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Research Article

Prediction of Stratified Flow Temperature Profiles in a Fully Insulated Environment

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Abstract: The aim of the study is to present an analytical model to predict the temperature profiles in thermal stratified environment. Thermal stratification is encountered in many situations. The flow of contaminants and hydrocarbons in environment often get stratified. The prediction of temperature profiles and flow characteristics are essential for HVAC applications, environment and energy management. The temperature profiles in the stratified region are successfully obtained, in terms of flow-operating functions. The analytical model agrees well with the published experimental data as well as the related closed-form solutions, which is helpful for HVAC applications. The model will be further developed and incorporated within a numerical model in order to investigate the flow field characteristics and establish correlations for a wide range of parameters.

Keywords: Insulated environment, stratification, temperature profiles, thermal stratification

INTRODUCTION

The phenomenon of stratification is encountered in environmental applications. In a fully insulated environment, smoke and toxic pollutants often get stratified in layers (Awad *et al*., 2008). The prediction of stratified flow characteristics such as temperature profiles, stratified layer thickness and degree of stratification at different flow functions is so important for preventing and managing HVAC in buildings (Awad, 2013). Computational and experimental simulations were performed in order to design effective safety programs and installation of HVAC equipment.

In a fully insulated environment, smoke and toxic pollutants often get stratified in layers. These layers may cause an explosion source or fire hazards. It may cause toxicity by absorption or inhalation of solvent vapours and fine over spray particles (Wander, 2002). As a result, ventilation is required to remove these to the external environment to be exhausted. Thermal stratification is so important for efficient ventilation, which affected by the flow functions and the heat transfer parameters that can be improved by controlling of these functions in order to refresh the selective environment where the extracted heat or pollutant concentration is highest (Hahne and Chen, 1998; Calay *et al*., 2000). Pollutants concentrations could be locked in the space at different levels (layers of pollutants). The distribution of these layers is very sensitive to disturbances; that can cause a great decrease in the local ventilation effectiveness (Mundt, 1994). Using small scale model, Linden *et al*. (1990) found that the stratification characteristics within a confined space depend on the entrainment produced by buoyancy sources. It depends on the geometry of the sources and the openings rather than the source strength, while the degree of stratification however depends on the source strength. In the same manor, Chen and Li (2002) found that the ventilation mode is a function of buoyancy source and geometries. Also they found that the location of the stratification interface level height is a function of the geometrical parameters and independent of the strength of buoyancy source.

Awad *et al*. (2006) studied the effect of input location, exhaust location and airflow rates on the stratified flow characteristics. The results showed that the stratification interface level height and the ventilation flow rates are two main factors in the design of natural ventilation system. Also the stratified flow characteristics are dependent upon the flow parameters and the geometry of the space. A comparison of winter heating demand using a distributed and a point source of heating in the case of constant mixing ventilation was predicted by Kuesters and Woods (2012). They demonstrated that strong two layer stratification was developed in the space, whereas with low ventilation flux or large heat supply the stratification is weak. With mixing ventilation, the temperature is maintained at the

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comfort temperature throughout in the occupied zone near the floor of the space.

Analytical and experimental investigations done by Mundt (1995) describe the temperature gradient and contaminant concentration in a room. While the temperature gradient is always positive and increases up to the ceiling, the contaminant concentration might have another form with a maximum somewhere in the middle of the room. The temperature gradient is highly dependent on the ventilation flow rate and not so much on the position of the heat sources (Mundt, 1995). Hagström *et al*. (2000) found that the contaminant removal effectiveness, in displacement ventilation, is a function of both the location and the strength of the sources in linked to the supply and exhaust openings. Analytical model was performed by Calay and Awad (2004) to examine the formation of stratification in two-phase flow in horizontal pipes. The predictions were in agreement with the experimental data of Abdul-Majeed (1997).

Numerical prediction on temperature stratification in a room with under floor air distribution system was utilized by Kong and Yu (2008). The different supply air conditions and heat loads were discussed. The results showed that the effect of three parameters, heat load, supply volume flux and supply air velocity, on room air temperature were expressed by the length scale of the floor supply jet. Cheng *et al*. (2013) showed that the thermal stratification reduces the heat transfer rate from vertical surface. They also found that the non-Darcian and thermal dispersion effects have significant influences on velocity and temperature profiles as well as the local heat transfer rate. Saïd *et al*. (1996) presented the predicted impact of thermal stratification on heating energy requirements. Measured stratification, expressed by floor-to-ceiling temperature differential, was in the range 4-11°C. Two air layers existed in the confined space, a warm upper air layer and a cooler lower air layer with a significant impact on the building's heating energy requirements.

A mathematical model performed by Awad (2013) was designed to investigate the stratified flow characteristics such as temperature profiles and temperature gradients in ventilated environment. The mathematical model is reasonably accurate in predicting the temperature profiles in the isolated chamber. The predictions were in agreement with the experimental data of Awad *et al*. (2008) with significant discrepancies found in these agreements as shown by the results of Awad (2013). As concluded by Awad (2013) additional theoretical and experimental work have been required for a better understanding and controlling the complex phenomena called (stratification).

In summary, most existing studies were either numerical or experimental or correlation for predicting flow characteristics in stratified fully insulated environment. Existing correlations were based on empirical data and their validity is a problem specific, thus cannot be employed. The needs for mathematical and analytical models are so important with special significance for both scientists and engineers. A simple mathematical model is developed to predict the vertical temperature profiles, temperature gradient, stratified layer thickness and height and compared available experimental and analytical works for validity.

It is the objective of the present study to analytically investigate the phenomenon of stratification in a fully insulated environment and to predict the temperature profiles at different flow functions. The prediction was conducted and compared with the published experimental data of Awad *et al*. (2008). It also compared with the published analytical data of Awad (2013) to present the similarities and differences between these predictions.

LITERATURE REVIEW

We consider a simple displacement model for a chamber of height, H ventilated by upper and lower openings of various airflow rates as shown in Fig. 1. It is assumed that the Richardson number of the air within the chamber is high, such that the flow is stratified; it is further assumed that the density within the chamber varies hydrostatically following the Boussinesq approximation. Density differences are supposed to be small and due to temperature variations; their effect is considered only in the buoyancy terms. The coordinates x denotes the direction of flow parallel to the flow, y the direction across the flow and z perpendicular to the floor, which is located at $z = 0$ and $y = h_1 + h_2$.

We consider a base flow of continuously varying viscosity μ for Ern *et al*. (2003) were the base flow viscosity μ is assumed to vary according to the law:

$$\mu(z) = \frac{\mu_1 + \mu_2}{2} + \frac{\mu_2 - \mu_1}{2} \tanh\left[\frac{2}{\Delta}\left(\frac{z}{h} - 1\right)\right] \quad (1)$$

where, the dimensionless $\Delta = \delta/H$ and δ is the stratified layer thickness shown schematically in Fig. 1.

The behavior of air flow shows that the viscosity of gases is strongly affected by the temperature. The viscosity of gases used for the calculation is the power law of temperature difference, which is given by:

$$\frac{\mu}{\mu_c} = \left(\frac{T}{T_c}\right)^{0.7} \text{ or } \frac{T}{T_c} = \left(\frac{\mu}{\mu_c}\right)^{\frac{10}{7}} \quad (2)$$

Substituting Eq. (1) into (2) yields the expression of stratified layer temperature distribution as:

$$T = T_c\left[\frac{1 + (R)^{0.7}}{2} + \frac{\left((R)^{0.7} - 1\right)}{2} \tanh\left[\frac{2}{\Delta}\left(\frac{z}{h} - 1\right)\right]\right]^{\frac{10}{7}} \quad (3)$$

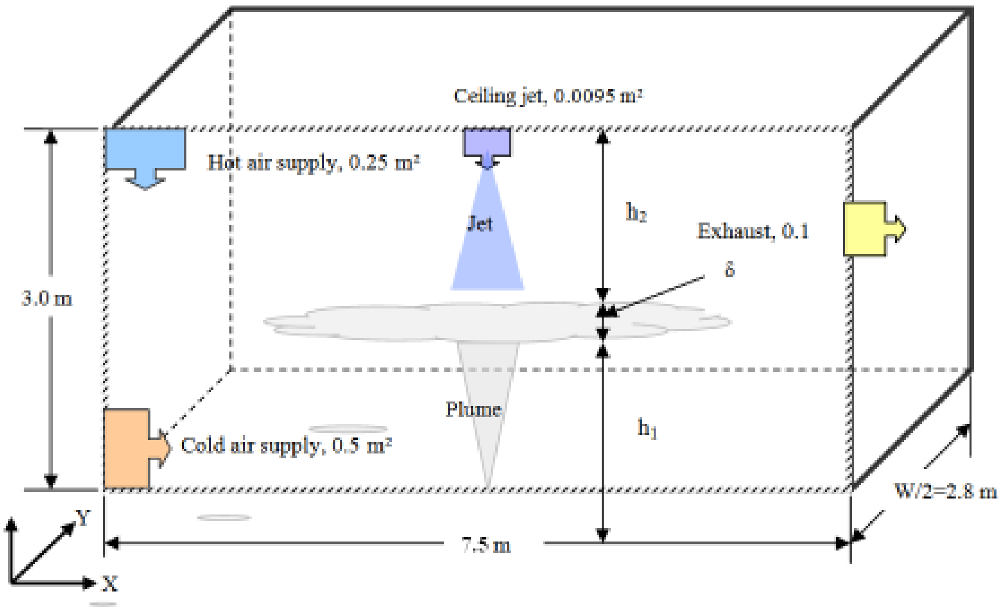

Fig. 1: Definition sketch of the environmental chamber showing a diagrammatic representation of the input airflow supplies, exhaust and ceiling jet

or,

$$\frac{T-T_c}{T_h-T_c}=\frac{1}{R-1}\left\{\left[\frac{1+(R)^{0.7}}{2}+\frac{((R)^{0.7}-1)}{2}\tanh\left[\frac{2}{\Delta}\left(\frac{z}{h}-1\right)\right]\right]^{\frac{10}{7}}-1\right\} \quad (4)$$

where, the temperature ratio $R = (\frac{T_h}{T_c})$, T is the base flow temperature, T_h and T_c are the hot and cold layer's temperatures at the top and the bottom of the space respectively, z is the local height and h is the stratified layer neutral height.

In order to validate the accuracy of the mathematical model, published experimental and analytical results were used for comparisons.

RESULTS AND DISCUSSION

The present analytical model was used to predict the stratified flow temperature profiles in a fully insulated environment. The vertical temperature profiles by the present prediction as well as the closed form solutions were illustrated graphically. The present approach appears to create acceptable prediction with closer confirmed results in all figures. The present analytical results showed a good agreement with the published experimental and analytical results over wide ranges of flow conditions.

The results show successfully the prediction of temperature and viscosity profiles for a thermal stratified flow in a fully insulated environment. The flow pattern temperature profiles were predicted over wide ranges of flow rates. In order to validate the present approximation, the mathematical results of Awad (2013) with the corresponding experimental data of Awad *et al*. (2008) were plotted in the figures as comparison. The model is validated for different volume flow rate. The volume flow rates and the input temperatures were chosen according to the flow rates of the experiments. The results presented were shown in Fig. 2 to 8.

The effect of thermal stratification over the viscosity profile along the flow direction of fully insulated environment is illustrated graphically in Fig. 2. Figure 2 shows the dimensionless vertical viscosity profile for different values of flow parameters. Comparison of the predicted values, for different flow conditions and the experimental data of Awad (2013) are presented in this figure. Figure 2 shows the predicted results and the experimental data of Awad (2013). The solid line indicates the predicted data while the symbols indicate the experimental data.

The results show the variations of viscosity with the dimensionless height at steady state conditions during the required period of time. It can be seen in Fig. 2 that the viscosity distribution of the chamber is in a well stratified condition. The viscosity distribution of the upper and lower part of the chamber is approximately constant, which is due to the induced turbulence near the walls strong enough to destroy the stratification. The viscosity distribution in middle part is increased with significant gradient gives the vertical height of the stratified layer is approximately 80 cm. The viscosity profiles in the stratified region are successfully obtained, in terms of flow-operating

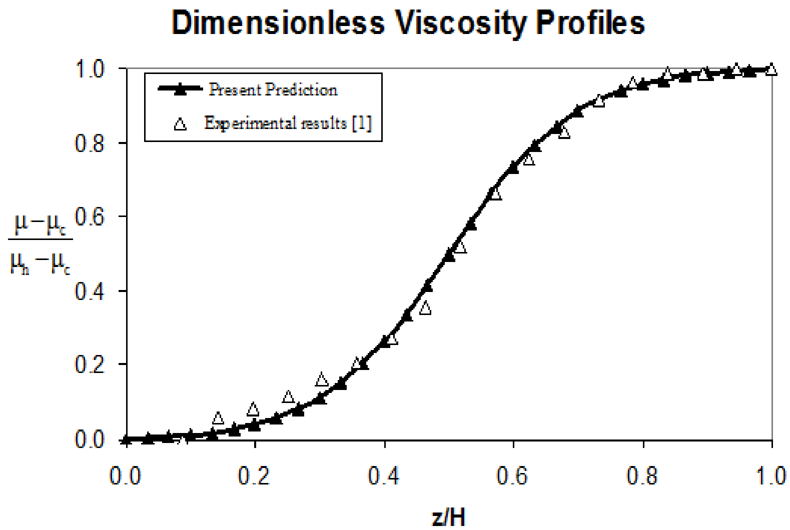

Fig. 2: Vertical analytical and experimental dimensionless viscosity for various air flow rates (Q_h = 2.0 m^3/min) hot airflow rate and (Q_c = 4.0 m^3/min) cold airflow rate at input and output locations of 2.0 and 1.5 m respectively at the centre of environmental chamber

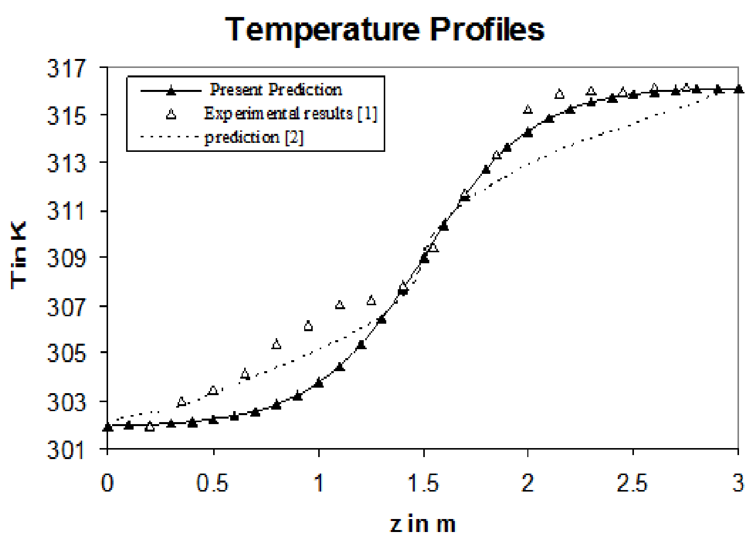

Fig. 3: Vertical analytical and experimental temperature profiles for various air flow rates (Q_h = 4.0 m^3/min) hot airflow rate and (Q_c = 6.0 m^3/min) cold airflow rate at input and output locations of 2.0 and 1.5 m respectively at the centre of environmental chamber

functions. The agreement between the predicted viscosity profiles and the experimental results of Awad *et al.* (2008) are exceptionally acceptable; although discrepancies were found in this figure in the lower zone, because of circulation of air streams near the floor as well as the experimental results always have some uncertainty due to slight variations in the conditions of experiments carried out. The percentage difference between the measured and predicted results is less than 2%.

Figure 3 to 8 show the predicted temperature profiles for different input temperatures T_c and T_h and various flow functions. Figure 3 to 8 illustrate the comparisons between two analytically predicted temperature profiles along with the experimental data performed in the literature. The predictions show a slightly better agreement with the experimental data of Awad *et al.* (2008) than the predicted data of Awad (2013). Also the predictions show a better agreement in the middle zone than the lower and upper zones with the same flow conditions.

Vertical temperature profiles seen in Fig. 3 show a well stratified condition ($\Delta T = (T_h - T_c) = 14°C$) inside the chamber. The predicted and measured data show a high degree of stratification in the studied cases. While the stratified layer thickness is approximately 80 cm,

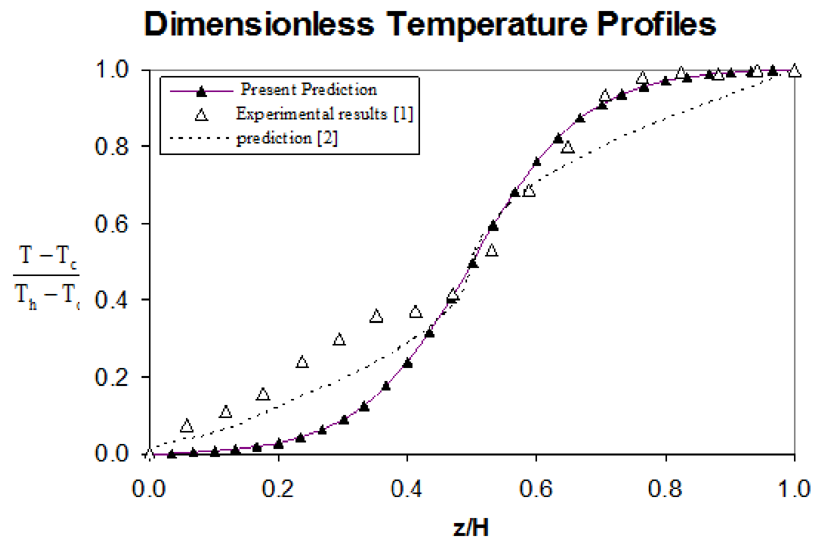

Fig. 4: Vertical analytical and experimental dimensionless temperature profiles for various air flow rates (Q_h = 2.0 m^3/min) hot airflow rate and (Q_c = 6.0 m^3/min) cold airflow rate at input and output locations of 2.0 and 1.5 m respectively at the centre of environmental chamber

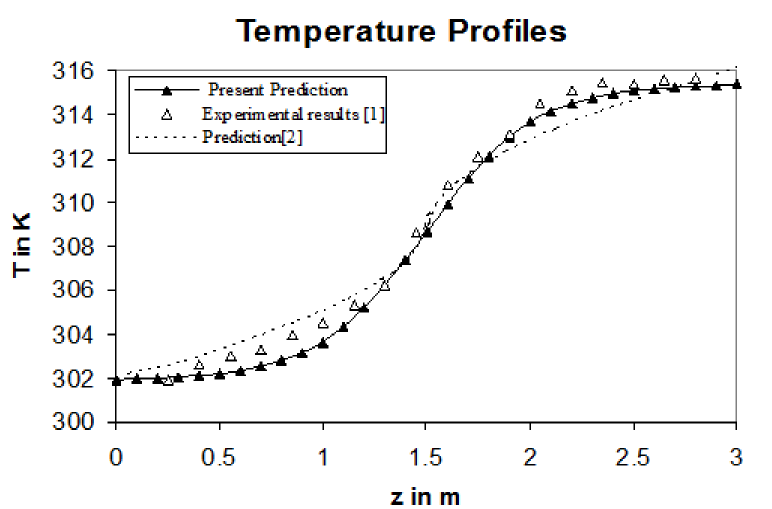

Fig. 5: Vertical analytical and experimental temperature profiles for various air flow rates (Q_h = 2.0 m^3/min) hot airflow rate and (Q_c = 4.0 m^3/min) cold airflow rate at input and output locations of 2.0 and 1.5 m respectively at the centre of environmental chamber

the stratified layer neutral height is 150 cm. The agreement between the predicted temperature profiles and the analytical results of Awad (2013) are acceptable. The agreement between the present predicted and the experimental results of Awad (2013) are particularly acceptable, although discrepancies were found in these profiles in some locations, because the experimental results always have some uncertainty due to slight variations in the conditions of experiments carried out. The small agreement in the lower zone is in combined with a good agreement in the upper zone and an excellent agreement in stratified zone. The percentage difference between the measured and predicted results ranged between (0.0 and 6.0%).

Figure 4 shows the normalized vertical profiles of the temperature increase $\frac{T-T_c}{T_h-T_c}$ with the normalized height z/H designed for different flow functions. The temperature distribution is responsive to the values of input temperatures difference ΔT. Higher values of ΔT tend to produce large temperature gradient concentrated in the middle zone of the chamber. Lower values of ΔT tend to produce low temperature gradient in both lower and upper zones. Comparison of the dimensionless temperature profiles between the predicted results and the experimental results (Awad *et al*., 2008) is shown at the same instance conditions in Fig. 3. It also shows a similar comparison between the predicted data and the

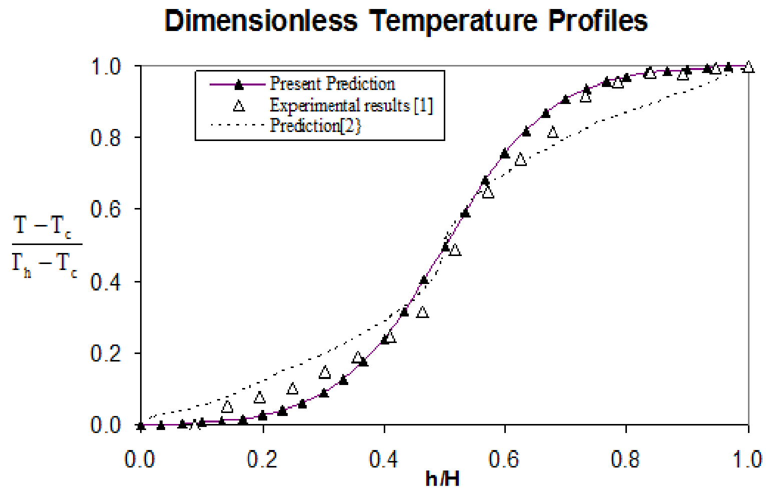

Fig. 6: Vertical analytical and experimental dimensionless temperature profiles for various air flow rates (Q_h = 2.0 m^3/min) hot airflow rate and (Q_c = 4.0 m^3/min) cold airflow rate at input and output locations of 2.0 and 1.5 m respectively at the centre of environmental chamber

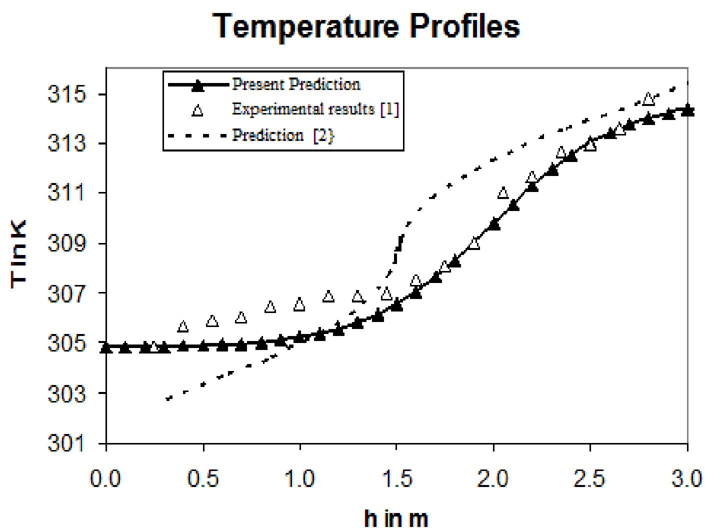

Fig. 7: Vertical analytical and experimental dimensionless temperature profiles for various air flow rates (Q_h = 2.0 m^3/min) hot airflow rate and (Q_c = 2.0 m^3/min) cold airflow rate at input and output locations of 2.0 and 1.5 m respectively at the centre of environmental chamber

mathematical results of Awad (2013). In general the temperature profiles compare well but the discrepancy between experiments and calculation become visible in the lower zone the reason of this kind of difference is considered due to the local turbulence of circulated air near the walls and the variations of experimental conditions. More detailed comparison data are presented in the Fig. 5 to 8.

Figure 5 shows a similar comparison between the predicted data and the published results but smaller temperature difference ΔT = 12°C. The results show a well stratified situation with a high degree of stratification in this case study. The stratified layer thickness is approximately 70 cm and the stratified layer neutral height is 160 cm. The agreement between the present prediction and the previous analytical and experimental results are successfully acceptable in spite of insignificant discrepancies found in these profiles as explained earlier. The percentage difference between the published experimental results and the predicted results ranged between (0.0 and 2.0%). Comparing with the results of Awad (2013) the present analytical model is reasonably accurate in predicting the temperature profiles as shown in the figure.

Figure 6 show that the predicted normalized temperature profile is in good agreement with the published experimental results at all zones of the chamber. In the upper zone, it is observed that the predicted values were consistently higher than the measured values, whiles it is at the opposite in the

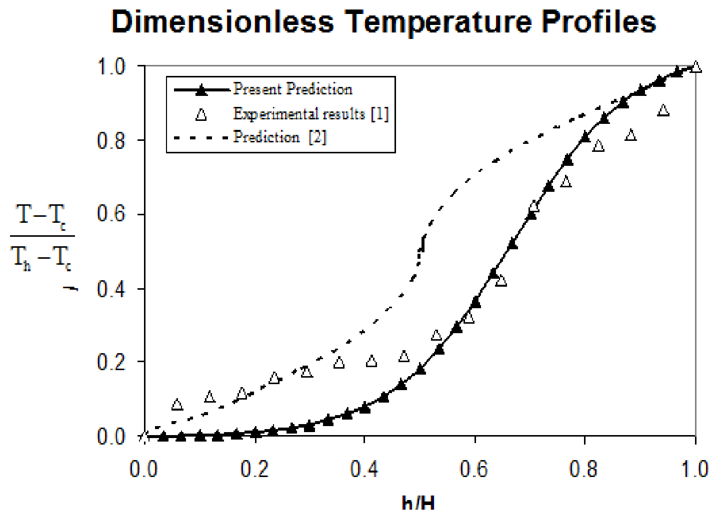

Fig. 8: Vertical analytical and experimental dimensionless temperature profiles for various air flow rates (Q_h = 2.0 m^3/min) hot airflow rate and (Q_c = 2.0 m^3/min) cold airflow rate at input and output locations of 2.0 and 1.5 m respectively at the centre of environmental chamber

lower zone. Comparing with the analytical results of Awad (2013), the present prediction is practically accurate in predicting the temperature profiles as shown in the figure.

Shown in the Fig. 7 and 8, the comparison between the predicted data and the published results for a smaller temperature difference ΔT = 10°C. From the results, the temperature gradient at the middle of the chamber was much larger than that in the lower and upper zones because of thermal stratification in the stratified zone. The degree of stratification is strongly dependent on the temperature gradient were the stratified region stands against the flow as a barrier between upper and lower zones.

A comparison between the present prediction and the analytical results of Awad (2013) is presented in Fig. 7, Figure 7 shows the temperature profiles predicted at ΔT = 10°C compared with the published experimental and analytical results. The stratified layer thickness is approximately 65 cm and the stratified layer neutral height is 200 cm. The agreement between the predicted results and the published experimental results of Awad *et al*. (2008) is really acceptable in both the stratified region and the upper zone. In the lower zone the agreement is practically acceptable and the predicted values were consistently lower than the published measured values. The present prediction is basically accurate in predicting the temperature profiles as shown in the figure. The percentage difference between the experimental and predicted results ranged between (0.0 and 5.0%). Comparing with the results of Awad (2013), the present prediction is practically accurate in predicting the temperature profiles as shown in the figure.

Figure 8 shows the predicted normalized temperature profile at ΔT = 10°C. Comparing the predicted observed shape of the vertical temperature profile with the published experimental and analytical results showed a good agreement especially in the stratified and upper zones. In the lower zone, it is observed that the predicted values were consistently lower than the experimental values but practically acceptable. Comparing with the analytical results of Awad (2013) the present prediction is much better.

Further results can be obtained by comparing the predicted observed shape of the vertical temperature profile in Fig. 4, 6 and 8, which shows normalized vertical profiles of the temperature increase with the normalized height calculated for different temperatures gradient ΔT. The shape of the calculated profile is responsive to the input temperatures difference ΔT. High values of input ΔT tend to produce large temperature gradient concentrated in the middle zone of the chamber were the flow is stratified. Low values of ΔT tend to produce low temperature gradient in both the lower and upper zones were the flow is less stratified. The analysis has shown that three possible flow regimes may develop as a result of variations in the relative size of chamber and temperatures distributions as shown in the figures. Two mixed zones at the lower and upper of the chamber in between a stratified zone with high temperature gradient and different flow properties. In the lower zone it is an upwards concave profile, while in the upper zone it is a downward concave profile. Similar results is also be obtained by comparing the predicted vertical temperature profile in Fig. 3, 5 and 7.

The prediction developed was conducted briefly and comparison was made with published experimental data from literature to present the similarities and differences between the present prediction and the experimental and analytical predictions. The prediction developed in this study is successfully validated against the published experimental and analytical data. The level of agreement with the available experiments is successfully accepted, which support the opportunity to use this simple model in practicing and designing the HVAC systems and applications.

CONCLUSION

An analytical model to predict temperature profiles in thermal stratified environment is developed. Comparison of the present analytical model with the previous works shows that the model provides favorable acceptable solutions for a whole range of flow parameters and ventilation scenarios. So the analytical model is reasonably accurate in predicting the temperature profiles in the isolated chamber. It can be used as guide lines for comparing the results from more complex and comprehensive numerical models. The following conclusions have been drawn in the present study:

- Thermal stratification in built environment is predicted, analytically. The results has shown good quantitative agreement with the experimental data of Awad *et al*. (2008) and the theoretical data of Awad (2013) for acceptable correction factor for all temperatures values.
- The prediction of viscosity profile was in a good agreement with the experimental data.
- The present approach is expected to serve as an approximate analytical tool for predicting thermal stratification in built environment.

In the light of the present analytical investigations, it can be concluded that additional theoretical and experimental information is required for a better understanding of the complex phenomena (stratification).

NOMENCLATURE

Ar : Archimedes Number
g : Gravity acceleration (m/sec^2)
ǵ : Reduced gravity (m/sec^2)
H : Height (m)
h : Stratified layer neutral height (m)
h_1 : Lower layer height (m)
h_2 : Upper layer height (m)
K : Instability dimensionless parameter
Re : Reynolds number
Ri : Richardson number
T : Temperature (°C)
T_c : Cold air input temperature (°C)
T_h : Hot air input temperature (°C)
ΔT : Temperature difference
x, y, z : Horizontal, transversal and vertical coordinates
Δ : Difference between variables, Dimensionless parameter
ν : Kinematics viscosity (m^2/sec)
μ : Dynamic viscosity (kg/m sec)
ρ : Density (kg/m)
δ : Stratified layer thickness (m)

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