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Estimation of convective heat transfer in vertical cylindrical tanks with insulated end-walls

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Introduction

The thermal performance of solar hot water heaters is characterized by static heat loss from storage tanks to the ambient air, especially during off-sunshine hours. Given that natural convection heat transfer inside a storage tank governs the rate of heat loss, several researchers provided heat transfer correlations to estimate natural convection heat transfer coefficient inside the tank. A shortcoming of existing correlations provided in the literature is that they were either dependent on parameters such as material and thickness of insulation (Oliveski et al., 2003) or time elapsed since the tank was fully charged (i.e. the entire tank was filled with hot water at uniform temperature) (Rodriguez et al., 2009). To overcome those limitations, the correlation that is most often used to estimate heat loss from the tank sidewall is that of a vertical flat plate, which may not be applicable to enclosures with relatively low aspect ratios. Having said that, this study aims to investigate if a well-established vertical flat plate correlation of Churchill and Chu [7] is suitable to predict heat transfer coefficient on the sidewall of cylindrical storage tanks, having different volumes and aspect ratios that fall within the range of solar domestic hot water tanks.

Numerical method

To estimate the natural convective heat transfer coefficient independent of time, it is necessary to keep the temperature difference between the water and the wall constant. This can be achieved by imposing uniform volumetric heat generation source inside the tank, which would maintain the water temperature constant. As such, a three-dimensional computational fluid dynamics (CFD) model of cylindrical tank with internal uniform heat generation was developed using the CFD code, ANSYS Fluent 19.2. The rate of volumetric heat generation is adjusted to keep the average temperature of water at 60°C, while subjected to insulated end walls and isothermal sidewall temperature of 59°C, as shown in figure 1.

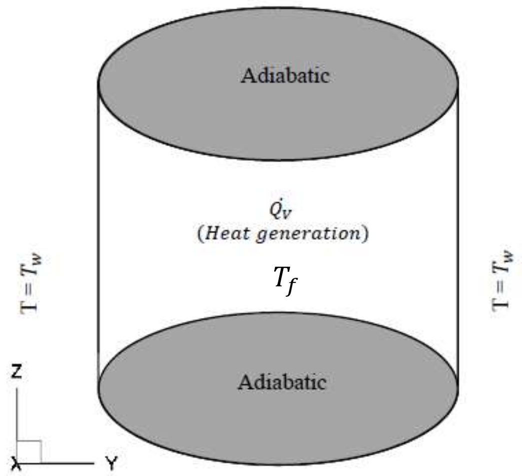


Figure 1. Schematic of the computational boundary conditions

Insulating the horizontal end walls would allow us to examine the sole influence of the vertical side wall on convective heat transfer by comparing the results to that from a standalone vertical flat plate. In this study, two tank volumes of 169 L and 269 L, having aspect ratios between 1 and 3, were considered since these falls within the typical range of solar domestic hot water cylinders.

The experimental study of (Steinberner and Reineke, 1978) on a rectangular cavity with internal heat generation and isothermal cooling on every wall showed that turbulence modelling is necessary for the range of Rayleigh number between 5×10^{12} and 3×10^{13}. The rate of volumetric heat generation required to keep the average temperature of water at 60° are in the order of 10^3 (W/m^3) for investigated cases. Thus, the expected Rayleigh number (based on volumetric heat generation) will be in the order of $10^{13} < \mathrm{Ra} < 10^{14}$. Given this, it was hypothesized that the flow regime is turbulent. With regards to modelling turbulent behaviour inside volumetrically heated liquid pools, (Dinh and Nourgaliev, 1997) showed that low Reynolds number k – epsilon models can provide reasonable estimates when comparing to experimental data of (Steinberner and Reineke, 1978). Thus, two-equation low-Re turbulent model proposed by Lam and Bremhorst was chosen in this study. Further, the Boussinesq approximation, which considers the density of water as a linear function of temperature only during the computation of body force, was used in the momentum equation.

A mesh independence study was performed with four meshes having cell sizes ranging from 60 mm to 3.75 mm and monitoring the convective heat transfer coefficient on the sidewall, as shown in Figure 2. The predicted heat transfer coefficients between the 7.5 mm and 3.75 mm mesh showed an error of less than 0.04%, indicating that a mesh with 1,087,655 cell elements with maximum grid sizing of 7.5 mm, was satisfactory.

Results and discussion

To validate the computational methodology of modelling a cylindrical tank with volumetric heat generation, a three-dimensional rectangular tank model was modelled and the resulting Nusselt number on each wall is compared with experimental data of rectangular layer of fluid subjected to isothermal cold walls reported by (Steinberner and Reineke, 1978).

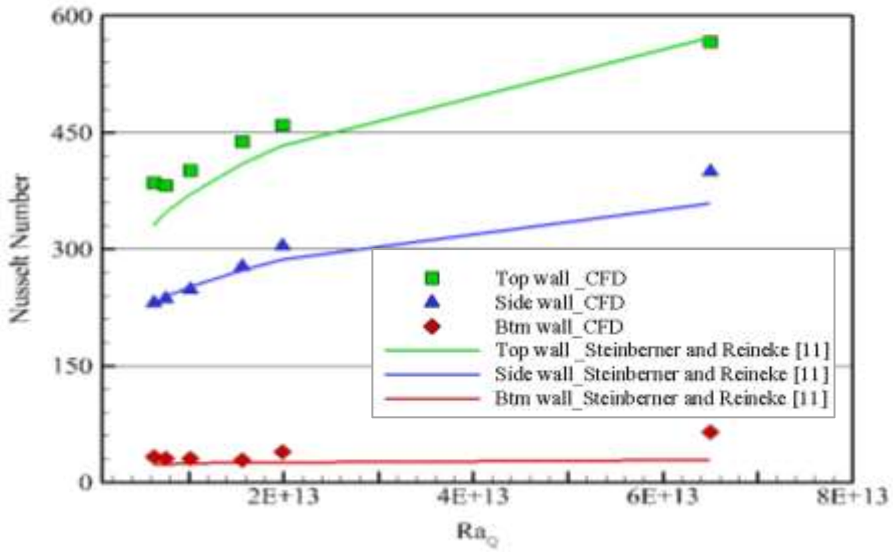
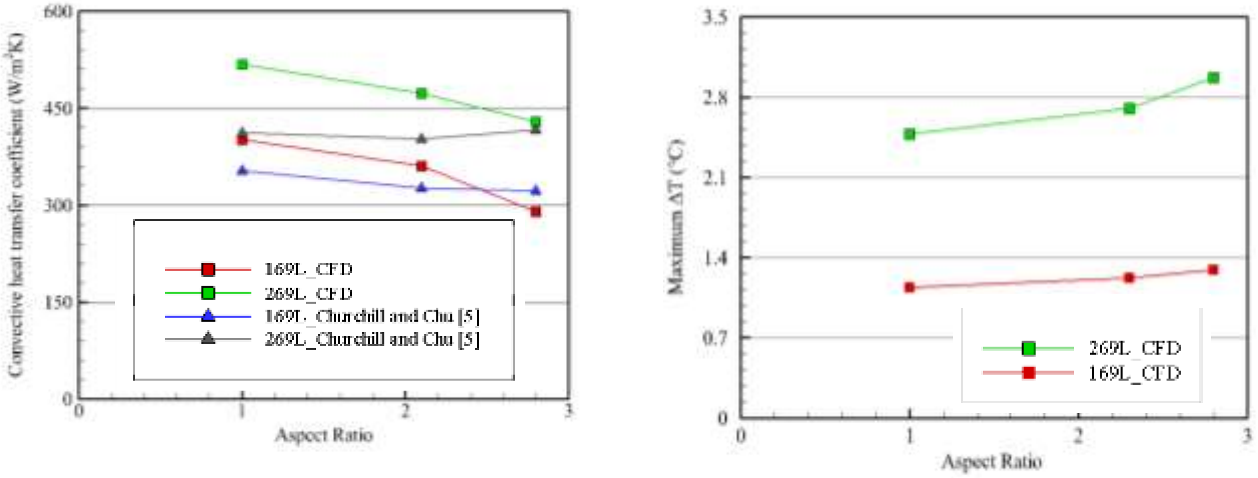


Figure 2. Validation of CFD method with published experimental Nusselt numbers from Steinberner and Reineke [9]

From figure 2, it is apparent that the simulated CFD results agree reasonably well with the published data of Steinberner and Reineke (Steinberner and Reineke, 1978) for each tank wall except the bottom wall. Although deviations up to 55% were found, it is important to note that rate of heat loss through the bottom wall contributes less than 6% of the total heat loss and thus, it is not likely to cause significant errors when predicting the rate of heat loss from the tank.

In considering the simulated results in figure 3 (a), it was apparent that increasing the aspect ratio of tanks led to a decrease in convective heat transfer coefficient on the side wall. This is because the degree of thermal stratification, as indicated by maximum temperature difference of water within the tank in figure 3 (b), becomes higher with increasing aspect ratio, and suppresses buoyancy driven boundary layer flow which leads to lower convection heat transfer on the side wall.



(*a*) (*b*)

Figure 3. (a) Comparison of sidewall convective heat transfer coefficient predicted by CFD model and vertical flat plate correlation of Churchill Chu (Churchill and Chu, 1975) and (b) Maximum temperature difference of water within the tank reflecting the degree of thermal stratification

It is also interesting to note that as the aspect ratio increases, estimations of convective heat transfer coefficient from vertical flat plate correlation become closer to those predicted by CFD model. This is because as the aspect ratio becomes higher, the vertical sidewall of a tank exhibits similar characteristics to that of a vertical flat plate. In low aspect ratios, a significant amount of mixing occurs near the bottom of the tank which increases convective heat transfer on the side wall. However, the intensity of mixing reduces drastically with increasing aspect ratio and only takes place near the bottom of the side wall. This phenomenon is more pronounced in the case of tank with 269L compared to 169L and is clearly illustrated by velocity contours in figure 4 (a) and (b). On the other hand, this behaviour is absent in the case of a vertical flat plate.

Conclusion

Natural convection heat transfer inside cylindrical enclosures, which is applicable to solar water storage tanks, has received little attention and because of this, there is a lack of relationships that can be used to determine the steady state rate of heat loss from such systems.

To address this, this work investigated the suitability of using a vertical flat plate correlation to predict convective heat transfer coefficient on the side wall of cylindrical tanks with various volumes and aspect ratios that fall in the range of domestic solar water storage tanks. The results show that although estimations of convective heat transfer coefficient from flat plate correlation gets closer to that of simulated data in tanks with low volume and high aspect ratio, a maximum deviation of from numerical data is observed in tanks with high volume and low aspect ratio, up to 21% compared to the numerical results. As such, there is still a significant amount of work to be undertaken in the development of relationships that can be used to accurately predict convective heat transfer coefficient inside cylindrical storage tanks.

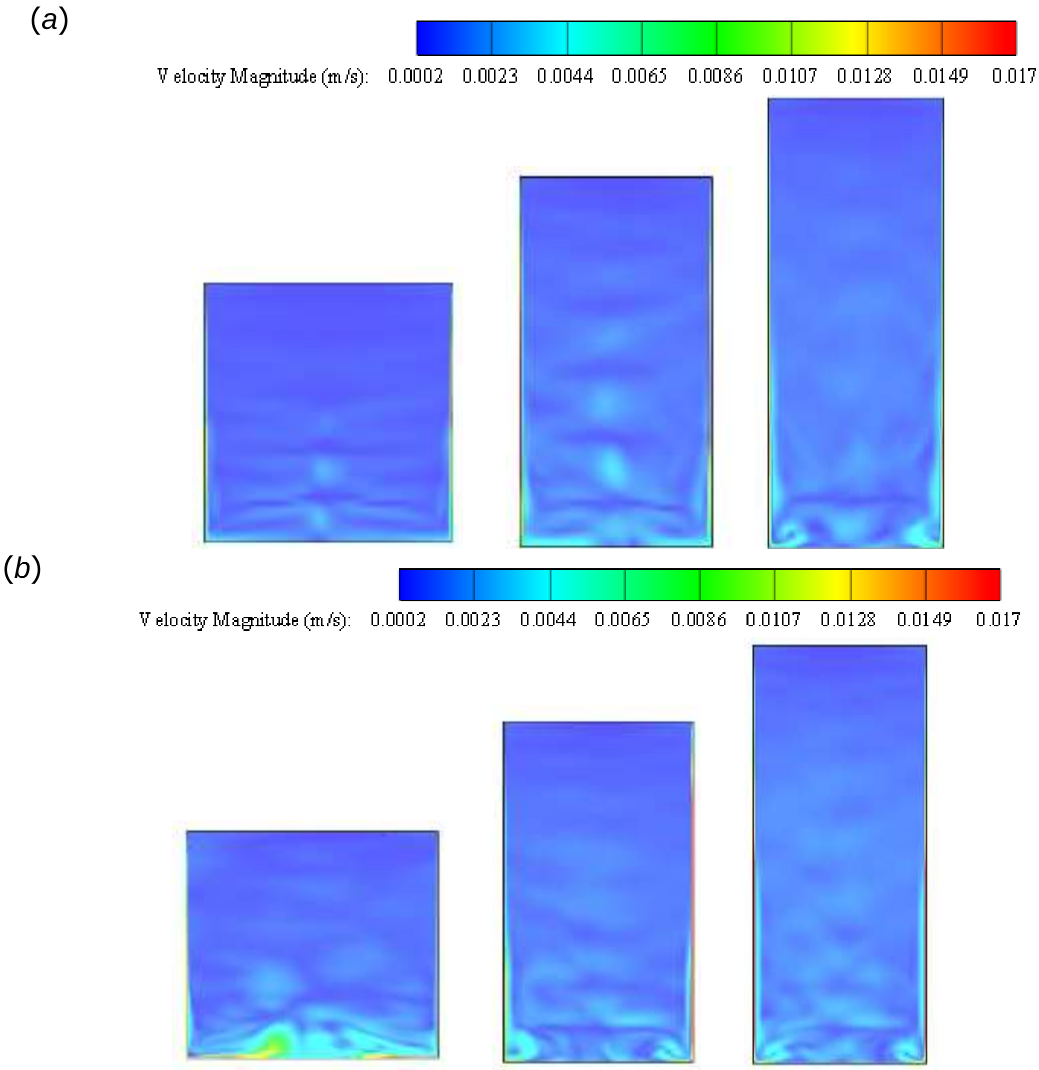


Figure 4. Velocity contours of tank models with various aspect ratios with tank volumes of (a) 169L and (b) 269L

References

Churchill, S. W. and Chu, H. H, 1975, 'Correlating equations for laminar and turbulent free convection from a vertical plate', *International journal of heat mass transfer,* 18**,** p1323-1329.

Dinh, T. and Nourgaliev, R, 1997, 'Turbulence modelling for large volumetrically heated liquid pools', *Nuclear Engineering Design,* 169**,** p131-150.

Oliveski, R. D. C., Krenzinger, A. and Vielmo, H. A, 2003, 'Cooling of cylindrical vertical tanks submitted to natural internal convection', *International journal of heat and mass transfer,* 46**,** p2015-2026.

Rodriguez, I., Castro, J., Perez-Segarra, C. and Oliva, A, 2009, 'Unsteady numerical simulation of the cooling process of vertical storage tanks under laminar natural convection', *International Journal of Thermal Sciences,* 48**,** p708-721.

Steinberner, U. and Reineke, H.-H, 1978, 'Turbulent buoyancy convection heat transfer with internal heat sources', *International Heat Transfer Conference Digital Library*, Begel House Inc.