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A MODEL OF A LOW FLOW SOLAR DOMESTIC HOT WATER SYSTEM

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ABSTRACT

The low-flow solar water heater – from 7 litres/hour to 15 litres/hour per solar collector area – is the most promising way for improving the solar water heater performance. This performance can be increased taking advantage of the low flow to obtain a better stratification in the tank. For this purpose, the most promising technology uses a mantle storage tank with injection of the collector fluid at several levels.

The aim of this article is to present some numerical and test results from the storage tank of a low-flow solar water heater.

INTRODUCTION

One approach currently explored in several European countries for improving the performances of solar water heaters consists in strongly decreasing the flow rates in the primary loop by a factor ranging from 5 to 10 in comparison with the one of a classic forced-circulation solar water heater, ie a flow ranging from 7 to 15 litres/hour per solar collector area instead of 50 to 70 litres/hour (International Energy Agency, 1996).

This new system – known as low-flow – has advantages compared with the classic system, whose principal asset is the reduction of the size of some components (pipes, valves, exchangers). This also enables us to use small diameter flexible pipes made of synthetic material, which results in easy assembling compared with copper or steel pipes. However, the low flow rate influences the system efficiency, which can be deteriorated if thermal exchanges in the solar collector or the exchanger are impeded by low velocity. On the other hand, the system efficiency can be improved by taking into account the low flow rate to lead to a good stratification in the tank (International Energy Agency, 1996), which allows the collector to be supplied with a colder fluid, hence a reduction of external losses and higher performance. Furthermore, hotter water is at the top of the tank, which in certain cases enables us not to have recourse to energy supply. Thus, this new system can be described as a future way for improving the solar water heater both in terms of performance and in terms of cost.

Various techniques allow to increase thermal stratification in the storage tank. The most promising technology uses a mantle storage tank with injection of the collector fluid into the mantle at several levels (see Fig. 1). There are several products available on the market and more particularly in Europe. The idea is to obtain the best stratification of temperatures in the tank by means of the injection of the collector fluid into the mantle at a level appropriate to its temperature.

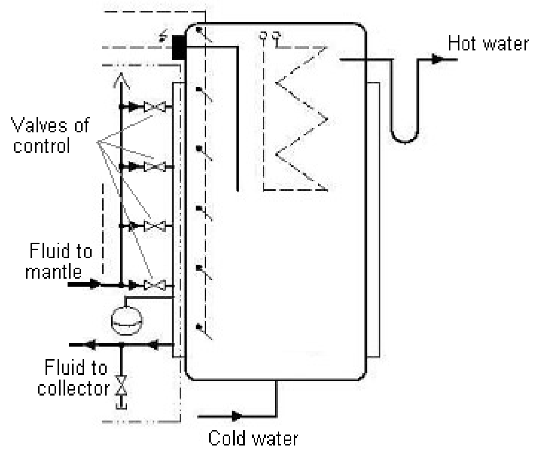

Figure 1 Mantle solar tank with injection at several levels.

SIMULATION AND EXPERIMENT

A model of mantle tank storage with injection of the collector fluid into the mantle at several levels has been developed under TRNSYS environment (Transient System Simulation Program).
This model is based on the principle of zonal modelling of heated water volumes and, the differential equations have been solved by a numerical scheme (implicit method). Figure 2 illustrates the numerical mantle tank model. The mantle tank was divided into 48 nodes and the model was developed in cylindrical coordinates. The fluid in the tank was divided into seven horizontal isothermal layers, each layer being itself also subdivided into two zones, ie a central and a parietal zone. This allows to reproduce the flows of the downstream cold and upstream hot boundary layers. These flows are the driving flows generating the thermal stratification in such systems. So, it is

essential to model them. In order to determine the horizontal temperature stratification, each layer is further divided into 3, 5 or 6 control elements. Two elements for the domestic water, one for the tank wall, one for the insulation and in the mantle layers further one element for the mantle fluid and one for the mantle wall. Each element is assumed to have a uniform temperature.

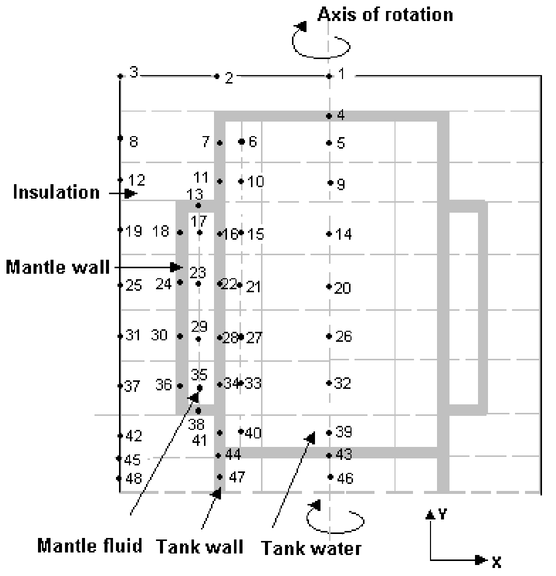

Figure 2 Numerical mantle tank model

Concerning the tank water model, the zonal model concept used does not take into account the momentum equations. So, some hypotheses are necessary for solving the problem (HUTTER, 1981) and (INARD et al., 1998). For that we impose the scenarios of the fluid flow studied.

Two cases of scenarios regarding the heated fluid flow in the tank were analysed. The first case is for a cold boundary layer corresponding to a vertical tank wall temperature (T_P) lower than the tank water (T_∞) (see Fig. 3) and the second one is for a hot boundary layer corresponding to a vertical tank wall temperature (T_P) higher than the tank water (T_∞) where flow direction is opposite the first case (see Fig. 4).

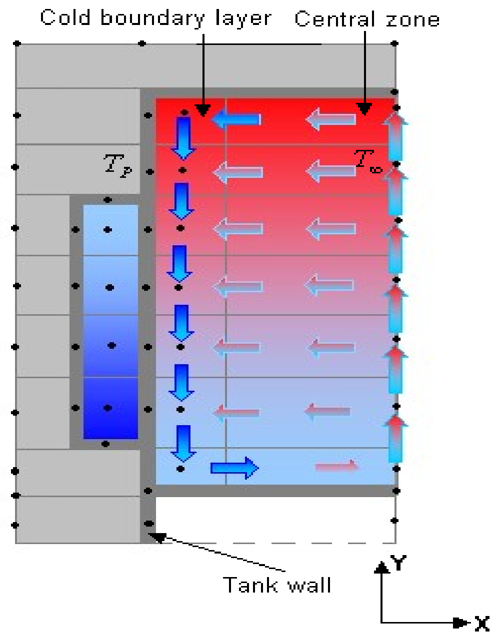

Figure 3 Exchange diagram relative to different zones where (T_P<T_∞).

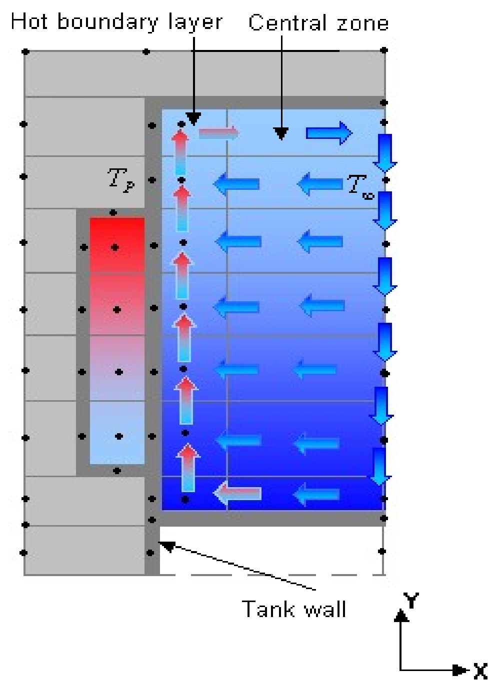

Figure 4 Exchange diagram relative to different zones where (T_P>T_∞).

To find the solution of the zonal model, we have to know every element's inflow and outflow and draw up the energy balance of each layer (the sum of mass inflows being equal to the sum of mass outflows).

The volume flow rate Q(Y) between each thermal boundary layer element is calculated using the equations of the turbulent thermal boundary layer resulting from the integral method.

The profiles of velocity v(X,Y) and temperature T(X,Y) for the turbulent boundary layer are given by equations (1) and (2) (BEJAN, 1995):

$$v_{(X,Y)} = V_{(Y)} \cdot (1 - \frac{X}{\delta_v})^4 \cdot (\frac{X}{\delta_v})^{1/7} \qquad (1)$$

$$T(X,Y) - T_\infty = (T_P - T_\infty) \cdot \left[1 - (\frac{X}{\delta_T})^{1/7} \right] \qquad (2)$$

where

δ_v	velocity boundary layer thickness	(m)
δ_T	thermal boundary layer thickness	(m)
T	temperature	(°C)
T_P	wall temperature	(°C)
T_∞	fluid temperature	(°C)
v, V	velocity	(m/s)
X	horizontal coordinate	(m)
Y	vertical coordinate	(m)

Furthermore we assume that :

$$\delta \approx \delta_T \approx \delta_v$$

As a result of the integration of equations (1) and (2) according to X, the expression of the volume flow rate is obtained:

$$Q(Y) = 0.0098\, a \cdot Pr^{1/15} \frac{1}{\left(1 + 0.494\, Pr^{2/3}\right)^{2/5}} \cdot \left[\frac{g \cdot \beta}{\upsilon \cdot a}\right]^{2/5} \left(T_p - T_\infty\right)^{2/5} Y^{6/5} \qquad (3)$$

where:

Q(Y)	volume flow rate	(m^3/s)
a	thermal diffusivity	(m^2/s)
g	gravity acceleration	(m/s^2)
Pr	Prandtl number	
ν	kinematic viscosity	(m^2/s)
β	volume expansion coefficient	(K^{-1})

Our tank model was then associated with other existing model components of the low-flow solar water heater (collector, pump…) resulting from the simulation software programme TRNSYS (Transient System Simulation Program), with a view to studying the thermal behaviour of the whole system so as to optimize its control and behaviour.

Two kinds of tests were carried out on a testing stand specially designed at CSTB for this purpose. A low-flow solar water heater was purchased on the market and instrumented. Nineteen temperatures and two flow rates were measured every ten seconds as well as solar radiation and power of electric supply. The state of aperture or closure of the valves is also recorded. A first series of tests aimed at validating the storage tank model we had developed. In order to reach this objective, tests were carried out on the tank without any collector (see Fig. 5). For this purpose, an electric boiler was used instead of a solar collector so as to bring the fluid to the temperature and flow rate expected. Using a boiler can also permit to submit the tank to temperature series and flow rate steps.

A second series of tests was conducted on the whole system (tank, collector, pump, etc.). These tests made it possible for us to have an approach to the water heater model as a whole. This series of tests was planned for analysing the thermal behaviour of a low-flow solar water heater in order to optimize the system control and behaviour.

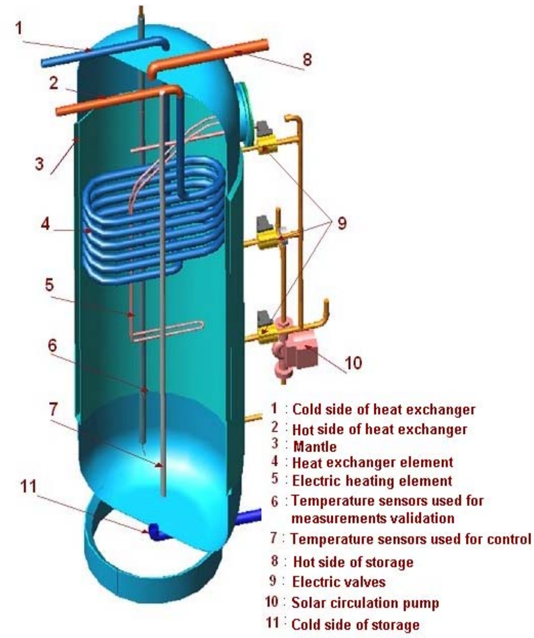

Figure 5 A vertical section of the instrumented storage tank

DISCUSSION AND RESULT ANALYSIS

We present the results of the validation of the storage tank model developed including the analysis of these results.

First of all and to show the importance of this model for low-flow systems, we will present a configuration that shows the execution of thermal stratification of fluid layers (in the tank and its mantel) according to (X) and (Y) axes.

Figures 6 and 7 represent the calculated vertical stratification according to Y during steady flow with an injection of the hot fluid at the highest level of the mantle. Because of the symetry, only half of the system is showned. These figures indicate that the fluid is almost divided into two parts, hot at the top and cold at the bottom. We also notice according to X that the fluid layers in the tank and its mantle are stable in the hot part (see Fig. 7). All these elements prove that the tank achieves a good thermal stratification. Furthermore, we observe at the lower part of the tank a large horizontal thermal stratification (see Fig. 6). This is because the bottom of the wall tank is not insulated while the vertical wall thank is heated by conductive heat fluxes.

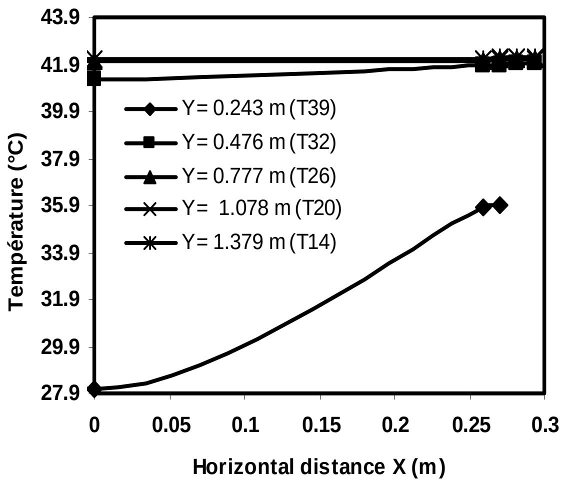

Figure 6 Compared temperatures according to X (radius) at different height levels of the tank.

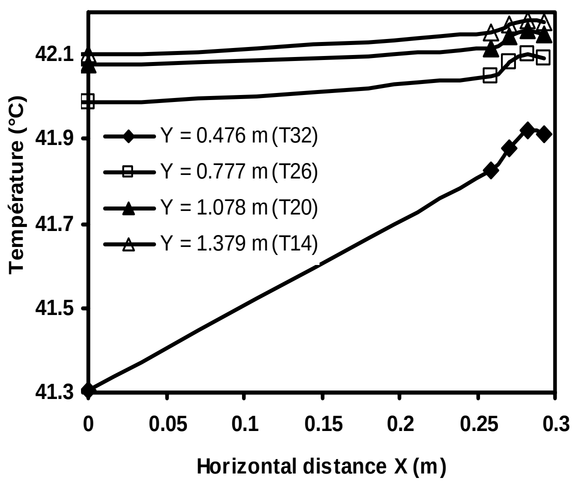

Figure 7 Temperature variation of the top part of the tank and its mantle according to X (radius) at different levels of the tank.

All the results presented afterwards, for the different cases of validation, consider three temperatures corresponding to T5, T20, T39 (see Fig. 2).

Figure 8 presents the results obtained for a case corresponding to a combination of two configurations (injection of the fluid at different levels in the mantle with electric supply in the tank).

This figure indicates that the model correctly reproduces the tested temperature profiles, more particularly at the level of thermal stratification in the tank (see Fig. 9) and at the lower part of the tank (temperature T39).

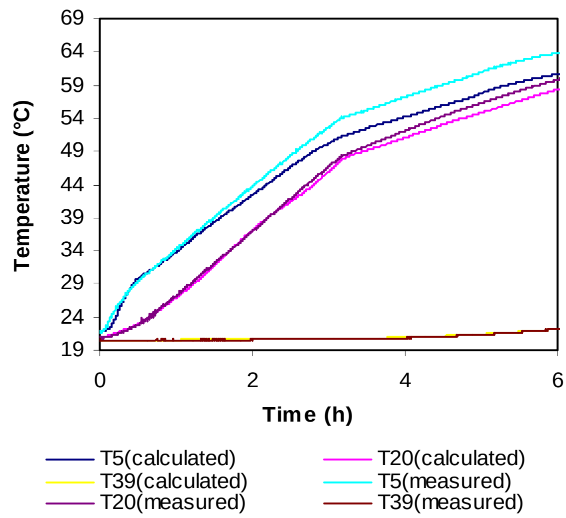

Figure 8 Variation of three temperatures calculated and measured in the storage tank for injection of the fluid at different levels in the mantle with electric supply.

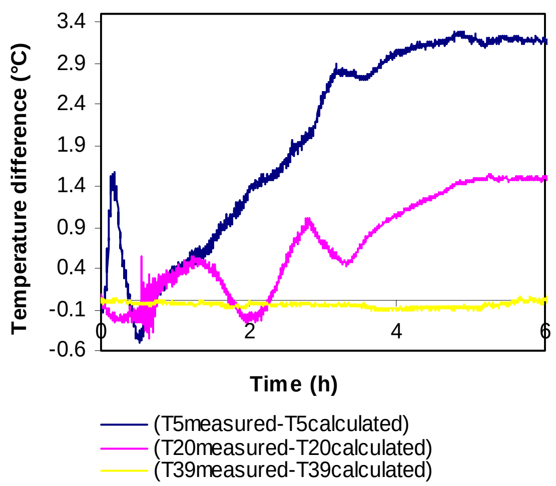

Figure 9 Differences between the three temperatures calculated and measured in the storage tank for injection of the fluid at different levels in the mantle with electric supply.

A second configuration was tested: it is the case of a step of the load flow rate (Mes) for one hour. We noticed that the plug model associated with time lag permitted to represent correctly the experimental fluid phenomena (see Fig. 10 and Fig. 11). However, the introduction of a jet model inside the tank which would lead to an increasing of the mixture could improve the results even more.

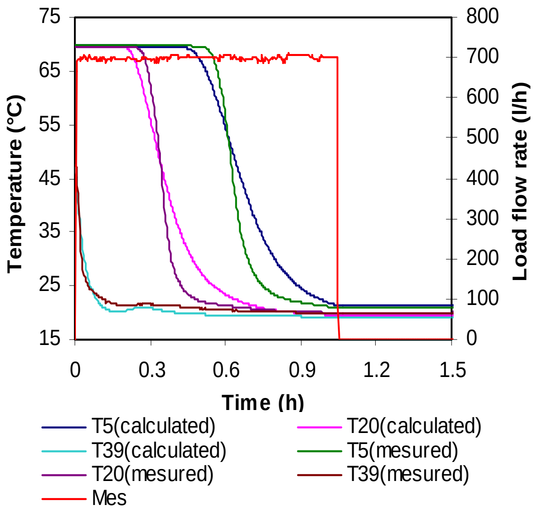

Figure 10 Variation of three temperatures calculated and measured in the storage tank for a step of load flow rate.

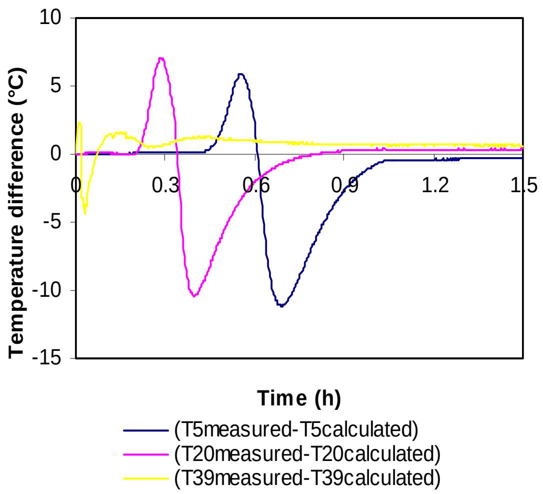

Figure 11 Differences between the three temperatures calculated and measured in the storage tank for a step of load flow rate

The tank model was incorporated into TRNSYS and produced a low-flow solar water heater with other components of the solar water heater (collector, pump, differential controller, etc.). Parametric studies on this model are being conducted so as to optimize this system control. Then, comparative studies will be carried out between this model and a classic solar water heater model in order to show the importance of this system when compared to a standard one.

CONCLUSION

The results of the test campaign have permitted to validate the mantle storage tank model developed within the framework of this study. This model with a good thermal stratification will be used for studying thermal systems, of which the tank is one of the components. This will be done with the incorporation of this model into the simulation software programme TRNSYS where it will be associated with other components. We thus find the means to optimize the low-flow solar water heater, a system whose operation is nowadays very empirical.

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