A ZONAL APPROACH FOR MODELING STRATIFIED SOLAR TANKS

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ABSTRACT

Thermal stratification in solar tanks is essential for a better performance of energy systems where these tanks are integrated. As a consequence, various technological solutions allow, on the one hand, to support stratification and, on the other hand, to decrease its disturbance. A state of the art on existing technologies and the various levels of modeling leads us to propose a pressure zonal model to predict annual performances of a generic solar tank.

KEYWORDS

Solar tank, thermal stratification, CFD, pressure zonal model

INTRODUCTION

Because of global warming, pollution and oil peak, renewable energies seem to be the best solution to these issues. Solar energy is a suitable solution for building needs. Solar thermal systems can be used in buildings to provide energy for Domestic Hot Water (DHW) and/or space heating. Heat storage for heating systems is required in order to accommodate the intermittent nature of solar radiation and energy resources. Besides, the performance of solar heating systems is strongly influenced by thermal stratification in the storage tank. Stratification allows an optimal use of the store with minimised heat losses and can also be used to ensure that the collector inlet is as low as possible. Furthermore, hotter water is at the top of the tank, which in some cases enables not to use energy supply. Annual performances can be increased by 37% with the use of a stratified solar tank (Hollands and Lightstone 1989).

THERMAL STRATIFICATION INFLUENCE ON SOLAR TANKS TECHNOLOGIES

Thermal stratification phenomena

A “stratified” tank is characterized by a thermocline - the zone of steepest temperature gradient separating the hot and cold fluid zones in the tank. The thickness of the thermocline zone is an important indicator of how well the stratified tank is designed. Several parameters play a role in this stratification quality. Amongst them, a large ratio H/D is essential to obtain a good stratification. Literatures advice a ratio H/D between 3 and 4 in order to enhance storage tank performance (Lavan and Thompson 1977). Nevertheless, the Richardson number [see the nomenclature for its formula], measuring the ratio of buoyancy forces compared with mixing forces, is the more representative parameter during the dynamic charging and discharging process of the storage tank (Hahne and Chen 1998). A small Richardson number means that the storage tank is mixed whereas a bigger Richardson number indicates the storage tank is stratified. As far as this number is concerned, the difference between inlet and tank temperature is the most important factor (Hahne and Chen 1998). In practice, a good thermal stratification is obtained by a charge via the top of the tank with an inlet temperature much higher than the temperature of the surrounding water (>20°C). Moreover, injecting at low flow rate does not to disturb water in the lower part of the store. During the dynamic phases, stratification is influenced by the tank geometry , its internal equipment and its various charge and discharge loops which condition the heat exchange that occurs: inputs/outputs flows, water and envelope conduction, convective exchange (water/envelope, envelope/surrounding) and radiative exchange (external envelope/walls).

These processes of thermal transfers may affect thermal stratification and lead to its degradation.

Then, the control parameters are the temperature difference between the upper and lower tank volume (hot and cold), the wall conductivity, the thickness of the wall, the type of insulation, the tank size, and the surrounding ambient temperature.

These various phenomena will have to be taken into consideration for the development of model because the various technologies that are used tend to increase thermal stratification in solar tanks.

Technical solutions of the market

To obtain stratification in a tank, a double challenge has to be managed: to provide a high level of stratification and to limit destratification in order to maintain the level of stratification.

To support stratification…

Various techniques allow supporting stratification during the solar tank charge. In the first family, 3-way valves operate in on/off function and are controlled according to the solar collector outlet temperature. The fluid is then injected at various tank levels according to its temperature. The number of injections is generally lower or equal to three due to the valve costs. Some manufacturers use a double solar heat exchanger: the primary fluid always passes through the lower heat exchanger but passes first through the higher heat exchanger if this is justified by the levels of temperature. Other manufacturers choose the direct charge/discharge at various levels in the store with an external heat exchanger associated with an appropriated regulation. Moreover, the use of 3-way valves can be associated to a mantle heat exchanger into which the fluid is injected at the correct level. Knudsen and Furbo (2004) advise, for this configuration, the use of a top inlet position for high temperatures and an intermediate height position for moderate inlet temperatures.

To support thermal stratification, a stratification device allows to distribute heat at the correct level by natural convection. The fluid rises up and exits the unit at the height with approximately the same temperature in the store, thus maximizing stratification (figure 1). The importance of “non-return valves” has been demonstrated (Shah et al.) by comparison with a stratifier without flaps which actually works more like a “mixing device” than a stratifying one because cold tank water is sucked into the stratifier. Moreover, it has been found that the stratifier is the most efficient for flow rates between 5L/min and 8L/min. As the investigated stratifiers are often used for volume flow rates far below 5L/min, it has been concluded that there is still a need for further development of these stratifier designs.

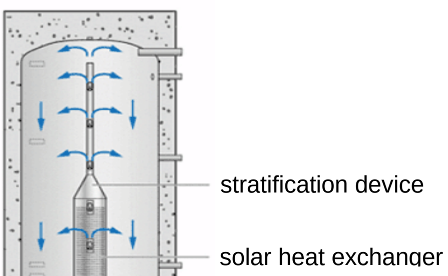

Figure 1 Charge via a stratification device

…and to maintain stratification

In order to limit the mixing during discharge, other technologies are used. DHW draw-offs lead to the injection of a cold water jet into the bottom of the tank. To limit stratification degradation, a cold water inlet device can be used or the fluid can be injected downwards at the bottom of the tank. The results of a study on the influence of a cold water inlet device on thermal stratification (Shah and Furbo 2003) show that entropy and exergy variations are influenced by the Richardson number, draw-off volumes and initial conditions.

Rather than injecting a cold jet directly into the store, it is possible to use a DHW quasi-instantaneous heat exchanger or a smaller tank inside a bigger one (“tank in tank” solution). This will allow to eliminate mixing by the injection of the cold jet. By this process, the DHW does not stagnate at the bottom of the tank: this avoids the proliferation of legionella.

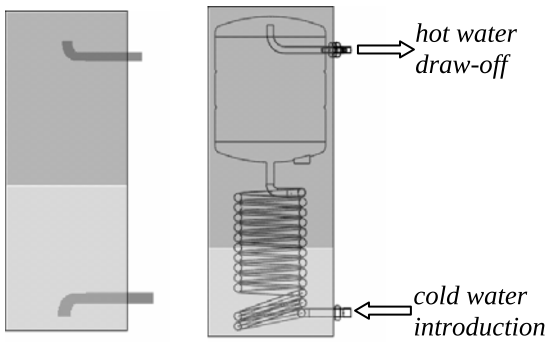

Figure 2 Limitation of mixing by good jet orientation (left) or “tank in tank” solution (right)

To limit destratification due to surrounding losses, the tank should be well insulated. The traditional insulation remains polyurethane foam. An air layer between the tank and a layer of polystyrene can be used in order to benefit from air insulation characteristics. However, the real heat losses from a store are generally much greater than the theorical ones, mainly due to air convection inside the insulation and to air leakages (Sutter 2001). Indeed, melamine resin can be fit closely around the tank. Thus, the conductivity of the materials is important but is not the only parameter influencing the choice of the type of insulation. A well-insulated tank has to enhance thermal stratification by minimizing vertical conduction transfer in the walls of the tank (Murthy et al. 1992). Some manufacturers then choose tanks made of synthetic material. This technological solution allows to reduce the additional thermal losses generated by the various tank connections. Nevertheless, the fluid cooled in hydraulic connections may cool the tank through natural circulation. While some manufacturers decide to incline the connection to the bottom, others use a convection break system (figure 3) for an increase in the annual performances from 10 to 20%, according to the manufacturer.

Figure 3 Convection brake

The presentation of the factors influencing thermal stratification within the tank and the various technologies representative of the market make it possible to set the requirements of the numerical model that has to be developed. Indeed, this generic model will have to reproduce the various phenomena associated with the above mentioned technologies.

DIFFERENT LEVELS OF ACCURACY IN MODELING

We previously emphasized the importance of stratification on the total energetic efficiency of the installation. In this section, we will focus on the different existing tank models.

Multi-layer models

The assumption retained for this model is to vertically divide the store into N volumes, each one at homogeneous temperature. An energy balance for each section describes the interaction between the sections. Then the model solves, as a function of time, a set of differential equations in temperature for each node. These multi-layer models are present in TRNSYS tank models (Klein et al. 2000) under various standard Types (4, 60, 74 and 140). Several alternatives exist among the multi-layer models (ideally mixed with only one layer, plug-flow models, etc.). Nevertheless, the most common model is the type 140 (Drück and Pauschinger 2000) because of the great number of equipments it can deal with (4 internal heat exchangers, mantle heat exchanger, stratification device, etc.). However, the reliability of the models with layers can be discussed: an effective thermal conductivity λ_{eff} simulates heat transfer by conduction and convection occuring between the layers. This parameter, essential in stratification description, does not have any physical meaning and must be obtained by measurements according to the tank type. When a cold layer is found above a hot layer, buoyancy and thermal transfers will physically destroy the inversion of temperature by mixing the fluid. Two methods are then used to simulate mixing in the multi-layer models. A first method consists in increasing effective conductivity to 10,000-20,000kJ/(m.h.K) until the end of the inversion. The other way of restoring the physical organization of the tank temperatures is to calculate the average temperature between the two layers concerned and to assign this temperature to the two layers. This numerical simplification employed by Type 140 and repeated as long as there is an inversion of temperatures, can be responsible for a non-physical rupture of the stratification of the tank. Lastly, the multi-layer models represent only one-dimensional phenomena for three-dimensional tank geometry. The convective movements are then described by λ_{eff} to try to correct the model. This type of model will not allow the simulation of the new tanks.

CFD Models

CFD Modeling, in addition to the possibility of simulating new cases, allow to describe the near reality of the physical phenomena and thus to better understand the flows inside solar tanks. In comparison with one-dimensional modeling, CFD modeling involves less assumptions and empiricism, and is thus more realistic and accurate. A wider range of flow thermal and hydrodynamic conditions as well as complex tank geometric parameters may be modeled. Oliveski and al. (2005) use a two-dimensional method with finished volumes, experimentally validated, to show stratification with an area at a constant temperature in the higher area of the tank. It is checked numerically with conditions of natural convection that two areas of opposite convective flows appear during the tank cooling (Oliveski et al. 2005): an area of flow going down by thermal boundary along the wall is opposed to the relatively slow ascending convective flow in the tank central part. The numerical simulation then allows to represent the evolution of stratification in a more realistic way. We initially decided to reproduce a simulation case found in the literature (Shah and Furbo 2003). The validation of three-dimensional modeling with the assumption of Boussinesq is carried out via Fluent. Very similar temperature repartition than the published results of Shah and Furbo is obtained for the 2 different inlets. A higher hot volume for the tank with an inlet cold device is also noticed. This allows us to validate our assumptions and then simulate new configurations. A relatively simple configuration of a load of 60°C to fixed height of a commercial 750-liter tank with a $1m^3/h$ inlet flow is selected, because easily reproducible in experiments and by other types of simulations. This corresponds in practice to the reheating of the top of the tank via a boiler at the time of insufficient solar energy. Dynamic simulation (0.5s fixed time step) uses the k-ε model of turbulence by informing the hydraulic diameter of 52mm and the intensity of turbulence (Fluent User's guide 1995) of 5.32% calculated according to the Reynolds number. We selected an inlet of 0.1^3m/s at 60°C and benefited from the tank symmetry plane to simulate only a half of its. Moreover, thermal transfer on the walls correspond to a 2mm tank thickness, followed by 10cm polyurethane with $h_{down}=6$ $W/(m^2.K)$, $h_{up}=7.5$ $W/(m^2.K)$ and $h_{side}=8.5$ $W/(m^2.K)$ as thermal transfer coefficients to the bottom, top and the side of the solar storage.

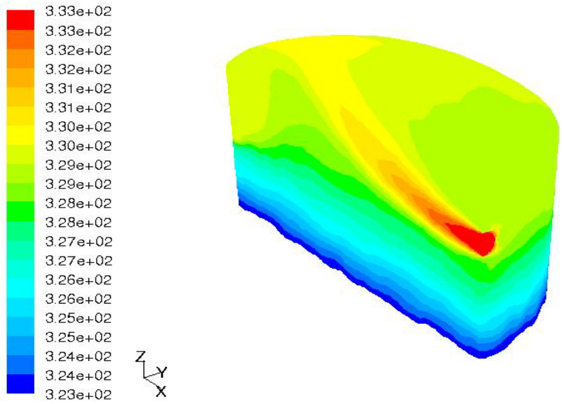

Figure 4 3D visualisation of a 60°C charge at t=20min from a 20°C initial tank

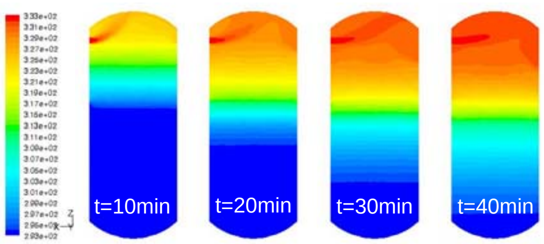

Figure 5 Dynamic temperature evolution from a direct 60°C charge

Dynamic simulation of this configuration enables to visualize the evolution of the jet trajectory (figure 5): initially ascending because of strong difference between its inlet temperature and the tank temperature, the jet will gradually become horizontal when its temperature is equal to the temperature of the surrounding tank fluid. In addition to this evolution of the jet, simulation visualises the dynamics of the load: the plug flow effect is quite real but the different horizontal layers are not at a uniform temperature (figure 4). Johannes and al. (2005) compared CFD results with those obtained by multi-layer models: the 60 and 140 Types used in TRNSYS environment predict a temperature lower than CFD simulation. This is mainly due to the fact that a layer is actually not at a uniform temperature. An isothermal zone is influenced by the dominant flows (jet, boundary layers) but also by the presence of obstacles (Altuntop et al. 2005) in the store (heat exchangers, inlet device, etc.). However, CFD simulations take a considerable computing time (around 5 days for one physical hour of simulation presented), making annual performance prediction impossible. The main conclusion of the multi-layer models and CFD comparison with experiments (Johannes et al. 2005) is the need to develop a zonal model, which is a compromise between reasonable calculation time and the accuracy of the results.

Temperature zonal Models

A temperature zonal model (Kenjo et al. 2002) is developed for annual performance predictions of a mantle heat exchanger tank . Taking into account the boundary layers makes it possible to determine scenarios of flow within the store according to the temperature of the mantle heat exchanger. This characterizes in a more realistic manner the flows inside the tank. However, the model developed for a mantle heat exchanger tank cannot be extended to other tanks.

DEVELOPMENT OF A PRESSURE ZONAL MODEL

The aim of the modeling to be developed is to predict annual performance of a large number of solar tanks. The physical phenomena to be considered are: stratification and the integration of the various specific technical devices (stratifier, heat exchangers, inlet device, insulation, thermal bridges, etc.), corresponding to the technological offer. We decide to develop a zonal model with pressure and temperature as state variables. A three-dimensional modeling approach of the store is chosen in order to consider the various devices. The tank is supposed to be cylindrical of height H and of radius R. Vertically, the cylinder is divided into N_h layers, each of them divided into N_R crowns and N_S sectors (figure 6).

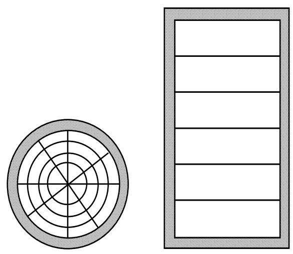

Figure 6 Tank mesh

A first pressure zonal model is developed in Matlab/Simulink environment. From the grid, the pressure and the temperature is calculated for each zone. Pressures P_i of the various zones are assumed to be hydrostatically distributed (1) with ρi function of T_i and P_{0i}, which are the N reference pressures at the bottom of each zone, unknown parameters of the problem.

$$P_i = P_{0i} - \rho_i . g . h_i \qquad (1)$$

The mass flow rate across boundaries are calculated by a power-law function, non-linearly relating the differential mass flow rate to the static local pressure difference between both sides of the separating boundary (2)

$$m_{ij} = \rho_{ij} . k . S_{ij} . \Delta P_{ij}^{\ n} \qquad (2)$$

where $\rho_{ij} = \rho_i$ for a flow from i to j and $\rho_{ij} = \rho_j$ for a flow from j to i. The flow coefficient is assumed to be $k=10^{-4} m.s^{-1} Pa^{-n}$ and the flow exponent is considered to be 0.5 for turbulent flow and 1 for laminar flow. For the moment the values of these coefficients are obtained from the analogy with zonal models used in building airflows prediction.

Mass balances of each zone (3) provide N-1 independent equations. Fixing a reference pressure P_0 in one zone enables to use the traditional iterative Newton method to solve the non-linear system of N-1 other reference pressures. Flow rates, calculated by (2), are then transmitted to the thermal module, which solves the linear energy balance (4).

$$\frac{dM_i}{dt} = \sum_{j=1}^{N} m_{ij} + m_{in} + m_{out} = 0 \qquad (3)$$

$$\frac{dQ_i}{dt} = \sum_{j=1}^{N} q_{ij} + q_{in} + q_{out} = 0 \qquad (4)$$

During a time step, the modules are coupled together using the “onions” method (Hensen 1995), where the module reiterates in one time step until convergence. The dynamic problem is solved by the Runge-Kutta algorithm with a fixed (or variable) time step depending on the number of zone N. The first results of the pressure zonal model are then confronted with the traditional multi-layer model and the experimental results of a direct load in a tank without particular stratification device (figure 7).

Temperature measurement is carried out punctually via a thermocouple line placed at different heights of the tank wall. For modeling, the tank is divided into 6 sections centered on the thermocouple heights. The TRNSYS Type 4 model allows to adopt the volume heights to the measurement grid. The zonal model uses the same heights but each layer is divided into 2 crowns and 3 portions (36 zones in total).

Temperature measured at the outer wall of the tank (between wall and insulation) are corrected for the 2 models to consider the resistance of the wall.

Figure 7, plotting the upper volume, show better agreement of the new model than using the Type 4.

The resluts confirms the need for a zonal model to predict solar tank annual performances (Johannes et al. 2005). The new model allows to better take into account the phenomenon of stratification in the tank. Nevertheless, more validation has to be carried out. It is planned to experimentally reproduce the configuration which was studied in Fluent. Temperature measurement will be performed on different vertical profiles around the tank and with two vertical profiles inside the tank.

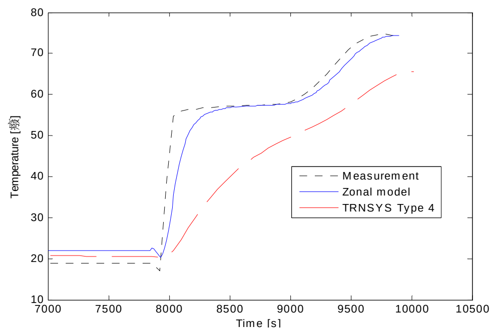

Figure 7 Pressure zonal model vs multi-layer model and experimental measurement

CONCLUSION

The new zonal model developed in this study has shown results very compared to a first run of measurements. However, the model needs to be optimized to decrease calculation time. Moreover, specific flows (boundary layers, plumes, jets, etc.) have to be taken into account to describe as close as possible the various existing solar tanks types. More validation has to be carried out.

NOMENCLATURE

Ri Richardson numberr $Ri = g.\beta.\Delta T.\Delta z / u^2$, [ ]

g acceleration due to gravity, [m/s^2]
β volumetric coefficient of thermal expansion, [1/K]
ΔT temperature difference in Δz, [K]
Δz caracteristical phenomena dimension, [m]
u fluid velocity, [m/s]
H tank height, [m]
D tank diameter, [m]
λ_{eff} effective conductivity, [W/(m.K)]
P_i zone i pressure, [Pa]
P_{0i} zone i reference pressure, [Pa]
h_i zone i centre height, [m]
ρ_i zone i density, [kg/m^3]
m_{ij} mass-flow rate between i and j, [kg/m^3]
m_{in} inlet mass-flow rate, [kg/m^3]
m_{out} outlet mass-flow rate, [kg/m^3]
S_{ij} border area between i and j adjacent zone, [m^2]
ΔP_{ij} pressure difference between i and j zone, [Pa]
k flow coefficient, [$m.s^{-1}Pa^{-n}$]
n flow exponent, [ ]
q_{ij} heat flux from i to j, [W]
q_{in} inlet heat flux, [W]
q_{out} outlet heat flux, [W]

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