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Assessment of Airwell Performance in Single-Storey Terraced Houses

Mohd Suffian Misaran Misran[1], Heng Jin Tham[2], Christopher Chi Ming Chu[2#], Djamila Harimi[3]

1 Mechanical Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, MALAYSIA.
2 Chemical Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, MALAYSIA.
3 Civil Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, MALAYSIA.
Corresponding author. E-Mail: chrischu@ums.edu.my; Tel: +6088-320000; Fax: +6088-320348.

ABSTRACT Single-storey terraced housing in Malaysia does not provide thermal comfort to its occupants due to poor dissipation of heat from solar irradiation unless mechanical cooling is installed, which adds to the urban heating island problem. This study is a simple assessment of natural ventilation performance of terrace houses which by law are built with an airwell and sized according to regulations. A typical room of 3 m × 4 m × 3 m with an adjacent airwell has been investigated by CFD simulation assuming ambient temperature of 30°C and atmospheric pressure of 101.3 kPa. The results show that with an airwell-chimney of 2.55 m above the roof the test room air velocity could reach 0.6 ms^{-1} for thermal comfort; while without the protruded chimney adverse cold inflow set in, and the indoor air flow velocity ranged from as low as 0.08 ms^{-1} to 0.21 ms^{-1}. However, when the protruded chimney was not installed, but with a wiremesh-based blocker of adverse cold inflow installed on the airwell outlet, the indoor air flow velocity consistently reached 0.2-0.3 ms^{-1}, which was about 45% higher than that without the blocker, and was within the recommended range for thermal comfort. The wiremesh blocker of adverse cold inflow could be an option to ventilate effectively single-storey terrace houses without the need of installing tall chimneys.

KEYWORDS: Airwell, Single-storey, Natural ventilation, CFD, Cold inflow
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INTRODUCTION

Current ventilation design of single-storey terraced houses in Malaysia for years has been studied as recently as 2019 to conclude that they are poorly ventilated for thermal comfort (Leng *et al.*, 2019; Tinker *et al.*, 2004). Localized heat sources in buildings may set up a steady thermally stratified environment during the day with a layer of warm air, of uniform temperature separated by a sharp density interface from a cooler layer below at ambient temperature. Natural ventilation is an attractive solution with little or no energy use in purging the air; it can also be an option for continuous ventilation. By incorporating a suitable wire mesh when designing an atrium, the flow is controlled, stabilized and the stale warm air discharged efficiently without reversal. An innovative atrium design through CFD simulation resulting in controlled, highly efficient and effective daytime ventilation of buildings can be achieved by ensuring it to be adverse cold-inflow free. The airwell can also control the height of the sharp interface between a warm air layer and the ambient air below to ensure thermal comfort. Massive energy saving in cooling load reduction by daytime natural ventilation of the cold inflow-free air well in single-storey terraced houses existing and new, can be achieved with thermal comfort.

Atrium is another name of air well for large buildings such as shopping complexes. Moosavi *et al*. (2014) concluded in their review of state of the art technology of atrium that although many studies have been carried out on the efficiency of natural ventilation in atrium, the knowledge about air well passive cooling design is incomplete regarding its complexity and lack of accurate measurement tools. Many of the relevant studies focus on validation of analytical methods. Comparing with other similar subjects, the investigated parameters of naturally ventilated atria have

TRANSACTIONS ON SCIENCE AND TECHNOLOGY

less detailed results. Therefore, they concluded that there is a requirement for further researches on innovative solutions for naturally ventilated atria and recommended developing reliable test procedures.

It is hypothesized that the use of wire mesh across an airwell / atrium cross-sectional total flow area, which is usually not small relatively, will provide a robust and stable upflow to discharge warm air throughout the day as well as for night purging. The airwell in buildings is specified in the Uniform Building By Law (UBBL) 1984, as a basic ventilation requirement for utility, mechanical room and washroom with stated sizes and dimensions. However, if mechanical ventilation is intended the law can be waived by the authority and no such space is allowed in the design. Another reason why some residents do not like to install an airwell is it opens a possible path for intruders.

The research questions to be asked are whether existing typical single-storey terraced houses in Malaysia suffer from adverse cold inflow, how would adverse cold inflow be eliminated and how much improvement in airwell performance would result? Adverse cold inflow or flow reversals, in solar chimney has been studied by Khanal & Lei (2012), among others. Chu *et al.* (2009) found that by eliminating cold inflow, the air flow rate of a natural convection air-cooled heat exchanger could be enhanced by 45 to 90 percent. The approach is to start with a CFD simulation on a typical terraced house and airwell similar to that analysed by Leng *et al.* (2019).

BACKGROUND THEORY

The Single-Storey Terraced House

The single-storey terraced house has the dimensions given in Leng *et al.* (2019) as shown in Figure 1. The house is a single room with dimensions 4 m long by 3 m wide and 3 m high, with a window of 1.5 m wide and 1.5 m high placed at the partition between the airwell, on the adjacent left of the building, and the room, and another at the opposite far right end of the room. The window is 0.9 m above the floor. A door is built at the left side of the house just to the right of the airwell. The door is closed since this is usually the case when there are people in the house. Both windows are opened under normal circumstances.

It is believed that a warm layer exists at the ceiling with a distinct interface and there is no flux crossing between the warm and cold air as theorized by Linden *et al.* (1990), but only plume-air interaction at the boundary.

METHODOLOGY

A model of a terraced house is built with similar geometry to Leng *et al.* (2019) dimensions with the following assumptions:

1) Windless condition in contrast to Leng *et al*. (2019) wind speed of 1.16ms^{-1} at 10 m height
2) Ambient temperature and pressure were constant at 30°C and 101.3 kPa respectively
3) Air humidity effect on air flow and temperature is negligible
4) Solar irradiation was constant at 800 Wm^{-2} over the roof area, in contrast to Leng *et al.* 988 Wm^{-2}K^{-1}.
5) The absorption rate of the solar irradiation was 0.5 resulting in 4.8 kW and 4.0 kW was set.
6) The heat loss from the system is negligible in contrast to Leng *et al*. wall conduction and convection.

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CFD Simulation

The main tool to be used was a computational fluid dynamic software Phoenics supplied by CHAM to solve the Reynolds-Averaged Navier-Stokes conservation equations. The model of a single-storey terraced house was constructed in the simulation environment. Turbulence model to be applied was the Chen & Kim (1987) k-epsilon method. The global convergence criterion was set at 0.01 percent. The software has been validated with thermal-pneumatic calculations using established equations of Haaland (1983) friction factor for pipe, and standard *K*- coefficients of 0.5 and 1.0 (Sinnott & Towler, 2009) for inlet and exit losses respectively on a 25 m x 100 mm diameter vertical cylinder operating under natural convection, and it resulted in a mass flowrate that agreed to within 7 percent, which is satisfactory. Temperature and velocity data were extracted and analyzed. The configuration with the industry recommended ACH for thermal comfort during daytime would be the optimum. Four cases are examined as shown in Table 1:

Table 1. Configuration of each case

Case	Configuration
1	1 Storey + Chimney
2	1 Storey + Chimney + Wiremesh Blocker
3	1 Storey without Wiremesh Blocker
4	1 Storey + Wiremesh Blocker

For mesh grid size optimization, the default grid meshing of 62, 63 and 57 cells in the X, Y and Z dimensions were doubled in the area of interest and found to differ in the simulated mass flowrate through the chimney by less than 2.5 percent in Case 1, which is satisfactory. The wire mesh blocker was modelled as a porous plate with resistance in the simulation.

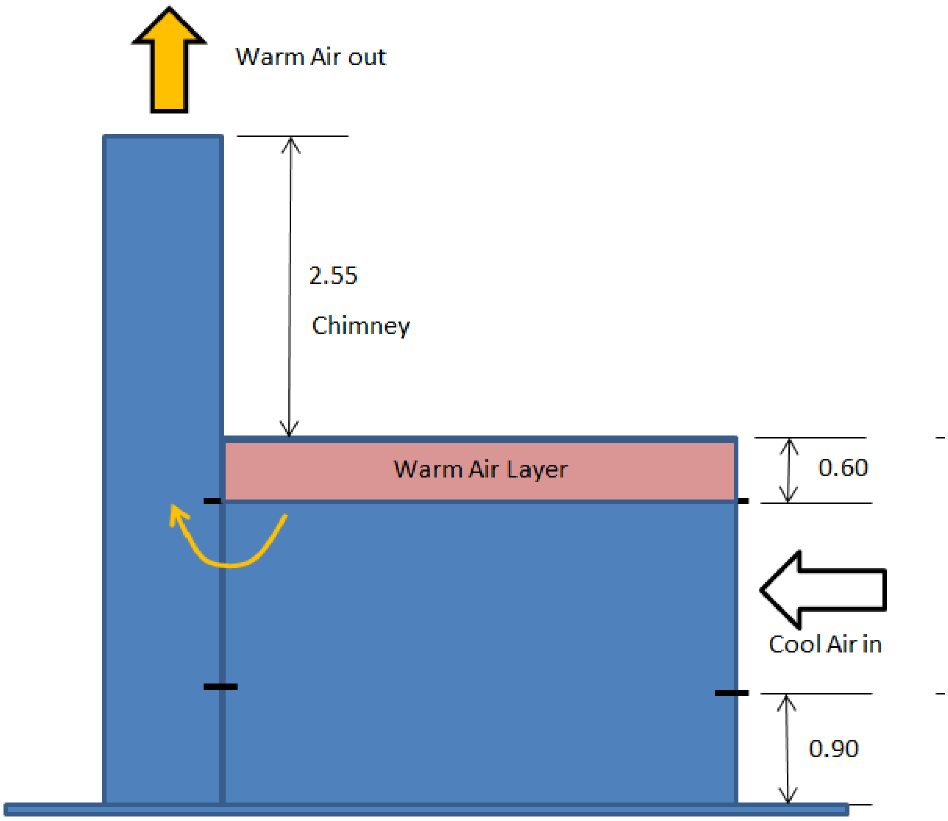

Figure 1a. Side view of Single-Storey Terraced House 4 m L × 3 m W × 3 m H fitted with a 2.55 m chimney extended from an airwell of 2 m L × 1 m W × 3 m H with a window acting as the air inlet and the chimney as the air outlet

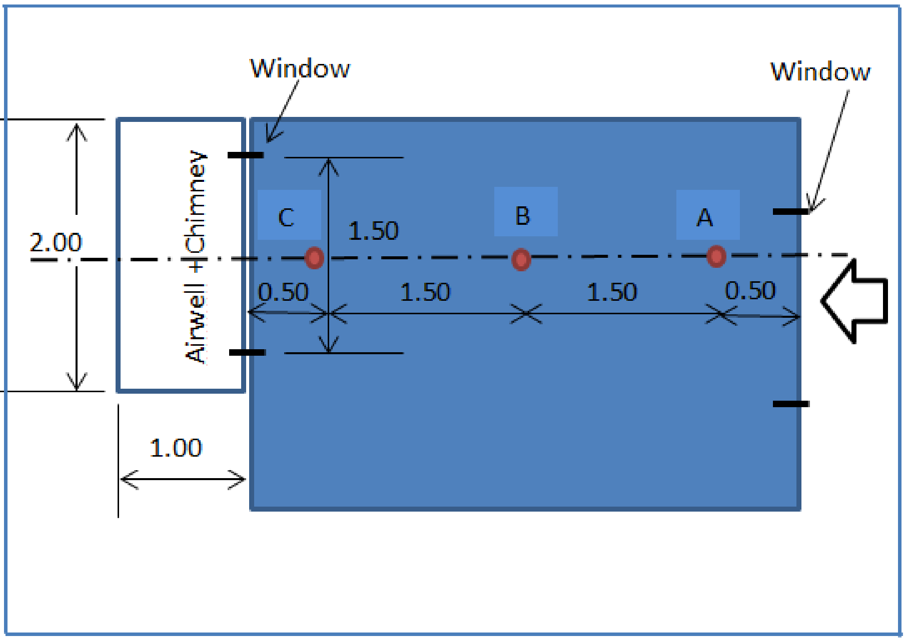

Figure 1b. Plan of Single-Storey Terraced House 4 m L × 3 m W × 3 m H fitted with a 2.55 m chimney extended from an airwell of 2 m L × 1 m W × 3 m H with a window acting as the air inlet and the chimney as the air outlet

RESULT AND DISCUSSION

The mean air velocity through the airwell inlet window (Left window in Figure 1) is tabulated in Table 2 for all cases. The mean was calculated by extracting the CFD cell values and weighted by mass flowrate; as this was shown to give true mean temperatures when the flow is experiencing reversals (Chu *et al.*, 2014). Case 1 which generated a mean test room velocity of 0.51 ms^{-1} is close to Leng *et al.*, (2019) measurement of their test room air velocity at 3 points (Figure 1b) of 0.45ms^{-1} (+13%), and the airwell shaft mean velocity at the airwell top exit was 0.44ms^{-1} compared to their's at 0.53ms^{-1} (-17%). This comparison serves to confirm that the model set up is typical to terraced houses. The cases with 2.55 m high chimney fitted (1 & 2) were first analysed by observing the temperature and velocity contours by the side view as seen in Figures 2 and 3 for case 1 and case 2 respectively. The section was sliced at the middle line of the airwell as shown in the plan view of Figure 1. The temperature contours of case 1 can be seen to show some back flow since the airwell temperature profile shows much of the near-exit region was close to the ambient value (Blue). while that of case 2 with much less sign of back flow, showing much lighter shade of blue in the same region. Referring to Figure 1b's points of measurement when visually-estimating Figure 2, the air flow velocity at the midplane appears to be quite high at 0.4-0.5 ms^{-1} for Case 1 at the level of human activity of 1.5 m, and at around 0.2-0.3ms^{-1} in Case 2 (Figure 3). In Case 3, shown in Figure 4, the velocity in the same region is at around 0.05-0.20 ms^{-1}, well below the recommended ventilation value of 0.25 ms^{-1} (ASHRAE 55, 2009), while Case 4 maintained it at between 0.2 and 0.3 ms^{-1} (Figure 5).

Table 2. Mean Air flowrate and Velocity at the Airwell Inlet Window

Case	1	2	3	4
Air Velocity at Airwell Window (ms^{-1})	0.39	0.18	0.07	0.10
Air Temperature at Airwell Window (°C)	33.9	37.2	38.2	36.2
Air Changes per hour (ACH)	87	40	15	22

Table 2 indicates that without a chimney the use of a wiremesh blocker of adverse cold inflow can maintain a steady ventilation rate for thermal comfort while without one a terraced house with the same height of airwell would not be well ventilated; and a chimney of 2.55 m would be needed to be installed to eliminate cold inflow at the airwell top and the flow stability is also not guaranteed despite achieving quite high velocity.

Table 3 shows the point values of temperature and velocities at points A, B and C of Figure 1b for cases 3 and 4 to show whether there is any improvement in the air flow and temperature. The mean air temperature in the room appeared to have dropped by 0.3 K while the mean velocity increased by 44%, which can be felt by the residents. Both case 3 and 4 seemed to have added a ventilation path via the inlet window as the airwell was not efficient in discharging the warm air. However, cases 1 and 2 also indicated some reversed flow at the window inlet. This means the airwell was probably adding some resistance to the outflow.

Table 3: Test Room Point Temperatures and Velocities at 1.5 m level (Figure 1b)

	Air temperature (°C)		Air velocity (ms^{-1})	
Point	Case 3	Case 4	Case 3	Case 4
A	30.2	30.0	0.18	0.21
B	30.3	30.0	0.21	0.26
C	30.4	30.1	0.08	0.21
Mean	30.3	30.0	0.16	0.23

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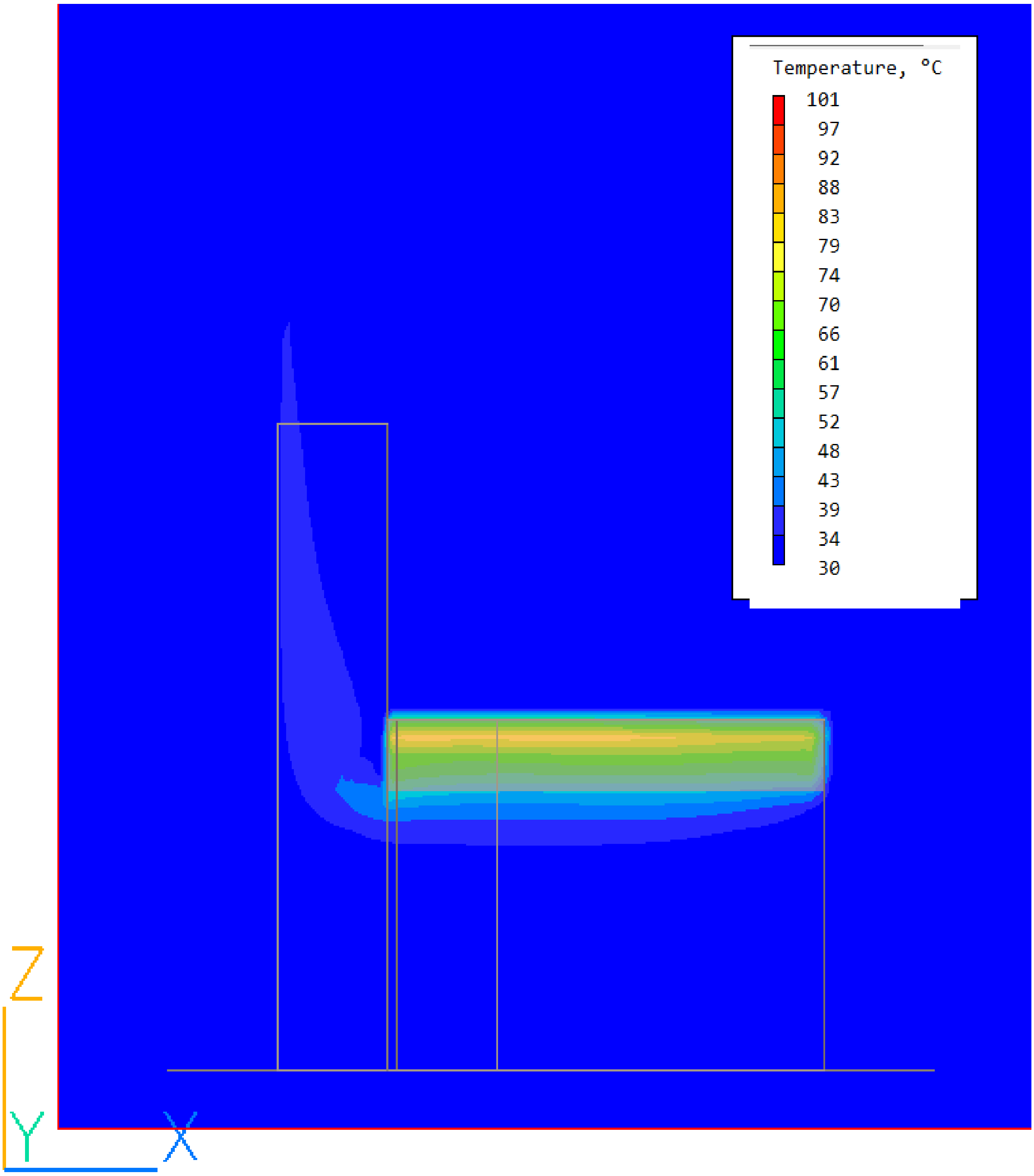

Figure 2a. Airwell Middle plane Temperature Contours of Single-Storey Terraced House fitted with a 2.55 m Chimney without Wiremesh-based Blocker (Case 1)

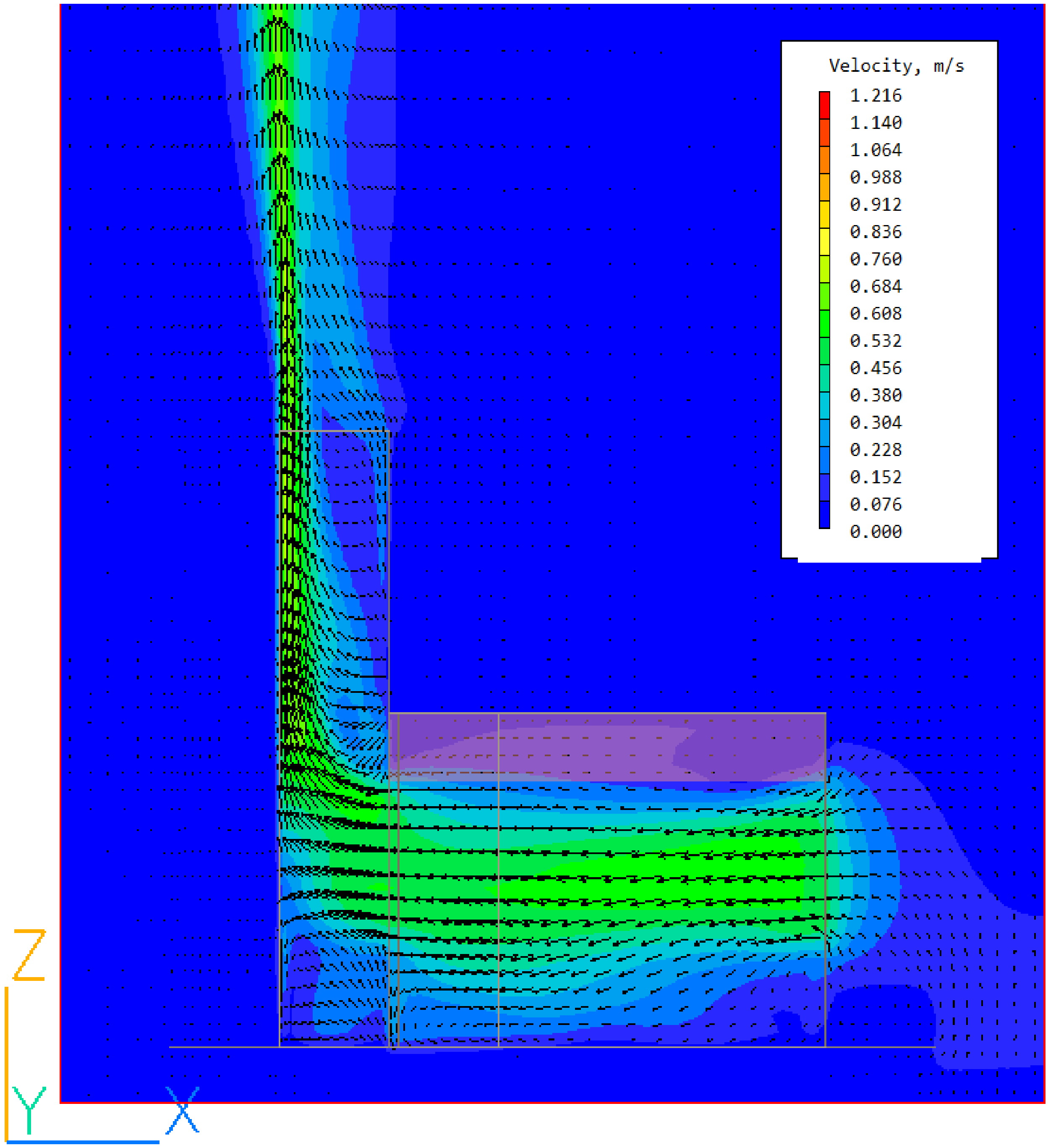

Figure 2b. Airwell Middle plane Velocity Contours of Single-Storey Terraced House fitted with a 2.55 m Chimney without Wiremesh-based Blocker (Case 1), where recirculation at the upper portion of airwell can be clearly seen.

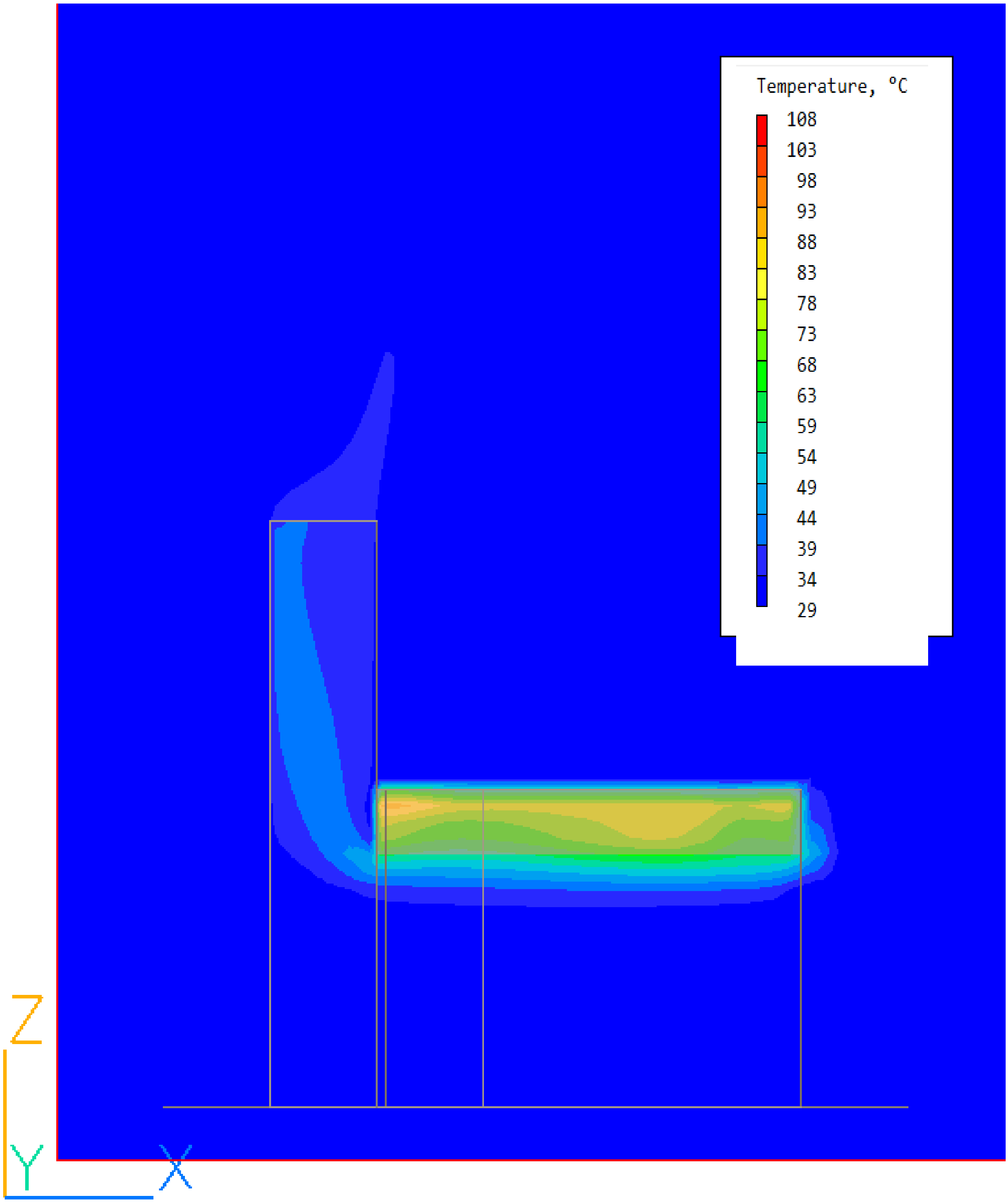

Figure 3a. Airwell Middle plane Temperature Contours of Single-Storey Terraced House fitted with a 2.55 m Chimney with Wiremesh-based Blocker (Case 2), where the temperature is slightly higher than the ambient.

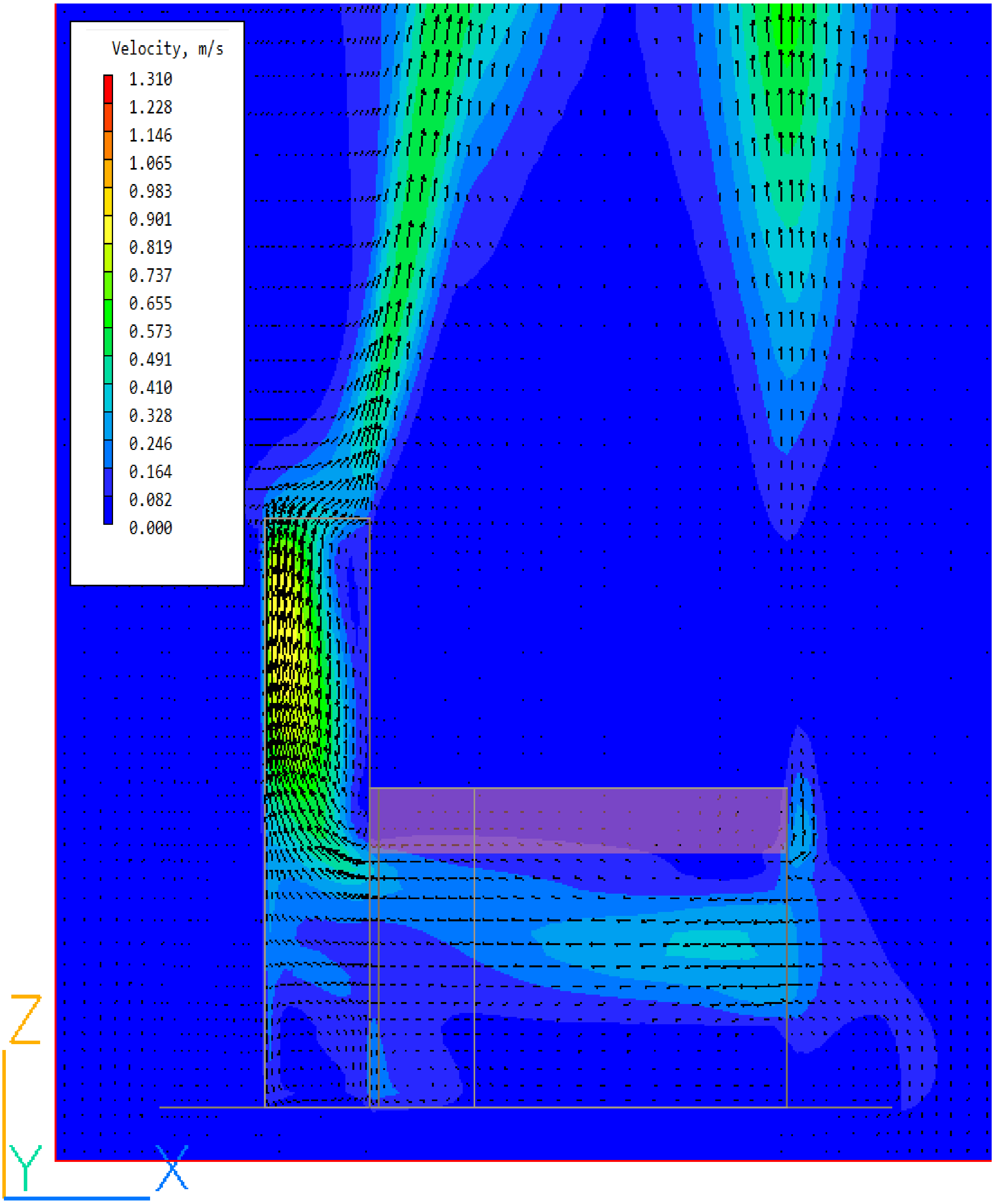

Figure 3b. Airwell Middle plane Velocity Contours of Single-Storey Terraced House fitted with a 2.55 m Chimney with Wiremesh-based Blocker (Case 2), where the recirculation at the airwell top exit has been lessened.

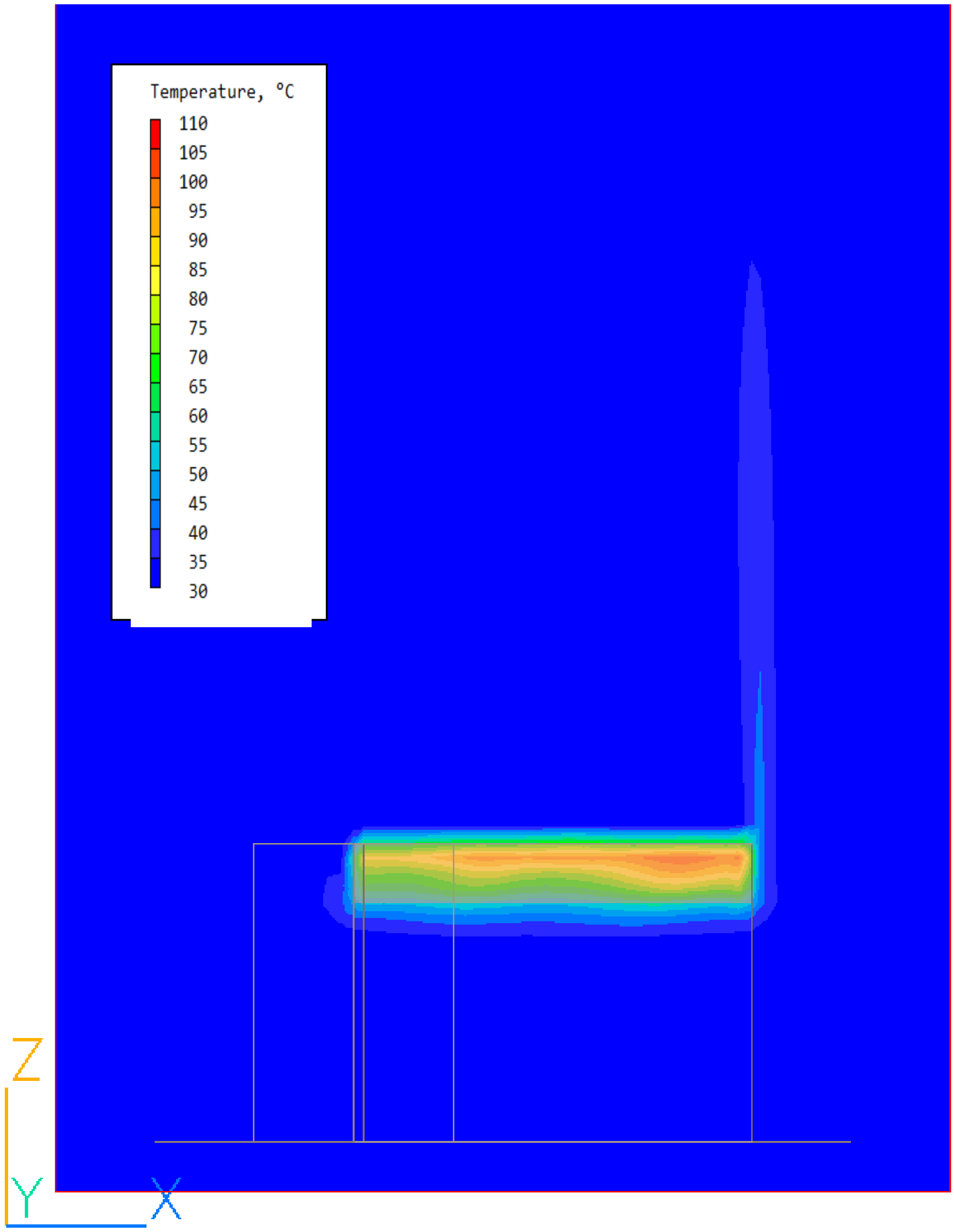

Figure 4a. Airwell Middle plane Temperature Contours of Single-Storey Terraced House without Wiremesh-based Blocker (Case 3), where the airwell can be seen to be non-functional with little increase in temperature.

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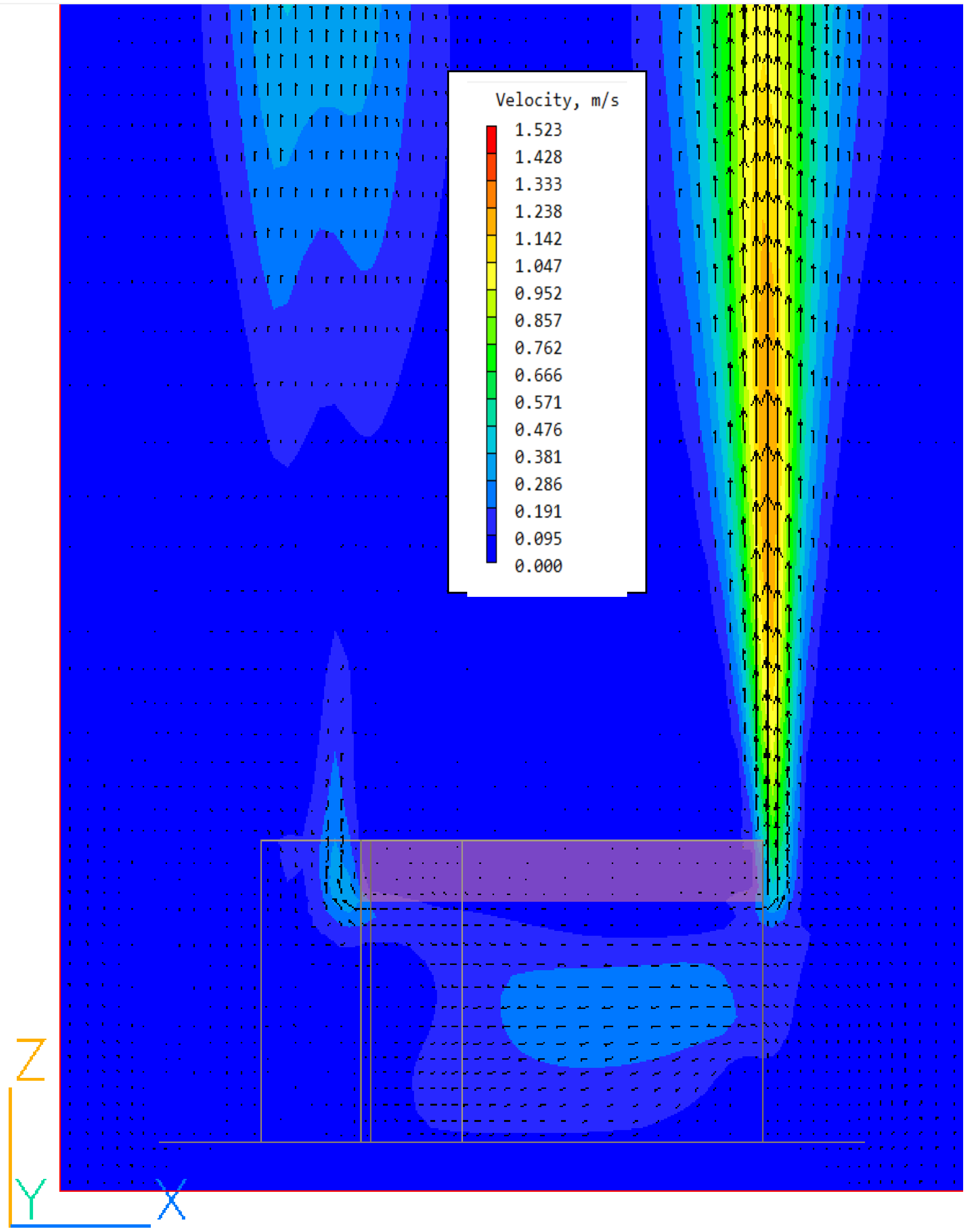

Figure 4b. Airwell Middle plane Velocity Contours of Single-Storey Terraced House without Wiremesh-based Blocker (Case 3), where the out flow appeared to occur at the air inlet window on the right instead of the airwell.

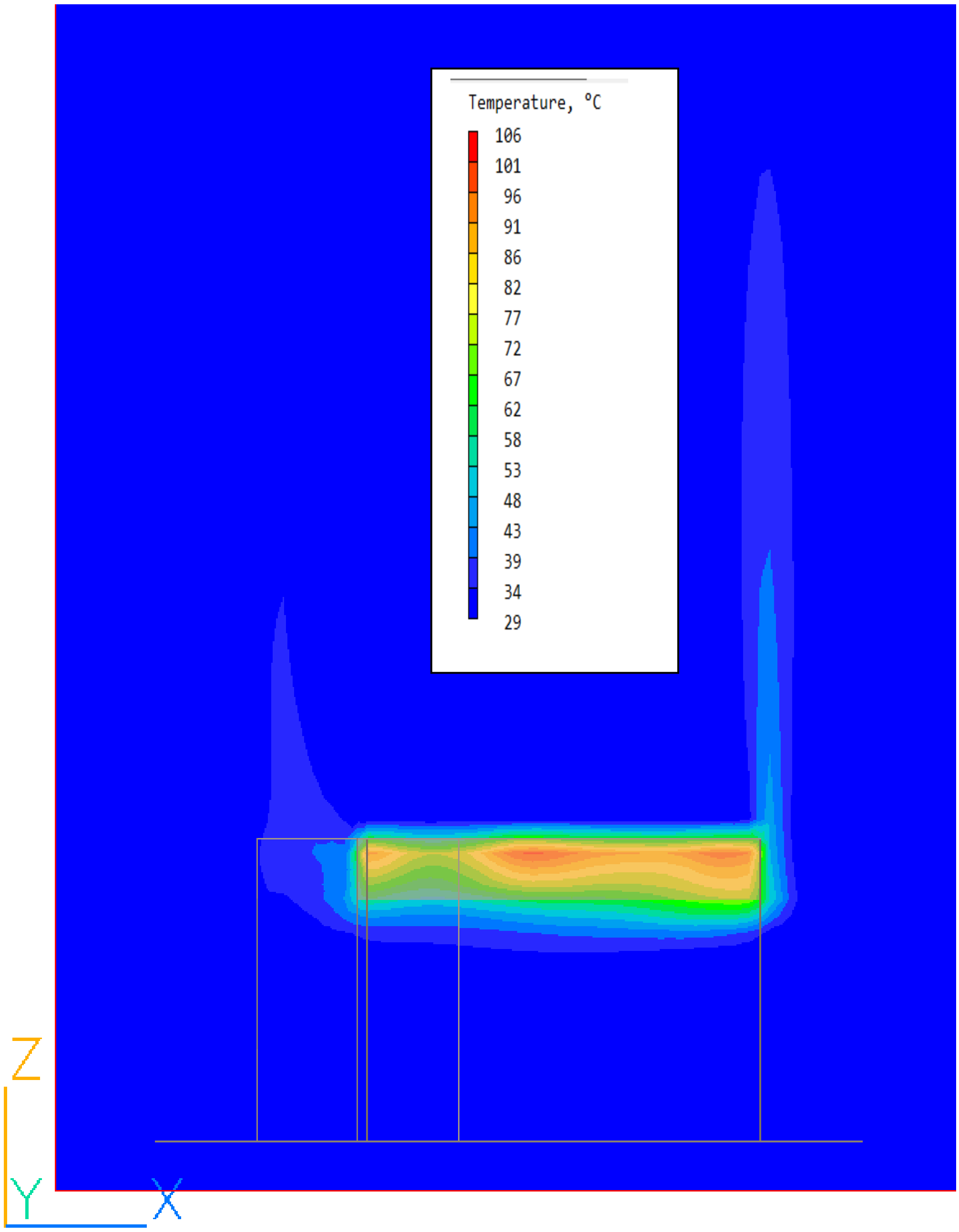

Figure 5a. Airwell Middle plane Temperature Contours of Single-Storey Terraced House with Wiremesh-based Blocker (Case 4), where the airwell temperature is showing more warm air drawn.

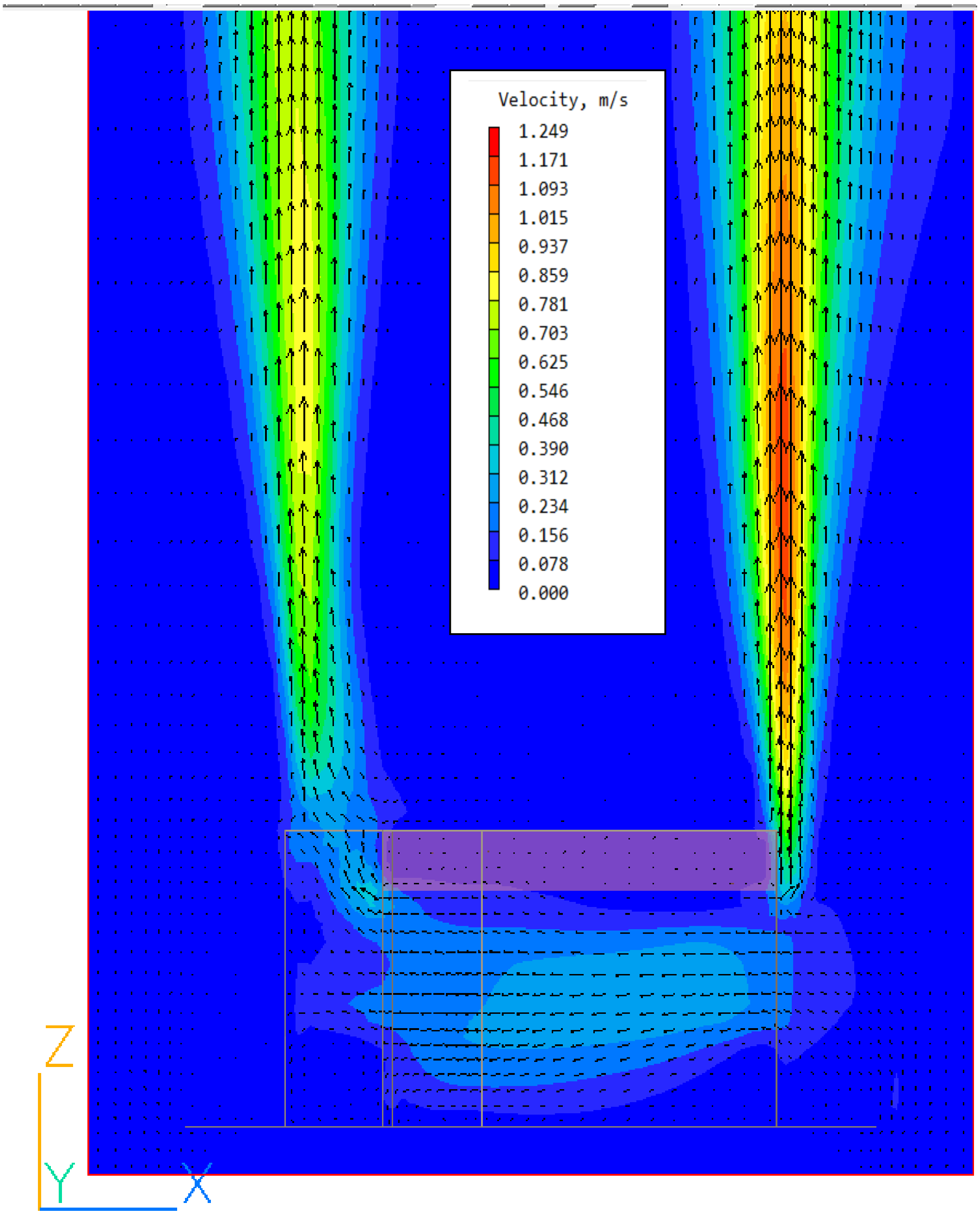

Figure 5b. Airwell Middle plane Velocity Contours of Single-Storey Terraced House with Wiremesh-based Blocker (Case 4), where the airwell is functioning satisfactorily even though there is additional un-designed outflow at the air inlet window.

Using wiremesh blocker of adverse cold inflow improves ventilation and promotes home security since the airwell top is fastened to physically block intruders. This study can be extended to improving the conditions in prison cells which have become a hotbed of infection in the current COVID-19 pandemic, one of the main reasons being poor ventilation in crowded cells. It was reported that by adopting the standard recommended by World Health Organisation (WHO) the transmission rate of tuberculosis was reduced by 38 percent (Urrego *et al.*, 2015).

CONCLUSION

A room in a single-storey terraced house built with an adjacent airwell and chimney has been simulated for natural ventilation performance for four cases. Case 1 appears to perform well in terms of ACH but requires additional construction and maintenance cost of a 2.55 m high chimney.

The use of wiremesh blocker in Cases 2 and 4 show that it enhances and stabilizes the ventilation by blocking the adverse cold inflow at the airwell top exit, so that even without a protruded chimney the airwell can provide stable air flow velocity at human activity level for thermal comfort in the current design of single-storey terraced houses. The wiremesh blocker can also act as a security against intruders.

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