NUMERICAL STUDY OF CIRCULAR JET DIFFUSER FOR TASK VENTILATION OF UNDER-FLOOR AIR SUPPLY SYSTEM IN TROPICS

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ABSTRACT

Bases on the concept of task/ambient ventilation, fresh air can be decoupled from re-circulated air so as to improving ventilation effectiveness in breathing zone. Ceiling mounted high velocity circular jet diffusers, which are regarded as remote personalized ventilation air terminal devices (PV ATDs) without affecting room aesthetic effects, can be utilized to supply fresh air without causing draft rating because tropically acclimatized occupants prefer slightly higher air movement. Under-floor air diffusers are used to supply re-circulated air. Corresponding mixing ventilation system by only utilizing under-floor air diffusers are compared with this task/ambient ventilation system. Numerical simulation using a validated computational fluid dynamics (CFD) model for circular jet diffusers is conducted to investigate the difference between task/ambient ventilation systems and mixing ventilation systems. Location weighted personal exposure effectiveness is utilized as an evaluation index for evaluating indoor air quality (IAQ). Air velocity and temperature are utilized as evaluation indices for evaluating thermal comfort level.

KEYWORDS

Task/ambient ventilation, Circular jet diffuser, Mixing Ventilation, Under-floor air supply

INTRODUCTION

Indoor air quality (IAQ) and thermal comfort become the most important characteristics of indoor environment because people spend more than 90% time indoors. The criterion for evaluating a mechanical ventilation and air conditioning system is whether it can provide a comfortable and healthy indoor environment for the occupants in an energy efficient manner. Mixing ventilation and task/ambient ventilation are the two main ventilation strategies for ventilation system.

For mixing ventilation, it can be categorized into normal ceiling supply mixing ventilation (MV), displacement ventilation (DV) and under-floor supply mixing ventilation (UV). The main feature of MV is the dilution of the air. The cool, clean air is forced into indoor space and mixed with old indoor air. The aim is to make the mixed air have good quality in the shortest time. However, the existence of the air exhaust implies a portion of outdoor air is wasted and if the indoor inducement is introduced, the involved system equipments must deal with a lot of air which has been disposed. DV discharges air at relatively low velocity near the floor. The supplied cool and clean air, which is 3-4° C lower than the old indoor air temperature, spreads and, because of its low temperature and high density, forms a pool of conditioned air over the floor. When this air meets a heat source, a convective thermal plume is generated due to the temperature difference and resultant buoyant force, which acts as a channel through which the warm and polluted air moves. The stratification, upper level (warm and polluted) and lower level (cool and clean), is the most obvious characteristics in DV. As a result, IAQ in occupied zone can be efficiently controlled. UV distributes air directly to the occupied zone that is substantially closer to the occupants. The supply air velocity is slightly higher than that of DV. Ventilation efficiency at breathing zone is improved especially for rooms with partitioned furniture, whereas MV may lead to poor air circulation at partitioned areas. Supply air temperature of at least 17° C is required to avoid draft and room air is often re-circulated into under-floor plenum to attain this temperature. For all these mixing ventilation systems, it is difficult to make full use of outdoor air to dilute indoor pollutants, such as carbon dioxide, in breathing zone because of pre-mixing of outdoor air and a re-circulated air in variable air volume (VAV) box of each zone.

Task/ambient ventilation is a method of providing occupants with control over a local supply of air so that they can adjust their individual thermal environment and air quality. The task/ambient ventilation system providing 100% outdoor air to the breathing zone of the occupants is termed as personalized ventilation (PV) system (Fanger 2000). Clean, cool and dry outdoor air, termed as personalized air, is served into breathing zone directly by extended PV air ducts. The majority of PV-related studies, especially those with human subjects involved, were conducted in temperate climate. Few similar studies in tropics show that tropically acclimatized occupants prefer cool and high local air movement, which suggests that air movement might be an important and positive factor in improving both air quality and thermal comfort in tropics (Sekhar et. al. 2003, Sekhar et. al. 2003, Tham et. al. 2004, Tham et. al. 2004, Sekhar et. al. 2005). After that, objective measurements of three PV ATDs, which include high turbulence circular perforated panel (High-Tu CPP), low turbulence circular perforated panel (Low-Tu CPP) and desk mounted grill (DMG), have been conducted by using breathing thermal manikin in tropics (Zhou 2005). Corresponding subjective responses of two of these three PV ATDs, High-Tu ATD and Low-Tu ATD, have been conducted by using tropically acclimatized subjects (Gong 2006). In order to avoid affecting aesthetic effects by extended PV air ducts, ceiling mounted circular jet diffusers, which can be regarded as remote PV ATDs, are utilized for task ventilation and corresponding higher PV air velocities are kept. More fresh air can be supplied into breathing zone in an energy efficient manner without causing draft rating (Yang and Sekhar 2007). As a result, ceiling mounted circular jet diffuser has potential to be task ventilation ATD and accompanied with MV, DV or UV as ambient ventilation system.

In recent years, ventilation strategy studies have been conducted with the aid of computational fluid dynamics (CFD) tools. Nielsen was one of the pioneers in using CFD methods to predict air movement and heat transfer in buildings (Nielsen 1974). CFD has been used to model different size of enclosures, different air change rate, intake and exhaust location, human bodies and office furniture. Some successful cases show the feasibility of CFD simulation. Awbi and Gan used CFD modeling to conduct predictions of air movement in a mechanically ventilated office module and a naturally ventilated office and obtained accurate results (Awbi and Gan 1994). Different ventilation strategies, which include MV, DV, UV and PV, were widely simulated. Cheong et al used CFD to predict airflow pattern in an air-conditioned seminar room in tropics and also got close results compared with experimental results (Cheong et. at. 1999). A computational model for ceiling mounted circular jet diffuser based on commercial CFD program was developed and tested using experimental data (Yang and Sekhar 2007). Some conclusions that CFD codes can be applied successfully to building airflow prediction but must be carried out with care and sound engineering judgment are given (Jones and Whittle 1992) and some uncertainties involved in CFD are highlighted (Chen 1997).

This paper attempts to compare and evaluate mixing ventilation strategy and Task/ambient ventilation strategy numerically. There are 4 cases in the comparison, (1)MV, (2)MV with jet diffusers, (3)UV, (4)UV with jet diffusers. The study is based on a field environment chamber (FEC) of the National University of Singapore. Commercial software FLUENT is used to simulate air velocity, temperature and fresh air percentage in flow field.

METHODS

Physical model and boundary conditions

Table 1 Geometry and boundary conditions

Entities	Dimensions(m)	Flow BC	Thermal BC	Species BC (FA percentage)
FEC	10×7×2.7			
Interior wall		Non-slip	adiabatic	
ceiling		Non-slip	adiabatic	
floor		Non-slip	adiabatic	
exterior wall		Non-slip	T=303K	
exterior window		Non-slip	T=303K	
Occupants		Non-slip	110W×8	
Lamps	0.6×0.6×0.1	Non-slip	54W×22	
Computers	0.4×0.4×0.4	Non-slip	110W×8	
MV-Jet				
MV diffusers	0.6×0.6	Velocity inlet y=-0.34m/s z=0.58m/s x=0.58m/s y=-0.34m/s y=-0.34m/s z=-0.58m/s x=-0.58m/s y=-0.34m/s	T=293K	0
Jet diffusers	D=0.04	Velocity inlet v=5m/s (Normal to boundary)	T=293K	1
UV-Jet				
UV diffusers	D=0.21, d=0.11	Velocity inlet v=0.54m/s (Normal to boundary)	T=293K	0
Jet diffusers	D=0.04	Velocity inlet v=5m/s (Normal to boundary)	T=293K	1

Total air flow rate=1800m^3/h, Fresh air flow rate=180m^3/h (6.25l/s.person)

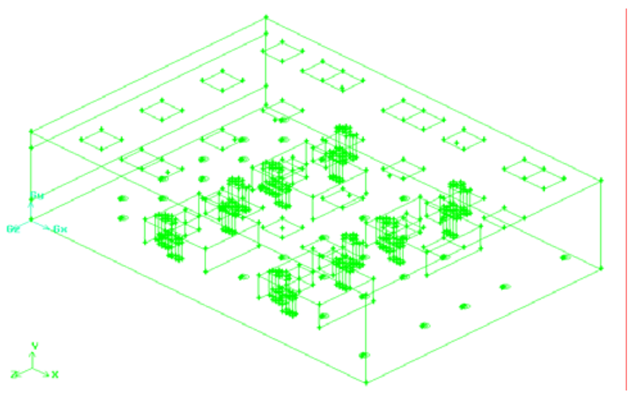

Figure 1 Geometry of UV with jet diffusers

Based on the FEC, three dimensional physical models were created. The dimensions of FEC are 10

× 7 × 2.7m^3. 8 workstations were allocated to simulate typical public office. 6 ceiling mounted square four-way diffusers or 33 under-floor diffusers are used to supply ambient air for MV or UV. 8 ceiling mounted circular jet diffusers are used to supply task outdoor air for 8 workstations respectively. 6 ceiling mounted return air grilles are used to circulate indoor air. The thermal boundary conditions of each wall except one exterior wall are adiabatic, including ceiling and ground. The thermal boundary conditions of exterior wall and exterior window are given as certain fixed temperatures. Because the occupants, lamps and other entities in the FEC have relatively complex shapes, some simplifications of different entities are made. Human bodies are simplified to be cuboids, whose dimensions are similar to that of seated people. The lamps, computers and furniture are also simplified to be cuboids. Tables are regarded as thin surfaces without thickness, whose thickness is defined in FLUENT later. The entities in office are also the heat sources.

Numerical method

It is assumed that the flow is three dimensional, steady state, turbulent, Newtonian and incompressible with constant physical properties. Forced convection is the main flow type and, at the same time, the effect of natural convection is also taken into consideration. Finite volume method is used to transfer partial differential equations to difference equations. Semi-implicit pressure linked method (SIMPLE) is used to solve pressure and velocity coupled problem. Boussinesq assumption is taken into consideration to simulate buoyancy effect. Renormalization (RNG) k- ε turbulent model is used. Species model is activated to simulate outdoor air percentage in the flow field.

Grid and converge criteria

The whole space of FEC, created by occupants, computers and other entities, forms to be an irregular volume. As a result, the direct meshing to such domain is much too difficult. As a result, non-uniform grids are applied and the grid is fine near solid wall, air inlet and outlet. The typical total grid number is about 2 to 3 million cells with the first grid size at 0.03 to wall, which is fine enough to obtain mesh-independent solution (Zhai and Chen 2004). The converged solution is obtained when the following criteria are satisfied for dependant variables:

$$\left|\frac{\phi^{i+1}-\phi^{i}}{\phi^{i}}\right| \le 10^{-3}; \phi = U,V,W,k,\varepsilon,C \qquad (1)$$

$$\left|\frac{\phi^{i+1}-\phi^{i}}{\phi^{i}}\right| \le 10^{-6}; \phi = T \qquad (2)$$

Simulated quantities

By utilizing experiment method, tracer gas sulfur hexafluoride (SF_6) is dosed into re-circulated air duct and the concentration of SF_6 in PV ATD, inhaled point and return air grill is measured to calculate personal exposure effectiveness (Melikov et. al. 2002).

$$\varepsilon_p = \frac{C_{R,SF6} - C_{I,SF6}}{C_{R,SF6} - C_{PV,SF6}} \qquad (3)$$

Based on the simulation results, outdoor air percentage near human mouth, jet diffuser and return air grill is obtained to calculate simulation based personal exposure effectiveness for each occupant approximately because respiration flow is not simulated. The expression of the formula is as follows.

$$\varepsilon_{pi} = \frac{P_{R,RA} - P_{I,RA}}{P_{R,RA} - P_{jet,RA}} = \frac{P_{I,FA} - P_{R,FA}}{P_{jet,FA} - P_{R,FA}} \qquad (4)$$

Evaluation index

The main purpose of using circular jet diffusers as task ventilation is to supply more outdoor air into breathing zones. Several indices, including ventilation effectiveness, pollutant removal efficiency, personal exposure index and personal exposure effectiveness (Melikov et. al. 2002), can be used to describe the ventilation ability quantitatively. For this ceiling mounted circular jet diffusers which are regarded as remote PV ATD, flow field changes not only in breathing zone but in the whole field. For MV jet system, coanda effect is also affected by the jet flow. As a result, the location of circular jet diffusers and ambient air diffusers influence the air flow so as to affecting personal exposure effectiveness. One new index which is called location weighted personal exposure effectiveness will be used as evaluation index for evaluating air quality in breathing zones. The expression of it is as follows.

$$\bar{\varepsilon}_p = \sum_{i=1}^{n} \varepsilon_{pi} / n \qquad (5)$$

Temperature and velocity distributions are mainly utilized to analyze the thermal comfort level.

RESULTS

Velocity distribution

1800 m^3/h of total volume air, which has 10% fresh air, is supplied into FEC for all these 4 cases. The difference between cases with jet diffusers or not is whether 10% outdoor air is supplied by jet diffusers separately or mixed with re-circulated air and supplied together. For cases with jet diffusers, 10% outdoor air is supplied by jet diffusers at mean discharge velocity 5m/s. One of the surface (x=6.6m) is chosen to show the velocity field. The core regions of jet flow can be extended to breathing zone without inducing much re-circulated air for the cases with jet diffusers. For MV jet case, coanda effect is affected because of the intervening distribution of square 4-way diffusers and jet diffusers. For UV jet case, the core region of jet flow becomes shorter than that of MV jet case because of the opposite flow directions of jet flow and underfloor air supply. For all the cases with jet diffusers, the air velocity in breathing zone is 0.2-0.4 m/s, which has reached or exceeded the threshold value (0.25m/s) of causing draft rating. According to previous research results (Sekhar et. al. 2003, Sekhar et. al. 2003, Tham et. al. 2004, Tham et. al. 2004, Sekhar et. al. 2005), air movement is an important and positive factor in improving thermal comfort for tropically acclimatized occupants.

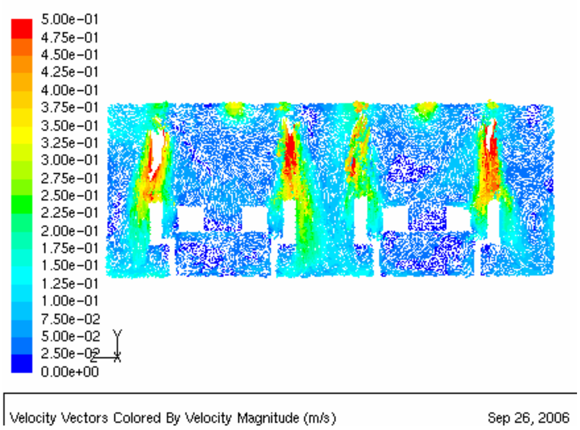

Figure 2 Velocity distribution for MV jet (x=6.6m)

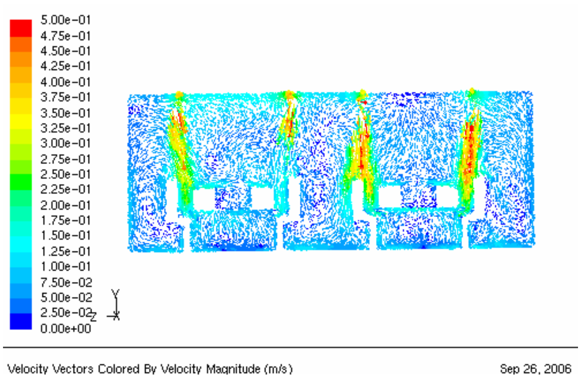

Figure 3 Velocity distribution for UV jet (x=6.6m)

Temperature distribution

The supply air temperature of jet diffusers, square 4 way diffusers and DV cylinders is 20 ° C. Room air temperature is kept at 24 ° C averagely for all 4 cases. For MV jet case, air temperature at breathing zone is slightly higher than that of UV jet case because the supply air cools down the upper space of FEC first.

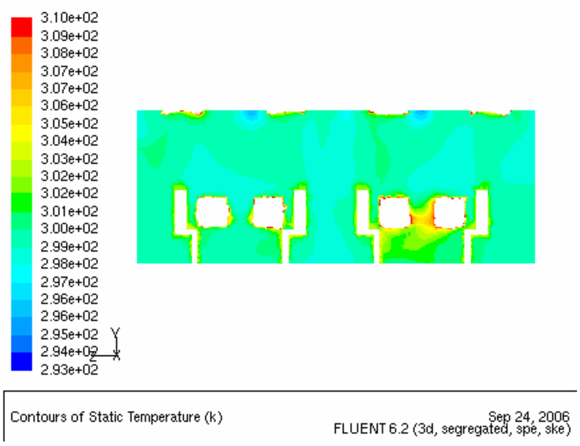

Figure 4 Temperature distribution for MV jet (x=6.6m)

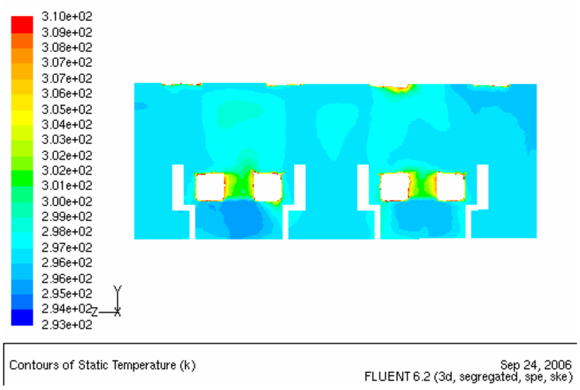

Figure 5 Temperature distribution for UV jet (x=6.6m)

Personal exposure effectiveness

For MV and UV cases, outdoor air and re-circulated air are fully mixed before supply. As a result, the outdoor air percentage is almost the same (10%) in all flow fields. From Figure 6 and Figure 7, outdoor air percentage increases twice in breathing zone for both MV jet case and UV jet case. The core region of jet flow can be kept to breathing zone without inducing much re-circulated air so as to improve the outdoor air percentage in breathing zone. The interaction between jet flow and other flows become obvious because of the long distance between jet diffuser and breathing zone. As a result, location weighted personal exposure effectiveness (Table 2) is utilized to evaluate the average effects of inhaled air quality for each person. The range of personalized exposure effectiveness is from 0 to 1. For MV and UV cases, it almost equals to 0 because of fully mixed outdoor air and re-circulated air. Higher the value of personalized exposure effectiveness is, the more outdoor air can be supplied into breathing zone. The value of personalized exposure effectiveness for jet diffuser is lower than that for normal PV (Melikov et. al. 2002) because of long distance between jet outlet and breathing zone. Many factors, which include locations of jet diffusers, other diffusers, return air grills and workstations, will affect the result.

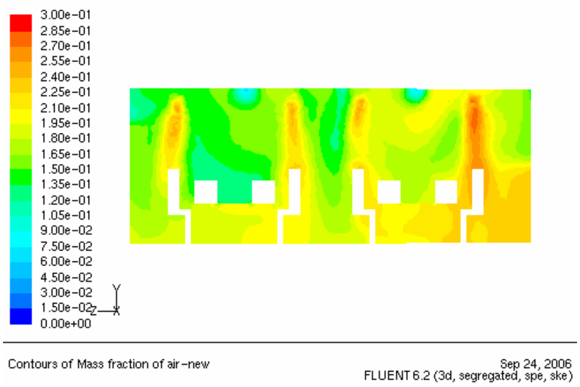

Figure 6 Fresh air percentage distribution for MV jet (x=6.6m)

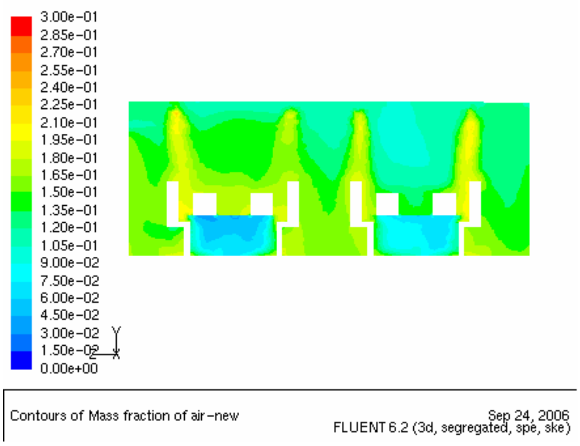

Figure 7 Fresh air percentage distribution for UV jet (x=6.6m)

	MV jet		UV jet	
	FA percentage	ε pi	FA percentage	ε pi
A	0.215	0.127778	0.173	0.081111
B	0.204	0.115556	0.128	0.031111
C	0.258	0.175556	0.166	0.073333
D	0.246	0.162222	0.123	0.025556
E	0.251	0.167778	0.206	0.117778
F	0.203	0.114444	0.158	0.064444
G	0.219	0.132222	0.186	0.095556
H	0.135	0.038889	0.197	0.107778
Average	0.216375	0.129306	0.167125	0.074583

Table 2 Location weighted personal exposure effectiveness

CONCLUSION

Ceiling mounted circular jet diffusers can be utilized as a kind of remote PV ATDs without influencing room esthetical effects.

Slightly elevated air velocity in breathing zone will be a positive factor for improving thermal comfort for tropically acclimatized occupants.

Coanda effect is affected by jet flow because of intervening distribution of jet diffusers and square 4 way diffusers for MV jet case.

Underfloor air supply has some offset effects for jet flow because of opposite flow directions.

MV jet case has slightly higher temperature in breathing zone because supply air for thermal load cools down upper space of FEC first.

A new method, based on simulation results, is utilized to calculate the value of location weighted personal exposure effectiveness.

The value of personalized exposure effectiveness for jet diffuser is lower than that for normal PV because of long distance between jet outlet and breathing zone.

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NOMENCLATURE

C outdoor air concentration

k turbulent kinetic energy

$P_{I,OA}$ outdoor air percentage in inhaled air

$P_{I,RA}$ re-circulated air percentage in inhaled air

$P_{jet,OA}$ outdoor air percentage in jet diffuser

$P_{jet,RA}$ re-circulated air percentage in jet diffuser

$P_{R,OA}$ outdoor air percentage in return air grill

$P_{R,RA}$ re-circulated air percentage in return air grill

T temperature

U x direction velocity component

V y direction velocity componen

W z direction velocity component

ϕ wildcard character

ε dissipation of turbulent kinetic energy

ε_{pi} personal exposure effectiveness

$\bar{\varepsilon}_p$ location weighted personal exposure effectiveness

n number of measuring points.