

## SIMULATING MULTIPLE STEADY STATES IN NATURALLY VENTILATED ENCLOSURES USING LARGE EDDY SIMULATION

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### ABSTRACT

This paper reports research carried out with the aim of evaluating the performance of Large Eddy Simulation (LES) and unsteady Reynolds-averaged Navier-Stokes (URANS) model for predicting multiple steady states in a naturally ventilated enclosure. Chenvidyakarn and Woods (2005) developed analytical models and conducted heat in water experiments to simulate air flow patterns through a large space with large heat gains. They showed that when the space contains two high-level stacks of different heights and a low-level opening, and is heated by a uniform source at the base, three different flow regimes are possible within a single set of boundary conditions. The geometry of the space and flow history determines which flow regime actually occurs. The focus of this work is to investigate how URANS and LES perform in predicting the three steady states.

### INTRODUCTION

Natural ventilation is an energy-efficient strategy for providing fresh air and thermal comfort to the occupants of a building. Buoyancy-driven natural ventilation harnesses the buoyancy forces associated with temperature differences between the interior and exterior environments to drive air flow through a building. The occupants and equipment inside the building can be exploited to produce this temperature difference and hence a ventilation flow through the building. However, in practice, this flow pattern is observed to change with changes in flow history regardless of building geometry.

Yuan and Glicksman (2007) suggest that multiple steady states exist in natural ventilation systems. For small disturbances the steady states can be stable but the systems can flip from one steady state to another if sufficiently strong perturbation is applied. The analysis was carried out with two types of perturbations i.e. fluctuations in heat source and variations in wind. The minimum perturbation time and minimum perturbation magnitude parameters were defined which help in determining the robustness of a steady state. These were successfully used to validate the results of other research. Yuan and Glicksman (2008) suggested a single zone where combined wind and buoyancy can exhibit three

steady states. Two of these are mathematically stable while the third one is unstable even to infinitesimal disturbance. They used a “*dynamical system*” method in their study which they propose can help designers avoid problems associated with the ventilation strategies switching from a desirable to an undesirable state by choosing a relevant parameter carefully.

Li et al. (2001) report multiple solutions for flow rates in a naturally ventilated enclosure under certain conditions. This is induced due to non-linear interactions between wind and buoyancy forces. In their paper they show that for even simple systems, natural ventilation flows can be quite complex. They investigated three cases experimentally using salt bath models, where they observe multiple solutions for a certain range of parameters.

Multiple solutions for the air flow rates in a naturally ventilated building were reported by Andersen (2007). In his paper it was analysed to what extent such a phenomenon should be considered under practical conditions. He explained that if the difference between the exterior and interior environments is known for a building a priori, unambiguous solutions could be achieved. Two parameters were investigated. These were the heat loss air exchange parameter,  $\beta$ , which measures the effect of conductive heat loss on the ventilation flow rate, and wind air change parameter,  $\gamma$ , which is a “*scaled*” ventilation flow rate induced by wind forces. For certain values of  $\beta$  and  $\gamma$  he described those unambiguous conditions which are valid.

Chen (2009) reviewed the methods used to predict the ventilation performance of buildings. In his review he found that analytical and empirical models had made minimal contributions to recent literature. Small-scale and full-scale model experiments were mainly used to generate data in order to validate numerical models. Ventilation performance of entire buildings were being predicted by improving multi-zone models. Coarse grid CFD was replacing zonal models with limited applicability. Chen found that 70% of the literature found was contributed by CFD models. The main applications of CFD were indoor air quality, natural ventilation, and stratified ventilation as these were difficult to predict with other models.

This paper reports on a study that investigated the use of popular computational methods, supplemented with experimental techniques, in predicting multiple steady states in buoyancy-driven natural ventilation. As a first step, the paper focuses on multiple steady states which are driven by buoyancy alone, as reported by Chenvidyakarn and Woods (2005), as opposed to ones driven by a combination of wind and buoyancy as reported in the other studies. The results obtained from Chenvidyakarn and Woods's paper are used here to validate the computational results of this study.

### ANALYTICAL AND EXPERIMENTAL WORK

Chenvidyakarn and Woods (2005) investigated natural ventilation in an open-plan office. The space is ventilated through two stacks (one shorter than the other) at the ceiling and a lower opening located near the base representing a doorway. They assumed a uniform distribution of heat across the floor to represent occupancy. It was reported that for the above mentioned scenario, up to three steady state ventilation regimes are possible (Figure 1).

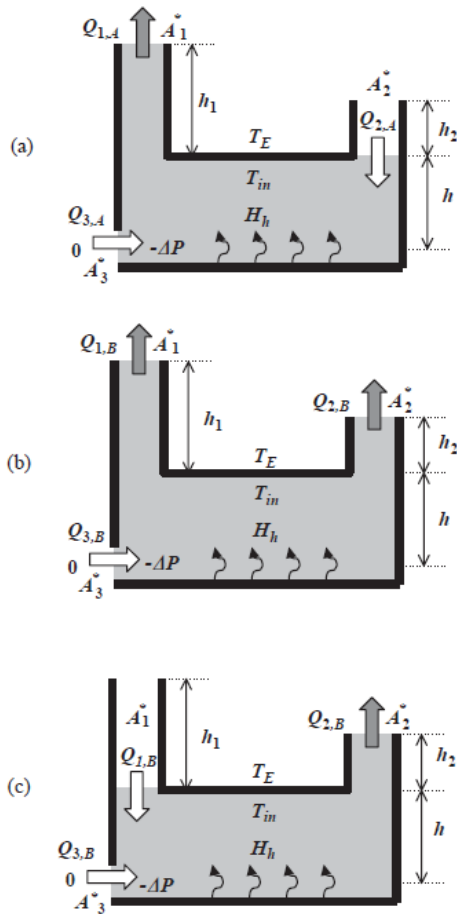


Figure 1: Schematics of three steady state ventilation regimes in an open plan office building (a) Regime A, (b) Regime B and (c) Regime C (after Chenvidyakarn & Woods (2005))

In the first regime, warm air exits through the taller stack while ambient air is drawn in through the shorter stack and bottom opening (Figure 1a). In the second regime, warm air exits through both the stacks whilst drawing air in through the bottom opening (Figure 1b). In the third regime, ambient air is seen to be drawn in through the taller stack and bottom opening whilst the warm air exits the office through the shorter stack (Figure 1c). They suggest that the factors affecting the final steady states attained are the geometry of the enclosure and the flow history.

In their paper they present a formulation for the temperature inside the room at steady state,  $T_{in,ss}$  ( $^{\circ}\text{C}$ ) as follows

$$T_{in,ss} = T_E + \left( \frac{H_h}{\rho C_p A^* \sqrt{g \alpha H}} \right)^{2/3} \quad (1)$$

where,  $T_E$  ( $^{\circ}\text{C}$ ) is the exterior temperature,  $H_h$  (W) is the heat gains from occupants and equipment,  $C_p$  (J/kg K) is the heat capacity of air,  $\rho$  ( $\text{kg}/\text{m}^3$ ) is the density of air and  $A^*$  is the effective area of the openings.  $A^*$  was formulated by Hunt and Linden (2001) to represent openings of area  $a_t$  and  $a_b$  at the top and bottom of the space respectively:

$$A^* = \frac{C_D a_t a_b}{\left[ \frac{1}{2} \left\{ \left( \frac{C_D^2}{C_e} \right) a_t^2 + a_b^2 \right\} \right]^{1/2}} \quad (2)$$

Also, Chenvidyakarn and Woods (2005) define a dimensionless room temperature,  $\theta$ :

$$\theta = \left( \frac{T_{in} - T_E}{T_{in,ss} - T_E} \right) \quad (3)$$

and dimensionless time,  $\tau$ :

$$\tau = \frac{t}{t_s} \quad (4)$$

where  $t_s$  (s) is a dimensional timescale to converge to equilibrium given by

$$t_s = \frac{V}{A^* (g \alpha H)^{1/2} (T_{in,ss} - T_E)^{1/2}} \quad (5)$$

where,  $V$  is the volume of the room ( $\text{m}^3$ ),  $g$  is the gravitational constant ( $\text{m}/\text{s}^2$ ) and  $\alpha$  is the volume expansion constant ( $1/\text{K}$ ).

They present a relationship between the dimensionless room temperature and the dimensionless time to converge to equilibrium (Figure 2). The Figure 2 shows that for  $\tau > 3.5$ ,  $\theta > 0.99$  and so the room has essentially reached steady state.

## NUMERICAL PROCEDURE

### Computational geometry and mesh

The geometry generated for the CFD simulation was identical to the small scale model reported by Chenvidyakarn and Woods (2005). Due to the high computational power requirements for LES, mesh was generated using good practice guidelines. To identify if the mesh generated for the computational geometry was sufficiently fine the  $L/\Delta$  ratio was used. Here  $L$  is the integral length scale while  $\Delta$  is the filter width for filtering the small scales. The mesh was assumed to be fine enough in regions where the  $L/\Delta$  value was above 12. In the case of URANS the mesh was considered appropriate when mesh independency was achieved.

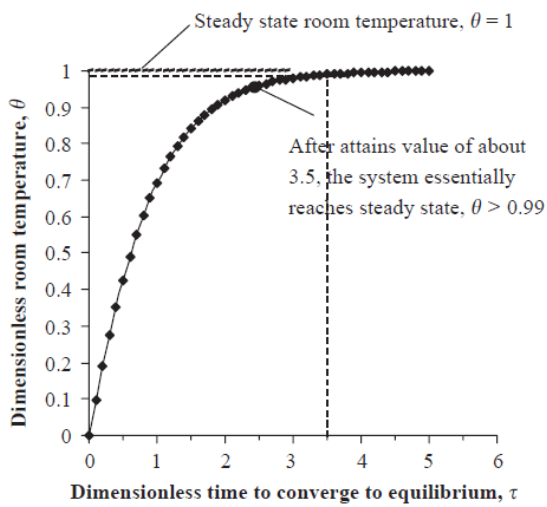


Figure 2: Relationship between the dimensionless room temperature,  $\theta$  and the dimensionless time to converge to equilibrium  $\tau$  (after Chenvidyakarn & Woods (2005))

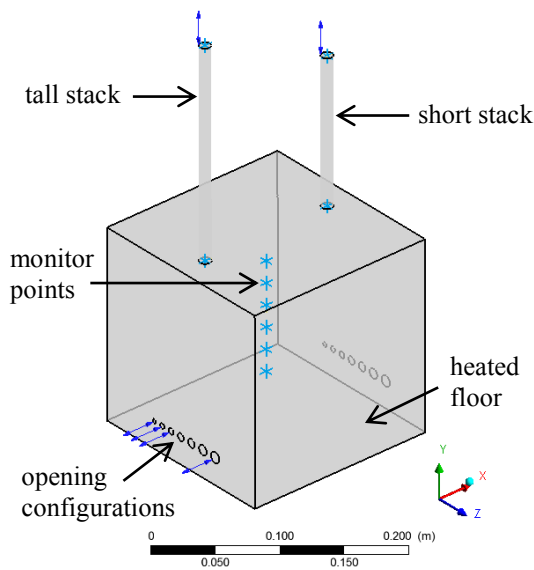


Figure 3: Computational domain

### Boundary conditions

Water at 23°C was used as the working fluid in the simulation. The floor was given the boundary condition of a distributed heat source with a total heat input of 90W which was in accordance with the original work. The stack openings as well as the bottom opening were assigned the boundary condition 'opening'. This 'opening' boundary allows fluid to flow in both directions and calculates the pressure drop using the equation:

$$\Delta p_{loss} = -\frac{1}{2}f\rho U_n^2 \quad (6)$$

where  $f$  is the loss coefficient and  $U_n$  is the component of velocity normal to the opening. Initially the fluid was assigned an ambient temperature with the three components of velocity equal to zero. The walls were assumed to be adiabatic and assigned the 'no-slip' boundary condition.

### The URANS and LES approach

CFX (ANSYS, 2012) was used to run both URANS and LES cases. This software uses the finite volume method to discretize the incompressible continuity, momentum and energy equations. The transient terms are discretized using a second order Euler scheme. The sub-grid scale model chosen for modelling the small scale eddies for LES was the Smagorinsky model (Lilly, 1967) as it has been reported to be successful in predicting buoyant flows (Bastiaans et al., 2000). The RNG  $k-\epsilon$  model (Yakhot et al., 1992) was used to represent turbulence in the URANS simulation. The convergence criterion for each time step was that the root mean square (RMS) residuals of the momentum, enthalpy and mass conservation equations should be less than  $1 \times 10^{-6}$ . The inner loops within each time step were kept within the range of 1-5.

The Courant number (CFL) is a stability indicator of the convective terms which is used in this study for time step selection. The CFL number reflects the portion of a cell that fluid will flow in one time step.

$$CFL = \frac{v \times \Delta t}{\Delta} \quad (7)$$

where,  $v$  is the linear velocity,  $\Delta t$  is the time step size and  $\Delta$  is the filter width (mesh size).

For LES, the CFL number was in the range of 0.5 to 1.0. Keeping the CFL number within this range ensures that the turbulence is not dampened. In the case of URANS the CFL number was maintained within a range of 1.0 to 5.0. Both of these ranges were selected on recommendations by ANSYS (ANSYS, 2012).

## METHODOLOGY

The main purpose of the current study was to study the capability of CFD for predicting the multiple steady states observed originally by Chenvidyakarn and Woods (2005). However for the presence of a certain regime the boundary conditions used were critical. From the original study, it was observed that for a 7mm diameter bottom opening, all three steady states existed. Thus using the same area for the bottom opening both URANS and the LES techniques were used.

### Regime B

Chenvidyakarn and Woods describe that the flow naturally evolves into regime B (Figure 1b). The original paper reported that “depending on the history of the flow, the heights of the room and stacks, the area of the bottom hole and the cross-sectional areas of the stacks, the system is capable of producing up to three steady state displacement ventilation regimes”. It was decided to keep all these factors constant except for history of the flow. In real buildings, history of the flow often changes due to changes in occupancy.

### Regime A and C

For regime A and C, ambient air was introduced into the building via the short and tall stack respectively (representing cold draughts that can occur in reality). This was done by changing the boundary condition at the opening from ‘opening’ to ‘inlet’ with a normal velocity component of 0.015m/s for regime A and 0.02m/s for regime C. These values were based on the outflow velocities from the same openings during regime B. Using these flow conditions as the starting point/history of the flow and keeping all other boundary conditions the same, the simulations were started. After a time period of 30s the ‘inlet’ boundary condition was changed back to an ‘opening’ boundary, thus retaining the flow history. It was observed that flow in each case continued to entrain ambient air from either stack and would continue to do so until reaching a statistically steady state. This helped develop both regimes A and C.

## RESULTS

### Steady state solution

Steady state was considered to be reached when the flow in the computational domain had evolved from the initial stagnant conditions to a steady flow pattern and that the transport of mass, momentum and energy within the flow had reached statistically steady rates. In order to determine if steady state had been reached within the domain, monitor points were placed in the centre of the domain (Figure 3). The lowest monitor was 5cm from the floor with 5 more monitors above it at intervals of 2cm. These monitor points would update information on the temperature and velocity conditions in the domain. Four other monitor points, placed at either end of both the stacks were used to

provide information about the flow direction in the domain. Steady state was considered to be achieved when the following criteria had been met:

- ventilation flow rate was unchanging;
- velocity, temperature and pressure values at all multiple monitor points were stable

Figure 4 shows the evolution of the average room temperature over time for both URANS and LES against theoretical predictions. It can be seen from the figure that both URANS and LES predict the room temperature very accurately (0.15% error for LES, 1.42% error for URANS). Both show the room to reach steady state in about 1.6 hours.

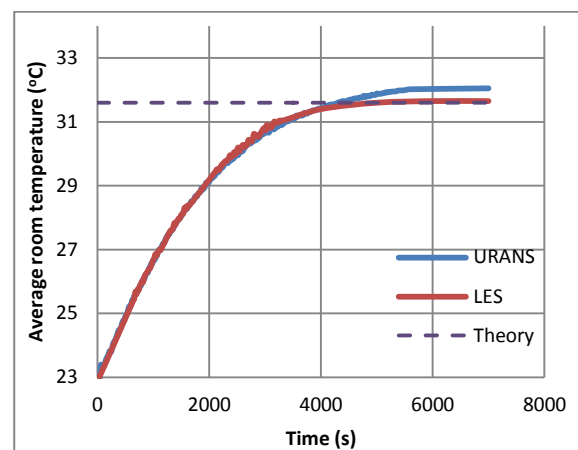


Figure 4: Comparison of the time to adjust to steady state as predicted by URANS, LES and the theory

It is worth investigating how the relationship between the dimensionless room temperature  $\theta$ , and the dimensionless time to converge to equilibrium,  $\tau$ , holds for both URANS and LES. According to the work of Chenvidyakarn and Woods (2005) when  $\tau > 3.5$  then  $\theta \sim 1$ . It can be seen from Figure 5 that LES performs more accurately in this regard than URANS which over-predicts  $\theta$  and has not reached steady state at  $\tau \sim 3.5$ .

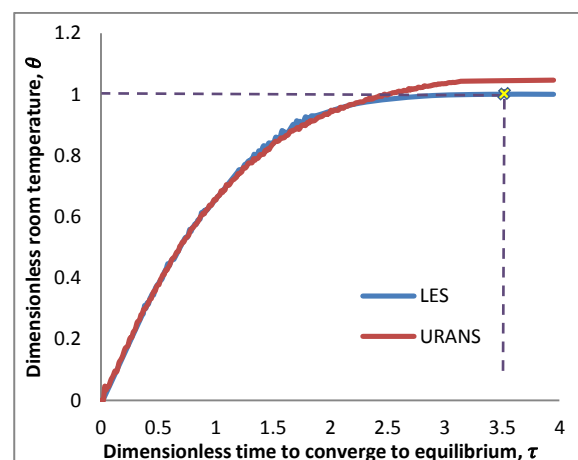


Figure 5: Relationship between the dimensionless room temperature,  $\theta$ , and the dimensionless time to converge to equilibrium,  $\tau$

### Multiple steady states

Snapshots for both URANS and LES simulations can be seen in Figure 6 and Figure 7 respectively. These illustrate temperature plots over a plane passing midway through the domain. Cold ambient air can be seen to be drawn into the domain down through the stacks to produce regimes A and C. It is interesting to compare the level of detail each CFD technique provides. From the URANS temperature profiles the shape and structure of the downward plumes from the stacks cannot be determined. LES, on the other hand, is able to elucidate this behaviour e.g. in regime A the plume takes on a more meandering behaviour whereupon reaching the floor it breaks down whilst in regime C the plumes are more turbulent and break down before they reach the mid

height of the domain. Additionally it can be seen that for regime B, LES predicts the presence of cold draughts at the right-hand end of the floor. URANS however, fails to capture such behaviour. This is expected due to the averaging techniques inherent in the URANS method.

Additionally, the room should be well mixed and thermally uniform. The URANS temperature plots however suggest a temperature interface (vertical temperature gradient) in all three regimes (see figure 6) at a height of approximately 14cm from the floor. LES results, however, suggest that this difference in temperature is due to large recirculating eddies caused by warm convection currents adjacent to the left wall.

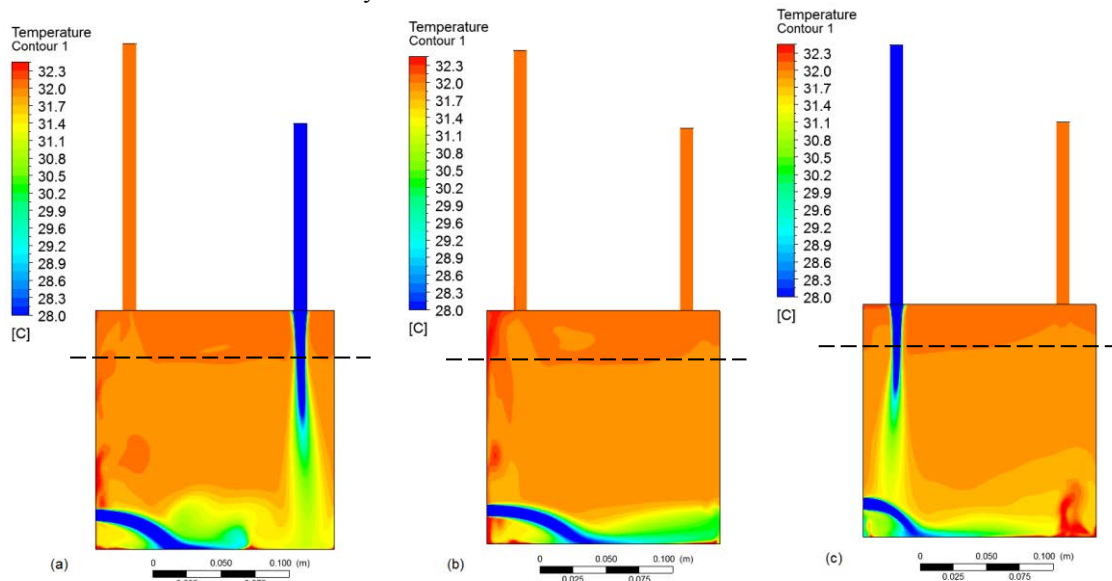


Figure 6: Temperature plot on a plane midway through the domain using URANS illustrating (a) Regime A, (b) Regime B and (c) Regime C (dotted black lines representing an interface)

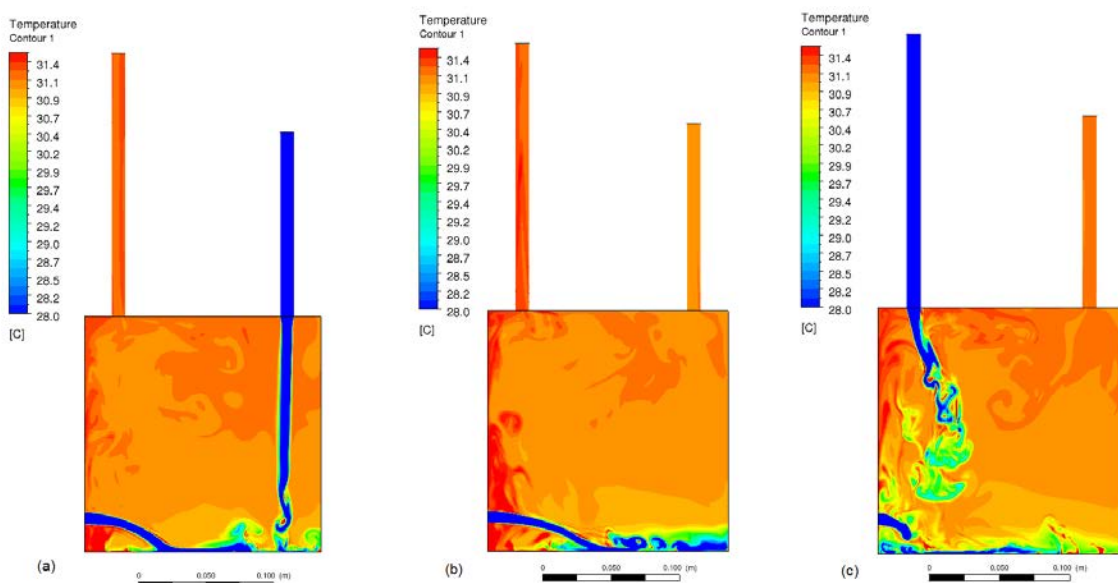


Figure 7: Temperature plot on a plane midway through the domain using LES illustrating (a) Regime A, (b) Regime B and (c) Regime C

### Comparison with analytical model

Figure 8 and Figure 9 show the theoretical predictions of the inside room temperature,  $T_{in}$  (dotted lines) for the three regimes with changes in the bottom opening ratio,  $A_3^*/A_1^*$ . CFD results are plotted accordingly as well (marker points). The figures plot dimensional temperature,  $T_{in,ss}^*$ .

$$T_{in,ss}^* = \frac{(T_{in,ss} - T_E)}{(T_H - T_E)} \quad (8)$$

where  $T_H$  is the temperature of the heat source.

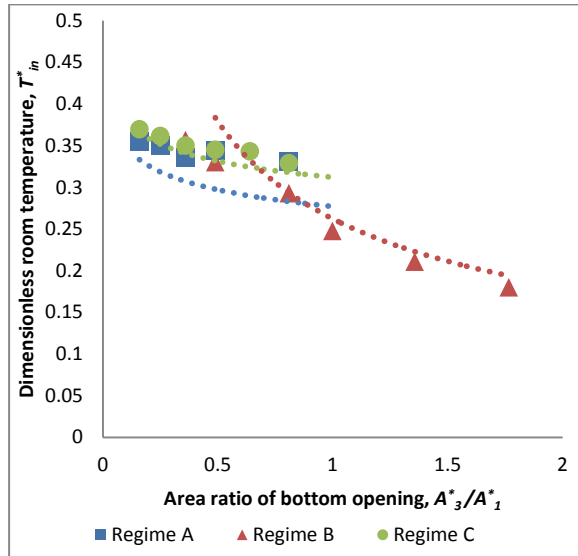


Figure 8: Comparison between theory and URANS predictions of dimensionless room temperature,  $T_{in}^*$  with changes in area of bottom opening,  $A_3^*/A_1^*$  (dotted lines show theory)

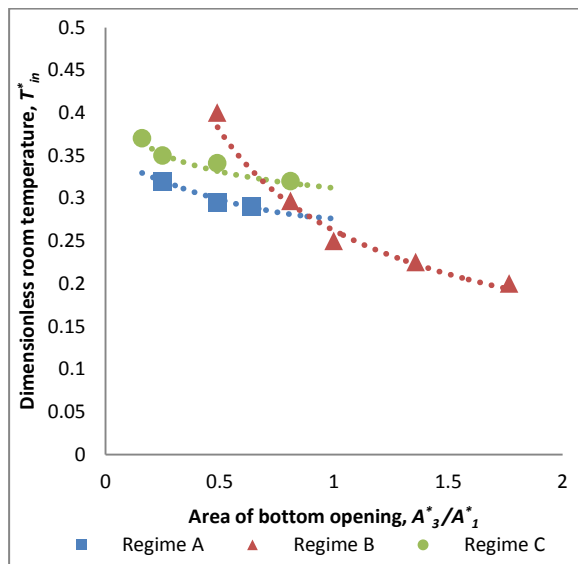


Figure 9: Comparison between theory and LES predictions of dimensionless room temperature,  $T_{in}^*$  with changes in area of bottom opening,  $A_3^*/A_1^*$  (dotted lines show theory)

Good agreement is observed between theory and CFD for regime B at larger doorway areas using URANS. However, as the doorway area reduces i.e.  $A_3^*/A_1^* < 1.0$  the dimensional room temperature is under-predicted for regime B and over-predicted for regime A and C. On the other hand LES appear to be more accurate. Note, however, that fewer LES runs were conducted than URANS as LES due to the computational requirements of LES.

### CONCLUSIONS

Multiple steady states in buoyancy-driven natural ventilation have been investigated using LES and URANS. The theoretical model shows that the average room temperature of the enclosure should be 31.6°C. LES predicted an average temperature of 31.65°C (0.15% discrepancy) and URANS predicted 32.05°C (1.42% discrepancy).

The relationship between the dimensionless room temperature  $\theta$ , and the dimensionless time to converge to equilibrium,  $\tau$ , was also predicted. According to theory, when  $\tau > 3.5$  then  $\theta \sim 1$ . This was predicted well by both modelling techniques although LES proved to be more accurate than URANS.

Using the 7mm bottom opening, three steady state regimes were predicted by both LES and URANS. The URANS method however was unable to capture the detail of the flow structures predicted by LES. This is expected due to the averaging techniques inherent in the URANS method. URANS also predicted a weak vertical temperature gradient in the domain which was not observed in the experimental work which suggests a well-mixed enclosure. This phenomenon was correctly predicted by LES which illustrated the flow to comprise recirculating convection currents in the region where URANS had predicted a vertical temperature gradient.

The differences between LES and URANS performance in predicting the different regimes for all values of the bottom opening area ratio and the respective room temperatures were investigated. It was observed that URANS did not perform well in predicting the room temperatures for opening size ratios with diameters less than 6mm. URANS over-predicted the temperatures, especially for regime A. LES on the other hand performed well for all area ratios. By its nature, LES requires far more computing power than URANS. In this work, the LES cases required approximately 500% more time than URANS (using the same hardware platform).

In conclusion it can be stated that LES was more successful than URANS in revealing the fluid dynamics of buoyancy-driven natural ventilation and predicting values of flow reported by Chenvidyakarn and Woods (2005).

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## NOMENCLATURE

$a_b$	area of the lower opening (m <sup>2</sup> )
$a_t$	area of the upper opening (m <sup>2</sup> )
$A^*$	effective area of the openings (m <sup>2</sup> )
$C_p$	heat capacity of air (J/kg °C)
$CFL$	courant number (-)
$C_D$	coefficient of discharge (-)
$C_e$	coefficient of expansion (-)
$\Delta$	filter width (m)
$\Delta t$	time step size (s)
$f$	loss coefficient (-)
$g$	acceleration due to gravity (m/s <sup>2</sup> )
$H$	total height of computational domain (m)
$H_h$	heat gains from occupants & equipment (W)
$L$	integral turbulent length scale (m)
$\Delta P_{loss}$	pressure loss across the opening (Pa)
$T_E$	the exterior ambient temperature (°C)
$T_{in,ss}$	indoor temperature at steady state (°C)
$T_{in,ss}^*$	dimensionless temperature (-)
$t_s$	dimensional timescale to converge to equilibrium (s)
$U_n$	normal velocity (m/s)
$V$	volume of the room (m <sup>3</sup> )
$v$	linear velocity(m/s)
$\alpha$	volume expansion constant (1/K)
$\beta$	heat loss air exchange parameter (m <sup>3</sup> /s)
$\gamma$	wind air change parameter (m <sup>3</sup> /s)
$\theta$	dimensionless room temperature (-)
$\rho$	density of air (kg/m <sup>3</sup> )
$\tau$	dimensional time (-)