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Personalized Ventilation System Modelling for a Metabolic-variant Manikin in an Asymmetrical Building Environment

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ABSTRACT

The computational stencil for the design of personalized ventilation system (PVS) is developed, especially for a metabolic-variant manikin in a built environment. The asymmetric space within the 2001 campus cafeteria is simulated using a two-dimensional finite volume formulation. Within the fairly ventilated cafeteria, the kitchen space is adjacent to the customers sitting area where unsatisfactory thermal conditions from the kitchen induces thermal discomfort to customers. Combination of the existing ventilation system and a thermal personalized ventilation system is proposed to create thermal satisfaction for occupants close to kitchen area. Using the existing experimental data, the performance of a thermal personalized ventilation system in a 2.7m x 2.6m space with outlet vent dimension of 0.2m is investigated. Parametric studies of the different comfort zones with variations in outlet vents are undertaken. The predicted results enable the identification of the discomfort zone and provide useful information for the design of a personalized ventilation system. It is anticipated that a performance analysis of the variation in metabolic activities of the manikin and the vents within the built environment will enhance the design of an optimal ventilation system.

Keywords: *thermal environment; computational fluid dynamics; personalized ventilation system; thermal sensation*

1 Introduction

Quest for suitable ventilation system for a sustainable human habitation has driven research advances in the field of thermal environment in buildings. The design of shelters and ventilation devices for the satisfaction of thermal comfort is often based on subjective combination of the variance in human physiological conditions and the dynamic metabolic activities. Personalized ventilation system (PVS) extends the possibilities of a controlled ventilation, based on subjective variation in occupant's physiological conditions and the dynamic metabolic

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activities. Rather than the analog setting of the level of space ventilation in the building, the rate of metabolic activity of occupants controls the quality of building ventilation, leading to an improvement in the degree of freedom in the selection of thermal comfort. With an increased metabolic activity within a built environment, demand for improved ventilation increases beyond the level of supply from conventional building ventilation system. Whereas, the quality of ventilation within a space represents an essential requirement for environmental comfort and productivity. Wyon [1] reported that productivity drops as much as 30%, if the temperature in the space increases by 10°F (5.5°C) above the comfort level.

The effect of global warming on the design of large glazing facades represents additional challenge in the art of architectural design, including the replacement of conventional lighting system with the natural lighting of the building space; and the accommodation of creative and entertainment rooms for modern work and living lifestyles. The solely use of the conventional heating ventilation and air conditioning (HVAC) systems in most building space provide uniform temperature and indoor air quality. Uniform mixing of the indoor space entails the use of mixed or displacement ventilation techniques, with the aim of maintaining the entire space at a fixed air temperature, regardless of space occupation. However, thermal tension is created with these systems in highly glazed spaces, which fails to satisfy thermal comfort needs. For instance, a person sitting near a window could feel warm and prefer a lower thermostat temperature. Whereas, another occupant sitting away from the window may feel cool and desire a higher thermostat temperature, leading to a conflict of thermal preferences [2]. Moreover, mixing ventilation techniques require higher energy consumption in order to deliver conducive air to a partially occupied open space with uniform temperature and homogenous indoor air quality. The 2001 Campus Cafeteria of the University of Lagos, with the kitchen and service area within the asymmetrical environment, provide ventilation through ceiling fans and extractors. The environment presents a casual dining experience, unlike other operational restaurant performance experiences. This environment is similar to the quick service restaurant (QSR) and institutional restaurant [3]. Therefore, the study of the indoor environment in commercial kitchens is imperative, in order to establish standardized methods and procedures.

Personalized ventilation system (PVS) allows occupants to control their own microclimate, by varying the flow rate on demand. The PVS ensures that there is a balance between the internal conditions of the occupant and the external conditions, giving rise to thermal neutrality. Thermal neutrality for a person is defined as a condition in which he prefers neither a higher nor a lower ambient temperature level. Thermal neutrality represents a necessary condition for a person to attain thermal comfort. However, a sufficient requirement ensures that no local warm or cool discomfort is experienced on any part of the body.

Fanger *et al.* [4] conducted an experimental investigation of the limits of asymmetric radiation on a man, under exposure without thermal discomfort. Antoun *et al.* [2] performed a related study in which a glazed wall affected the atmosphere of a space occupied by a human body. A coaxial PVS was used to investigate the thermal comfort of an occupant subjected to radiation symmetry caused by the glazed wall. It was observed that high performance windows can reduce thermal discomfort through a reduction in the effect of radiation asymmetry and the presence of PVS. In a related development, the influence of the dispersion of indoor pollutants in the case of two open windows with cross ventilation was studied by Sapkota *et al.* [5].The study explored the fluid flow profile, temperature profile by solving the Navier-Stokes equations in order to analyze velocity profile and temperature distribution throughout different sections of the kitchen. Based on the parametric study of different parameters, such as inlet velocity, number and the position of ventilation, proper positioning of the ventilation with minimum impact of pollutant to the person working in the kitchen was determined. Tsikaloudaki *et al* [6] studied the cooling energy performance of windows with respect to their thermal and optical characteristics. Hwang and Shu [7] evaluated the effect of different types of glass building envelope on both thermal comfort and energy saving potential. Similarly, Cappelletti *et al.* [8] evaluated the energy glazing performance by maintaining fixed comfort conditions and calculating the predicted mean vote (PMV), while considering the effect of the solar radiation. In addition, Huizenga *et al*. [9] assessed the window performance on human thermal comfort for different fenestration systems (i.e., the various combinations of solar heat gain coefficient, U-value, solar transmittance, window areas and frames, view factors and incident radiation.

Unlike in the previous studies, this paper investigates the influence of a variation in human metabolic rate on the level of thermal discomfort. The criteria for the design of a suitable personalized ventilation system (PVS) for a metabolic-variant manikin is proposed. Using a box creation methodology, with a two-dimensional finite volume formulation, for the domain discretization of a space-variant manikin in an asymmetrical environment, a step-by-step procedure for the design of a PVS for the 2001 cafeteria at the University of Lagos is outlined. The objective of the study is the presentation of suitable box creation methodology for the imposition of metabolic-variant boundary conditions on a space-variant manikin in asymmetrical environment, towards the design of a reliable PVS.

2 Discretization of the Asymmetrical Environment

Figure 1 shows the 2001 Campus Cafeteria at the University of Lagos, where main hall represents an asymmetrical environment. The asymmetrical environment comprises of a two-dimensional space with the top, left, right, and bottom boundaries carrying the air inlet, air outlet, kitchen area and floor area respectively (see Figure 2). The environment parameters for temperature around the body were imposed by boundary conditions around the body (see Table 1). The governing equations for the building simulation are:

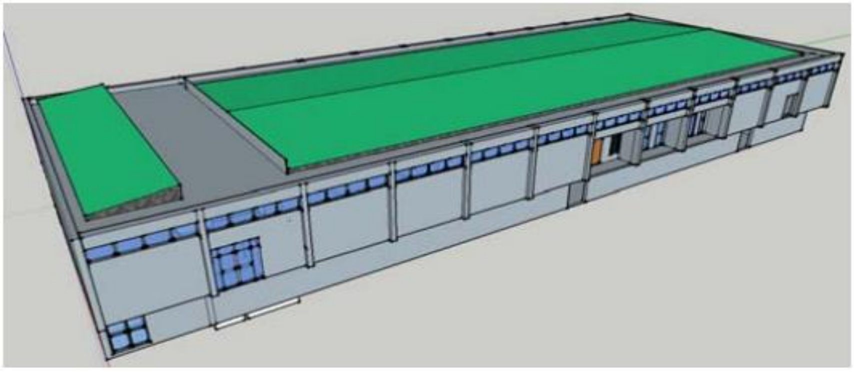


Figure 1: The 2001 Campus Cafeteria at the University of Lagos

Continuity Equation:

$$\frac{\partial(\rho)}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (1)$$

X-momentum Equation:

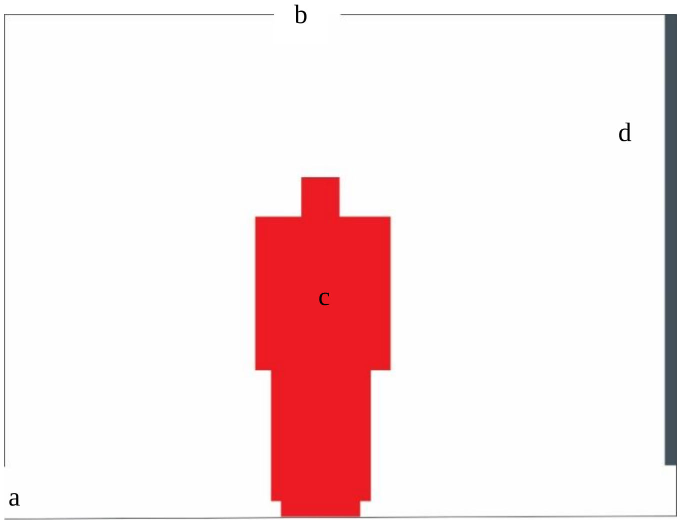
$$\frac{\partial(\rho U)}{\partial t} + \rho\left\{u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right\} = -\frac{\partial P}{\partial x} + \mu\left\{\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right\} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.\dots\dots. (2)$$

Y–momentum Equation:

$$\frac{\partial(\rho V)}{\partial t} + \rho\left\{u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right\} = -\frac{\partial P}{\partial y} + \mu\left\{\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right\} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

Energy Equation:

$$\frac{\partial(\rho C_p T)}{\partial t} + C_p T\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{\partial P}{\partial t} + k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + Q \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$



a = Air outlet
b = Air inlet
c = Occupant
d = Kitchen Area

Figure 2: Schematic Diagram of the Eatery within the Asymmetrical Environment

Equation (1) represents the continuity equation that allows accounting for the density variation inside the space and mass conservation. Equations (2) and (3) indicate the momentum transport equations for the modeling of the flow dynamics in the computational domain. These relate the inertia term on the left-hand-side to the pressure gradient and the shear stress term. Equation (4) represents the energy equation that relates the convective heat transfer on the left-hand-side to the energy transfer due to conduction and the energy source term (Q) for internal energy generated by the body in the space. Table 1 shows the Macro boundary conditions imposed on the outer computational domain.

Table 1: Macro Boundary Conditions Imposed on the Computational Domain

Inlet	Newman Boundary and Uniform (T_{air} and U_{air})
Outlet	Dirichlet Boundary (T and U)
Walls and Ceiling	All are adiabatic except inlet and outlet vents
Kitchen	Uniform and constant temperature
Occupant	Constant heat flux

The kitchen environment presents different thermal conditions than those studied in office or residential building environment, as typified by the composition in the schematic diagram shown in Figure 2. The two-dimensional model appears adequate because of the relatively longer length of the cafeteria, compared to the orientation of the wall along the width and breadth directions. Table 2 presents the data of metabolic rate for basic activities as documented in ISO 8996:2004 and Table 3 presents the data collection from the experimental work of Simone and Olesen [10] in four (4) Danish commercial kitchens. The temperature and relative humidity for the different types of kitchen were recorded during different time of the working day and during high working activity demand. The procedure for evaluating the indoor thermal environment in commercial kitchens was established, focusing on modelling the processes that characterizes the kitchen space.

Table 2: Estimates of Metabolic Rate for Basic Activities [3]

Basic Activity	**Estimates of Metabolic Rate (Wm^{-2})**
Lying	45
Sitting	58
Standing	65

Table 3: Average of Measured Physical Parameters by Kitchen Type and Thermal Zone [3]

Kitchen Type	**Kitchen Zone**	**T (°C)**	**RH (%)**
Casual	Cooking	31.3	36
QSR	Cooking	26.3	39

Figure 3 shows a typical staggered mesh arrangement for discretizing the control volumes for the calculation of the scalar and vector transports within the computational domain. Staggered mesh has being known to be popular remedy for checker boarding. While the pressure is stored at centroids of the main cells, the velocity components are stored on the faces of the main cells, as shown with the staggered cells. The *u* velocity is stored on the *e* and *w* faces and the *v* velocity is stored on the *n* and *s* faces.

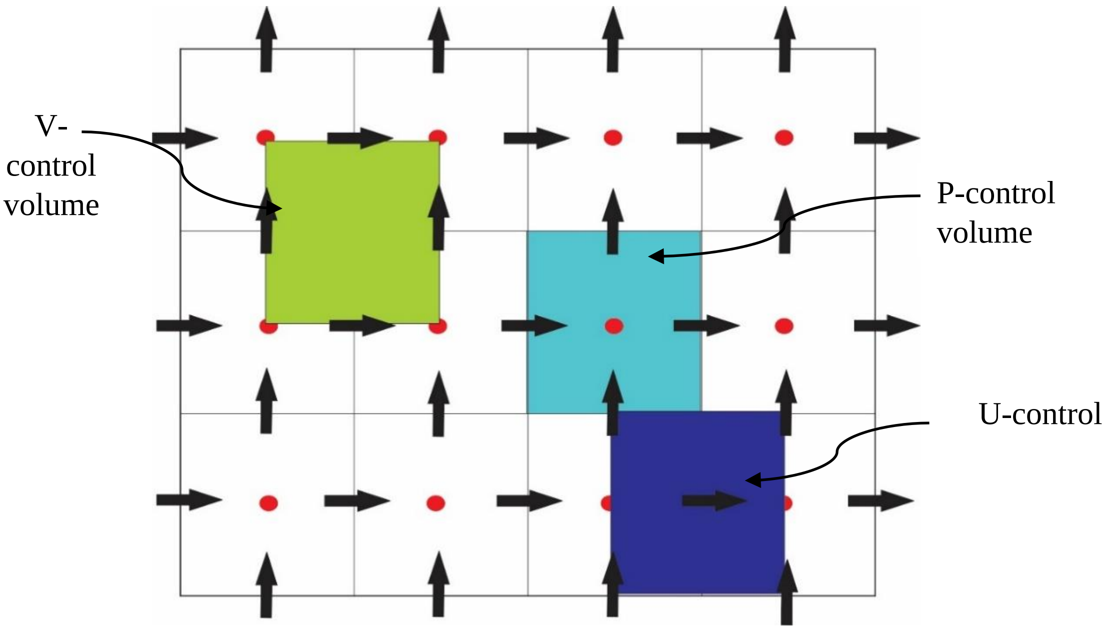


Figure 3: Staggered grid arrangement for U, V, and P

Pressure and velocity are coupled using the SIMPLEC formulation. The flow chart of the calculation process is given in Figure 4. The net flows across a control volume boundary are the sum of integrated flux term in equations (1) to (4) for the four control volume edges. The scalar conservation equation can be represented in the following summation form (Seidu *et al.* [11]; Ogedengbe *et al.* [12]):

$$a_p\, \emptyset_p = \sum a_{nb}\, \emptyset_b + b \quad \text{……………………………,,……………………………(5)}$$

where a, $\emptyset$ and b are the finite volume coefficient, the scalar variable (such as velocity component and temperature) and the source term, respectively. The subscripts p and nb refer to the central and neighboring nodes respectively.

The discretized form of the steady transport equation of property Ø in Eqn. (6):

$$\dot{m}_e\emptyset_e - \dot{m}_w\emptyset_w + \dot{m}_n\emptyset_n - \dot{m}_s\emptyset_s + \Gamma_e A_e \left[\frac{d\emptyset}{dx}\right]_e + \Gamma_w A_w \left[\frac{d\emptyset}{dx}\right]_w + \Gamma_n A_n \left[\frac{d\emptyset}{dx}\right]_n - \Gamma_s A_s \left[\frac{d\emptyset}{dx}\right]_s = \hat{S}\Delta V \quad \text{………………………..……………………………………(6)}$$

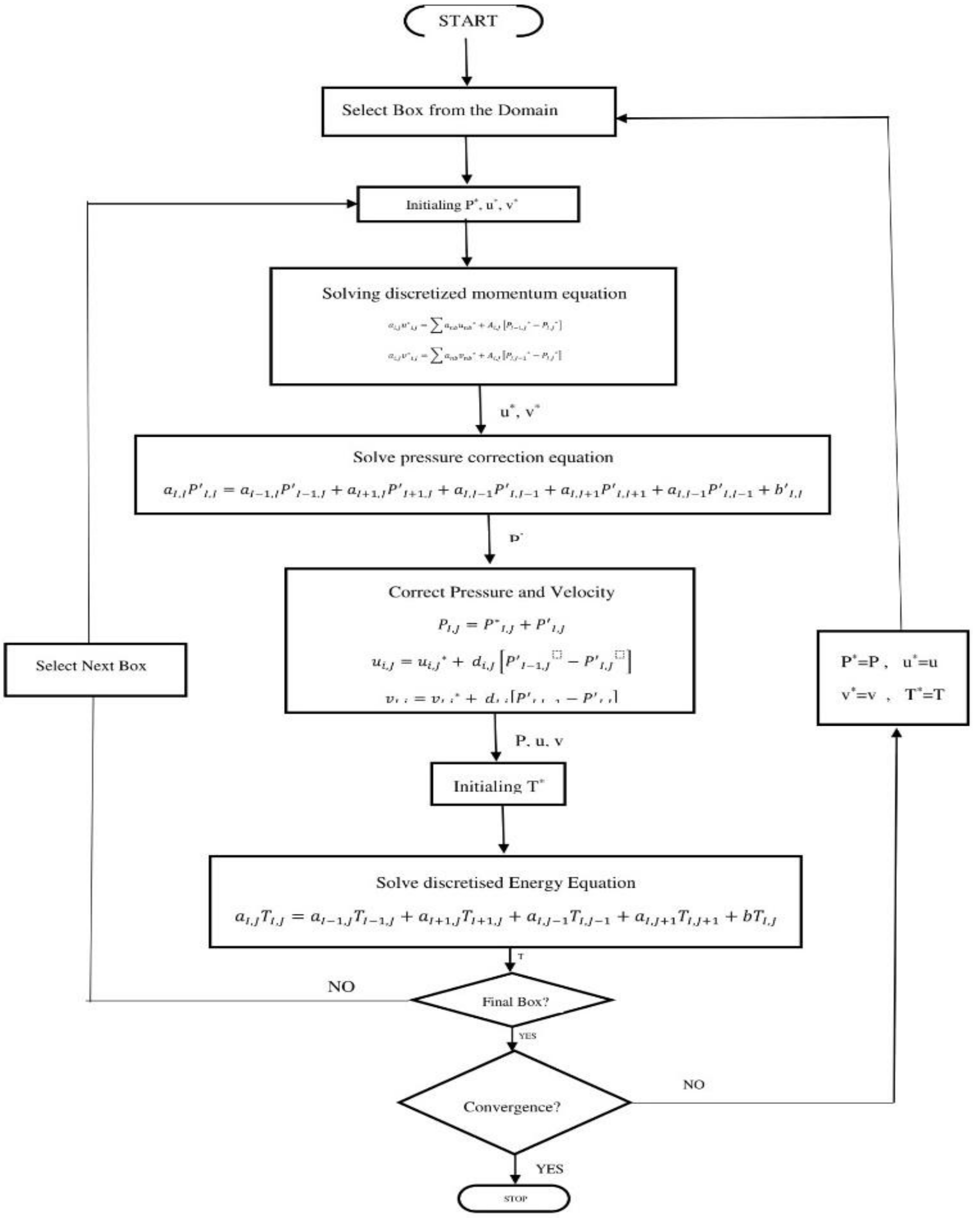


Figure 4: Computatonal Flow Chart

3 Numerical Technique

A manikin is located in the flow domain, thereby interacting with the inlet air (density, ρ = 0.8836 kg/m^3; thermal conductivity, k = 0.0271 W/m K; specific heat capacity, Cp = 1.005 J/Kg K; dynamic viscosity, μ = 1.983e^{-2} kg/m s). In carrying out the needed computation for the domain, a unique approach to solving a two dimensional problem using the MATLAB programming environment is employed.

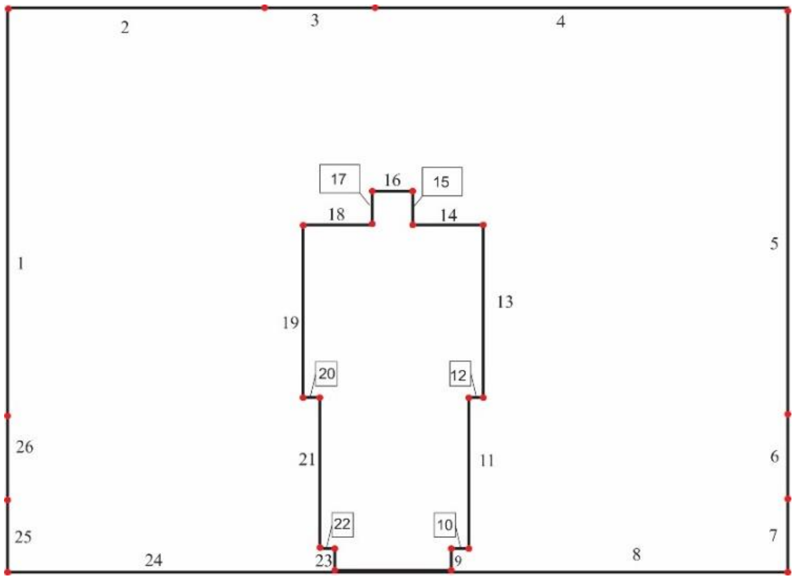


Figure 5: Boundary Numbering from Box Creation Arrangement (All internal nodes are not visible for simplicity)

The two-dimensional domain shown in Figure 2 is divided into sections using the X and Y axes as a reference in relation to the various dents created by the manikin in the space. Figure 5 shows the box creation arrangement, with a total of eight lines are made from the x-axis; and a total of four lines are created from the y-axis. These lines crossing each other creates a series of boxes which are numbered. These boxes, numbered from 1 to 45, are treated as individual parts of a large domain with each part having its coordinates (north, south, east and west). The results of this box creation arrangement indicate the requirement of a total number of 26 boundary conditions to be imposed, including the micro-boundary conditions around the space-variant manikin.

4 Results and Discussion

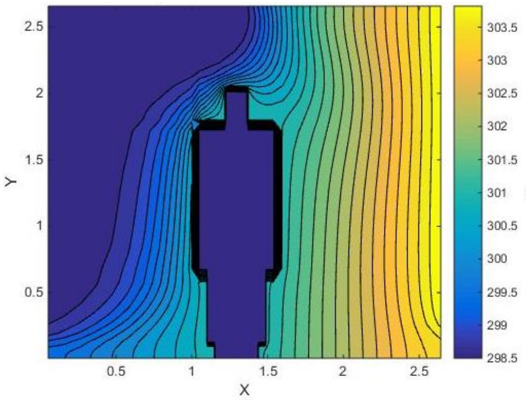
Figure 6 shows the temperature contours for the asymmetrical environment at different metabolic rates of human activities. The geometric arrangement and numerical technique used to arrive at the temperature contours are seen in Figure

2 and 3 respectively. Using information obtained from Table 1 for the metabolic rate and the constant heat obtained for cooking area from Table 2, the boundary conditions for the manikin and kitchen area are imposed on appropriate boxes within the generated computational stencil from the box creation methodology. Inlet velocity and temperature were 0.2ms^{-1} and 25.5^{o}C respectively were used to run the computation. Maintaining the inlet conditions at these operating conditions is required in order to minimize energy consumption in a space [13]. Seidu *et al*. [11] had compared the convective heat transfer coefficient, h_c, of this manikin, but seated either at the centre of the kitchen area or at about 1.8 m from the east wall, with the work of Schellen *et al*. [14] and Fiala [15]. While the procedural determination of the h_c enables the calculation of the predicted mean vote (PMV) and the percentage of person dissatisfied (PPD), accurate positioning of a personalized ventilation system varies with changes in the metabolic activities of the manikin.

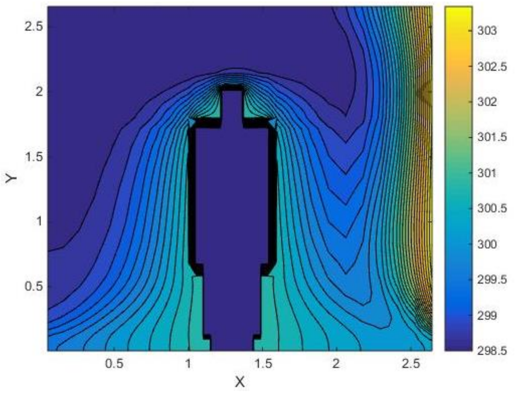
Figures 6 (a) and (b) give the temperature contour for lying metabolic rate for single and double outlets respectively. The contour in the Figure 6(a) shows a clear cooler region to the right of the occupant. The draft can be accounted for by the presence of a single outlet caused by the movement of the cooling air towards the exit. Since the exit is located at the base of the computational domain, a better cooling action is enabled by natural convection. The lower part of the body at the cooler region appears warmer, compared to the other parts, owning to the loss of energy by the draft of cool air on that part of the occupant. The left region of the occupant is warmer because of the heat coming from the kitchen, causing local thermal dissatisfaction to the occupant. Consistently with all variation in metabolic activities, it is observed that a sense of thermal dissatisfaction is significant on the left of the domain, due to heat dissipation from the kitchen area. However, a different scenario is created in Figure 6(b), where a cooler region around the occupant is noticed, showing a limited effect of heat dissipation from the kitchen area. The air is seen to move towards that direction with presence of an outlet vent, causing a comfortable draft of cooling air on the body. Therefore, this effect justifies the design of a PVS that enables better cooling around the body of the occupant.

Figures 6 (c) and (d) give the temperature contour for sitting metabolic rate for single and double outlets respectively. The temperature variation is higher in the case of this human activity because more heat is generated from this activity, compared to the lying position. Figure 6(c) shows a cooler region to the right of the occupant. This can be accounted for by the presence of a single outlet caused by the movement of the cooling air towards the exit. Also, a different situation is seen in Figure 6(d), similar to Figure 6(b), where a cooler region surrounds the occupant.

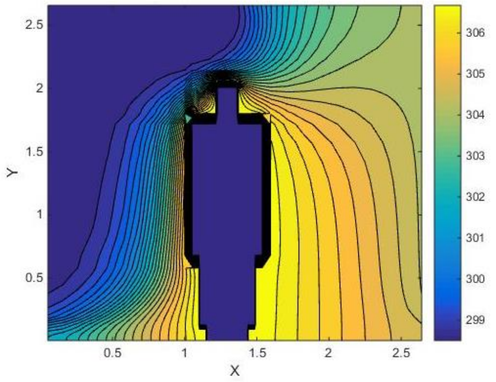
Figures 6 (e) and (f) gives the temperature contour for standing metabolic rate for single and double outlets respectively. By comparison of the three activities, the standing position predicts the highest variation, due to the nature of the heat associated with the activity. Figure 6(e) shows a similar pattern as in Figures (a) and (c), illustrating that the right of the occupant being cooled better. The air is observed to move towards that direction with the presence of an outlet vent, causing the natural convection of the cooling air on the body. This draft appears to result in the observed cooler effect around the occupant, with an exception of the legs for a similar reason, as observed in Figure 6(d).



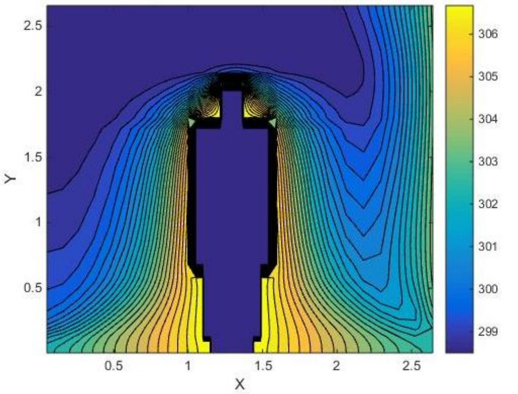
(a)



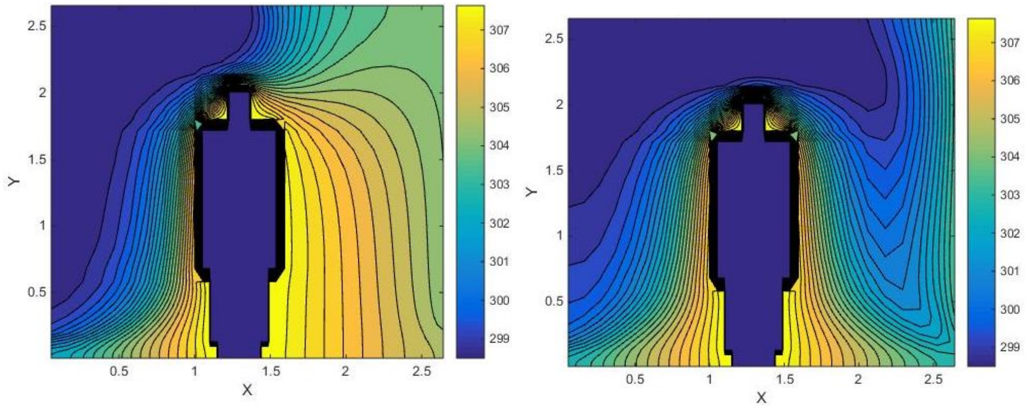
(b)



(c)



(d)



(e) (f)

Figure 6: Temperature Contours for Single Outlet and Double Outlet at $V_{in} = 0.2$ ms^{-1} in Different Metabolic Activity; (a) Lying with Single Outlet; (b) Lying with Double Outlets; (c) Sitting with Single Outlet; (d) Sitting with Double Outlets; (e) Standing with Single Outlet; and (f) Standing with Double Outlets

5 Conclusions

A box creation methodology for imposition of relevant boundary conditions for the design of a personalized ventilation system (PVS) for the University of Lagos 2001 cafeteria was proposed. The simulation results provided the proper design specifications for a PVS, which provides better quality of air to the occupants in a built environment. The simulated restaurant space, with floor area of 2.7m x 2.6m, promises more comfortable experience for the occupant exposed to heat influx from the adjoining kitchen. Using a two-dimensional finite volume formulation for the study of thermal distribution of indoor air, a personalized ventilation technique was developed for a space-variant occupant. It is important to have air flow effectively around the occupant, in order to determine the choice of the number of air outlets to be located in the domain. It is observed that the design of a PVS can alleviate the thermal tension from local discomfort. More research can be carried out to determine the behavior of the environment around a kitchen and its adjoining environment, especially with a combination of a variable heat influx from the kitchen, variation in kitchen activity, and at different position of the occupant from the kitchen.

NOMENCLATURE

C_p: Specific heat $\left(\frac{J}{kgK}\right)$

$\dot{q}$: heat flux

A: Area over a control Volume

CV: Control Volume
h: Convective heat Coefficient $\frac{\mathrm{W}}{\mathrm{m^2k}}$
H: Metabolic Rate
k: Thermal Conductivity
P: Pressure
Q: Energy source term
T: Temperature (°C)
$\mathrm{u = u - component\ of\ velocity}$
$\mathrm{v = v - component\ of\ velocity}$
μ: Dynamic Visocity
ν: Kinematic Viscosity ($\mathrm{m^2/s}$)
ρ: Density ($\mathrm{kg/m^3}$)
V_{in} = Velocity at Inlet

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