

Effect of occupant age and activity level on the performance of a displacement ventilation system

Farah Youssef^{*}, Stéphane Hallé, Katherine D'Avignon

École de technologie supérieure, Montreal, Quebec H3C 1K3, Canada

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ABSTRACT

Displacement ventilation (DV) systems rely on occupant-generated thermal plumes to drive upward airflow and maintain vertical thermal stratification. As heat output strongly influences DV performance, we investigate system behavior with pre-pubertal child occupants producing substantially less heat than adults and at lower elevations. We use a child-specific heat balance model to tabulate sensible and latent heat generation values for pre-pubertal children, pertinent for HVAC design of elementary classroom environments, currently unavailable in literature. A computational fluid dynamics model of a DV-conditioned room with two heated cylinders representing 8-year-old occupants is developed and experimentally validated. Using the validated model, we compare system performance for 8-year-old children and adult females under low, medium, and high metabolic rates, while maintaining identical DV design parameters intended for adult occupancy. Results show child occupants substantially weaken vertical thermal stratification by 1.9 °C and modify airflow patterns, particularly at lower activity levels. This shift modified the diffuser flow, producing a largely isothermal supply-air trajectory in the low-activity child case. With child occupants, indoor air quality indicators showed reduced performance compared to adults; age of air increased by 11% and ventilation efficiency within the occupied zone decreased by 10%. Overall, results demonstrate that DV system behavior changes notably when children occupy spaces designed for adults, particularly at low-activity conditions, affecting airflow, stratification, and air quality. These findings emphasize the need to reassess DV performance in child-dominated environments such as classrooms. The presented sensible and latent heat tables also provide practical reference for future HVAC simulations and thermal comfort evaluations with child-occupants.

1. Introduction

Displacement ventilation (DV) systems have been shown to provide enhanced air quality, reduced energy consumption, and good thermal comfort [1]. By promoting vertical stratification of heat and contaminants, DV systems create a cleaner, cooler air zone within the occupied region. However, their effectiveness is highly sensitive to variations in the space's sensible heat load strength in Watts [2–4] and their elevation [3–5]. Park [5] demonstrated how the elevation of the heat source influences the thermal and velocity fields in a room with DV. Simulating a square heat source of 1000 W, they found that placing it at lower elevations reduced the stratification height, temperature gradient and hindered the cascading effect of the diffuser flow. Zhao [2] explored the effect of occupant activity levels on the performance of a DV system. They simulated an adult occupant with a height of 1.8 m with sensible heat generation rate ranging from 125 W to 402 W and found a strong

positive correlation between heat generation rate and both thermal stratification and velocity magnitude of the thermal plume. Lastovets [6] and Kosonen [7] found an increase in the number of heat loads in an office environment (from 3 to 6 to 12 occupants) led to a higher degree of thermal stratification. Similarly, Schmeling [8] experimentally investigated the effect of the shape and sensible heat generation rate of train passengers, represented by thermal manikins and heating mats, on the thermal velocity fields in a train compartment equipped with a DV system. They found reducing the occupant sensible heat generation rate from 105 W to 60 W reduced the temperature gradient from ankle to head, and the thickness of the velocity boundary layer around the occupant, with the 60 W manikin exhibiting a 10% reduction in the maximum velocity around the chest and legs. Child occupants, particularly pre-pubertal children, through their lower sensible heat generation rate and elevation in the space, are therefore likely to hinder plume development in DV systems, altering airflow behavior and pollutant dispersion.

^{*} Corresponding author.

E-mail address: farah.youssef.1@ens.etsmtl.ca (F. Youssef).

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Nomenclature**Abbreviations**

CFD	Computational fluid dynamics
DV	Displacement ventilation
GCI	Grid convergence index
IAQ	Indoor air quality
MV	Mixing ventilation
S2S	Surface to surface
SST	Shear stress transport
UDF	User-defined function

Symbols

D	Body surface area (m^2)
A_t	Total diffuser face area (m^2)
C	Rate of heat loss by convection from the outer surface of the clothed body (W)
C_k	Steady-state concentration (ppm)
C_{in}	Species concentration from the inlet (ppm)
C_p	Local species concentration (ppm)
C_{res}	Rate of sensible heat loss through respiration (W)
DR	Draught rate (%)
g	Gravity (m/s^2)
H	Total occupant heat generation (W)
H_{room}	Room height (m)
k	Turbulent kinetic energy (m^2/s^2)
PMV	Predicted Mean Vote (unitless)
$\dot{q}$	Heat generation rate (W)
$\dot{q}''$	Heat flux (W/m^2)
Q_t	Total flow rate into the room (m^3/s)
R	Rate of heat loss by radiation from the outer surface of the

	clothed body (W)
Ri	Richardson number (unitless)
Ri_{room}	Richardson number for the room (unitless)
S_ϕ	Source term ($\text{kg/m}^2 \cdot \text{s}^2$ (momentum equation), K/s (energy equation), $\text{kg/m}^3 \cdot \text{s}$ (species transport equation), m^2/s (age of air equation))
T	Air temperature ($^\circ\text{C}$)
T_{in}	Inlet air temperature ($^\circ\text{C}$)
TI	Turbulence intensity (%)
T_o	Exhaust air temperature ($^\circ\text{C}$)
T_{ref}	Room reference temperature ($^\circ\text{C}$)
t	Time (s)
u	Air velocity (m/s)
u_i	Air velocity in coordinate directions x (y (and z (m/s)
u_s	Air velocity from the diffuser (m/s)
ΔT	Temperature difference from floor to ceiling ($^\circ\text{C}$)
y^+	dimensionless wall distance (unitless)

Greek symbols

β	Thermal expansion coefficient (K^{-1})
δ	Characteristic length (m)
ε_a	Air change efficiency (unitless)
ε_c	Contaminant removal effectiveness (unitless)
ω	Specific dissipation rate (s^{-1})
θ_{age}	Age of air (s)
$\bar{\theta}_{age}$	Spatial average of the age of air (s)
τ_n	Nominal time constant (s)
$\Gamma_{\phi,eff}$	Effective diffusion coefficient (m^2/s)
ρ	Air density (kg/m^3)

Due to their superiority to mixing ventilation (MV) systems with regards to air distribution, contaminant removal effectiveness and energy saving potential [9], DV systems have been used in Early Childhood Education (ECE) facilities for a number of years [10,11]. Despite this, most standard design methods, such as those outlined by ASHRAE [3] and REHVA [1], use solely adult occupant characteristics (i.e. heights and sensible heat loads) in all design examples they provide for ‘classrooms’, overlooking any potential issues when such spaces are predominantly occupied by pre-pubertal children. Knowing that pre-pubertal children, who are the dominant population of ECE facilities (ie. daycares, preschools, primary and elementary schools), are of smaller heights and generate less sensible heat than adults [12], would warrant special consideration in the design of a DV system for these environments [13].

While a number of studies have analyzed the performance of DV systems in adult and adolescent occupied classrooms and schools, both experimentally and numerically, as well as the thermal comfort of adult students and teachers [10,14–22], research on the combination of DV systems and pre-pubertal child occupant physiological characteristics remain rather limited. Studies that have analyzed the combination of DV and classrooms mostly simulate adult students, with adult heights and heat generation rates [10,14,15,19–22] that do not correspond to children's sedentary activities. Kosonen [23] analyzed the performance of a DV system in a mockup classroom using Computational Fluid Dynamics (CFD) simulations with a heat generation rate and a height appropriate for sedentary adolescent occupants. Though varying occupancy levels were studied, a single heat generation rate was used, making it impossible to generalize results to other age groups or activities. Additionally, their choice of performance indices was limited to local velocity measurements and flow visualization; they did not explore key DV performance indicators such as vertical thermal stratification or any air quality

indicators. Zhao [18] used the same experiments to study thermal comfort and left unexplored the effect of adolescent occupants on the ventilation performance and air quality deliverance of the DV system. It is worth noting that their local experimental measurements showed that thermal stratification ceased to exist beyond the height of the adolescent occupants, but their limited measurements beyond the 1.8 m height made it impossible to examine if thermal stratification was present in the upper part of the room, and whether the total vertical thermal profile followed the outline typical of a DV system [1,3].

Recent investigations point to possible underperformance of DV in spaces mostly occupied by pre-pubertal children. Smedje [11] experimentally compared contaminants concentrations at breathing height, indoor air quality (IAQ) indicators as well as students' IAQ perception under MV and DV systems in fifth grade classrooms (students aged 10–11). They found no significant difference between the performance of the two systems, despite various anterior research pointing at DV's superior delivered IAQ in similar environments occupied by adults [15,22]. Similarly, Ouazia [24] measured the thermal stratification and contaminant removal effectiveness, (ε_c) in 4 Canadian kindergarten and elementary classrooms equipped with DV. They found ε_c ranging from 0.86 to 1.16, which is markedly lower than the 1.06 to 6.05 values measured in environments with adult occupants [25]. To the author's best knowledge, no study has yet studied the effect of pre-pubertal children's reduced height, size and heat generation rate on the performance of a DV system. Despite these indications that DV may be unsuitable for environments dominated by pre-pubertal children, it continues to be implemented and recommended for such settings [26].

In light of this, this paper seeks to evaluate the effect of the combination of reduced occupant height, size and heat generation rate, characteristics of pre-pubertal children, on DV system performance. For concision, these combined effects will hereafter be referred to under the

umbrella term ‘age’. For this purpose, we use CFD modeling to compare the performance of a DV system designed for adult thermal loads under scenarios involving either adult or pre-pubertal child occupants. To validate the numerical model, experimental measurements were carried out in an environmental chamber and compared to reference case simulations. Heat load tables representing pre-pubertal child occupants were developed, and a series of simulations varying heat source size and heat generation rate were conducted to evaluate the effect of occupant ‘age’ and activity level on DV system performance.

Section 1 outlines the simulation methodology, where two cylindrical heat sources representing human occupants are modeled within a DV-conditioned room. Section 2 presents the experimental methodology and the validation of the numerical model by comparing simulated and measured vertical temperature profiles and age of air (θ_{age}) at various heights. In Section 2.4, children's heat load tables are introduced, and the validated model is applied to investigate system behavior under identical environmental conditions while varying occupant height and heat generation rate between an adult and an 8-year-old child. Finally, Section 3 presents the resulting room temperature and velocity fields, diffuser flow characteristics and IAQ indicators for the different occupancy scenarios and analyzes how occupant age and activity level influence system performance.

2. Numerical simulation

2.1. Geometry and governing equations

Ansys Fluent (2022 R2) [27] was used to model a room ($2.9 \text{ m} \times 1.93 \text{ m} \times 2.4 \text{ m}$) with a DV diffuser and two cylindrical heat sources. Numerical modeling of the wall-mounted DV diffuser is presented in Section 1.3. Fig. 1 illustrates the position of the heat sources, hence forth referred to as “mockups”, and measurement locations in the room. Unsteady three-dimensional Navier-Stokes equations coupled to the energy, mass, and species conservation equations are solved on an unstructured grid, as represented in the general transport equation in 1.

$$\rho \frac{\partial \phi}{\partial t} + \rho u_i \frac{\partial \phi}{\partial x_i} - \frac{\partial}{\partial x_i} \left[\Gamma_{\phi, eff} \frac{\partial \phi}{\partial x_i} \right] = S_{\phi} \quad (1)$$

where ρ represents the air density, u_i is the velocity component in the x, y, and z directions, $\Gamma_{\phi, eff}$ represents the effective diffusion coefficient, and S_{ϕ} represents the source term in each equation. ϕ represents u_i , T , and C in the momentum, energy, and species concentration respectively. For $\phi = 1$, $\Gamma_{\phi, eff}$ and S_{ϕ} become null, and Eq. (1) then becomes the continuity equation.

The SST k- ω turbulence model was chosen as previous research has found it the most capable in reproducing the thermal plume around the occupants and the thermal stratification in a room with DV [28]. As this model resolves the viscous sublayer, no wall functions are needed, and a y^+ value of around 1 is maintained along the walls, including the mockups. The Boussinesq approximation, which is often used in DV simulations [5,29,30], was used. This model assumes a constant value for the air density in all the solved equations with the exception of the momentum equation, where it is approximated as a function of the temperature difference and the thermal expansion coefficient (β) [31]. The Surface to Surface (S2S) model was used to model the thermal radiation in the environment. This radiation model calculates the radiative heat exchange between the gray-diffuse surfaces in the environment, which depends on the view factors between the surfaces. The S2S model assumes that the fluid in the environment is a nonparticipating medium in the radiative heat exchange, which is a reasonable assumption for indoor air [32]. The solution is considered to have converged when the error on the residuals reaches 10^{-5} for the mass, continuity, momentum, and species transport equations, 10^{-6} for the energy equation.

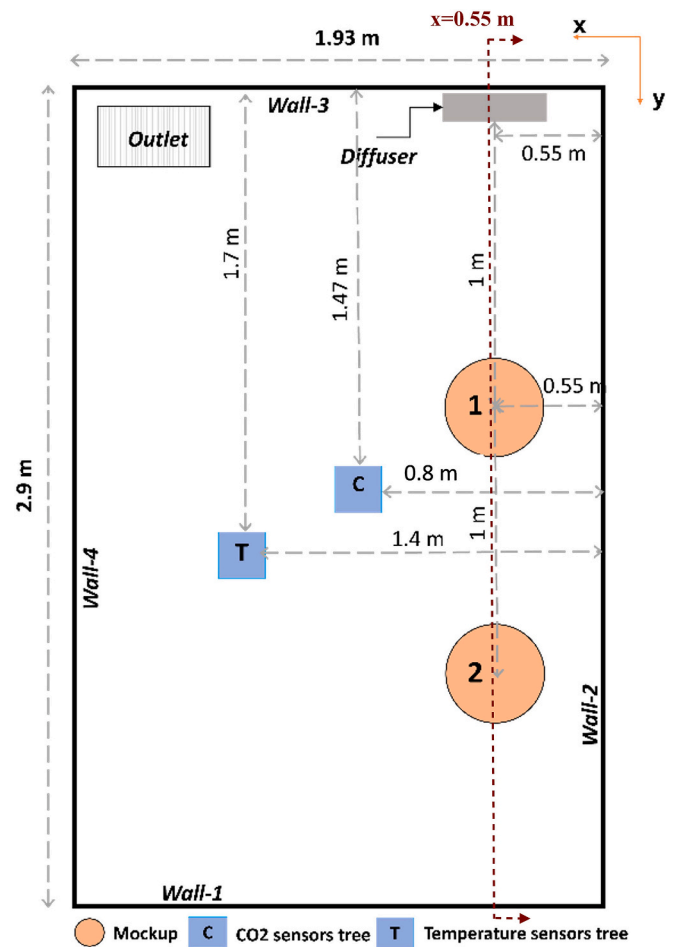


Fig. 1. Top view of the environmental chamber illustrating the position of the heat sources and measurement locations. This figure is not to scale for clarity.

2.2. Grid selection

Fluent's mosaic Poly-Hexcore meshing was used to discretize the room geometry, which uses octree hexes in the main room region, with high-quality poly-prism layers near walls, and connects them with conformal polyhedral elements. A grid independence study was conducted to determine the adequate mesh size. The grid convergence index (GCI) [33] was calculated after increasing the number of cells in the computational domain from 2,449,641 cells (mesh A) to 5,470,552 cells (mesh B), to 13,103,489 cells (mesh C). The local age of air (θ_{age}) at heights of 0.6 m (point 1), 1.2 m (point 2), and 1.9 m (point 3) along line C (see Fig. 1) was retained as the variables of interest as it represents the duration that a given quantity of outdoor air has remained in a space [34]. Experimentally, θ_{age} can be calculated following the decay method, where a quantity of gas is injected into the environment and is well mixed, after which the concentration decay is measured through time. The time dependent gas concentration ($C_p(t)$) in the measurement location is used to calculate θ_{age} following Eq. (2) where $C_p(t=0)$ represents the initial concentration at the start of the test, and $C_p(\infty)$ represents the final (background) concentration.

$$\theta_{age} = \frac{\int_{t=0}^{\infty} (C_p(t) - C_p(\infty)) dt}{C_p(t=0) - C_p(\infty)} \quad (2)$$

Numerically, θ_{age} can also be calculated using Eq. (2) and by solving the species transport equation in the transient mode. In a steady state calculation, θ_{age} can be solved instead by introducing an additional transport equation and defining θ_{age} as a passive user-defined scalar that

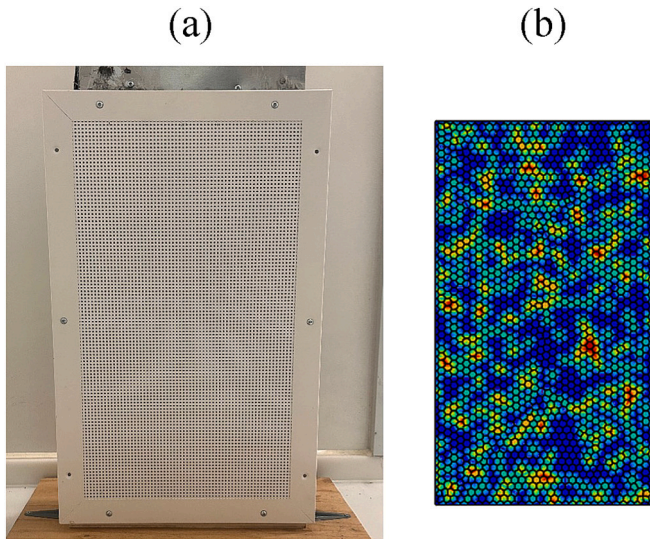


Fig. 2. (a) picture of the DV diffuser (b) velocity contour on the modeled diffuser using the momentum method.

follows the flow direction. The first transient method was used in the grid independence study. The average temperature profile along line T in Fig. 1 was calculated with the three meshes. The *GCI* for all the studied variables was reduced to below 1% after mesh B. Therefore, mesh B was selected for future simulations.

2.3. Diffuser modeling method

The DV diffuser used in the experimental validation, shown in Fig. 2a, has a face size of 300 mm × 530 mm and a total area (A_t) of 0.159 m². The perforated plate comprises a 23% opening area [35]. As shown in Fig. 2a, the real-life diffuser features numerous small openings, making direct modeling computationally intensive. To overcome this challenge, a simplified method, developed by Zhang et al. [36] and validated experimentally, was employed to approximate the airflow from the diffuser. In this approach, a user defined function (UDF) was used to set the velocity boundary condition on the perforated inlet.

2.4. Reference cases boundary conditions

The boundary conditions for the CFD reference cases are listed in Table 1. The turbulence intensity was set at 4%. Previous numerical simulations of DV diffusers have used higher values of 5% [14], 8% [36], and even 30% [37]. However, experimental measurements of *TI* at a close distance of DV diffuser by Fatemi et al. [38] and Magnier [39] showed that *TI* is largely below 10%. As *TI* mainly depend on diffuser configuration and flow velocity, experimental measurements of the air velocity in the current study confirmed the choice of 4% by an accordance of numerical prediction and experimental measurement at multiple heights in front of the diffuser. To include the whole range of sensible heat generated by an 8-year-old occupant, two cases were

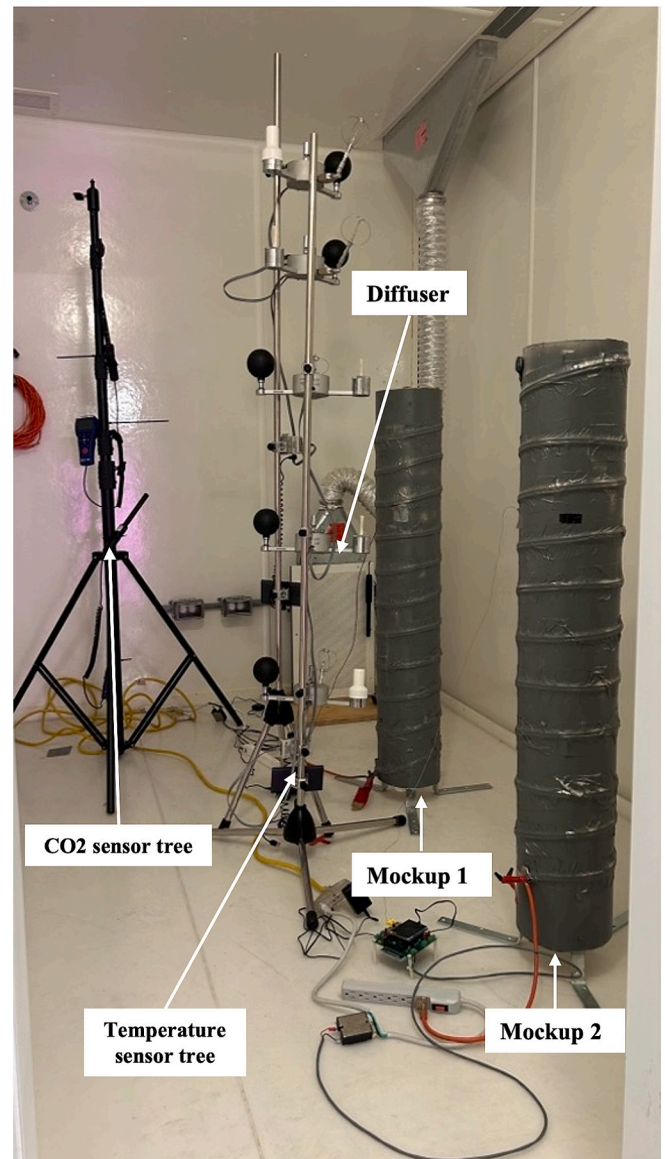


Fig. 3. Experimental setup.

validated experimentally: a ‘Low Heat’ case where the mockups are generating $\dot{q} = 39$ W (corresponding to heat flux $\dot{q}'' = 51$ W/m²), and a ‘High Heat’ case where the mockups are generating $\dot{q} = 77$ W (corresponding to $\dot{q}'' = 98$ W/m²). These values correspond to the lower and upper limits of the sensible heat generated by female occupants aged 6–9 years old (see Table 3), which were established based on the occupant heat loads documented in Section 2.4.1 It should be noted that breathing was not simulated, only the dry heat lost from the skin. The inlet air temperature (T_{in}) and the flowrate into the room (Q_t) were the same for both cases. A no slip boundary condition was used for the

Table 1

Boundary conditions for the simulation used in the experimental validation.

Boundary surface	Type	Variable	Set value
Inlet	Velocity inlet	T_{in}	16.8 °C
		u_s	0.734 m/s
		C_{in}	635 ppm
		<i>TI</i>	4%
		Constant heat flux $\dot{q}''$	51 W/m ² (Low Heat case) 98 W/m ² (High Heat case)
Mockup 1, Mockup 2	Wall		
Walls, floor, ceiling	Wall	adiabatic	0 W

velocity on the walls and the heat sources. Q_t was measured using a tracer gas test, and u_s was calculated based on the perforated diffuser area. To calculate θ_{age} , the species transport equation was solved, and the solution was initialized with a CO_2 concentration of 1500 ppm everywhere in the room. The total simulation time was around 30 min.

3. Experimental procedure

The reference cases detailed in the previous section were experimentally recreated in an environmental chamber, shown in Fig. 3 to validate the CFD code. The positions of all elements seen in Fig. 1 are identical to the simulation. The DV diffuser, placed against Wall-3 is the Wall-Mounted Displacement Diffuser (DFW) of unit size 381 mm $\times$ 609.6 mm provided by Price Industries [35]. According to manufacturer's specifications, a distance greater than 0.9 m between the diffuser and an occupant is required to prevent draft, so the first mockup is placed at 1 m from the diffuser face, as indicated in Fig. 2a. This distance will also give the jet flow from the diffuser enough space to spread on the ground. The second mockup is placed at a distance of 1 m from the first to avoid the interaction between the thermal plumes of each mockup.

3.1. Child mockups

The sensible heat generated by each child occupant is modeled using a mockup, whose geometrical characteristics are shown in Fig. 4. They were constructed using aluminum cylinders with a height of 1.23 m and a diameter of 0.2 m, resulting in a total surface area of 0.96 m² including the top and bottom disk surfaces which corresponds to the body surface area (A_D) of the 50th percentile 8-year-old American girl [40,41]. The cylinders are mounted on three supports, so their overall height is 1.3 m. The hollow cylinders are filled with polyurethane insulation foam. A 6 m long heating wire is wrapped around the cylinders in a helical shape

with a spacing of 10 cm. The thermal power of the wire is set and maintained by an Arduino microcontroller. The maximum thermal generation rate output of each child mockup is 168 W, however the heat generation rate is maintained constant for each case as explained in Section 1.4. A K-type thermocouple is attached to the outer surface of each mockup to monitor its surface temperature. An immersion temperature sensor was inserted in the center of the cylinder to measure its core temperature and to determine if a temperature gradient between the core and the surface was present. The test revealed that after 40 min the surface and core temperatures reach equal and steady state values.

3.2. Experimental conditions

The set values of Q_t and T_i used in the experiments were determined following the ASHRAE Displacement Ventilation Design Procedure developed by Chen and Glicksman [3]. The design procedure was carried out assuming adult occupants with heat generation rates ranging from sedentary to highly active conditions, and to achieve two setpoint temperatures in the environment, 20°C and 24°C. This led to a range of Q_t between 24 and 40 L/s, and T_i of 16°C. The flowrate into the chamber was determined to be 26.85 L/s $\pm$ 3 L/s using a tracer gas test. T_i was measured to be 16.8 $\pm$ 0.3 °C using a 753 Testo multifunction indoor air quality sensor, with a negative temperature coefficient (NTC) air temperature sensor (accuracy of $\pm (0.2^\circ\text{C} + 0.5\%$ of the measured value) in front of the diffuser.

3.3. Experimental measurements

After steady state conditions were reached in the chamber, measurements began. Sensor pole T (see Fig. 1), equipped with RTD temperature sensors at heights of 0.45 m (T1), 0.9 m (T2), 1.35 m (T3), 1.8 m (T4), and 2.25 m (T5) (range of -20 to 60°C and accuracy of ± 0.3

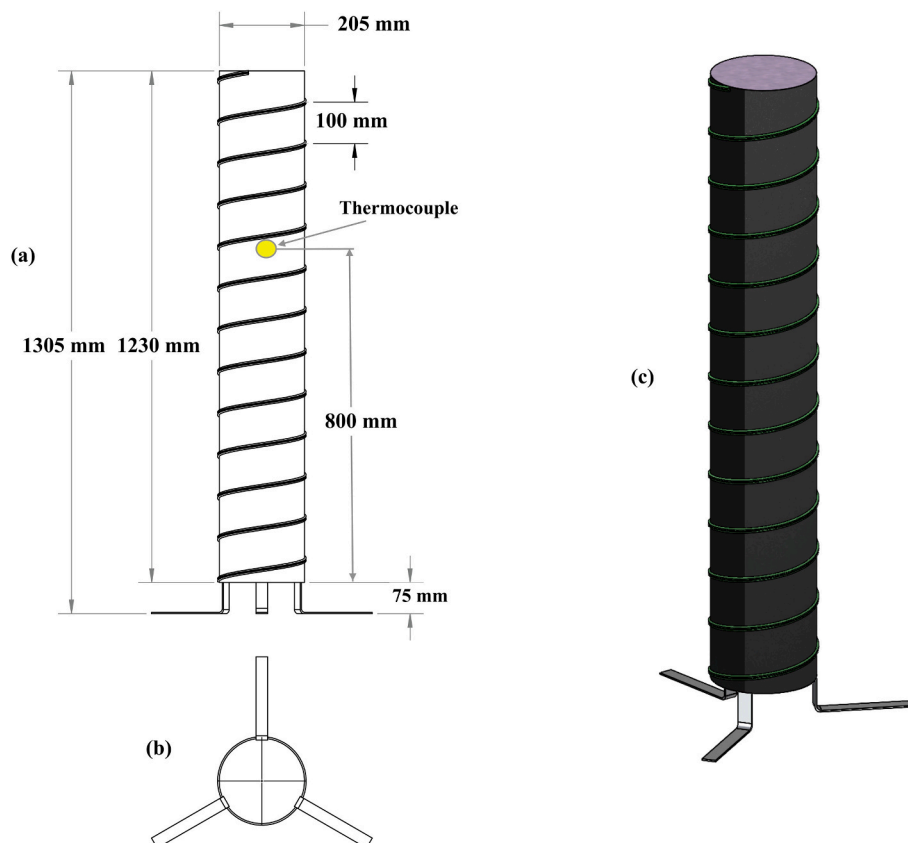


Fig. 4. Sketch and geometrical characteristics of mockup. a) front view with dimensions, b) top view, c) isometric view.

°C), was used to measure the vertical thermal profile in the chamber. The temperature was measured for 15 min at a rate of one measurement every 10 s. The vertical temperature profile in this location was compared to that obtained numerically.

Sensor pole C is located in the center of the room (see Fig. 1) and carries three non-dispersive infrared (NDIR) CO₂ sensors (TSI 7525, uncertainty ± 50 ppm or 3% whichever is higher) [42] at heights 0.6 m (C1), 1.2 m (C2), and 1.9 m (C3). The decay tracer gas method was chosen to calculate the inlet flowrate into the room as well as to validate θ_{age} in the three locations selected. Around 1500 ppm of CO₂ was injected into the chamber and mixed with room air using a fan, after which the door was shut and the CO₂ concentration decay was measured for a period of 30 min (i.e. time required for the concentration to reach a steady state final concentration in all three positions on pole C), at a rate of 1 measurement every 2 s. The CO₂ profile as a function of time was used to calculate θ_{age} .

3.4. Results of the experimental validation

As indoor environments with DV systems are characterized by vertical thermal stratification [1,4,43], the steady state vertical air temperature measured experimentally was plotted and compared to the numerically obtained results for the $\dot{q} = 51$ W/m² (Low Heat) and $\dot{q} = 98$ W/m² (High Heat) cases, as can be seen in Fig. 5. The simulation and experimental vertical thermal profile share a similar pattern, with a more limited thermal stratification in the Low Heat case both experimentally and numerically. The simulation thermal profile mostly falls within the experimental uncertainty for the Low Heat scenario, with more discrepancy in the High Heat scenario near the floor and ceiling. A similar discrepancy was found near the floor and ceiling in validation studies by Lin et al. [44] and Gilani et al. [28] while using surface convection and constant surface temperature respectively as boundary conditions. In our experiment, infrared measurements revealed non-uniform surface temperature distributions on the floor, ceiling, and walls, discouraging the use of constant surface temperature boundary conditions. Adiabatic boundaries being common practice in controlled indoor airflow and displacement ventilation CFD studies [5,14,37,45,46] and providing a consistent framework for comparing cases while minimizing uncertainties associated with unmeasured or case-dependent surface conditions, they were considered the most appropriate choice for the present study. It however remains possible that the treatment of the floor and ceiling as adiabatic boundaries may cause part of the discrepancies noted at these surfaces.

Additionally, the imposition of a spatially uniform heat flux on the mockup surfaces in the simulation can also be identified as a potential cause. In the experimental configuration, the cylindrical mockups are

heated using a resistive wire wrapped around their surfaces, which likely produces circumferential and axial variations in surface heat flux. Such non-uniform heating patterns are not explicitly represented in the numerical model and may contribute to the observed differences between simulated and measured results. Nevertheless, the maximum discrepancy, average discrepancy, and Cumulative Variance Root Mean Square Error (CVRMSE) represented in Table 2 are on par with discrepancies reported in similar investigations of DV systems in literature (maximum discrepancy of 1 °C in [28], 1.1 °C in [37], 1.5 °C in [2], 1.5 °C in [47], 3.8 °C in [44]) which were deemed acceptable.

The comparison of the numerically and experimentally obtained values for θ_{age} at C1, C2, and C3 on pole C for the two cases are shown in Fig. 6. The simulation predicted θ_{age} within the experimental uncertainty at points C2 and C3. Larger discrepancy is found at C1 in both cases (78 s difference for High Heat and 82 s difference for Low Heat), which may be attributed to the well mixed assumption in the tracer gas test, as well as the presence of small obstacles on the floor in the experimental setup (mockup controllers, cables, sensor trees) that disturb flow and were not recreated numerically. Nonetheless, the discrepancy remains acceptable when compared to literature, such as the differences of 278 s found in [3] and 200 s in [44]. The CVRMSE of θ_{age} was calculated at 14% and 12% for $\dot{q} = 51$ W/m² and $\dot{q} = 98$ W/m² respectively, which is lower than the CVRMSE of 20% we computed based on the values reported in [3]. Based on these comparisons, the model is considered validated within the range of conditions considered.

4. Effect of occupant age and activity

4.1. Heat load tables for child occupants

To study the effect of children's unique sensible heat generation rate on an indoor environment with a DV system, accurate values of said heat generation rates were needed. However, no current reference could be found offering tabulated values of children's heat generation rate for

Table 2

Maximum discrepancy, average discrepancy, and Cumulative Variance Root Mean Square Error (CVRMSE) between the experimental measurements and numerical results for the vertical air temperature profile.

Variable	Case	Maximum discrepancy	Average discrepancy	CVRMSE
Temperature	Low Heat	0.4 °C	0.3 °C	2%
	High Heat	1 °C	0.6 °C	3%

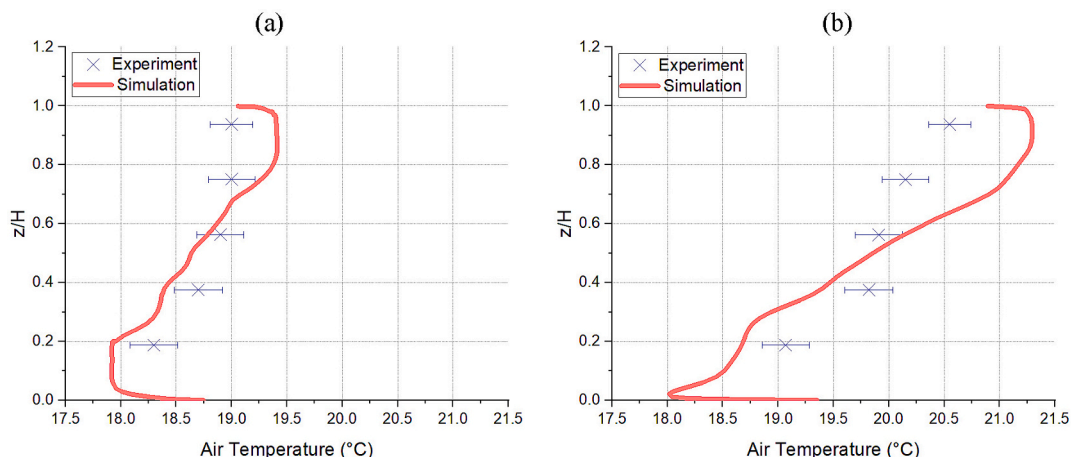


Fig. 5. Comparison of the vertical thermal profile along line T between simulation and experiment for: a) Low Heat case, b) High Heat case.

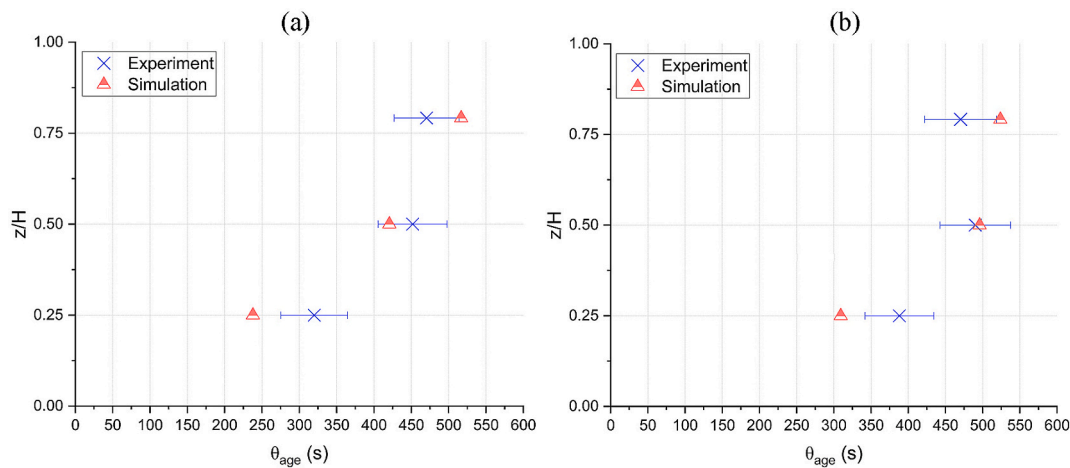


Fig. 6. Comparison of θ_{age} along line C between simulation and experiment for: a) Low Heat case, b) High Heat case.

Table 3

Load table for the female (F) the male (M) child occupants aged 6–9 years old and 10–12 years old, presenting total, sensible, latent, and radiative heat in W.

Degree of activity	Location	Age category (y.o.)	Gender	R + C (W)	Sensible heat (W)	Latent heat (W)
Seated at theatre	Theatre, cinema	6–9	F	39	40	16
			M	39	40	16
		10–12	F	52	53	20
			M	51	52	20
Seated, light schoolwork	Classroom	6–9	F	39	40	16
			M	39	40	16
		10–12	F	52	53	20
			M	51	52	20
Moderately active schoolwork	Classroom	6–9	F	39	40	32
			M	39	40	33
		10–12	F	52	53	38
			M	51	52	42
Light exercise	Gymnasium	6–9	F	69	72	71
			M	70	72	75
		10–12	F	93	96	86
			M	91	94	94
Moderate exercise	Gymnasium	6–9	F	73	77	119
			M	73	78	125
		10–12	F	98	103	150
			M	97	102	163
Heavy exercise	Gymnasium	6–9	F	77	84	188
			M	78	85	197
		10–12	F	105	112	238
			M	104	112	259
Playing	Indoor playground	6–9	F	73	77	119
			M	73	78	125
		10–12	F	98	102	147
			M	96	102	161
Playing instruments	Music room	6–9	F	39	40	32
			M	39	40	33
		10–12	F	52	53	38
			M	51	52	42
Moderate dancing	Dance hall	6–9	F	41	44	93
			M	42	45	98
		10–12	F	56	60	129
			M	95	99	140

multiple activities which differentiated between the sensible and latent loads emitted. This separation is necessary as solely the sensible loads are drivers of the natural convection flows required in DV systems. In light of this, load tables were constructed based on the modified equations of the child specific heat balance model developed by Youssef et al. [13]. Table 3 presents the resulting heat loads including total, radiative and convective ($R + C$), sensible and latent heat generation rates of both male and female child occupants aged 6–9 years old and 10–12 years old. The separation of the heat loads according to these age categories facilitates their use in elementary (also termed primary or grade school) and middle school (or lower secondary) classrooms for HVAC designers.

Based on the approach taken in [44] with regards to the tabulation of adult thermal load data, the tabulated values for child occupants of Table 3 are based on the following assumptions: 24 °C dry bulb air temperature, 50% relative humidity, air velocity of 1 m/s. The clo factor was assumed to be 0.36 in the activities performed in a gymnasium or dance hall, and 1.01 in all other environments. The total heat (H) was calculated as the sum of the sensible and latent heat loads, which were individually calculated following the equations presented in [13].

Metabolic heat production depends on activity level rather than environmental conditions, so total heat, H , should be constant across environmental conditions for the same occupant age and activity.

However, environmental conditions influence how this heat is dissipated between sensible and latent pathways. Sensible and latent heat losses were calculated individually following [13], and a sensitivity analysis was conducted for dry bulb temperatures of 22 °C, 24 °C, and 26 °C and relative humidities of 30%, 50%, and 70%. Increasing the dry bulb temperature from 24 °C to 26 °C reduced sensible heat loss by approximately 20%, with a corresponding increase in latent heat loss while decreasing it to 22 °C increased sensible heat loss by 19%, with an equivalent decrease in latent heat loss. The reduction in sensible heat recommended by ASHRAE [48] in the heat load tables for adult occupants at various activities when environmental conditions increase from 23.9 °C to 26.7 °C dry bulb temperature was equally 20%. Relative humidity had a comparatively minor influence, changing sensible heat loss by only 1–2% across all temperature conditions.

4.2. Boundary conditions of tested cases

A set of simulations were conducted to address the effect of the occupant's age and activity level on the indoor environment with a DV system. Neither our simulations nor experiment modeled the respiration of the occupants, thus the rate of sensible heat modeled is only that lost through the skin, i.e. $R + C$ taken from Table 3. Based on calculations following the child heat balance model in [13], the rate of sensible heat loss through respiration (C_{res}) which is neglected through this decision constitutes on average 3.58% of the total rate of sensible heat loss and a maximum of 7.48%. This is deemed reasonable as thermal plume formation in DV environments is primarily driven by heat exchange at the body surface, particularly convective heat transfer from the skin. Previous research [49,50] has shown that neglecting respiration has a limited influence on the overall room airflow field, whereas accurate modeling of surface heat transfer and thermal radiation is essential [37]. Therefore, representing the mockups using solely the skin sensible heat loss $R + C$ was considered appropriate for the objectives of this study. While 2025 ASHRAE Handbook – Fundamentals [48] offers tabulated data of the heat loads of adult men and women for common activities differentiating between sensible and latent, as well as the radiative portion of the sensible heat generation rate, they do not offer tabulated data for $R + C$ for each activity required for our sensitivity analysis. Therefore, further calculations were conducted to remove C_{res} from the overall sensible heat generation rate of adults, using equations provided in the Handbook [48]. The 8-year-old and adult occupants were each simulated with three levels of $R + C$ heat generation rates (low, medium, and high), tabulated in Table 4. As DV can be used in ECE classrooms and gymnasiums, a wide range of occupant activity can be expected. For the 8-year-old, the activities retained correspond to seated doing light schoolwork (8-Low), exercising at light intensity (8-Medium), and heavy exercising (8-High). $R + C$ for the adult occupants corresponds to seated, very light work (A-Low), walking 4.8 km/h, light machine work (A-Medium), and heavy work (A-High). The heat values for these activities are derived from Table 4 in [48] for female occupants. As adult women generate less heat than adult men for the same activity, their selection as the comparison group to the 8-year-old children constitutes a conservative assessment in an adult-child comparison.

Table 4

Simulation boundary conditions for the sensitivity analysis. L designates a low activity level, M a medium activity level, and H a high activity level for each occupant age.

Simulation case	Mockup height (cm)	Mockup heat generation rate (W)	Mockup heat generation per A_D (W/m ²)
8-Low	130	39	51
8-Mid		69	88
8-High		77	98
A-Low	162	68	41
A-Mid		90	54
A-High		144	87

The boundary conditions for each simulation are listed in Table 4. The age of the modeled occupant will impact the height and surface area (A_D) of the mockup. A_D is calculated based on the DuBois equation [51], with the height and weight representing the 50th percentile of that age category based on CDC data [40,41]. The age and activity combination of the occupant will impact the heat flux (q'') from the mockup in each simulation. Heat is only generated from the cylinder outer surface to reflect experimental conditions, where the boundary condition set on the mockups is q'' calculated from q (in W) for each occupant and age (seen in Table 4) and the cylinder outer surface area (0.79 m²). The upper and lower disks of the cylinder are set to adiabatic.

4.3. Performance metrics

The simulations are used to assess the influence of the combined effect of occupant height, size and heat generation rate (associated with age) and activity level on the thermal and velocity fields as well as the IAQ in the environment. The metrics used to quantify the performance of the DV system are: vertical temperature and velocity profiles along line T, the maximum temperature difference from floor to ceiling (ΔT), the temperature and flow characteristics of the diffuser jet, and local and average values of θ_{age} and the air change efficiency (ϵ_a) in key locations in the environment, as well as qualitative representations of the mean temperature and velocity distributions within the room. ϵ_a is calculated following Eq. (3) where $\bar{\theta}_{age}$ is the average of the θ_{age} values in a volume or plane and τ_n denotes the nominal time constant, calculated as the ratio of the room volume to the inlet flowrate [52,53]. These metrics provide the basis for evaluating the effects of occupant age and activity level on indoor airflow, thermal stratification and the IAQ, which are presented in the following section.

$$\epsilon_a = \frac{\tau_n}{\bar{\theta}_{age}} \quad (3)$$

5. Results and discussion

5.1. Effect on the temperature profile

The air temperature along the same vertical line (line T in Fig. 1) for each of the simulated cases is shown in Fig. 7, where z/H is the elevation normalized to room height. For each age category, increasing the intensity of the activity, which translates into higher heat generation rate, implies a more important thermal stratification in the environment, as

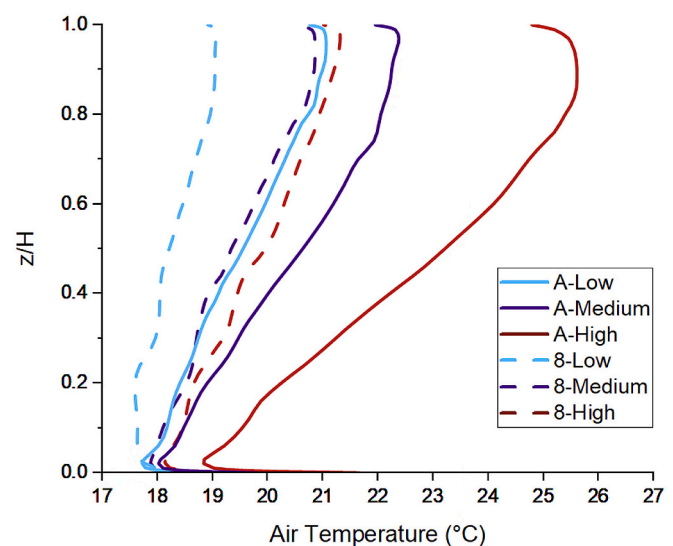


Fig. 7. CFD results of the vertical thermal profile along line T for the tested cases.

shown by a steeper temperature curve. For 8-Low, the environment exhibited a maximum temperature difference from floor to ceiling (ΔT) of only 1.5 °C, whereas for 8-High, the difference jumped to 3.2 °C. For A-Low on the other hand, ΔT was 3.4 °C and jumped to 6.8 °C for A-High. These results are consistent with the findings of Zhao et al. [2] that equally showed that an increase in the heat generation rate of occupants significantly impacts the temperature gradient in a room with DV. The cases of 8-Medium, 8-High and A-Low have heat generation rates of similar magnitudes (69 W and 77 W for 8-Medium and 8-High, and 68 W for A-Low) and resulted in similar vertical temperature profiles (ΔT of 3.2 °C for 8-High and 3.4 °C for A-Low). This signifies that under the simulated conditions, the difference in occupant height between the child and adult does not have a significant effect on the thermal stratification in the environment when the two are generating similar heat rates in Watts. In addition, these findings indicate that under the same ventilation conditions (i.e same Q_t and T_{in}), the presence of child occupants in lieu of adult occupants significantly reduces the temperature stratification in a room with DV, particularly when those children are sedentary as exemplified by the 8-Low case. The ΔT of 1.5 °C in the 8-Low case is markedly lower than the values found in studies analyzing DV systems in classrooms (3.5 °C in [22], 3.36 °C in [3], 3 °C in [7]). This is due to these studies modeling students' heat generation rate at 75 W, which is unrepresentative of sedentary child occupants. This highlights the consequences of modeling pre-pubertal child occupants with adult heat generation rates; it leads to an incorrect assessment of the resulting thermal environment.

Fig. 8 shows a volume rendering of the air temperature in the

environment under the different activity levels. The volume rendering is colored based on air temperature, with transparency simultaneously mapped to the same variable, ranging from fully transparent at 16.8 °C to fully opaque at 26 °C. Fig. 8 shows that the vertical temperature profile seen in Fig. 7 is representative of most of the indoor environment. An increase in activity level for the 8-year-old and the adult increases the air temperature in the environment and the level of thermal stratification. As was the case in Fig. 7, Fig. 8 confirms that 8-Medium and 8-High create a thermal environment that is similar to that with the presence of an adult at low activity. The environments of A-Medium and A-High exhibit higher temperatures and larger thermal stratification. It should be noted that the temperature around the breathing height of the adult mockups in A-High is around 26 °C, which is relatively elevated, however this is probably due to the low ceiling height which is likely trapping the air at low elevations. Nevertheless, the temperature difference between ankle and head for A-High is around 4 °C, which is at the maximum allowed temperature difference for a standing person. The environment with 8-Low shows the least amount of thermal stratification, however it is nonetheless present.

5.2. Effect on the velocity fields

The air velocity magnitude profile along line T is plotted in Fig. 9 with the child and adult occupants. All six cases exhibit their highest velocities near the floor ($z/H < 0.2$). Between z/H of 0.3 and 0.7, the environments with the adult occupants exhibit very low velocities (below 0.01 m/s). The distinct pattern observed for the adult—namely,

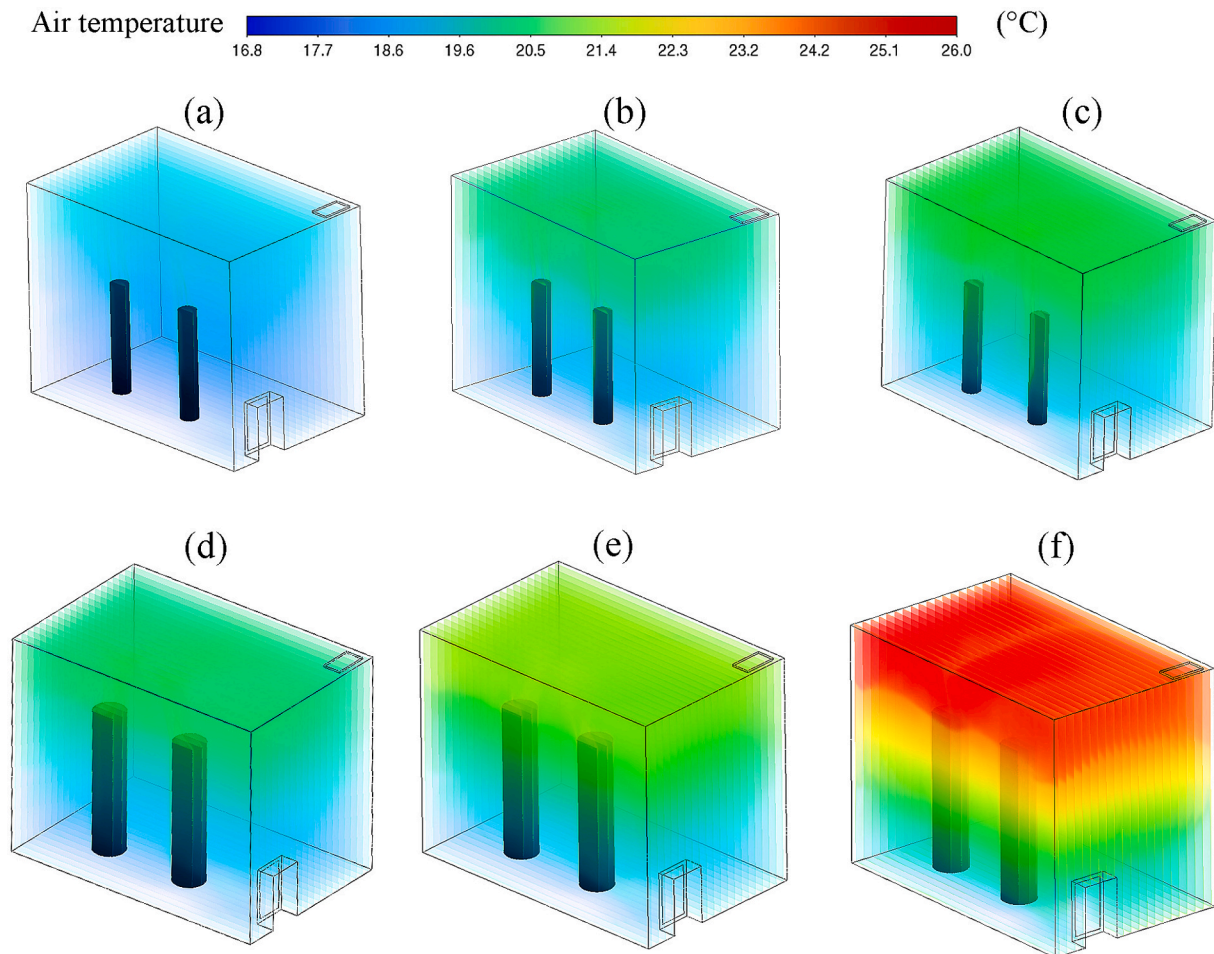


Fig. 8. Volume rendering of the air temperature in the indoor environment with: 8-year-old child at (a) low activity (b) medium activity (c) high activity and adult at (d) low activity (e) medium activity (f) high activity.

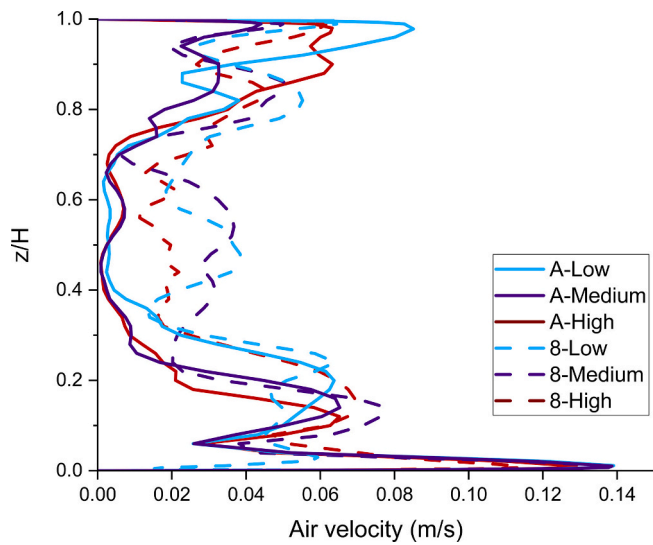


Fig. 9. CFD results of the vertical velocity profile along line T for the tested cases.

higher velocities near the floor ($z/H < 0.2$) and ceiling ($z/H > 0.9$) with reduced magnitudes in between, is common in DV literature [2,3,18] where a similar dip in the velocity in the middle section of the room is

observed. Zhao et al. [2] observed velocities below 0.02 m/s in the mid-section of the room outside the thermal plume. Comparably, Yuan et al. [3] measured velocities less than 0.025 m/s in the z/H region between 0.3 and 0.7 far from occupant thermal plumes in their DV studies of classroom with adult occupants. The 8-Low and 8-Medium cases exhibit comparatively higher velocities at these heights ($0.3 < z/H < 0.7$), with mean values of 0.026 m/s and 0.027 m/s, standard deviations of 0.008 m/s and 0.009 m/s, and peak velocities reaching 0.039 m/s and 0.037 m/s, respectively. By comparison, at equivalent activity levels, the A-Low and A-Medium cases exhibited substantially lower velocities, with mean values of 0.005 m/s and 0.004 m/s, lower vertical variations represented by standard deviations of 0.004 m/s and 0.002 m/s, and maximum values of 0.010 m/s and 0.009 m/s, respectively. The absence of a well-defined low-velocity zone in the middle of the room suggests a more vertically uniform velocity field in all three cases with child occupants. When considered alongside the weak thermal stratification previously observed, these elevated mid-height velocities suggest a departure from strongly stratified displacement flow. It is logical in an environment with DV to have significant velocity fields around the thermal plumes, along the floor as the diffuser flow is spreading, and along the ceiling as the air is moving toward the exhaust. However, the presence of noticeable velocity magnitudes in other regions of the room in the 8-year-old cases suggests a level of mixing that is atypical of a displacement ventilation system.

Although the similar heat generation rates of cases 8-Medium and A-Low resulted in nearly identical thermal stratification patterns in Fig. 7,

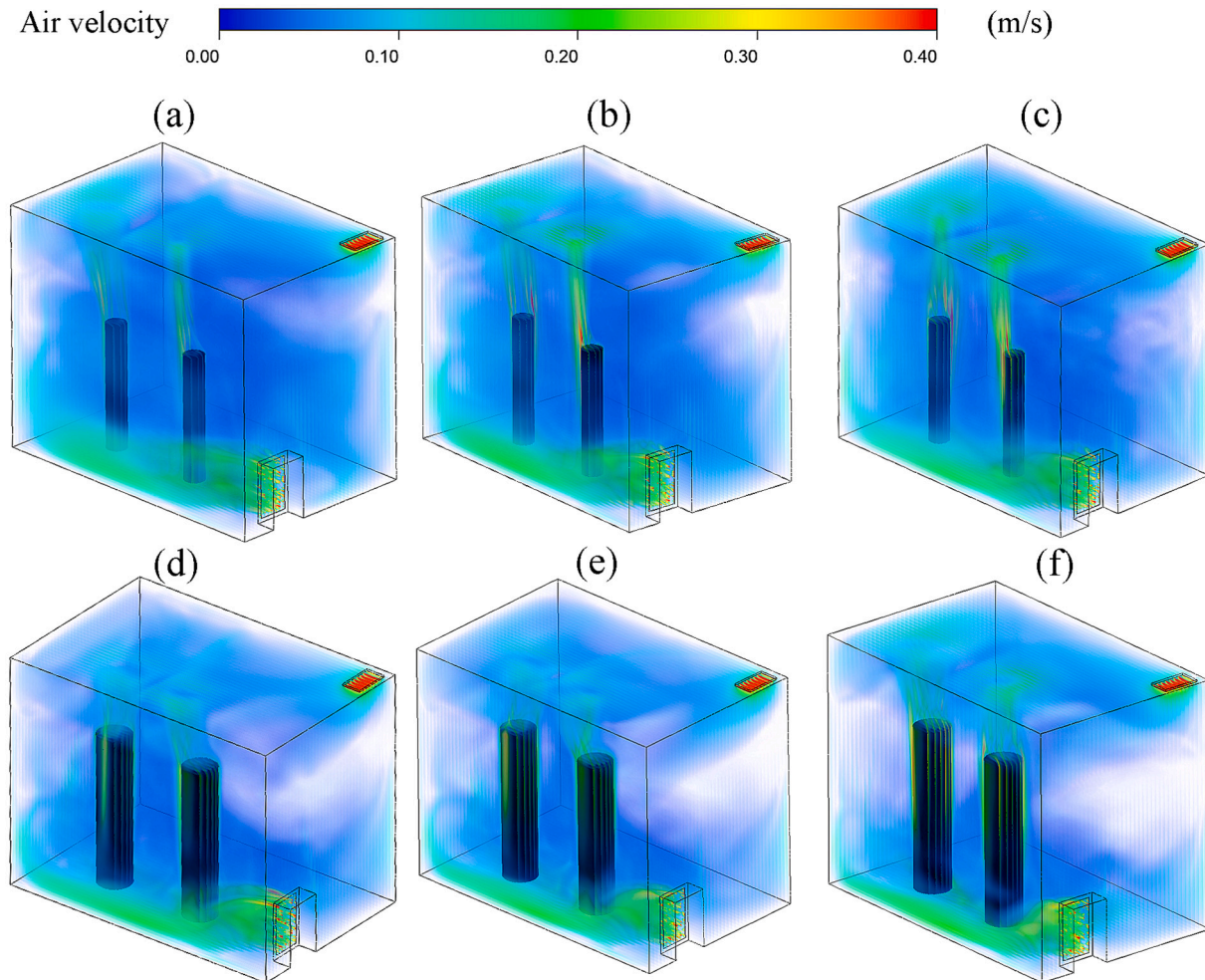


Fig. 10. Volume rendering of the air velocity in the indoor environment with: 8-year-old child at (a) low activity (b) medium activity (c) high activity and adult at (d) low activity (e) medium activity (f) high activity.

all adult cases consistently exhibited very low air velocities in the mid-section of the room, as can be seen in Fig. 9. This suggests that occupant size has a stronger influence on the airflow structure than on the temperature field, particularly within the central region of the room corresponding to z/H values between 0.3 and 0.7.

Similar observations can be made when examining the volume rendering of the air velocity in Fig. 10. The volume rendering is colored by velocity magnitude, with transparency simultaneously mapped to the same variable, ranging from fully transparent at 0 m/s to fully opaque at 0.4 m/s. In environments occupied by adults, the mid-section of the room away from the occupants does not display significant velocity magnitudes, as illustrated by the fully transparent sections in Fig. 10. These sections of low velocity magnitude do not exist in the cases with the 8-year-olds, where velocity magnitude appears more uniform. The thermal plumes around the adults are naturally wider than those around the 8-year-olds, as the cylinder diameter is bigger for the adults. With increasing activity level, the convective flow velocities within the thermal plumes increase for both child and adult cases. The thermal plumes for the child and the adult both reach the ceiling in all cases, and it can be seen that the convective flows are diffusing along the ceiling then moving to the outlet to be extracted. Fig. 10a clearly demonstrates that, at a ceiling height of 2.4 m, the thermal plume generated by a standing 8-year-old child is capable of exiting the occupied zone and reaching the ceiling even at sedentary heat generation.

More notably, however, is that the thermal plume around the child mockup appears to rise predominantly on the side opposite to the incoming diffuser flow—particularly evident for the first child mockup (Mockup 1), even in cases of high heat generation. This suggests that forced convection effects may be influencing plume development in the child cases but not in the adult cases. The diffuser flow further explains this behavior: for the adults, supply air tends to sink rapidly and spread along the floor, while for the children the supply jet remains unidirectional. This distinction likely results from weaker thermal stratification in the child-occupied environments, indicating that the degree of thermal stratification strongly affects how diffuser airflow spreads across the

floor. This phenomenon is examined in further detail in Section 3.3.

5.3. Effect on pattern of diffuser flow

Low velocity diffuser flows in DV are typically characterized by a downward gravity current caused by the interaction of the cold inlet air and the warmer room air. This gravitational current causes a cascading effect of the diffuser flow, rather than a jet-like effect, which is an important characteristic of DV systems as it enables the diffuser flow to spread along the floor in the environment [1]. The intensity of this downward gravitational current is dependent on the dimensionless Richardson Number (Ri) which, as can be seen in Eq. (4), is the ratio of the buoyant forces and the momentum forces.

$$Ri = \frac{g\beta\delta(T_{ref} - T)}{u^2} \quad (4)$$

where β is the volumetric thermal expansion coefficient in K^{-1} , g the gravitational acceleration in m/s^2 , δ is the characteristic length in m, T is the local air temperature and T_{ref} is the reference air temperature in $^{\circ}C$, and u is the local air velocity in m/s [38]. This formulation, often mischaracterized in the literature as the Archimedes number, is helpful in characterizing the nature of the mixed convection flow from the diffuser, indicating whether natural or forced convection is predominant. For this purpose, the value used for δ is the elevation from the floor [3,5] and T_{ref} is the room air temperature in $^{\circ}C$.

Fatemi et al. [38] thoroughly analyzed the flow from a non-isothermal DV diffuser under several experimental conditions. They identified 4 characteristic zones in the flow pattern, each with their own distinctive velocity profiles. Fig. 11 illustrates representative flow profiles for each of the 4 zones as identified by Fatemi et al. [38] which provides a comparison basis for the numerical results of the current study.

The effect of the age and activity level on the flow from the diffuser discussed earlier was explored further by plotting the air temperature, air velocity magnitude, vertical air velocity, and Ri along a vertical line

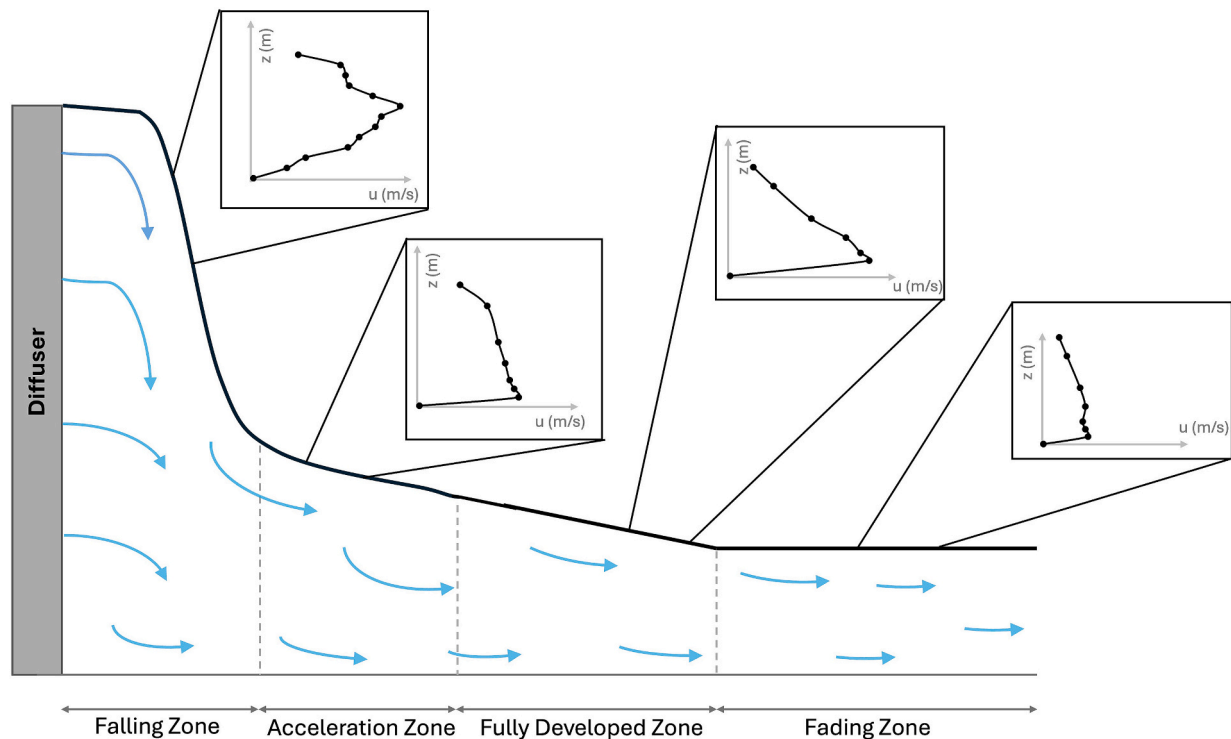


Fig. 11. Pattern of a non-isothermal displacement ventilation diffuser flow, adapted from Fatemi et al. [38]. Velocity profiles reflect measurements at a given distance in each zone.

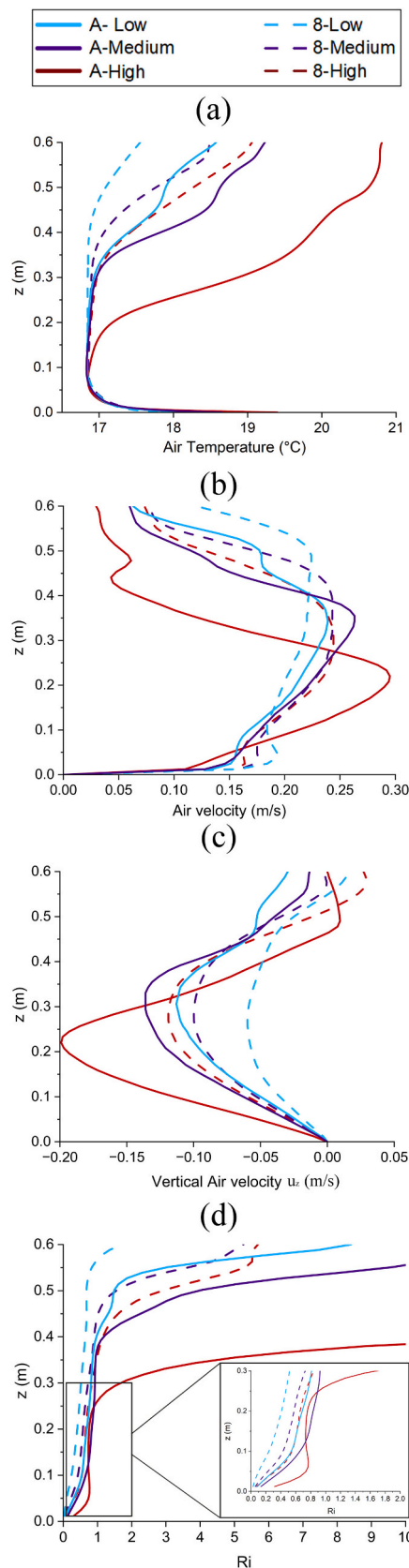


Fig. 12. Plots of a) air temperature, b) air velocity, c) vertical air velocity profile, and d) Ri along a vertical line 0.5 m in front of the diffuser.

of 60 cm height, positioned 0.5 m in front of the diffuser for all the simulated cases. The results are shown in Fig. 12.

Fig. 12a shows that the increase in age and activity level has an important effect on the air temperature in the diffuser flow at the considered distance. As the occupants' heat generation rate increases, a larger vertical temperature gradient develops. The observed vertical temperature difference is 0.8°C for the 8-Low case, 4°C for the A-High case, and ranges between 1.5°C to 3°C for the other cases. Fatemi et al. [38] reported a vertical temperature gradient of 3.8°C at 0.5 m, for which only A-High exhibits a comparable value. As these gradients depend on many parameters such as diffuser flowrate, size, and geometry, no absolute values can be used as a reference. However, even within the initial "falling zone" [38] of Fig. 11, Fatemi et al. [38] reported values of 1.4°C and 2.5°C (at distances of 0.1 m and 0.3 m, respectively), both markedly higher gradients than the 0.8°C of the 8-Low case. The present results confirm that under identical diffuser design and operating conditions (Q_d and T_d), the lower heat output from the sedentary child (8-Low case) produced a markedly reduced vertical temperature gradient relative to all other cases tested in the present paper as well as those found in DV literature. When compared to results of Fatemi et al. [38], diffuser flow for the 8-Medium, 8-High, A-Low, and A-Medium can be considered to be in the "falling zone" even at a distance of 0.5 m from the diffuser.

Following Eq. (4), it is a natural consequence that the reduced temperature gradient for the 8-Low case will result in a reduction in the gravitational forces governing the diffuser flow. Fig. 12b shows that for the adult cases, the thickness of the jet envelope begins to reduce at 0.5 m from the diffuser due to the gravitational forces, which causes an increase in the air velocity within a narrower jet portion, and a marked velocity gradient along the vertical line. A similar trend was observed by [38] at the same distance of 0.5 m, which the authors ascribed as the beginning of the "acceleration zone" [38] (see Fig. 11). It can be observed on Fig. 12b that the height of the maximum velocity reduces as heat generation increases. The 8-Low case exhibits its highest velocity at a height of 0.5 m, near the top of the diffuser. This suggests jet-like behavior, atypical of DV at any distance from the diffuser. Comparing to Fig. 11, no such pattern was found by Fatemi, even within the "falling zone", closest to the diffuser. For the 8-Low case, the vertical velocity gradient is rather limited, due to the domination of the momentum forces, which is a result of the weak temperature difference.

The effect of the occupants' heat output on the downward flow direction from the diffuser is also clear in the vertical air velocity u_z plot in Fig. 12c. It can be seen that the maximum absolute value of u_z is highest for the A-High case, and lowest at the 8-Low case. Even while comparing two sedentary occupants, the maximum value of u_z in the A-Low case is double that of the 8-Low case.

Fig. 12d shows the calculated Ri number along the vertical line at 0.5 m in front of the diffuser. For all examined cases, Ri increases at higher elevations from the floor, which is consistent with the findings of Fatemi et al. [38]. Increasing occupant heat generation rate lowers the height at which Ri rapidly increases. This reflects a shift toward buoyancy-dominated behavior occurring closer to the diffuser as heat loads increase. In the 8-Low case, Ri remains relatively small, reaching only about 1.7 at the highest point. In contrast, the 8-Medium and 8-High cases reach Ri values of 5.2 and 5.6 respectively, demonstrating a substantially stronger buoyant influence relative to momentum forces. A similar pattern appears in the adult scenarios: the A-Low case reaches an Ri of ~ 8.5 , approaching the threshold at which forced convection becomes negligible ($Ri > 10$). For A-Medium and A-High, Ri increases dramatically with height, reaching 12 and 82, respectively (values not shown in the figure for clarity), two cases considered to be predominantly buoyancy-driven at higher elevations.

The close-up of Fig. 12d, shows the 8-Low case rarely drops below an Ri value of 0.1, the threshold below which the flow is predominantly forced and dominated by momentum forces. Although this lower limit is seldom crossed in DV literature, Ri values consistently remaining below

0.5 for $z = 0$ to 0.3 m indicate that momentum forces remain dominant, with forced convection playing a much greater role than natural convection in this case.

Variables used to calculate the Richardson Number can be adjusted to quantify the balance between the buoyant forces and the momentum forces at the scale of the room [3,54]. For this purpose, Eq. (4) is changed into Eq. (5), where the room height (H_{room}) is used as the characteristic length, the air temperature at the exhaust (T_o) is used as the reference air temperature (T_{ref}), the inlet air temperature in °C (T_i) is used as the local temperature (T), and the diffuser air velocity (u_s) in m/s is used as the local air velocity (u).

$$Ri_{room} = \frac{g\beta H_{room}(T_o - T_i)}{u_s^2} \quad (5)$$

The results for each case are shown in Table 5. In all child cases, the reduced Ri_{room} indicates a lower contribution of buoyant forces in comparison to the adult cases. It is also clear that with higher activity levels, and therefore higher occupant heat generation rates, there is a higher contribution of the buoyant forces in the room.

5.4. Effect on the age of air and air change efficiency

To examine the effect of age on the IAQ, θ_{age} and ε_a in key planes and locations were calculated for the 8-Low and A-Low cases. These cases were chosen for comparison as the 8-Low case presented the lowest thermal stratification, which could possibly lead to DV system underperformance in delivering adequate IAQ. Fig. 13 shows contours of the θ_{age} in a vertical mid plane passing through the mockups (at $x = 0.55$ m on Fig. 1) and on the horizontal breathing planes, which are at $z = 1.2$ m for the child simulation and $z = 1.52$ m for the adult simulation. These breathing heights were determined using the UMTRI human body shape generator [55] for a child and an adult woman, where the breathing height of the standing occupants was selected as the nose height. Fig. 13-a and Fig. 13-b show that θ_{age} around the heads of the mockups is higher in the 8-Low simulation than the A-Low simulation (reaching 602 s), indicating lower air quality around the child mockups. Fig. 13c and d show the contours of θ_{age} along the respective breathing planes for the child and adult simulations. It can be seen that even at lower height, θ_{age} in the child simulation ($z = 1.2$ m) is higher than that of the adult simulation ($z = 1.52$ m). This points at a possible stagnation of the room air around the child occupants under the same design conditions.

Average values of θ_{age} and ε_a calculated in the occupied zone and on the breathing plane for the sedentary child and adult cases are shown in Table 6. The results indicate that the sedentary child case shows a slightly higher θ_{age} in the occupied zone and at the breathing height than the sedentary adult case. Consequently, ε_a in the occupied zone and at the breathing height is superior for the sedentary adult cases than for the sedentary child cases under the same design conditions. All this points to the possible underperformance of a DV system in providing good IAQ for child occupants when designed for adult occupants.

6. Discussion

The effect of the age of the occupant on their interaction with the environment as a heat source is reflected in their size (as in height and body surface area) and their heat generation rate for a specific physical activity. In this study, these age-related characteristics were represented by modifying the cylinders' geometry (height and diameter) and thermal boundary conditions. Although these parameters are intrinsically linked

through occupant age, their influence on indoor airflow and thermal behavior was found to differ.

Children's lower heat generation rates produced weaker buoyancy-driven thermal plumes, limiting the entrainment and upward transport of heat within the room. Following plume theory and associated analytical models [1,56], the convective airflow rate in a thermal plume increases with heat source intensity; therefore, reduced metabolic heat release leads to weaker plume development and a less pronounced thermal stratification. This behavior is consistent with findings reported in the displacement ventilation literature [2]. The dominant role of heat generation is further illustrated by examining cases 8-Medium and A-Low, which exhibited nearly identical heat generation rates (69 W and 68 W, respectively) despite differences in occupant size. They result in similar vertical temperature profiles suggesting that thermal stratification is governed primarily by convective heat release, while occupant size has a comparatively limited influence on the overall thermal field.

The influence of reduced occupant size was more evident in the velocity fields than in the thermal stratification itself. Cases 8-Medium and A-Low exhibited similar heat generation rates and comparable vertical temperature profiles, however, their airflow patterns differed substantially. The child cases displayed elevated air velocities in the mid-section of the room, an atypical characteristic for displacement ventilation, whereas the adult cases exhibited near-quiet conditions in the room center more consistent with conventional DV behavior.

This difference can be attributed to the effect of heat source geometry on thermal plume development. Analysis using empirical plume correlations [56] for vertical cylindrical heat sources showed that, even at comparable heat generation rates, the smaller child cylinders generated lower plume entrainment flow rates than the adult cylinders. Reduced entrainment weakens the upward transport associated with the thermal plume and modifies the interaction between buoyancy forces and the supply jet. Consequently, less air is captured into the plume, leaving higher residual airflow velocities in the room mid-section, consistent with the velocity fields observed in the child cases.

These findings indicate that occupant age—manifesting in a different height, body surface area, and heat generation rate—affects DV performance through the combined influence of reduced sensible heat generation and reduced body dimensions. Weaker thermal plumes diminish the vertical displacement of heat and contaminants that underpins displacement ventilation performance, resulting in lower indoor air quality compared with adult cases. The results also suggest that matching heat generation rate alone is insufficient to reproduce occupant–environment interactions in DV systems, as occupant geometry independently influences plume entrainment and room airflow behavior.

7. Limitations and future works

The results of this study highlight the significant impact of the presence of pre-pubertal child occupants in DV spaces designed for adults, particularly when performing sedentary activities. However, there are limitations to the conclusions drawn from these simulations. As the numerical code was experimentally validated in an environmental chamber, we were limited by the small chamber size and low ceiling height available (2.4 m). Though DV systems are generally recommended for environments with ceiling heights above 2.7 m [1], as Skistad et al. [1] posits that 2.3 m is the limit below which performance becomes compromised, this chamber height was deemed acceptable. However, though thermal plumes from child occupants reached the ceiling in all three cases modeled, this finding should not be generalized to spaces with ceiling heights exceeding 2.4 m or with a higher population density. Investigating these phenomena in larger spaces, such as realistic classrooms, would be valuable, especially given that the current results indicate the diffuser's cold airflow along the floor may be compromised when sedentary children are the sole heat source.

Additionally, only the child cases were experimentally validated.

Table 5
Richardson number for the simulated cases.

Case	8-Low	8-Medium	8-High	A-Low	A-Medium	A-High
Ri_{room}	0.34	0.58	0.65	0.61	0.79	1.25

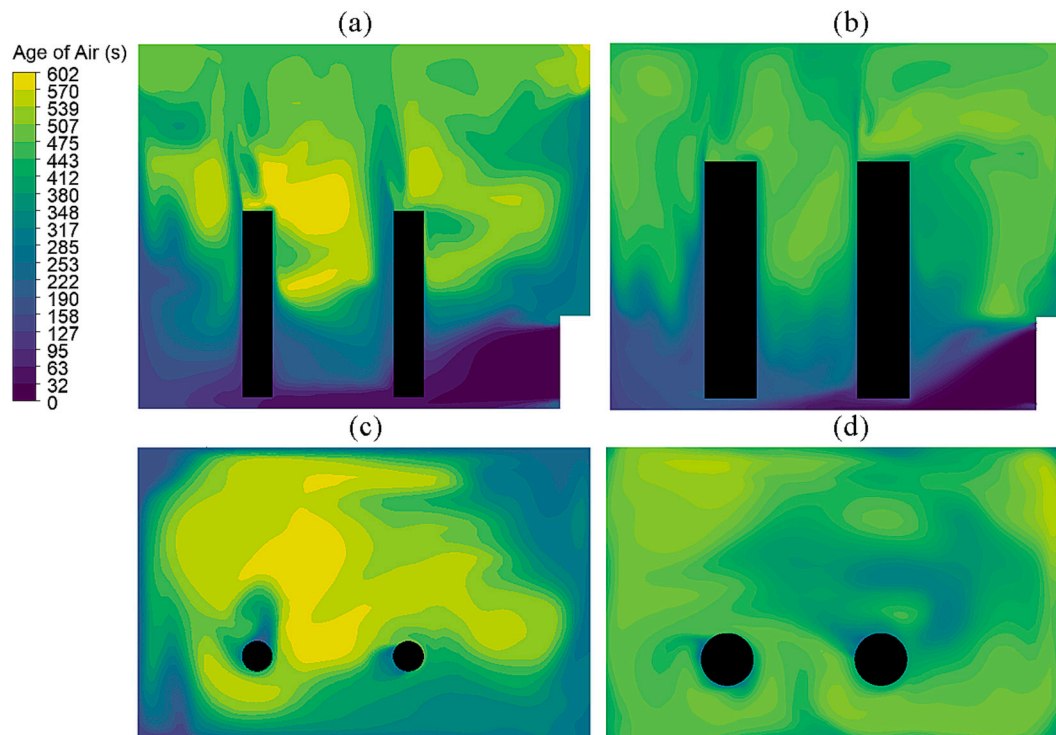


Fig. 13. Age of Air in a vertical mid-plane ($x = 0.55$ m) for a) 8-Low and b) A-Low simulations, and on the horizontal breathing plane c) $z = 1.2$ m for 8-Low and d) $z = 1.52$ m for A-Low simulations.

Table 6

$\bar{\theta}_{age}$ and ϵ_a in key location in the child low and adult low simulations. * The breathing height is taken to be 1.2 m for child mockups and 1.52 m for the adult manikin.

Results	Child	Adult
$\bar{\theta}_{age}$ in the occupied zone	386.9 s	347.8 s
$\bar{\theta}_{age}$ at the breathing height*	446.8 s	431.6 s
ϵ_a in the occupied zone	1.29	1.44
ϵ_a at the breathing height*	1.12	1.16

Although this validation encompasses the full range of heat generation rates for the 8-year-old child occupants considered in this study, applying the findings to adult occupant cases, which involve larger cylinder sizes and higher heat generation rates, constitutes an extrapolation beyond the validated range and may introduce additional uncertainty.

The heat sources' heights in this study reflect the heights of standing occupants. While this reflects the common approach in the literature [2,37], studying seated child occupants in a room with DV is a necessary next step to conclude on outcomes in classroom settings. Differences in both the heat source height and shape, associated with the seated posture, could have a significant effect on thermal plume development and maximum height.

Although this study shows that IAQ is compromised around pre-pubertal child occupants, indicated by higher $\bar{\theta}_{age}$ and lower ϵ_a , these metrics do not provide a complete evaluation of ventilation performance. While they assess the delivery of fresh air to specific locations, they do not reflect the system's ability to remove internally generated contaminants, a fundamental objective of ventilation. Future work should therefore track internally generated pollutants and evaluate additional indicators, such as contaminant removal effectiveness (ϵ_c), in a realistic environment to achieve a more comprehensive assessment of DV performance under child-dominated occupancy.

Another limitation to the generalization of the results is the use of

heat loads representative of female occupants. As women have lower heights [41] and lower heat generation [57] than men, the cases selected were conservative and do not represent the widest possible differences between adult and pre-pubertal child occupants. As the stature and heat generation rate differences would be higher between an 8-year-old boy and an adult man, further tests using these occupant characteristics are needed to appreciate the breadth of influence of occupant age on DV performance. This will be particularly relevant as HVAC references and guides mostly use heat generation rates of adult men as the default occupant for design.

A significant contribution of this study is the thermal load tables of child occupants aged 6–9 and 10–12 years old presented in Table 3. Similar to adult thermal load data reported in 2025 ASHRAE Handbook – Fundamentals [48], the values are derived under specific environmental conditions (24 °C, 50% RH, 1 m/s air velocity) and based on limited assumptions regarding clothing insulation and body characteristics. Given the individual variations in body surface area, metabolic heat generation, and clothing amongst children, and environmental conditions found in classrooms, these values should be taken as approximations. Though suitable when used as HVAC design parameters, prudence should be exercised when using these values outside the boundary conditions defined above.

This study highlights important limitations in the application of DV systems in environments predominantly occupied by children, particularly with respect to maintaining adequate IAQ. These findings indicate the need for further investigation into design refinements and optimization strategies tailored to child-occupied spaces. Future research should systematically evaluate modifications to current DV design methodologies, including adjustments that account for children's lower metabolic heat generation and its influence on stratification and airflow patterns, in order to improve overall system performance. It is recommended that thermal load tables for child occupants be included in HVAC references and guidelines to facilitate their use by professionals in HVAC system design. Additionally, future research should explore different occupant sitting postures, particularly modeling seated

occupants in rooms with larger heights, to obtain more generalized conclusions regarding children's thermal plumes' capacity to escape the occupied zone. Knowing that the Predictive Mean Vote (PMV) metric is not specifically designed for children and has only been validated with adult occupants [58–60], alternative thermal comfort metrics should be explored to adequately assess children's comfort under different HVAC system operational conditions. Indicators that rely on environmental factors such as the Draft Rate (DR) and the temperature difference from head to ankle may be reasonable alternatives.

8. Conclusion

This study developed and validated a CFD model to investigate the performance of displacement ventilation in spaces occupied by children. Experimental validation in an environmental chamber confirmed the reliability of the numerical model. Comprehensive heat load tables were developed for children aged 6–9 and 10–12 years, providing a useful resource for HVAC designers and researchers. Simulations were then performed to investigate how occupant age and activity influence the temperature and velocity fields within the room, as well as the resulting IAQ. The results show that both occupant age reflected in altered height, size and heat generation rate and activity level significantly influence thermal stratification. Children at medium or high activity levels generate a thermal environment comparable to that of a sedentary adult, whereas sedentary children produce very weak stratification. Regarding airflow, the simulations indicate that thermal plumes from standing child occupants can rise above the occupied zone; however, it remains unclear whether this holds true for seated, sedentary children or in spaces with higher ceilings. Thermal plume velocities increase with activity, and the plume magnitudes appear similar between children and adults. Nonetheless, the weaker thermal stratification in child-occupied spaces affects the diffuser jet, limiting its spread along the floor and modifying local airflow patterns. As the flow becomes isothermal, a domination of forced convection over natural convection is present for child occupants cases but absent from adult cases. Overall, gravitational effects in the room are more limited for child occupants than adult occupants, especially at a sedentary activity, expressed by a lower Richardson number at the room scale (Ri_{room}). Additionally, the results of this study revealed a slight reduction in IAQ indicators such as θ_{age} and ϵ_a on sedentary child occupants in comparison to sedentary adult occupants under the same DV design conditions. Since significant differences were identified between prepubertal children and adult women in this study, it can be reasonably inferred that comparable or larger differences would exist between children and adult men, given the higher heat generation rates typically associated with the later. These findings highlight that child-specific characteristics must be considered when designing displacement ventilation systems, as they can significantly alter indoor airflow patterns, thermal comfort and IAQ.

Considering the importance of thermal comfort and IAQ for student well-being and performance, these findings carry significant implications for the design of educational spaces. Future work will extend these simulations to full classroom environments and expanding IAQ metrics to better inform ventilation strategies that optimize both comfort and cognitive performance for children as well as limiting transmission of airborne respiratory diseases in classrooms.

CRedit authorship contribution statement

Farah Youssef: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stéphane Hallé:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Katherine D'Avignon:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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