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**Entrainment and its Implications on Microclimate Ventilation Systems: Scaling
the Velocity and Temperature Field of a Round Free Jet.**

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Abstract

Research on microclimate ventilation systems, which mostly involve free jets, point to delivery of better ventilation in breathing zones. While the literature is comprehensive, the influence of contaminant entrainment in jet flows and its implications on the delivery of supplied air is not fully addressed. This paper present and discuss entrainment characteristics of a jet issued from a round nozzle (0.05 m diameter), in relation to ventilation, by exploring the velocity and temperature fields of the jet flow. The results show a trend suggesting that increasing the Reynolds number (Re) reduces ambient entrainment. As shown herein, about 30% concentration of ambient air entrained into the bulk jet flow at Re 2541 while Re 9233 had about 13% and 19 % for Re = 6537/12026 at downstream distance of 8 diameters (40 cm). The study discusses that “moderate to high” Re may be ideal to reduce contaminant entrainment, but this is limited by delivery distance and possibly the risk of occupant discomfort. Incorporating the entrainment mixing factor (the ratio of room contaminants entrained into a jet flow) in performance measurements is proposed and further studies are recommended to verify results herein and test whether this is general to other nozzle configurations.

Keywords: Entrainment, Round free jet, Microclimate ventilation systems, Temperature field, Velocity field, Entrainment mixing factor

Practical Implications

Entrainment is an important factor that influence delivered air quality in microclimate ventilation systems. The study herein suggests and explores the entrainment mixing factor as a foundational concept to explain entrainment characteristics of the ventilation jet flow in relation to the surrounding concentration of ambient fluid. The observations herein illuminate on the importance of incorporating entrainment measurements to accurately estimate the percentage of ambient contaminants entrained into the flow or simply the air quality delivered at a specific point in microclimate ventilation systems.

Nomenclature

D = nozzle diameter, m

A = nozzle area, m²

x = axial distance from nozzle, m

r = radial distance, positive outward from the jet axis, m

$r_{1/2}$ = jet half-width, m

Q = mass flowrate, kg/s

ρ = fluid density, kg/m³

V = time – averaged axial velocity, m/s

r.m.s = root mean square

u' = r.m.s value of radial fluctuating component of velocity, m/s

v' = r.m.s value of axial fluctuating component of velocity, m/s

$r_{0.1}$ = distance from jet axis to location where $V = 0.1 V_0$, m

T = time – averaged temperature, K

t' = time – averaged r.m.s value of temperature, K

ψ = non-dimensionless entrainment determined by velocity measurements

ψ_c = jet centerline non-dimensionless entrainment estimated with temperature measurements

- C = entrainment constant
- Re = Reynolds number
- $f_{en - mix}$ = entrainment mixing factor
- ϵ_v = Ventilation effectiveness

Subscripts

- a = room ambient
- m = maximum
- 0 = jet exit plane
- ∞ = time – averaged ambient condition
- e = entrained
- c = centerline value
- x = axial position downstream from the nozzle exit

1. Introduction

Jets, defined as the discharge of fluids from an opening into a larger body of the same or different fluid, ¹ are widely used in engineering applications due to their fundamental characteristics. One such characteristic is the dependence of the flow behavior on the nozzle type or geometry. ²⁻⁶ This dependence is critical in determining the choice of the nozzle type for specific engineering applications, see Mi et al. ^{3,7} and references therein. To illustrate, a pipe nozzle is simple to manufacture and issues a jet that emerges as a fully developed turbulent jet making it popular in many practical applications. Comparatively, jets issuing from smooth contracting nozzles have a low pressure drop in the supply pipe and the flow is predominantly laminar in the initial region which makes it favorable for wide industrial applications like burner nozzles and impingement cooling. ⁷ Jets issuing from rectangular/square nozzles, i.e. planar jets, are known to be more sensitive to disturbances near the orifice than elsewhere. ⁸

The present study examines a round free jet issuing from a smooth contracting nozzle and its application on microclimate ventilation systems, e.g. personalized ventilation systems

(individually controlled air distribution system aimed at improving the quality of inhaled air and the thermal comfort of each occupant)⁹, particularly on entrainment of room ambient contaminants into the supply flow. It is worthwhile to consider the general effect entrainment has on air distribution in microclimate ventilation systems especially that the supplied air quality is dependent on it.

1.1. Jet entrainment hypothesis

Entrainment, drawing in of surrounding fluid outside the flow boundaries into the main stream flow,¹⁰ is an interesting jet flow characteristic as it results in increase in the jet mass flowrate with axial distance downstream. This consequently influences the jets outward spread and the decay of the axial velocity.¹¹ For example, jets issued from different nozzle configuration have different mixing effect.¹² Therefore, depending on initial conditions, the interaction between the jet flow and the ambient will affect jet development with regard to vortex separation, roll up and pairing, free turbulence evolution and viscous/inviscid interactions.^{13,14} This in turn will influence the rate of ambient entrainment into the jet.

A nozzle with diameter D has a mass flowrate $Q(x)$ at any distance downstream defined as

$$Q(x) = 2\pi \int_0^{\infty} \rho(x,r) V(x,r) r dr \quad (1)$$

where ρ is the fluid density, V is the fluid velocity in the axial direction (x) and r is the radial distance from the jet centerline. If Q_0 is the initial mass flowrate (at the nozzle exit), experimental evidence shows that the ratio $Q(x)/Q_0$ is greater than unit and increases with downstream distance, which means that the jet entrains more fluids as it travels downstream.¹⁵ Entrainment rate (E) can then be define as the rate at which the jet mass flowrate grows with axial distance,¹⁰ namely

$$E = \frac{dQ(x)}{dx} = C \left(\frac{Q_0}{D} \right) \left(\frac{\rho_\infty}{\rho_0} \right)^{0.5} \quad (2)$$

where, ρ_∞ is the density of the surrounding fluid, D is the nozzle diameter, ρ_0 the jet flow density at exit and C is the entrainment constant (determined experimentally). Equation 2 is the classical approach of universal similarity, which states that the jet flow forgets its initial conditions as it asymptotically attains a self-similar (or self-preserving) state and as such no dependence exists on the nozzle geometry. ⁷

Disagreement exist on whether the classical hypothesis is universal across nozzle configurations and whether it applies even in the initial region. Hill ¹⁶ noted that C increases nonlinearly in the initial region and is different for the fully developed region, while Donald and Singer ¹⁷ found that C in the region $x < 14D$ was not significantly different from the fully developed region. Falcone and Caltado ¹⁰ found typical values to range between 0.1 and 0.23 in the initial region and between 0.185 and 0.34 in the fully developed region. A detailed discussion is presented in Mi et al, ⁷ although most of the considered studies involved slightly higher Reynold numbers and mainly focused on fully developed region in comparison to the typical values and flow regions used in microclimate ventilation systems.

The same confusion is drawn on the influence of Reynolds number and the global density ratio (ρ_∞/ρ_0). Pitts found that the statistical behavior of the jet in the fully developed region is independent of the Reynolds number (Re) and the (ρ_∞/ρ_0). ^{18,19} The same results were reported on the asymptotic state of the scalar field of a jet. ²⁰ Other researchers ^{7,21} found the classical hypothesis to be flawed and recommended that it should be ignored. The works of Hussain and George were among those who earlier questioned the classical hypothesis. ^{22,23}

1.1.1. Methods of estimating entrainment

The common method of determining entrainment flow is applying the integral solution (Equation 1) of streamwise velocity profiles at various downstream distances.^{24,25} The entrainment flowrate (Q_e) up to a point x downstream can be determined by the relationship

$$Q_e = Q_x - Q_0 \quad (3)$$

or defined dimensionless as

$$\psi = \frac{Q_e}{Q_0} = \left(\frac{Q_x}{Q_0} \right) - 1 \quad (4)$$

where Q_x and Q_0 are corresponding flowrates at point x and the nozzle exit, respectively.

The major challenge is measurement uncertainties associated with low velocities (e.g., at the tails of the radial velocity profiles), especially at large axial distances from the nozzle exit or at low Reynolds numbers.⁵ It is common to restrict the integral region within $r = \pm r_{0.1}$, where $r_{0.1} = 0.1 V_0$. This means flow regions that scale below 10% of the exit velocity value are excluded from the calculation. It is discussed that the results obtained with this arbitrary approach does not significantly differ to those obtained with velocities veered to zero.^{26,27}

There are other methods that involve velocity measurements, like the quadrant analysis method that fragment fluctuating velocity components into four events to determine entrainment. This method is outside the scope of this paper but details for interested readers can be found in Wallace²⁸ and Viggiano et al.²⁵

Another method that perhaps is more common in ventilation performance measurements pertains to tracing concentration in the jet flow. Challenges with this method include influence of global density ratios if the tracer is very different from the ambient fluid, or complexity in measurement of concentrations across the jet with minimal intrusion. Temperature has been

used and discussed as a passive tracer in characterizing and understanding jet flows.^{27,29} Mi et al.⁷ gave a detailed discussion of studies^{30–32} that investigated the temperature field and made a general observation that the scalar field is more sensitive to differences in turbulence structures and jet exit conditions. Thus, the effect entrainment has on heat transfer in turbulent jets is quite pronounced.²⁷ In the current study, the radial temperature profiles were viewed as a distribution of a passive contaminant across the jet flow and the heat transfer into the jet axis was used as a representation of entrainment into the centerline defined as

$$\psi_c = \frac{\Delta T_e}{\Delta T_0} = \left(\frac{\Delta T_x}{\Delta T_0} \right) - 1 \tag{5}$$

where ΔT_e is the change in jet flow temperature difference between point x and the exit due to fluid entrainment, ΔT_x and ΔT_0 are the corresponding local and exit centerline temperatures differences in relation to the ambient temperature, respectively. Alternatively, one can estimate entrainment by tracing the heat flux across the jet flow, see S1 in the supporting information.

Other researchers^{16,33} have performed direct measurements of entrainment. Ricou and Spalding³³ made a classical study that measured bulk entrained flow into a variety of gas jets and Hill¹⁶ directly measured local entrainment. Interesting methods, among others, include non-intrusive method referred to herein as “Edge detection method”, which has promising application in entrainment studies to investigate the physical processes of turbulent entrainment at the flow edges. Details for interested readers are in Burrige et al³⁴.

1.2. Entrainment and ventilation flows.

Depending on the desired ventilation goal, the problem of entrainment can vary from requirements of high to low entrainment. Traditional air distribution systems (e.g. mixing ventilation) have sought higher entrainment to increase the systems dilution or mixing capacity.

¹ Today, there is a call for a paradigm shift in indoor air distribution from total volume systems

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2
3 to microclimate systems, ^{35,36} whose optimal operation (delivery of clean supply air) depend
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5 on low entrainment e.g. personalized ventilation systems. ^{37,38} Earlier, we raised the importance
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7 of distinguishing between total volume ventilation systems (operate on dilution of room air ^{1,39})
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9 in which high entrainment is sort after and microclimate ventilation systems that require low
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11 entrainment. ⁴⁰ Microclimate ventilation systems were described as delivery capacity systems
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13 because they seek to deliver as much of the supply conditions as possible to the occupants
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15 sitting or breathing zones. ^{37,38} In this study, from here onwards, microclimate ventilation
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17 systems are referred to as delivery capacity systems.
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21
22 A significant amount of research has been done on microclimate ventilation particularly on
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24 personalized ventilation systems, see Melikov and references therein ³⁶. While the literature is
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26 comprehensive, the influence of contaminant entrainment in the jet flow and its implications on
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28 the delivery of supplied air is not fully addressed. It is clear that pollution of the supply jet flow
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30 occurs in two phases with the initial being dependent on nozzle entrainment characteristics
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32 which occurs as the jet develops and the second being due to the interaction of the jet flow and
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34 the human convective boundary layer. ^{37,41} Substantial research^{38,41–44} has been done to address
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36 the latter while, with the former, no fundamental studies exist in relation to microclimate air
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38 distribution albeit studies^{37,45–47} that looked at diffuser designs that extend exit conditions
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40 further downstream.
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46 The goal of the current study was to gain insight on the implications of entrainment into a basic
47
48 round free jet in relation to distribution and delivery of air in microclimate ventilation systems.
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50 This understanding is critical and can be extended to help formulate design guidelines and
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52 performance testing of various types of delivery capacity diffusers.³⁷ To the authors' knowledge
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54 no studies have yet emerged that propose incorporating entrainment as a performance measure
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56 in delivery capacity diffusers. Thus, there is an opportunity to re-explore methods of
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58 determining entrainment and consequently guidelines or performance testing methods
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60

regarding air distribution in delivery capacity systems. This study offers a first step towards filling this gap.

2. Methods

In the present study, two measurement fields were investigated as will be discussed in subsequent sections. Temperature was used as a marker to obtain insight on the scalar field of a round free jet in relation to entrainment behavior. Additional information was extracted from the PIV measurements to showcase the qualitative and quantitative response of the velocity field and entrainment characteristics, permitting assessment and comparison of dominant flow structures at different initial conditions.

2.1. Measurements of the velocity field

Particle image velocimetry (PIV), 2 dimensional – 2 components, measurements were performed under isothermal conditions in a room with dimensions of 3(W) × 2.5(H) × 4.2(L) [m³], see Figure 1A. The nozzle setup was vertically mounted and installed in the middle of the room at 1.8 m from the floor. A specially designed smooth contracting nozzle (diameter, $D = 0.05$ m) was used, the nozzle is presented in Figure 2B.

The PIV system comprised of a 15-Hz New Wave Solo PIV 50-mJ double-pulsed Nd:YAG laser operating at 6 Hz as a light source, and placed at about 0.85 m from the nozzle centerline and at the height of 1.5 m from the floor. A double-frame, high-sensitivity 12-bit CCD camera (HiSense MKII) with resolution of 1344 x 1024 pixels mounted with an AF Micro Nikkor objective with a focal length of 60 mm was used for imaging. The camera was installed 1 m away from the nozzle centerline and placed on a traversing system moving perpendicular to the laser sheet and parallel to the jet axial axis. A SAFEX FOG 2001 smoke generator with “normal power mix” as fog generating liquid was used and gave satisfactory measurement results.

Figure 1: Experimental setup of PIV measurements and nozzle design

All measurements were performed in a closed room setup with air re-circulation in the jet stream to make it possible to achieve a well-distributed global seeding, a prerequisite for high-quality PIV measurements. The delay between laser pulses was adjusted depending on the flow-field and was optimized for the interrogation region. The imaging region was 11.93 cm (W) x 8.66 (H) cm and five regions were measured corresponding to about $0.01 < x/D < 8$ downstream. The statistical mean velocity field was obtained with an ensemble of 650 images of instantaneous velocity fields for each experimental case. The cross-correlation was performed with interrogation region of 32 x 32 pixels with a typical overlap of 50%. Peak and range validation were applied to identify spurious vectors respective of the flow field. Overall, spurious vectors were rejected and substituted with interpolated vectors within the spatial region in the mean PIV field. For the current study, the statistical errors were $\leq 10.2\%$ in the time averaged velocity field using the central limit theorem.⁴⁸ PIV measurements uncertainties are influenced by various error sources, which can either be systematic or statistical errors.⁴⁹ Statistical errors are mainly due to random sampling,^{48,50,51} while systematic errors relate to the experimental setup and procedure with likely sources of error originating from tracking

behavior, seeding density, background noise etc. Indoor airflow measurements with 2 dimensional PIV have systematic errors less 2%.^{50,52}

2.2. Measurements of the temperature field

Temperature has been used as a passive contaminant⁷ to mark the scalar field. The statistics of temperature fluctuations provide a fundamental and practical understanding of the mixing behavior of the jet⁵³ from which much insight can be obtained by analyzing the behavior of the jets centerline.^{2,18}

Measurements of the temperature field were performed over a flow region of $0.04 < x/D < 10$ downstream in the same room and same nozzle setup as PIV measurements but with an open airflow setup, see Figure 2. The jet supply air was taken outside the room and conditioned to satisfy the desired supply requirements. The room had two air exhaust terminals installed on one side of the wall.

Figure 2: Experimental setup of temperature measurements and thermocouple test rig with centering knob

T-type thermocouples (class 1) with a tip diameter of 0.6 mm and a factory accuracy of $\pm 0.3\text{ }^{\circ}\text{C}$ were used in the temperature measurements. A total of 18 thermocouples spaced 1 cm apart

were mounted on an in-house manufactured test rig, shown in Figure 2B. The thermocouples were calibrated in the range of 10 – 30 °C with 2 Hz frequency operation mode at uncertainty of ± 0.1 °C. LabVIEW software was used to monitor and record all measurement data.

The test rig was connected to a traversing system which was controlled in two directions, radial (r) and axial (x) planes of the jet axis. Measurements were done with a radial resolution of $0.05D$ for all points with $0 \leq r/D \leq 1.85$ and a resolution of $0.2D$ for $r/D > 1.85$ across the jet, while axial (downstream) resolution was $0.5D$ for $x/D \geq 1$.

A temperature differential was used to mark the scalar field, with the supply jet flow slightly cooled relative to the surrounding room ambient air. A nominal temperature difference (ΔT) of about 4 °C between the jet centerline exit temperature and the average room ambient temperature outside the jet stream (average of various axial points in the plane $r/D = 5.3$) was used. The resulting experimental temperature difference across conditions was 4 ± 0.4 °C. This was to minimize the differences on the influence of buoyancy between the considered Reynold numbers.

2.3. Experimental conditions

Five experimental cases listed in Table 1 were investigated. The cases were defined by the Reynolds numbers in the range used by Yang et al.⁵⁴ and scaled with a relationship, $Re = V_0 D / \nu$, where V_0 is the nozzle bulk exit velocity determined from a 35 mm diameter orifice plate airflow measurements with a relationship between the differential pressure and the air flowrate defined as, $Q = 0.38337 \Delta P^{0.4981}$, D is the nozzle exit diameter and ν is the kinematic viscosity of the fluid, $\nu = 14.8 \times 10^{-6} \text{ m}^2/\text{s}$.⁵⁵

Table 1: Experimental conditions

Case	Re	ΔP [Pa]	Q (m ³ /s)	V_0 [m/s] *	T_s [K] (°C) [#]	T_{amb} [K] (°C) [#]
1	2541	15.1	0.00148	0.75	291.85 (19.7)	296.45 (23.3)
2	4629	50.3	0.00269	1.37	291.95 (18.8)	296.05 (22.9)
3	6537	100.1	0.00380	1.93	291.95 (18.8)	295.95 (22.8)
4	9233	203.7	0.00537	2.73	291.45 (18.3)	295.15 (22.0)
5	12026	340.4	0.00699	3.56	290.65 (17.5)	294.65 (21.5)

*The bulk exit velocity presented here is determined by the relationship $V_0 = 4Q/\pi D^2$, D is the nozzle diameter and Q is the flowrate estimated through the orifice plate measurements. [#] The values presented in parenthesis “()” are in °C. The temperature measurements presented here are applicable only in the scalar field measurements.

3. Results and Discussion

3.1. The instantaneous velocity field

The instantaneous streamline contour plot showed distinctly different responses, see Figure 3. As observed, the jet flow for Re 2541 was oscillatory and the flow disintegrated into the ambient within a short downstream distance from the nozzle exit, while Re 9233 and Re 12026 had steadier jet flow with longer penetration distance before disintegration. The oscillating manner of the jet creates flow instabilities as also evidenced in an earlier study. ⁵⁶ The main factor governing the resulting nature of the flow is the momentum flow ($F = \rho A (V_0)^2$). Momentum flow is critical in delivery capacity systems because it determines the jets penetration distance (practical distance to which the jet delivers the supply air satisfactorily). A weak momentum flow is undesirable because it requires occupants to be very close to the diffuser.

As observed in Figure 3, Re 2541 and Re 4629 have larger eddies (vortices) compared to Re 9233 and Re 12026. Additionally, at high Reynolds numbers the formation of eddies draws closer to the nozzle exit and secondary eddies are observed along the stream flow especially at Re 12026. Jet theory dictates that entrainment is a combined effort of large and small-scale eddies.⁵⁷ Oscillatory flow is dominated by the large-scale eddies which induces irrotational ambient fluid into the main jet flow (engulfment), steady flow is dominated by small scale eddies in which entrainment is driven by nibbling. Figure 3 gives an insight that low Reynolds numbers may have higher entrainment rate since engulfment entrains more surrounding fluids than nibbling.⁵⁷

Figure 3: Instantaneous velocity fields with velocity vectors, streamlines and contours of their magnitudes. These images are selected arbitrarily out of 650 images and presented here as typical flow for each experimental condition

3.2. The mean flow field

3.2.1. Mean velocity field

Figure 4 shows a qualitative representation of the normalized mean velocity contour plots which reveals that the flow spreads out gradually at all Reynolds numbers and changes very little for the considered cases herein. As demonstrated, the potential core region is approximately uniform and diminishes at $x/D \leq 4.8$ for all cases except for Re 12026 which occurs at $x/D \leq 5.4$. This suggests that exit conditions at Re 12026 are extended further downstream and consequently has a higher penetration distance. Quantitatively a top-hat exit velocity profile, that diffuse out to a Gaussian profile within the first 4 – 6 diameters, ⁵⁸ typical of free round jets was obtained. ^{1,59,60} Details of the statistical mean streamwise velocity profiles are presented in Figure S2 in the supporting information.

Figure 4: Normalized mean velocity field at various Reynolds numbers. Plots are normalized with maximum centerline axial velocity (V_m)

A detailed qualitative characterization of the mean velocity fluctuations is described by the cartesian plot of the root mean square (r.m.s) of the radial velocity component (u') shown in Figure 5, details of the quantitative description is presented in Figure S3 in supporting information. Low Reynolds numbers showed more fluctuations, which intensified at Re 4629, compared to higher Reynolds numbers. The physical mechanism responsible for the increased radial r.m.s fluctuations in Re 4629 is unclear but may be related to the emergency of marginally unstable jet or ambient conditions during measurements. Measurements and analysis of all three velocity components is recommended as this may be due to higher fluctuations on the third velocity component not measured herein. Overall, one can distinguish a general trend that with increase in Reynolds numbers the fluctuations shift towards the nozzle exit due to increased influence of the shear layer or vorticity layer stemming from the nozzle lips. This agrees with Figure 3 which shows emergence of small-scale eddies on the shear layers of the jet very close to the nozzle exit. Although this suggests that the mixing effect of jet flow with ambient begins near the nozzle exit at higher Reynolds numbers compared to low Reynolds numbers (mostly laminar close to the nozzle exit), the mixing effect in the transitioning region is expected to be lower at higher Reynolds due to the dominance of small-scale eddies.⁵⁷

Figure 5: Normalized r.m.s of radial velocity field at various Reynolds numbers. Plots are normalized with maximum centerline axial velocity (V_m)

3.2.2. Mean temperature field

Fig. 6 shows the normalized mean temperature distribution and variation between Reynolds numbers for half of the jet from the centerline outwards in a radial direction. Here the temperature difference (ΔT) is the difference between the axial measurement point (x) and the average ambient temperature of the surrounding room air. The plots are normalized by ΔT_m which is maximum temperature difference on the jet's axis. The exit temperature cross-sectional profiles resemble a “bell-shape” and appears to be much narrow to that of the velocity field.

Figure 6: Lateral distribution of normalized mean temperature difference

Perhaps, the most significant and interesting feature of the mean temperature profiles is the wobbling effect observed as the temperature profile develop downstream. As observed in Figure 6, after $x/D = 1$ the temperature profile shows a strange shift (wobble) around $r/D = 0.46$

which slowly die out with downstream distance as it assumes an inverted “V-shape”. Further examination (see Figure 7) reveals that the relative variation of the wobbling effect appears at about $x/D = 1$, peaks at $x/D = 3$, dies out gradually after $x/D = 4$ onwards. This is assumed to be a result of a gradual increase in the mixing effect on the sheer layers of the core region, which consequently increases the rate of heat transfer into the thermal core region resulting in its gradual disintegration (at about $x/D = 4$). Figure 7 illustrates the wobbling effect between the exit and $x/D = 5$ for Re 6537 (similar behavior was observed for other Reynolds numbers). Lower Reynolds numbers (Re 2541 and Re 4629) had slightly wider sweeps which may be attributed to increased mixing effect due to engulfment.⁶¹

Figure 7: Cross-sectional temperature profile at Re 6537 highlighting mixing effect attributed to shear stress on layers of thermal core region

A contour plot of the normalized temperature difference in Figure 8 illustrates the increased mixing (distinct temperature gradient) on the sheer layers of the thermal core region. From this representation, the thermal core region is sustained to about $x/D = 4$, except for Re 12026 which occurs at $x/D = 4.5$. Additionally, qualitative information can be obtained on the dilution of the jet into the ambient with downstream distance. As seen, the penetration of the initial temperature conditions is higher and wider with increase in Reynolds numbers except for Re

2541 and 4629 which appear to be similar. This suggests that at higher Reynolds numbers the jet has a wider and increased delivery of supply conditions further downstream, which is consistent with the mean velocity field in Figure 4. Similarly, Khalifa et al ³⁷ found that a higher primary nozzle flow improved significantly the delivery of supply conditions and consequently the proposed air quality index therein.

Figure 8: Contour plots of cross-sectional temperature profile showing mixing effect on shear layers of thermal core region

The statistical analysis of the r.m.s of the temperature shows peaks along the axis stemming from the nozzle lips (which can be attributed to the shear layer) but appear flat in inner regions of the jet suggestive of the potential thermal core region, see Figure 9. A distinct difference of the r.m.s profiles between the velocity and temperature fields is that the velocity field has lower fluctuations at low Reynolds numbers (2541 and 4629) which slowly increase and overtakes the higher Reynolds numbers after $x/D = 4$. As shown, a slight difference appears between x/D

= 4 and $x/D = 7$ that shows that fluctuations reduced with increase in Reynolds numbers. The increase in fluctuations (for low Reynolds numbers) between this axial range can be explained by the self-induction, vortex stretching and reconnection dominating the mixing effect of the jet.³ In all cases, the general direction of the scalar results also indicate that for the considered experimental conditions, the flow structure will have a high influence on entrainment.

Figure 9: Lateral distribution of radial r.m.s temperature fluctuations

Most of the studies on entrainment with temperature as tracer have either only concentrated on centerline conditions or have focused on the far field and did not examine cross sectional profiles close to the nozzle at low Reynolds numbers, see review of Mi et al.⁷ This makes it difficult to compare findings especially that available data is for high Reynolds numbers or high temperature differences between the jet and the ambient.^{4,27} These test conditions are more representative of industrial applications as opposed to building ventilation systems. Therefore, we rely on knowledge of jet characteristics with velocity measurement to explain the results herein, for example that the wobbling effect is due to the influence of sheer stresses introduced by the radial and axial components of air movements. In this regard, further investigation is

recommended both to verify the observations herein and to determine whether the results are general and can stand for other nozzle configurations investigated for air distribution in delivery capacity systems.^{38,45,62}

3.2.3. Centerline characteristics

Figure 10 shows the centerline characteristics with respect to the mean velocity decay (A), r.m.s of the radial velocity component (B), the normalized centerline temperature difference (C) and the respective centerline r.m.s temperature fluctuations (D). An important feature in both the velocity and temperature fields show a common trend in the characteristic behavior of centerline in relation to the Reynolds numbers. For example, in both mean flow fields, increase in Reynolds numbers reduced the centerline decay rate (10A and 10C), even though the observed difference is small across the considered cases for the velocity field. This observation is supported by the r.m.s fluctuations (Figure 10B and 10D) which show that lower Reynolds numbers had higher fluctuations with peaks occurring at about $x/D = 5.5$ (Figure 10B) and about $x/D = 5$ (Figure 10D).

Figure 10: Centerline characteristics of velocity (left) and temperature (right) fields: (A) centerline velocity decay; (B) r.m.s of radial velocity component; (C) distribution curves for centerline temperature difference; (D) r.m.s fluctuations for centerline temperature

The profiles in Figure 10 illustrates the influence of increase in momentum mixing at the end of the potential core especially on flow structures with large-scale eddies, see also results from Russ and Strykowski.⁶³ Large scale eddies entrain large amounts of ambient fluid which result in a rapid drop in the centerline temperature difference as observed in lower Reynolds numbers. In contrast, flow structures at higher Reynolds numbers (turbulent exit boundary layers) with flow structures dominated by smaller eddies had much less pronounced mixing and consequently less temperature decay on the jet centerline.

In both the velocity and temperature field, the results suggest that the influence of entrainment on the centerline velocity and temperature in the considered axial region increases with reduction in Reynolds number. This will have implications on air distribution as will be discussed later.

3.2.4. *The spreading rate of the jet*

Generally, the half width is used as a representation of the jet spread and is defined as the width from the jet centerline to the point where the cross-section profile drops to half its centerline value²⁶. In the current study, the half width was estimated by visually fitting a curve through the cross-sectional profiles of the mean velocity field (Figure S2 in the supporting information) and temperature plots (Figure 6). Figure 11 shows the variation of the half width between the measurement fields and across Reynolds numbers. The jet spread, as illustrated by the velocity field, reduces with increase in Reynolds numbers (except Re 9233 which has a much-reduced spread) while minimal spread differences are observed within the temperature field. Additionally, as the Reynolds number increases, the difference between the slope of the spread between the velocity and temperature field increases in favor of the temperature field. This is consistent with earlier observations^{27,29,64} of a wider spread for temperature than velocity field.

Figure 11: Plot of half width for temperature and velocity fields

According to this, the scalar field spreads much more rapidly for higher Reynolds numbers when compared to velocity field, implying that higher Reynolds numbers are expected to diffuse supply-jet concentrations slightly wider and faster. This effect at higher Reynolds numbers can be seen both as a positive and as a negative because clean air is well spread in the jet flow and at the same time it increases the likelihood of mixing clean air with contaminated room air. However, at higher Reynolds numbers the structure of the flow field as reported in this study is dominated by small eddies and generation of secondary eddies which may help to minimize the mixing interaction of the jet flow and surrounding air.

3.3. Entrainment characteristics

Entrainment was determined by integrating graphically the mean cross-sectional velocity profiles. The velocity profiles were faired to $0.1 V_0$ which was used as an arbitrary integral limit to minimize the effect of unreliable low velocities near the jet boundaries. Applying Equation 4, we obtained local mass flowrates at respective downstream points. Figure 12A shows nondimensional plot of entrainment for the considered experimental conditions in the velocity field. The influence of Reynolds numbers and axial distance on entrainment is clearly illustrated: Increasing the Reynolds number reduces entrainment, and in each case, entrainment increases with axial distance from the nozzle exit. Using the least square technique, we

determined entrainment rate to be 0.0556 for Re 2541, 0.0275 for Re 4629, 0.0278 for Re 6537, 0.0157 for Re 9233, and for Re 12026 it was nonlinear for $x/D \leq 3$ ($0.0427/Z$; where $Z = x/D$) and increased linearly after $x/D > 3$ at 0.0158. These results are much lower than those suggested by earlier researchers¹⁰ and in contrast to suggestions¹⁶ that entrainment rate increases nonlinearly in the initial region.

Figure 12B shows the nondimensional plot of temperature in relation to the ambient entraining into the jets axis based on Equation 5. Here, the overall effect of entrainment can be stated as, the larger the mass flowrate of surrounding fluid entrained into a jet, the higher the rate of change of the jet centerline temperature in relation to room ambient temperature. The entrainment rate into the jets axis increased nonlinearly and was estimated to be $0.67/Z$ for Re 2541, $0.51/Z$ for Re 4629, $0.49/Z$ for Re 6537, $0.48/Z$ for Re 9232 and $0.42/Z$ for Re 12026; $Z = x/D$. The centerline entrainment characteristics observation are in agreement with what is reported in literature.^{10,16} Assessing only the centerline entrainment characteristics (Figure 12B) shows that at about 10 diameters supply air in the jet is less than 50% clean, similar results were reported for a personalized ventilation jet.⁴¹

Figure 12: Entrainment characteristics of jet (A) based on graphical solutions of velocity fields and (B) Entrainment of temperature into jet centerline

A consistent pattern between the entrainment results on the temperature and velocity field, show that, for the setup herein, increasing the Reynolds numbers reduced the entrainment rate and

thus will likely have a less mixing effect between the jet flow and the ambient than lower Reynolds numbers. This can be related to findings by Ricou and Spalding³³ who reported that entrainment rate in near exit positions was higher for $Re < 10^4$. Likewise, Viggiano et al.²⁵ found that turbulent jets at lower Reynolds numbers exhibit higher entrainment and velocity fluctuations than experienced at $Re > 8000$ due to smaller eddies that develop along with the shear layer.

Overall, part of the entrainment results agrees with what is found in literature and others differ substantially, however the obtained results herein are important because they do not support earlier conclusions⁵ that entrainment rate is essentially independent of Reynolds number in the initial region. Thus, the influence of entrainment is an important aspect that should be considered when designing delivery capacity systems, and it should be clear how much of the supply conditions a specified nozzle will deliver at a designated point. This can be expounded on by using the concept of a mixing factor due to entrainment.

3.3.1. The entrainment mixing factor (f_{en-mix}).

A global measure of the mixing between the jet and the ambient fluid can be estimated by the mixing factor. The mixing factor due to entrainment or simply put the entrainment mixing factor (f_{en-mix}) is defined as the amount of ambient air entrained divided by the local mass flowrate at position x ⁴⁰ which is expressed as

$$f_{en-mix} = \frac{Q_e}{Q_x} = 1 - \frac{Q_0}{Q_x} \quad (6)$$

Equation 6 shows that the entrainment mixing factor is a fraction of the flow consisting of room ambient air and has a theoretical limit of 1. Hypothetically, if $Q_x = Q_0$ there is no fluid entrained into the jet flow then $f_{en-mix} = 0$. On the other hand, when $Q_0 / Q_x = 0$ then $f_{en-mix} = 1$, this means the point is fully mixed with the surrounding fluid. This would occur when there is no

exit flow ($Q_0 = 0$; no dilution) or when Q_x approaches an asymptotic value that renders Q_0 insignificant ($Q_x \gg Q_0$), likely at a point when the jet concentration equals the room ambient concentration, see section 2.5 of Sandberg et al.⁴⁰ A similar concept was introduced by Xu et al.⁴¹ to assess the percentage of clean air inhaled by occupants.

The entrainment mixing factor represents the ratio or percentage of room air mixed with the bulk jet flow at a respective point downstream. Figure 13 shows plots of the entrainment mixing factor as a function of downstream distance at different Reynolds numbers, derived from velocity measurements and based on Equation 6. The mixing factor follows the entrainment characteristics of jet flow, with high entrainment (see Figure 12A) exhibiting a high mixing factor. Likewise, there is a dependence on the Reynolds numbers with an exception of Re 12026, which has a high rate of mixing near the nozzle exit and reduces with increase in axial distance. In all cases, the axial distance is critical because the further off the nozzle exit the higher the mixing factor.

Figure 13: Entrainment mixing characteristics of jet

According to Figure 13, at a downstream distance of 8 diameters (in this setup 40 cm) $f_{en-mix} = 0.3$ for Re 2541, $f_{en-mix} = 0.13$ for Re 9233, and $f_{en-mix} = 0.19$ for both Re 6537 and 4629.

These results are a ratio (or percentage) of room air mixed into the bulk jet flow. Therefore, it

shows the growth of the contaminant concentration in the jet for a given constant distribution of ambient concentration. The nozzle used in this study can be said to have a delivery capacity of 0.7 at Re 2541 (meaning 70% of supply conditions are delivered), 0.87 for Re 9233 and about 0.81 for both Re 6537 and 4629 at 40 cm from the nozzle exit. Overall, these results support the suggestion that the asymptotic state of the flow and the mixing characteristics varies with different initial conditions.^{22,23}

An index related to ventilation effectiveness (ϵ_v) is mostly used to assess and determine the quality of delivered air.^{41,45} Figure 14 shows a plot of ventilation effectiveness of centerline temperature measurements in the transitional region, defined by the ratio $(T_0 - T_a)/(T_0 - T_x)$ where T_0 is nozzle exit centerline temperature, T_a is the average room ambient temperature and T_x is the centerline temperature at a point downstream. As shown, the ventilation effectiveness reduces with increase in downstream distance and the difference between Reynolds numbers is small. For example, at about 10 diameters (50 cm) downstream $\epsilon_v = 1.2$ (Re 2541), $\epsilon_v = 1.5$ (Re 4629), $\epsilon_v = 1.6$ (Re 6537), $\epsilon_v = 1.7$ (Re 9233) and $\epsilon_v = 1.8$ (Re 12026).

The implications of ϵ_v obtained may be hard to understand in relation to supply air delivery. A much clearer explanations would be the reciprocal of ventilation effectiveness index which gives a ratio of the concentration of entrained air into the jet flow in relation to room ambient air, see S4 in the supporting information. Additionally, comparing results of the entrainment mixing factor (involves the bulk flow) and $1/\epsilon_v$, we can deduce that the entrainment mixing factor has much lower results of entrained flow. We suggest interpreting measurements with only centerline concentrations with caution as it is not representative of the bulk flow. Studies^{37,41} have shown that concentration distribution vary in the cross-sectional profile, and thus pollution levels will equally differ. Therefore, it is suggested that the entrainment mixing

factor or delivery capacity as demonstrated herein will offer clear interpretation of diffuser delivery characteristics and performance.

Figure 14: Ventilation effectiveness

3.4. Practical implications on delivery capacity systems

Low mixing between jet flow and ambient fluid is important and desirable in delivery capacity systems that use jets to deliver fresh air to the breathing point, which may usually be a few diameters ⁴⁵ or much further ⁵⁴ from the nozzle exit conditions. As shown herein, the concentration of room ambient conditions at a point in the jet will be determined by the mixing factor and the only way to deliver more supply conditions is to reduce entrainment. In the current study, the picture of entrainment portrays practical limitations that may have serious implications on the performance of delivery systems. For example, points close to the nozzle exit will have little entrainment of room contaminants as opposed to points further downstream. Therefore, to increase the quality of delivered air (supply air with minimal entrained contaminants), diffusers need to be placed very close to occupants which is the working principle of desk and headset personalized ventilation. ³⁶ The problem here is that the spread of the jet is reduced near the nozzle exit as opposed to points further downstream and this will consequently limit beneficial supply flow within a small confined area. This implies use of much larger nozzles which may be challenging for ergonomic or aesthetic considerations. Another important point highlighted by the relationship between entrainment and axial

distance, is that applications with increased distance between occupants and diffusers, e.g. ceiling mounted personalized diffusers,⁵⁴ may be more problematic with regard to air quality as they would entrain more ambient contaminants by the time the jet flow reaches the delivery point.

The results herein showed that Reynolds number (defined by nozzle exit velocity herein) influenced flow stability (higher Reynolds numbers sustained the flow further downstream) and entrainment rate e.g., increasing the Reynolds number reduced entrainment rate of ambient conditions. The practical implication here is that delivery capacity systems will be optimal within a range of “moderate to high” Reynolds numbers which will facilitate a longer and non-oscillating jet flow downstream. Additionally, as shown herein, these Reynolds numbers will have a lower mixing factor since entrainment will be dominated by nibbling. Caution should be taken and further investigation done as supplying at these “moderate to high” Reynolds numbers and close to occupants may increase the risk of occupant thermal discomfort or problems associated with eye irritation and dry skin.^{65,66}

3.5. Limitations

The experimental setup and measurements were simplified to minimize the complexity of the study. For example, in this study we assumed a unit density ratio (ρ_{∞}/ρ_0) between the jet flow and the ambient. Practically, this is not the case as many ventilation jets and indoor air flows as well as natural jets interact under conditions of density differences, and are therefore buoyant.⁶⁷ In this study, the influence of buoyancy, inertial forces and free convection on the jets flow were not considered. We assumed that this influence would be negligible since the jet temperature was lower than the ambient, the temperature difference between the jet and the ambient was small (4 °C), and the nozzle exit velocity was strong enough to offset any induced influence. If these factors are included, the results may differ.

We should also mention that temperature measurements involved an intrusion method which may also affect the obtained results. However, we tried to design the test rig to minimize the influence of intrusion at the measurement points. Another issue of interest is that we have tried to explain the results of the temperature field by analyzing the qualitative behavior of the flow using PIV measurements. It should be noted that PIV measurements were done under isothermal conditions to minimize errors and improving the quality of measurements, while temperature was done under dynamic temperature conditions (non-isothermal). Considering the small temperature used between the jet flow and the ambient under temperature measurements, we see this difference in setups to be insignificant. Thus, we hold the comparison and explanation associated with the two setups to be valid.

A critical limitation in the current setup is that it does not consider jet flow interactions with the human thermal boundary layer. Studies have shown that the thermal boundary layer has a huge influence on the quality of inhaled air ^{41,42} and has influence on the jet flow characteristics. ⁴³ The focus of the current study was to assess ambient entrainment and system performance downstream and thus the influence and penetration of jet flow into the human thermal boundary layer was outside the scope. Additionally, the results reported herein apply to a nozzle projecting a jet vertically downwards, flow conditions may differ for horizontal jets like in desk mounted personalized systems, as such further studies are recommended for horizontal jets. Overall, the current study and its results are limited by the setups and experimental conditions used herein.

4. Conclusion

The entrainment behavior of a round free jet issuing from a round contracting nozzle under conditions pertinent for air distribution in delivery capacity systems has been studied by exploring the temperature and velocity fields. Based on the setup and results presented herein,

we conclude that entrainment characteristics are higher at low as compared to high Reynolds numbers (the Reynolds numbers are defined by nozzle exit velocities herein) and conditions closer to the diffuser have much clean air with less contamination from room air than conditions far field. The delivery capacity of the smooth contracting axisymmetric round nozzle was found to be 70% (Re 2541), 81% (Re 4629, 6537 and 12026) and 87% (Re 9233) at a delivery point of 8 diameters downstream. The practical implication is that delivery capacity systems may need to be operated with “moderate to high” Reynolds numbers to benefit from the reduced entrainment mixing factor to deliver much cleaner air. Additionally, entrainment limits the target distance at which delivery systems may be effective. We recommend further studies to explore whether the findings herein are replicable and whether they are general to different nozzle configurations.

We suggest that when doing performance testing of delivery capacity diffusers, entrainment characteristics of the resulting jet should be explored. One way could be to assess and present the entrainment mixing factor of the nozzle, because different nozzle configuration will deliver different conditions at the breathing point. Here we strongly emphasize on developing appropriate testing methods to test air distribution in delivery capacity systems, as applying traditional methods commonly used in dilution capacity systems may not accurately rate or estimate the system performance.

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PROOF

Entrainment and its Implications on Microclimate Ventilation Systems: Scaling the Velocity and Temperature Field of an Axisymmetric Free Jet.

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S1. Heat flux and the Heat Content

If a jet is discharged at a temperature different to that of the surroundings its temperature will decrease or increase as it flows downstream depending on whether the entrained fluid is colder or warmer. The heat transfer between the ambient and the jet flow at any downstream distance will depend on the entrained mass flow rate but the heat content at any respective downstream distance will be conserved across the flow. The heat flux $H(x)$ at any downstream location is given by

$$H(x) = 2\pi C_p \int_0^\infty \rho(x,r) V(x,r) T(r,x) r dr \quad (S 1)$$

and the heat content, $h(x)$, defined by

$$h(x) = 2\pi C_p \int_0^\infty \rho(r,x) T(r,x) r dr \quad (S 2)$$

In Equation S 1 and 2, T is the temperature and C_p is the specific heat capacity of the fluid. Using Equation S 1, we can estimate the heat transfer due to entrainment into the jet flow by

$$H_e = H_x - H_0 \quad (S 3)$$

or defined dimensionless as

$$\psi_h = \frac{H_e}{H_0} = \left(\frac{H_x}{H_0} \right) - 1 \quad (\text{S } 4)$$

In Equation S 3 and S 4, H_e is the entrained heat flow between point x and the nozzle exit, H_x and H_0 are corresponding heat fluxes at x and the nozzle exit, respectively.

One of the challenges with using heat flux to estimate entrainment and consequently the mixing factor is that the method is sensitive to the influence of buoyancy, inertial forces and free convection on the jet flow. Thus, accurate measurements of density, velocity and temperature across the jet flow is needed. This increases the complexity of the measurements.

In the current analysis, we estimated the heat content by integrating graphically the mean cross-sectional temperature profiles across the jet flow. The mean temperature profiles were not faired to any arbitrary integral limit unlike the velocity profiles. Figure S1 shows the calculated values of the heat content. Like the vector field in which momentum is constant across the flow ¹, the obtained plot of the heat content ratio (normalized with the exit value) infer that the heat content, as defined herein, likewise is conserved at consecutive cross-sections across the jet flow.

Figure S1: Normalized plot of the heat content across the Reynolds numbers at different downstream distances.

S2. Mean velocity field.

A quantitative characterization of the velocity profiles are presented in Figure S2 and, as observed, in all cases a top-hat profile typical of free round jets²⁻⁴ was obtained. The exit top-hat velocity profiles diffused out gradually to a Gaussian profile within the first 4 diameters⁵. As observed, after the zone of flow establishment, the Reynolds number dependence manifests at about 6 to 8 diameters which may be deduced as part of a critical transitional region where the jet changes from laminar to turbulent flow.

Figure S2: Development of the cross-sectional velocity profile with respect to downstream distance at various Reynolds numbers.

S3. The r.m.s of the radial velocity field

Figure S3 show the lateral distribution of the r.m.s fluctuations of the radial velocity field. At exit, the profile is U-shaped with peaks occurring around the points stemming from the nozzle lips, indicating the existence of a shear layer or vorticity layer at the nozzle exit. Increase in streamwise distance diminishes the flat profile (potential core) and the observed hump on the nozzle lips is larger for higher Reynolds numbers until after $2D$ when the fluctuations increase with little distinguishable differences across Reynolds numbers. After $4D$ the fluctuations are lower for higher Reynolds numbers as compared to lower Reynolds numbers.

Figure S3: Lateral distribution of the r.m.s fluctuations of the radial velocity component.

S4 Ventilation effectiveness

Ventilation effectiveness index is widely used to assess the performance of delivery capacity systems i.e., personalized ventilation. Usually, researchers use concentration measurements of a tracer along the jet centerline to determine the index based on the relationship

$$\varepsilon_v = \frac{C_n - C_{ex}}{C_n - C_x} \quad (\text{S } 5)$$

in which C_n is the concentration of a tracer at the nozzle exit, C_{ex} is the concentration in the exhaust which hypothetically should be equal to the mean ambient concentration relative to the jet flow, and C_x is the concentration in the jet flow measured at point x . The divisor in Equation S 5 represents the change in concentration due to entrainment in the jet flow while the numerator is the mean ambient concentration in the room. Assuming a high dosage of contaminant concentration is in the room and clean air is supplied in the jet flow, typical of ventilation system scenarios, the reciprocal of the Equation S 5 gives the ratio of ambient contaminants present in the jet flow at a respective point. Figure S4 shows plots of ventilation effectiveness index against the axial distance and Figure S5 demonstrates a plot of the reciprocal of ventilation effectiveness to represent the ratio of entrained room air concentrations present in the jet flow.

Figure S4: Ventilation effectiveness index against the axial distance

Figure S5: The reciprocal of ventilation effectiveness against the axial distance

The values of ventilation effectiveness obtained in the core region are high especially just after the exit as the concentration of the flow is the same. Comprehending ventilation effectiveness and its implications on supply air delivery is ambiguous as opposed to its reciprocal (which as defined earlier is the ratio of ambient contaminants entrained into the jet flow). As shown (Figure 5S), in most cases herein and about 8 diameters (40 cm) downstream the concentration of ambient air entrained $\leq 50\%$.⁶ Comparing this to the mixing factor (involves the bulk flow), we can deduce that using only the centerline measurements as representative values of bulk flow entrainment may overestimate entrainment of delivery diffusers.

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