Numerical simulation of the long-term cooling process applied to a storage tank with an internal gas flue

HMOUDA Imen[1], *RODRIGUEZ Ivette*[2] *and BOUDEN Chiheb*[3]

[1]Energy in Buildings and Solar Energy, National School of Engineers of Tunis
ENIT B.P. 37 1002 Tunis – Belvédère Tunisia
E-mail: ih_tn@yahoo.fr
[2]Centre Tecnològic de Transferència de Calor (CTTC), Universitat Politècnica de Catalunya (UPC), C. Colom 11, 08222, Terrassa, Barcelona, Spain
[3]Energy in Buildings and Solar Energy, National School of Engineers of Tunis
ENIT B.P. 37 1002 Tunis – Belvédère Tunisia

ABSTRACT

The transient cooling of a fluid initially at rest, inside a storage tank with an internal gas flue submitted to heat losses to the ambient is studied. In order to identify the relevant non-dimensional groups that define the transient natural convection phenomenom that occurs, a non-dimensional analysis is carried out. A parametric study by means of several numerical simulations led to correlate the Nusselt number to feed simplified models based on global balances.

Index Terms- Storage tanks, CFD simulations, unsteady natural convection

1. INTRODUCTION

Both, in the heating and cooling processes, heat is transferred within the tank by diffusive effects in certain regions and advective effects in others. All these complex phenomena, make the optimisation of the storage tank a difficult task that needs the deep understanding of the involved thermal and fluid dynamics phenomena. Inspite of these difficulties, the numerical codes used to optimise the storage tanks are very often based on simple mathematical models (based on global mass and energy balances) [1-3]. However, when a complication is introduced in the system (such as a gas flue inside the tank), the one-dimensional model becomes inadequate. Thus, empirical models have to be introduced in order to model the global system.

In the present work, the transient heat transfer phenomena inside a storage tank with an internal gas flue submitted to unsteady natural convection has been investigated by means of CFD and heat transfer numerical simulations. In order to investigate the different physical phenomena occurring in the storage tank during the long-term cooling process and due to heat losses to the environment and to the gas flue, different tank parameters and working conditions have been studied, varying the external aspect ratio, the gas flue aspect ratio, the initial temperature, the convection heat transfer coefficient and the tank volume.

A simplified mathematical model using the mean fluid temperature inside the storage tank and the mean gas temperature in the flue has been developped. This model has been used to characterise the transient behaviour of a storage tank during the long-term cooling process. In order to feed this global model with the significant coefficients, a non-dimensional analysis has been performed. From this analysis, the relevant non-dimensional groups that define the case have been identified. Scaling relations to correlate the heat transfer coefficient to the relevant parameters have been proposed. To adjust the results of the detailed numerical simulations to the heat transfer relation, a parametric study has been carried out for a wide range of configurations and working conditions of a storage tank with an internal gas flue.

2. PROBLEM DEFINITION

The composite walls of the tank under study are made of 3 mm steel, 2 cm of polyurethane thermal insulation and 1 mm of steel at the external part. A chimney with a diameter (Dc) is crossing the tank from the bottom to the top (Hc), which gives a supplementary heat exchange surface between the hot gas and the water in the tank. The chimney is connected to a combustion chamber located at the bottom part of the tank. An schematic of the vertical cylindrical storage tank is shown in Fig. 1. Different water volumes = 0.06 ÷ 0.45 m^3, with an external aspect ratios Hc/D = 2 ÷ 3 , with an gas flue aspect ratios Hc/Dc = 7.8 ÷ 15.5 and with a constant height ratio Hc/H = 0.82 have been considered. The values of these parameters cover a wide range of commercial storage tanks.

The initial temperature of the tank, including solid walls and insulation material, has been considered in the range of T_0 = 40÷70ºC while the ambient temperature has been fixed to T_{env} = 20ºC during the whole cooling process. Two different convection heat transfer coefficients between the external tank wall and the ambient have been considered: h_{ext}= 2 and 10 $W/m^2\,K$.

A total number of 36 situations for the transient numerical simulation of the cooling process of the tank has been released.

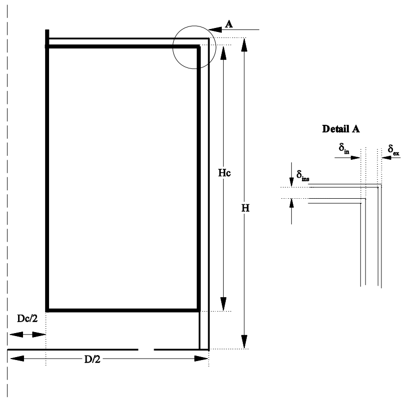

Figure 1. Schematic of the geometry of the storage tank under study.

3. MATHEMATICAL FORMULATION

The domain involves the two fluids (water inside the store and air inside the flue), an internal steel wall, and a polyurethane insulating material covered by an uniform thin layer of steel at external walls.

The fluid flow and heat transfer phenomena for the problem under study is governed by the Navier-Stokes and the energy conservation equations.

In the model, laminar flow and constant physical properties except density variations in buoyancy terms of the momentum equations (Boussinesq approximation) have been assumed.

3.1. Boundary conditions

Considering the symmetry of the problem defined, the computational domain has been assumed to be axisymmetric. No-slipping conditions have been used as boundary conditions for the momentum equations at all solid walls, while at the axis, symmetry boundary condition has been imposed. In the energy equation, every external tank wall (bottom, side and top) has been submitted to external convection actions.

3.2. Numerical approach

The numerical solution has been obtained over the whole domain by discretising the governing equations by means of finite volume techniques as described by Patankar [4]. Fully implicit first order temporal differentiation using cylindrical grids on a staggered arrangement has been implemented. Diffusive terms have been evaluated using second order central differences scheme, while convective terms have been approximated by means of high order SMART scheme using a deferred correction approach [5]. The pressure-velocity coupling has been solved by using a SIMPLE-C algorithm [6]. The resulting equation for pressure has been solved using the direct Band LU solver [7] while the algebraic system of linear equations for the velocities and temperature have been calculated using TDMA line by line solver [4].

3.3 Non-dimensional analysis

Considering governing equations and boundary conditions for the problem analysed, the fluid temperature inside the store depends on the following non-dimensional groups:

$\theta = f(\vec{r}^*, \tau, Ra, \hat{U}, Hc/D, Hc/Dc, Hc/H, Pr, \theta F)$

The mean flue temperature depends on the following non-dimensional groups:

$\theta_F = f(\vec{r}^*, \tau, Re, \hat{U}F, Hc/D, Hc/Dc, Hc/H, Pr, \theta)$

where, $\vec{r}^* = \vec{r}/H$ is the non-dimensional coordinate, $\tau = t\alpha/H^2$, is the non-dimensional time, Ra, the Rayleigh number referred to the temperature difference between the initial temperature and the ambient, $\hat{U} = UHc/k$, $\hat{U}_F = U_F Hc/k_F$, are the non-dimensional overall heat transfer coefficients, between the ambient and the inner wall of the storage, for the gas flue walls respectively.

being k, k_F are the thermal conductivities of the fluid and the air inside the gas flue respectively.

3.3.1. Nusselt numbers

To characterise the long-term behaviour of the fluid cooling by evaluating the transient average fluids temperature in the storage tank and the gas flue, a global model has been proposed. To feed this global model, scaling analysis for Nusselt numbers at the cooling walls have been developed:

- the average Nusselt number which defines the heat exchanges between the water and the ambient air (through the external vertical and top walls);
- the average Nusselt number which defines the heat exchanges between the water and the gas flue (through the inner vertical and bottom walls of the storage tank);
- the average Nusselt number which defines the heat exchanges between the gas flue and the water (through the inner vertical and bottom walls of the gas flue).

4. RESULTS AND DISCUSSION

The data set from the several computations carried out has been fitted to the scaling relation proposed for the Nusselt numbers. The fitting process performed in order to find the values of the constants has been done by means of the GNURegression, Econometrics and Time-series Library (gretl) [8]. The actual fitting process has been done using the Levenberg-Marquardt algorithm [9] implemented in this library.

4.1. The average Nusselt number at the external wall of the storage tank (ambient side)

The scaling relation (1) has shown a good agreement with all the data set with a goodness of the fit of $R^2 = 0.97$, as can be observed in Fig. 2.

$$Nu = 4.181\, \tau^{-0.188} Ra^{0.095} (Hc/D)^{0.398} (Hc/Dc)^{-0.221} (Hc/H)^{0.514}\, \hat{U}^{0.394} \quad (1)$$

In the figure 2, the numerical data and results from the correlation have been arranged in order to express all the data as a function of the non-dimensional time (τ). In Fig. 2 (b) the relative errors between the fitted data and results from the correlation are also shown. The maximum relative error has been found below 18% and the average relative error is in the order of 3.26%.

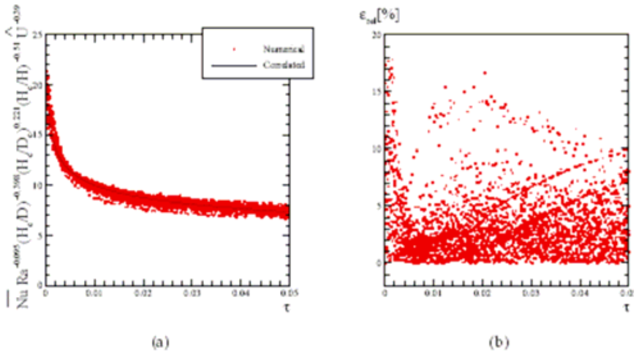

Figure 2. Results from the curve fitting. Nusselt number at the external wall of the storage tank. (a) Comparison between fitted data and correlated obtained. (b) Relative errors between numerical results and correlation.

4.2. The average Nusselt number at the internal wall of the storage tank (chimney side)

The scaling relation (2) has shown a good agreement with all the data set with a goodness of the fit of $R^2 = 0.95$, as can be observed in Fig. 3.

$$Nu_{WF}=0.964\,\tau^{-0.204}Ra^{0.064}(Hc/D)^{0.333}(Hc/Dc)^{0.371}(Hc/H)^{-1.784}\,\hat{U}^{-0.324} \quad (2)$$

In the figure 3, numerical data and results from the correlation have been arranged in order to express all the data as a function of the non-dimensional time (τ). In Fig. 3(b) the relative errors between the fitted data and results from the correlation are also shown. The maximum relative error has been found below 25% and the average relative error is in the order of 3.99%

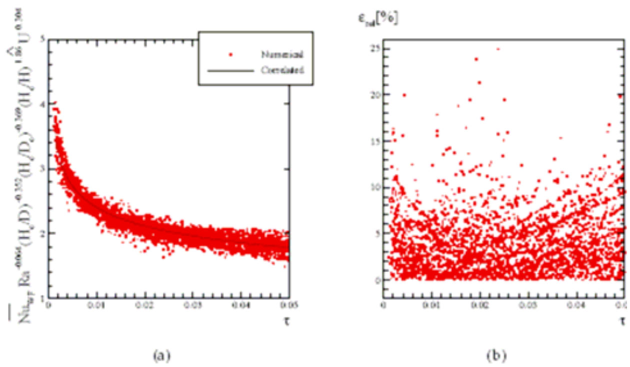

Figure 3. Results from the curve fitting. Nusselt number at the internal wall of the storage tank. (a) Comparison between fitted data and correlated obtained. (b) Relative errors between numerical results and correlation.

4.3. The average Nusselt number at the internal wall of the gas flue

The scaling relation (3) has shown a good agreement with all the data set with a goodness of the fit of $R^2 = 0.97$, as can be observed in Fig. 4.

$$Nu_F=3.66\,\tau^{0.055}(Hc/D)^{-0.281}(Hc/Dc)^{0.898}(Hc/H)^{-3.96}\,\hat{U}^{-0.028} \quad (3)$$

In the figure 4, numerical data and results from the correlation have been arranged in order to express all the data as a function of the non-dimensional time (τ). In Fig. 4 (b) the relative errors between the fitted data and results from the correlation are also shown. The maximum relative error has been found below 9% and the average relative error is in the order of 2.72%.

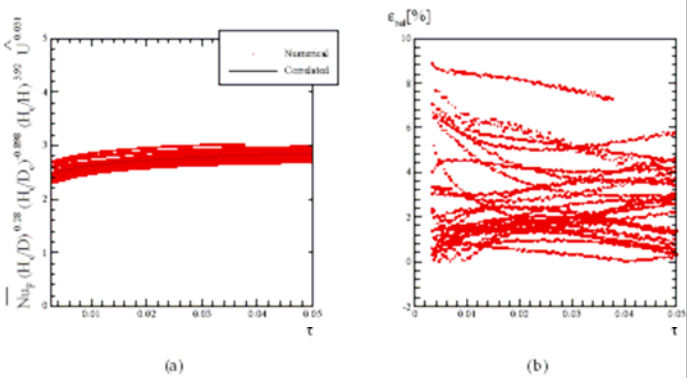

Figure 4. Results from the curve fitting. Nusselt number at the internal wall of the gas flue. (a) Comparison between fitted data and correlated obtained. (b) Relative errors between numerical results and correlation.

5. CONCLUSIONS

A parametric study has been carried out in order to study the transient cooling process of a storage tank with an internal gas flue submitted to heat losses through top, bottom and lateral walls. The range of parameters considered are in the range of most commercial solar domestic hot water storage tanks. From the numerical results, numerical correlations to quantify the Nusselt number at each wall have been proposed and deviations of the residuals show a good agreement between raw data and correlated results

6. REFERENCES

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