optimise passenger flow and operational efficiency. Figure 1 illustrates part of the baggage reclaim area at Kuwait International Airport, showcasing its architectural design, functional layout and passenger pathways. The image highlights the interplay of spaciousness and operational efficiency, setting the context for the study.

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Fig. 1. Baggage reclaim area at Kuwait International Airport

Ensuring thermal comfort in large, high-occupancy areas is particularly challenging, especially in hot-arid climates like Kuwait, where external temperatures can exceed 50°C [1]. Thermal comfort is a key component of sustainable building design, impacting occupant well-being and energy consumption. The Leadership in Energy and Environmental Design (LEED) certification emphasises the importance of thermal comfort, as reflected in its Indoor Environmental Quality (IEQ) credit. This credit requires compliance with ASHRAE Standard 55 [2], which optimises indoor conditions while maintaining energy efficiency [3].

Displacement ventilation (DV) has emerged as a promising alternative to traditional mixing ventilation (MV) for improving indoor air quality (IAQ) and energy efficiency in enclosed spaces. By supplying cool air near the floor at low velocities, DV allows air to rise naturally as it warms, creating a stratified airflow pattern that reduces unnecessary cooling energy demand, Skistad *et al*., [4]. In contrast, a conventional MV system introduces air at a higher velocity from the ceiling, resulting in a well-mixed environment, but potentially higher energy consumption due to cooling the entire volume. These conceptual advantages of DV over MV have been documented in various studies; however, careful design is necessary to avoid issues such as short-circuiting or stagnation in DV systems [5].

Several studies have demonstrated that direct displacement ventilation (DV) improves indoor air quality (IAQ), enhances energy efficiency and provides better thermal comfort than mixed ventilation (MV) systems. For instance, Zhang *et al*., [6] proposed a cooling load estimation model for non-uniform thermal conditions and found that DV can reduce energy usage by 20% to 75% while improving IAQ. Similarly, Chen *et al*., [7] analysed the impact of DV on pollutant removal and ventilation rates, concluding that reducing unnecessary air mixing lowers energy consumption without compromising air quality. Expanding on this, Cheng *et al.,* [8] found that combining floor radiant cooling with DV provides even better temperature stability, minimising fluctuations often occurring with traditional cooling methods. In a similar approach, Al Assad *et al*., [9] found that an intermittent personalised ventilation (IPV) system combined with DV significantly enhanced overall thermal comfort compared to steady personalised ventilation and standalone DV systems. Variating the IPV frequency improved comfort levels and achieved considerable energy savings compared to steady personalised ventilation. Relaxing the DV supply temperature while maintaining comfort resulted in additional energy savings.

Beyond its role in commercial and residential buildings, DV has also been evaluated in high-occupancy environments such as offices, classrooms and healthcare settings. Park *et al*., [10] explored a hybrid DV system with integrated air purifiers, showing that reducing stagnant air zones improves IAQ in partitioned spaces. In a similar study, Namba *et al*., [11] introduced a breathing-zone DV approach, which field studies confirmed to be effective in enhancing air quality while minimising energy consumption. Further emphasising DV's adaptability, Chaloeytoy *et al*., [12] used CFD analysis to assess ventilation strategies in a dental school, identifying optimal supply and return air configurations that significantly mitigate airborne infection risks.

Given its benefits, DV has also been tested in transportation settings, where maintaining passenger comfort in confined spaces is crucial. For instance, Wu *et al*., [13] analysed the performance of DV in high-speed train cabins, concluding that a hybrid approach combining DV and MV enhanced comfort by addressing each system's limitations. Similarly, Fan *et al.,* [14] investigated DV in aircraft cabins, highlighting its ability to reduce overcooling while ensuring consistent air distribution. Supporting this, Schmeling *et al.,* [15] found that sensible heat release in train compartments enhances DV efficiency, preventing excessive cooling near the floor level while maintaining the upper layers in a thermally stable state.

Further studies have explored CFD-based ventilation optimisation in aviation-related environments. Al-Ammari *et al*., [16] applied CFD modelling to enhance local exhaust ventilation in an aviation fire-test lab, demonstrating that strategic airflow adjustments significantly improved IAQ by reducing CO, CO_2 and NO concentrations by over 80%. Although this research highlights the effectiveness of ventilation design in enclosed aviation facilities, it primarily focuses on contaminant removal rather than thermal comfort, leaving a gap in understanding passenger comfort in large public spaces like airport terminals.

Concerning industrial and public facility environments. Ahmad *et al*., [17] investigated thermal conditions in a commercial laundry facility using CFD and found that poor temperature uniformity due to internal heat sources caused discomfort across 85% of the workspace. Their validated CFD model highlighted the direct impact of layout and ventilation strategies on indoor thermal environments. Similarly, Feng *et al*., [18] used CFD to analyse airflow and air residence times in restrooms, concluding that despite meeting air change standards, poorly ventilated corners posed a high risk of airborne infection due to stagnant airflow. Such analysis aligns with DV's strength in minimizing recirculation zones and controlling contaminants. Roslan *et al*., [19] compared underfloor air distribution (UFAD) and overhead systems in a cinema using CFD, showing that UFAD achieved smaller vertical temperature variations and enhanced occupant comfort underscoring the broader applicability of stratified ventilation concepts like DV in entertainment or public spaces.

While DV has been shown to improve IAQ and energy efficiency, several studies have highlighted its potential limitations, particularly concerning thermal stratification and localised discomfort. Han *et al*., [20] compared MV and DV in office environments, revealing that DV can lead to uneven temperature distribution, particularly between ankle and head levels. In a different analysis, Staveckis *et al.,* [21] found that impinging jet ventilation enhances IAQ but can introduce excessively high airflow velocities, resulting in occupant discomfort. Similarly, Liu *et al*., [22] observed that DV systems produce higher vertical temperature differences, sometimes causing occupant dissatisfaction due to cold feet and warm upper body regions.

In airport environments, Baddar *et al*., [24] evaluated DV performance in a departure concourse, highlighting localised discomfort issues near diffusers. Although their research provides valuable insights into airflow behaviour in airport terminals, it does not explicitly address baggage reclaim areas with different occupancy densities, thermal loads and air distribution characteristics. This distinction highlights the need for further research on the application of DV in high-traffic airport spaces.

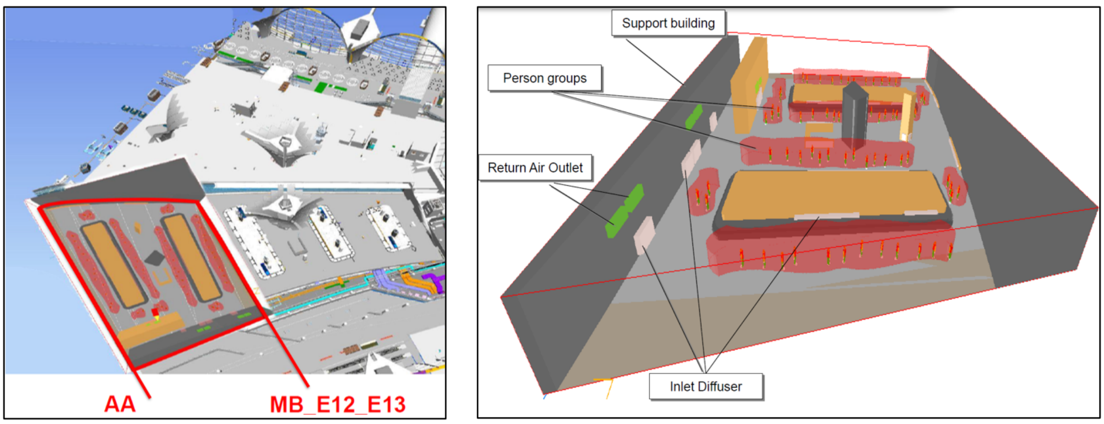
Although DV has been widely studied for its effects on IAQ, thermal comfort and energy efficiency, most research has focused on controlled environments such as offices, classrooms, healthcare facilities and transportation settings. While some studies have explored DV applications in airport terminals, its performance in baggage reclaim areas remains largely unexamined. Unlike departure concourses, where airflow is more directional due to continuous passenger movement, baggage reclaims areas present unique ventilation challenges, including variable crowd densities, architectural obstructions and intermittent occupancy patterns, which can significantly impact the effectiveness of airflow and thermal comfort.

This study aims to bridge the research gap by employing CFD simulations to evaluate the performance of a DV system in the baggage reclaim area of Kuwait International Airport under extreme hot and arid conditions. The analysis focuses on key thermal comfort metrics, including vertical temperature gradients, air velocities and localised discomfort, ensuring alignment with ISO 7730 and ASHRAE 55 standards. Furthermore, the study examines the practical implications of DV implementation, considering energy efficiency, sustainability and potential system optimisations.

By identifying critical airflow characteristics, thermal comfort variations and optimisation strategies, this research provides actionable insights for enhancing the performance of DV systems in large-scale airport spaces. It contributes to both thermal comfort improvements and sustainable HVAC strategies in high-occupancy environments.

2. Methodology

This study evaluates the performance of a DV system implemented in the baggage reclaim area of Kuwait International Airport. The investigation used CFD simulations to assess airflow distribution, thermal comfort and localised discomfort under operational conditions. The computational domain spans an area of 3,556 m², situated between grid lines MB_E12_E13 and AA, featuring baggage carousels, passenger pathways and support structures. The DV system supplies low-velocity cool air and returns warmer air through outlets, ensuring a stratified airflow pattern. Figure 2 illustrates the computational domain and key system components. Figure 2(a) provides an overview of the analysis zone within the airport, highlighting grid lines MB_E12_E13 and AA, while Figure 2(b) presents a 3D representation of the DV system, including inlet diffusers, return air outlets and passenger groups.



(a) Overview of the baggage reclaim area (b) CFD model of the DV system with Boundary conditions

Fig. 2. Computational domain and key features of the baggage reclaim area

2.1 CFD Simulation Setup

The simulation used a steady-state Reynolds-Averaged Navier-Stokes (RANS) approach with the k-ε turbulence model, chosen for its robustness in capturing airflow behaviour in large indoor spaces. A structured computational grid (mesh) was generated automatically using the CFD Design Builder ™ meshing module. The meshing algorithm generated predominantly hexahedral cells, with local refinements near critical areas such as diffuser outlets, occupant zones and walls, to capture large velocity and temperature gradients. Figure 3 illustrates the computational grid for the baggage reclaim area.

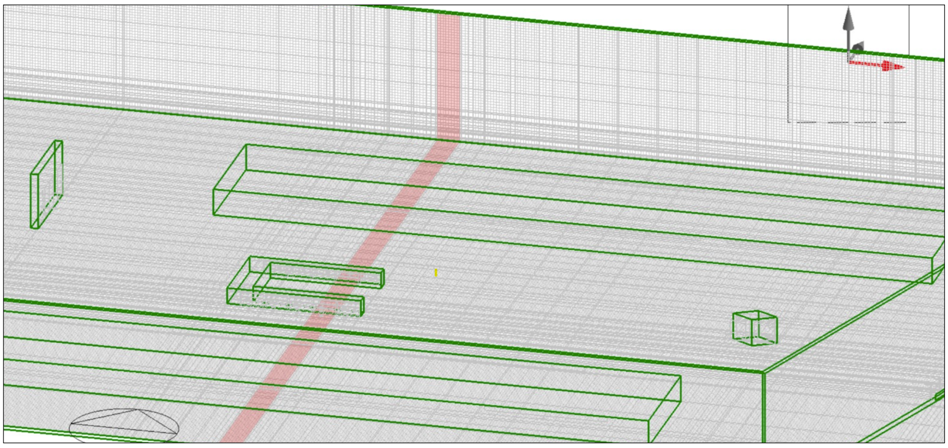


Fig. 3. Part of the structured computational grids for the baggage reclaim area

The final mesh consisted of approximately 8 million cells. This grid size was determined through iterative refinement testing to ensure sufficient resolution for accuracy while keeping computational costs feasible. Boundary conditions were defined based on operational parameters: a supply air temperature of 16°C, supply air velocity of 0.267 m/s, total airflow rate of 62,283.6 m^3/h and a total heat load of 170.4 kW.

The ISO 7730 standards evaluated thermal comfort [23], focusing on three key metrics: Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), Draught Rating (DR) and vertical temperature difference. PMV is an index that predicts the average thermal sensation vote of a large group of people on a 7-point scale (from cold (- 3) to hot (+3) based on the heat balance of the human body in the given environment. It is calculated from environmental variables (air temperature, mean radiant temperature, relative humidity and air velocity), as well as personal factors (metabolic rate and clothing insulation). In general, PMV values between -0.5 and +0.5 are considered comfortable (near neutral) and correspond to Category B comfort according to ISO 7730, which corresponds to a PPD of less than 10% (meaning that at least 90% of occupants are predicted to be satisfied). PPD is derived empirically from PMV and indicates the percentage of occupants likely to feel thermal discomfort; for example, PMV = 0 corresponds to PPD ≈ 5% and PMV = ±0.5 corresponds to PPD ≈ 10%. The equations that are related to these indices are defined below:

$$PMV = [0.303\exp(-0.036M) + 0.028]\,\{(M-W) - 3.05\times10^{3}\,[5733 - 6.99(M-W) - P_a] - 0.24[(M-W) - 58.15] - 1.7\times10^{-5}M(5967 - P_a) - 0.0014M(34 - T_a) - 3.96\times 10^{-8}f_{cl}[(T_{cl}+273)^4 - (T_r+273)^4] - f_{cl}h_c(T_{cl} - T_a)\} \quad (1)$$

$$T_{cl} = 35.7 - 0.028(M-W) - I_{cl}\{3.96x10^{-8}f_{cl}[T_{cl}{}^4 + T_a{}^4] + f_{cl}h_c(T_{cl} - T_a)\} \quad (2)$$

$$f_{cl} = \begin{cases} 1.00 + 1.29\, I_{cl}, I_{cl} \leq 0.078\, m^2K/W \\ 1.05 + 0.645\, I_{cl}, I_{cl} > 0.078\, m^2K/W \end{cases} \tag{3}$$

$$h_c = \begin{cases} 2.38\,(T_{cl} - T_a)^{0.25}\ for\ 2.38\,(T_{cl} - T_a)^{0.25} > 12.1\sqrt{V_{ar}} \\ 2.38\,(T_{cl} - T_a)^{0.25}\ for\ 2.38\,(T_{cl} - T_a)^{0.25} < 12.1\sqrt{V_{ar}} \end{cases} \tag{4}$$

$$PPD = 100 - 95 \cdot \exp(-0{,}033\,53 \cdot PMV^4 - 0{,}217\,9 \cdot PMV^2) \tag{5}$$

Where M is the metabolic rate in W/m^2, W is the adequate mechanical power in W/m^2, I_{cl} is the clothing insulation in m^2·K/W, f_{cl} is the clothing surface area factor; T_a is the air temperature in °C, T_r is the mean radiant temperature in °C, V_{ar} is the relative air velocity in m/s, P_w is the water vapour partial pressure in Pa, h_c is the convective heat transfer coefficient in W/(m^2·K) and T_{cl} is the clothing surface temperature in °C. The relations between the PMV and PPD are clarified in Figure 4.

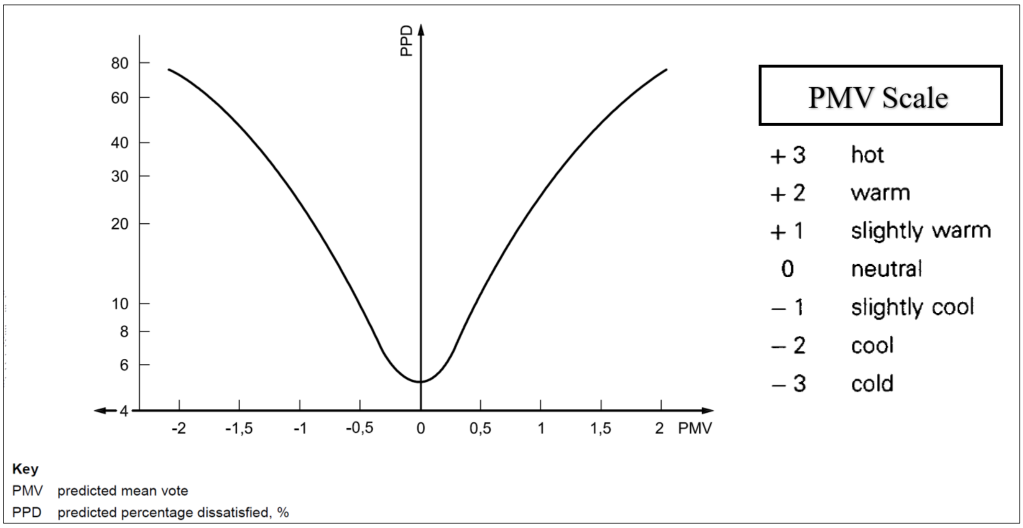


Fig. 4. PPD as a function of PMV

The metabolic rates and clothing insulations can be found in specific tables in the given standard [23]. Additionally, the standards address specific discomfort caused by factors such as draught, radiant and vertical air temperature differences.

The third index, Draught Rate (DR), quantifies the risk of draft discomfort; the percentage of people predicted to be bothered by unwanted local cooling of the body due to air movement. DR is a function of local air velocity, air temperature and turbulence intensity. A DR of less than 20% is typically considered acceptable (Category B) for most occupied zones. Draught rate as per the following equation:

$$DR = (34 - t_l)(v_l - 0.05)(0.37\, v_l\, .Tu + 3.14) \tag{6}$$

Where t_l is the local air temperature, in degrees Celsius, 20 °C to 26 °C; v_l is the local mean air velocity, in metres per second, < 0,5 m/s; Tu is the local turbulence intensity, in percent, 10 % to 60 % (if unknown, 40 % may be used).

Finally, A high vertical air temperature difference between the head and the ankles can cause discomfort. Figure 5 illustrates the relationship between vertical temperature and PPD.

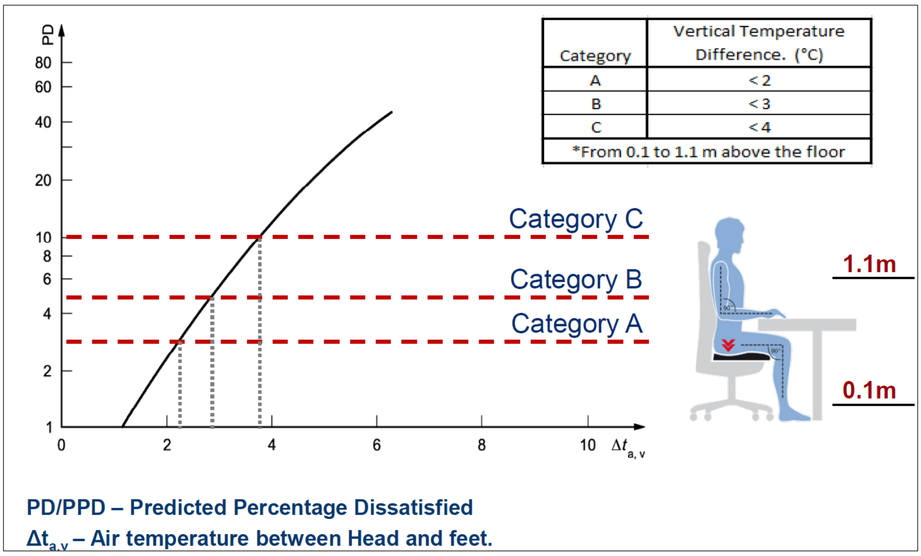


Fig. 5. Local discomfort caused by vertical air temperature differences is related to the thermal comfort category

The classification criteria for thermal comfort, based on ISO 7730 and ASHRAE 55, are summarised in Table 1.

Table 1
Summary of the categories of thermal comfort based on the ISO7730 and ASHRAE 55

Category	Thermal Balance of the whole body		Local discomfort	
	PPD %	PMV	DR %	Vertical gradient C°
A	< 6	-0.2<PMV<0.2	<10	<2
B	< 10	-0.5<PMV<0.5	<20	<3
C	< 15	-0.7<PMV<0.7	<30	<4

2.2 Validation and Sensitivity Analysis

To ensure the reliability of the CFD findings, on-site velocity and temperature measurements were taken at five critical locations in the baggage reclaim area. Measurements were conducted using an anemometer (velocity meter) at heights of 0.3 m and 1.1 m, corresponding with CFD output points. The simulation and real-world data comparison showed an average error of approximately 4.5%, remaining within an acceptable accuracy threshold of ≤5%, confirming the model's applicability for predicting airflow behaviour.

Additionally, a grid independence test was conducted by refining the computational mesh up to 8 million cells, beyond which results showed negligible variations, validating that further refinement would not significantly impact accuracy. Additionally, a sensitivity analysis was conducted to assess the impact of key operational parameters, including variations in supply air temperature from 16°C to 18°C. The results indicated that increasing the supply temperature by 2 °C resulted in slight reductions in thermal stratification.

3. Results

This section presents the CFD simulation results for the Baggage Reclaim Area at Kuwait International Airport, focusing on the performance of the displacement ventilation system in delivering acceptable indoor environmental conditions. The analysis is structured to evaluate thermal comfort based on PMV and PPD indices, assess air velocity and draught risk, investigate compliance with international standards for vertical temperature stratification and examine system sensitivity to changes in supply air temperature. Each of these aspects is discussed in the following subsections.

3.1 Thermal Comfort Assessments

The thermal comfort analysis conducted at a height of 1.1 m indicates that most of the baggage reclaim area meets the comfort criteria for Category B, as defined by ISO 7730. Over 90% of the occupants are expected to be satisfied with the thermal conditions, as indicated by the PPD values, which remain below 10% across most of the space. The results demonstrate that the DV system maintains thermal comfort in the occupied zone. Localised zones near diffusers and heat sources exhibit slightly higher PPD values, as depicted in the yellow and blue regions of Figure 6. However, these areas are typically not designated for prolonged occupancy, minimising their impact on overall comfort. Similarly, the PMV values at this height ranged from -0.5 to +0.5, aligning with the comfort criteria for Category B. This range ensures the thermal environment is perceived as neutral or slightly cool, providing acceptable comfort for most occupants. The results confirm that the DV system maintains an even temperature distribution across the occupied zone, with minimal discomfort due to localized variations.

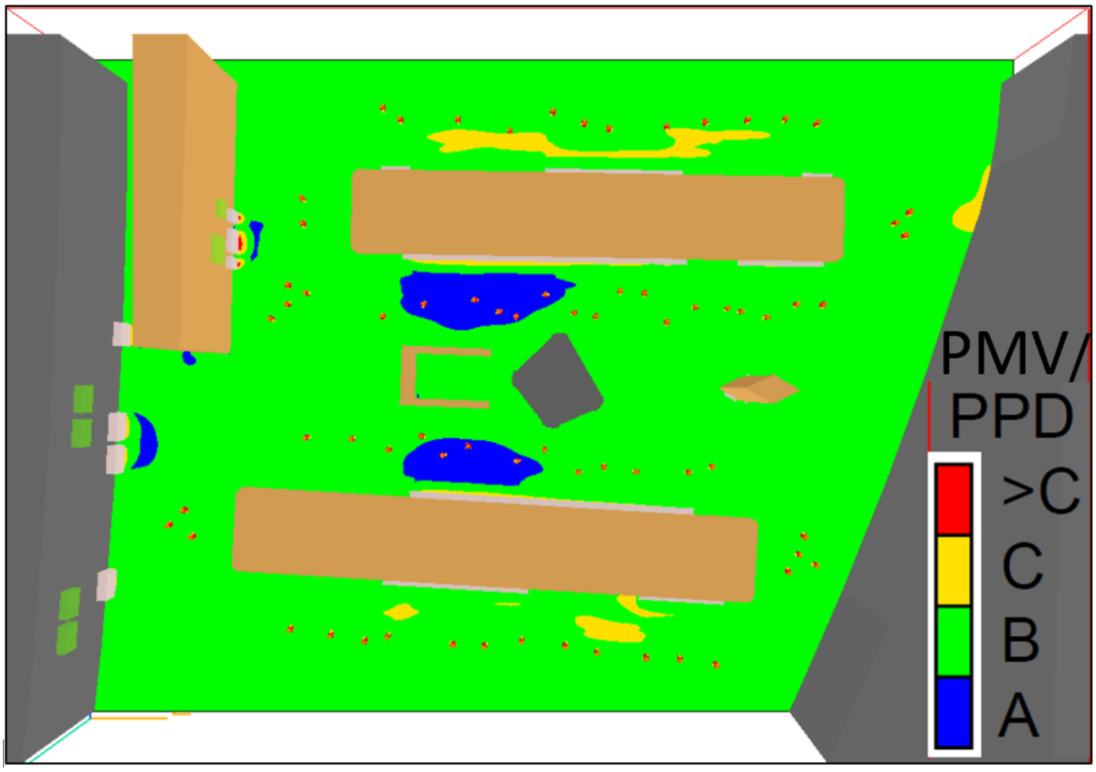
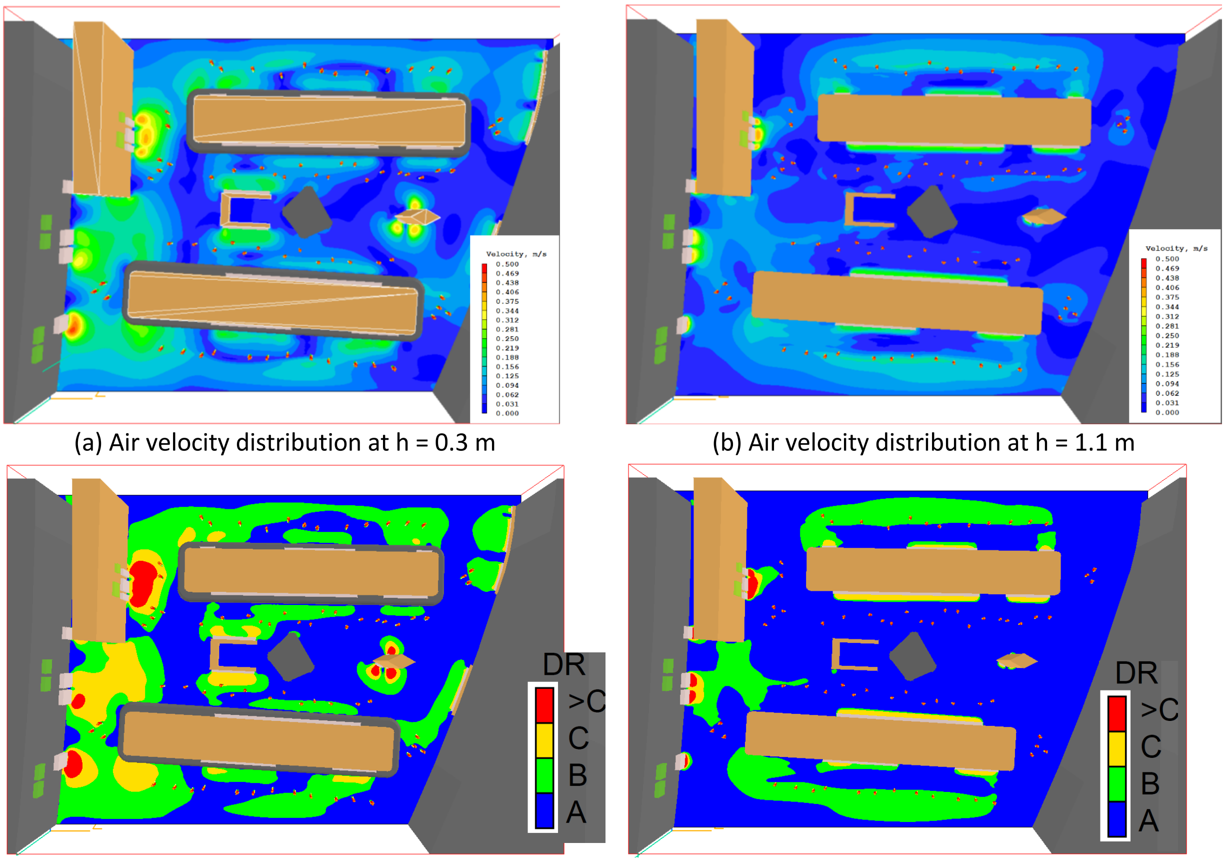


Fig. 6. Thermal comfort evaluation at 1.1 m height based on PMV and PPD

3.2 Air Velocity and Draught Rating (DR) Distribution

The evaluation of air velocity and DR provides critical insights into the performance of the DV system in the baggage reclaim area. As illustrated in Figure 7, these parameters were analysed at key heights of 0.3 m and 1.1 m.



(a) Air velocity distribution at h = 0.3 m
(b) Air velocity distribution at h = 1.1 m
(c) Draught rate at h = 0.3 m
(d) Draught rate at h = 1.1 m

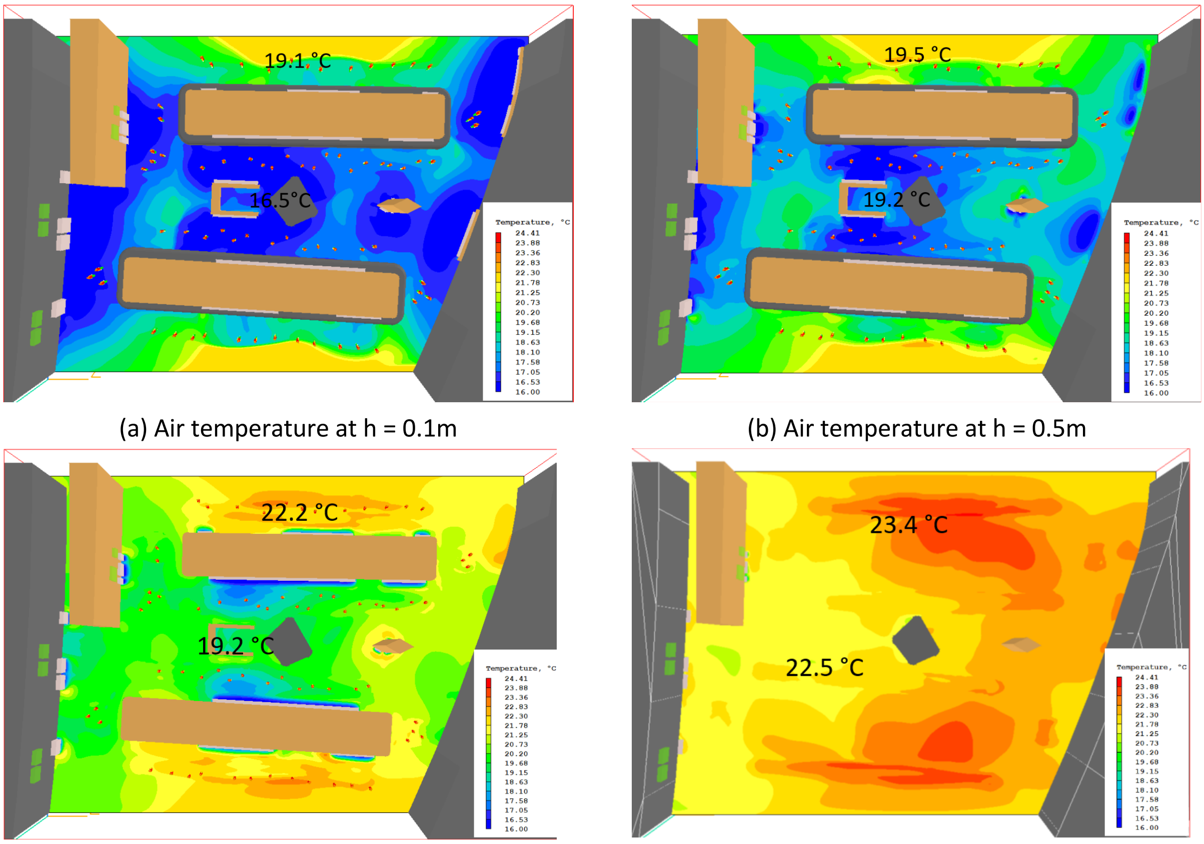
Fig. 7. Air velocity distribution and draught rating at different heights in the baggage reclaim area

The air velocity and DR were assessed to ensure that air movement within the space does not cause discomfort to occupants. The results indicate that the air velocity is generally low, which is favourable for displacement ventilation systems. At a height of 0.3 m, the air velocity ranged from 0.0 m/s to 0.5 m/s, with most areas experiencing velocities below 0.3 m/s. The DR, calculated based on local air temperature and velocity, showed that most of the area falls within Category B (DR < 20%). In comparison, some regions near the diffusers reached Category C (DR < 30%). Similarly, at a height of 1.1 m, the air velocity remained low, with most areas below 0.25 m/s and the DR was within acceptable limits, predominantly falling within Category B. These findings suggest that the air movement in the space is well within comfort standards for occupants.

3.3 Air Temperature Distribution

This section examines the vertical temperature gradient in the occupied zone to assess compliance with international thermal comfort standards, such as ASHRAE 55 (2023) and ISO 7730. These standards define a maximum allowable vertical temperature difference between ankle and head level to ensure comfort and prevent local discomfort due to thermal stratification.

Figure 8 presents air temperature fields at multiple heights (0.1 m, 0.5 m, 1.1 m and 2.0 m), illustrating a gradual increase in temperature with elevation. At 0.1 m, temperatures are around 16.5 °C, consistent with the supply air and they increase to ~20.7 °C at 1.1 m and further to ~23.3 °C at 2.0 m. This layered distribution reflects the expected performance of a displacement ventilation system, where cooler air remains in the lower occupied zone while warmer air rises.

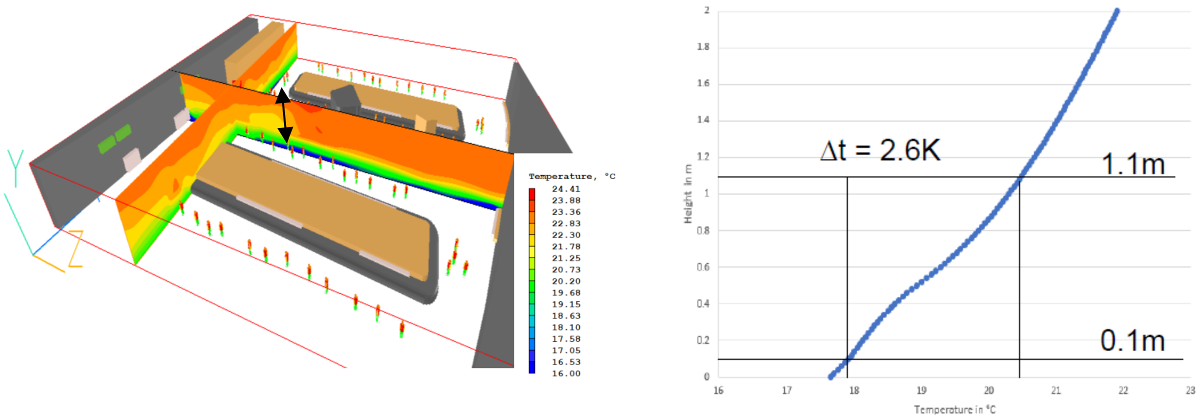


(a) Air temperature at h = 0.1m
(b) Air temperature at h = 0.5m
(c) Air temperature at h = 1.1m
(d) Air temperature at h = 2.0m

Fig. 8. Air temperature distribution at different heights: (a) 0.1 m (b) 0.5 m (c) 1.1 m (d) 2.0 m

To directly assess the vertical temperature gradient, Figure 9(a) displays a 3D temperature field, with a marked double-arrow line indicating the location used for extracting the vertical profile shown in Figure 9(b). This location lies near the centre of the baggage reclaim area, approximately equidistant from several floor-level diffusers and was selected to represent a typical region of the space away from local disturbances.

The vertical temperature profile in Figure 9(b) confirms a moderate and uniform gradient, with the temperature rising from ~16.5°C at 0.1 m to 22.8–23.3°C at 2.0 m. The difference between 0.1 m (ankle level) and 1.1 m (head level) is about 2.6 K — within the ISO 7730 recommended maximum of 3 K for Category B environments. This result confirms that the DV system effectively maintains vertical thermal comfort and complies with established standards.



(a) 3D temperature distribution showing stratification

(b) Vertical temperature profile from 0.1 m to 1.1 m heights

Fig. 9. Vertical temperature distribution and gradient in the baggage reclaim area

3.4 Sensitivity Analysis

A sensitivity analysis was conducted to assess the impact of changes in discharge air temperature and discharge air velocity on thermal comfort in the DV system. When the supply temperature was increased from 16°C to 18°C, the average temperature at 1.1 m rose to 22.1°C, with a minor effect on PPD in some areas. While still within ISO 7730 Category B limits, the vertical temperature difference decreased from 2.6 K to 2.1 K, which slightly improved vertical thermal comfort; however, overall comfort uniformity declined due to elevated air temperatures in central zones farther from the diffusers.

4. Discussion

The displacement ventilation system in the baggage reclaim area effectively supplies the zone with cool air, maintaining comfortable thermal conditions across most occupied spaces. However, areas near the diffusers, particularly those at a supply temperature of 16°C, exhibited reduced comfort due to localised droughts. These draught-prone zones were identified in regions without seating, where air draughts primarily occurred in a thin layer near the floor or within a localised radius of the diffusers, consistent with existing literature as found by Baddar *et al.,* [24]. The supply air velocity of 0.267 m/s contributed to this effect. In the central zones of the baggage reclaim area, temperatures dropped as low as 18°C, particularly near the waist level of standing occupants, as highlighted in the ISO surface temperature analysis. Despite these localised variations, the overall temperature at a height of 1.1 m averaged 20.7°C, demonstrating adequate comfort under the defined boundary conditions and heat loads. The overall comfort level was categorised as Class B, per ISO 7730 standards, indicating that more than 90% of occupants are satisfied with the thermal environment. This highlights the system's ability to provide satisfactory comfort levels for most of the baggage reclaim area, with minor areas for improvement identified near the diffusers.

5. Limitations

While this study provides valuable insights into the performance of DV systems in airport baggage reclaim areas, several limitations should be acknowledged. First, the CFD simulations assumed steady-state conditions, which may not fully capture transient effects such as sudden changes in occupancy or external weather conditions. Second, the validation process was limited to air velocity and temperature measurements; additional parameters, such as humidity and CO_2 levels, could provide a more comprehensive assessment of indoor air quality. Finally, the study focused on a single airport terminal and further research is needed to generalise the findings to other airport designs and climatic conditions. Despite these limitations, the results demonstrate the potential of DV systems to enhance thermal comfort and energy efficiency in large, high-traffic spaces under extreme climatic conditions.

6. Conclusions

This study evaluated the performance of a DV system in Kuwait International Airport's baggage reclaim area under hot arid conditions. CFD simulations assessed thermal comfort, air distribution and localised discomfort, providing valuable insights into the system's effectiveness in large-scale airport facilities.

The results demonstrated that the DV system successfully maintained thermal stratification, with cooler air concentrated in the occupied zone and warmer air displaced to the upper unoccupied layers. The vertical temperature distribution aligned with ISO 7730 standards, ensuring thermal comfort for most occupants. At the critical level of 1.1 m, the average temperature was approximately 20.7°C, categorising overall comfort as Class B, with more than 90% of occupants satisfied with the thermal environment.

Localised discomfort was observed near the air diffusers due to high air velocities and draughts. However, these regions are not designated for prolonged occupancy, minimising their impact on overall comfort. Adjustments to diffuser placement and airflow velocity may further optimise these areas for improved thermal conditions.

This study highlights the potential of DV systems to enhance thermal comfort and energy efficiency in large, high-traffic spaces under extreme climatic conditions. Future research could focus on integrating real-world measurements with simulation data, optimising diffuser designs or exploring alternative configurations to minimise localised discomfort. Additionally, investigating the energy consumption and sustainability implications of DV systems in large-scale airport terminals could further support their adoption in climate-sensitive environments.

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