Presentation of two thermal models of an innovative patented solar drainpipe

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Abstract—We developed a new concept of water solar collector integrated into a drainpipe. This collector is made of several serial modules. The drainpipe keeps its water evacuation function. After a brief presentation of the energy situation in France, the new concept of solar collector is described; the experiment, the collected data and the first experimental results are presented and discussed. Numerical calculations are performed in Matlab® environment, using a finite difference model and an electrical analogy. A second approach using a thermal modeling by Comsol® software is also presented.

Keywords—solar collector; heating; renewable energy.

I. INTRODUCTION

The rapid increase in energy consumption in building sector is seen in many countries. In France, 30 millions of housings use about 50% of final energy and produce 25% of green house gazes. For Europe, 500 millions inhabitants in 160 millions housings consume half the energy. The residential and tertiary sector is the first energy consumer in France (Fig. 1) with 69.4 Mtoe [1] the percentage (43%) stays stable but the absolute value increases (+25% in 1973-2008). In France, energy costs are mainly devoted to domestic heating (72%), followed by lighting and appliances (11%), hot water (11%) and cooking (6%) (Fig. 2) [2].

A European citizen uses 36 litres of 60 °C hot water daily with tendency for increase in future. The energy to produce hot water is rising slightly because the comfort level sought now is greater than the level accepted in the past. In older buildings, this sector is only 6% of overall energy consumption, but with a reduced heating need mainly due to a better thermal insulation, the hot water production represents 30% of energy consumption in a modern housing. Using solar collectors is a good and sustainable solution for heating water. They can efficiently provide up to 80% of the hot water needs, without fuel cost or pollution and with minimal O&M expense. The European Union’s solar thermal market has clearly outstripped forecasts with 51.4% growth in 2008, or about 3 238.5 MWth. The collectors that contribute this additional power cover a surface of over 4.6 million m22, which is 1.6 million m2 more than in 2007 [3]. Then, an important renewal in researches for improving and conceiving thermal collectors is occurring.

Introducing innovating and environmentally positive solutions is difficult, the obstacles are numerous: financial, technical, psychological obstacles, or too conservative building standards [4]. We must find an innovative concept of heating system easily building-integrated, reducing visual impact (psychological obstacle), easy to install in both new and old houses (technical obstacle), not too costly (financial obstacle) and with an environmental positive solution. Our “basis” idea consists in making actives passive parts of building: in past years, a shutter was transformed into a solar air collector [5], now we develop a water collector integrated into a gutter, recovering rainwater and solar radiation.
II. Presentation of the Solar Gutter

The new concept of solar water collector (SWC) patented and named H2OSS® presents a high building integration without any visual impact. The SWC is arranged so it can also be used on north oriented walls (SWC being oriented south into the drainpipe). It is totally invisible from the ground level thanks to the drainpipe integration (Fig.3). The drainpipe preserves its role of rainwater evacuation. The canalizations connecting the house to the SWC are hidden in the drainpipe. An installation includes several connected modules. One module is about 1 m length and 0.1 m in width (individual houses). The modules number depends on the drainpipe length. From top to bottom, it is composed by a glass, an air space, a highly selective absorber and an insulation layer. First, the cold fluid from the tank flows through the inferior insulated tube and then in the upper tube in thermal contact with the absorber.

III. The Experimentation

An experimental wall is built in Ajaccio with 3 objectives: testing the thermal behavior, validating a thermal model and increasing performances by parameters adjustments. A drainpipe comprises 18 serial modules (about 2m²) split in two rows (Fig. 4). The input fluid temperature is taken constant by a control loop which heats the fluid if it is too cold and cools it in the other case.
Every minute are collected: solar irradiance, ambient temperature, humidity, wind speed and direction, fluid flow rate and input and output fluid temperatures (for each module). The flow rate was fixed at 0.120 m$^3$.h$^{-1}$.

Fig. 5 shows inlet and outlet collector temperatures, ambient temperature, wind speed, solar irradiance and instantaneous efficiency defined by:

$$\eta = \frac{\rho Q_c \eta_s (T_{\text{outlet}} - T_{\text{inlet}})}{1 \cdot \Delta c} \quad (3.1)$$

The maximum gap between inlet and outlet temperatures is 9°C. Tm is not constant in this experiment. The instantaneous efficiency, up to 60% at the steady-state, decreases rapidly after noon because the wall is south-east oriented. We measured temperatures located on the upper tube between each module. The profile is linear (Fig. 6). The maximal useful length has not been reached because the temperature continues to increase, thus we can install efficiently more than 18 serial modules. If the output temperature begins to stabilize, it will be necessary to modify the configuration using parallel modules. In the input tube located into the insulation, the fluid temperature increases by 1°C for 18 m length before entering in the absorber.

The efficiency ($\eta$) at stationary state is plotted (Fig. 7), (European standard) vs. reduced temperature, Tr (3.2) [6]. We calculated the linear regression and we obtain with a correlation coefficient at 0.96 (3.3):

$$Tr = \frac{T_m - T_{\text{amb}}}{\Phi} \quad (3.2)$$

$$\eta = -15.095 Tr + 0.83 = -K Tr + B \quad (3.3)$$

with $\Phi$ the solar irradiance, Tm the average temperature of the SWC, Tamb the ambient temperature, B the optical efficiency and K the thermal looses [7] higher than for conventional SWC with simple glass and highly selective absorber (Fig. 7). The average value of K is usually $5 \text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ [6]. This difference is due to the geometry of the H2OSS® modules. The thermal looses on the sides of the modules are more important and so the performances decrease rapidly when the reduced temperature increases.

![Figure 5](image_url)  
**Figure 5** Experimental results for the collector

![Figure 4](image_url)  
**Figure 4** Experience and temperature control loop

![Figure 6](image_url)  
**Figure 6** Temperature evolution vs. the length

![Figure 7](image_url)  
**Figure 7** Efficiency and temperature control loop

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The aim of the presented thermal modelling is to improve the performances of the collector. The first step is to get accuracy a good accordance between numerical and experimental results, to be able, in a later step to optimize the thermal properties. In this paper, we present only the accuracy part.

Two complementary thermal models have been developed. The first one using a Matlab® environment, and the second one a Comsol Multiphysics software. The Matlab model, complex to develop, offers a huge flexibility of all the model parameters. One the other hand, the Comsol model is relatively simple to build and allows a good visualization of the thermal phenomenon occurring inside the collector. The concordance between the thermal results of the two models has been checked.

A. Thermal model under Matlab® environment

We present a bi-dimensional model with the thermal transfers composed of a serial assembling of one-dimensional elementary models. Each model is based on a nodal discretisation. The domain is broken up into 52 elementary isotherm volumes, and for each node, we write a thermal balance equation using an electrical analogy (Fig. 8) where temperatures, flows, flow sources and imposed temperatures are assimilated to potentials, currents, current generators and voltage generators. The three different types of thermal resistances represent the convection, the conduction and the radiation exchanges. Thermal properties are constant. This model uses as input physical parameters: Total solar irradiance Φ, ambient temperature Tamb, air speed in front of the collector v, ground and sky temperatures and cold fluid temperature values was calculated and minimized and for each node, we write a thermal balance equation using an electrical analogy (Fig. 8)

\[
p_{\text{glass}}C_{\text{glass}}\frac{dT}{dt} = A_t\phi_{\text{glass}}(\theta - \theta_{\text{glass}}) + A_t f_{\text{1-skyl}}(T_f - T_{\text{sky}}) + \frac{T_{\text{amb}} - T_f}{R_{\text{cold}} + R_{\text{v}}} + \frac{T_{\text{amb}} - T_f}{R_{\text{cold}} + R_{\text{v}}} + \frac{T_{\text{amb}} - T_f}{R_{\text{cold}} + R_{\text{v}}}
\]

with A area, α absorption coefficient, Φ total solar irradiance, ε emissivity coefficient, f geometrical factor, T temperature and R thermal resistance.

For the circulating fluid’s thermal equation, there were 3 equations with 4 unknown factors. In order to solve this system, the outside fluid temperature is estimated using the NUT equation (Eq. 4.2). It corresponds to the temperature profile of a fluid circulating inside a homogeneous tube (Ta) with an internal surface Sfc, at steady state [7]

\[
T_{f/c} = T_a + (T_{f/e} - T_a) e^{-NUT}
\]

(4.2)

\[
NUT = h_{f/c} S_{f/c} / m_{f/c} \cdot C_p_{f/c}
\]

(4.3)

Using Eqs. (4.2) and (4.3), we can calculate the outside fluid temperature from the inside fluid and tube temperatures. The 52 thermal equations for the 52 elements were developed and are solved using a direct implicit method.

The values of some thermal parameters are difficult to determine particularly the unknown thermal resistances due to physical contact between the various element parts, and the heat transfer coefficients (due to the complexity of the solar collector geometry); thus, we tested empirically various numerical values for these resistances in such a way that we obtain a good accuracy. The adjusted values of these parameters are checked to be sure that they are physically acceptable. In order to find the best coefficients, the root mean square error (RMSE) between experimental and numerical outside fluid temperature values was calculated and minimized and the optimized values are recorded. Fig. 9 shows an experimental verification for a given day for the outside water temperature.

IV. THERMAL MODELS

Figure 7 Efficiency for our collector and for conventional solar ones: without glass (a); with one (b) and two glasses (c), with a selective absorber and one glass (d) and vacuum collector (e).

Figure 8 Electrical analogy of the collector.
We calculate the RMSE for 17 days, with variables meteorological conditions and physical entries. The average RMSE is 1.9 % (0.37°C). Considering that the accuracy of the used thermal sensors only is close to 0.2°C, this result is considered sufficient.

B. Thermal model under Comsol Multiphysics® environment

Comsol Multiphysics is a simulation software environment using finite elements method. The used equations are, for the most part, preloaded. In this model, we consider isothermal finite elements, but with a really small size : there are about 5500 elements for the bi-dimensional view, presented in Fig. 10, and 500000 elements along the entire 3 dimensions view, Fig 11. The thermal properties are temperature dependent. We developed a bi-dimensional and a tri-dimensional model. The 3D model was developed in order to study the edges effects in the length direction. One important point is that we did not model the fluid because it was too time and space memory consuming. We focused on the collector itself. The temperatures of the inside of the tubes are imposed referring to the experimental data.

We study only stationary configurations. The results we obtained are presented in Figs. 12-13.

The white arrows represent the total heat flux. One of the first observations that could be done is that the fins of the absorber seem too wide because the heat flux isn’t unidirectional. The second point is that the insulation between the side of the absorber and the exterior is really too small. The temperature gradient in this part is very important, one of the most important of the collector.

On the 3D model, despite there is an insulation part on both length side of the collector, we can see that the edges ef-
effects exist but are not too significant which justify the utilization of a 2D-thermal model as the Matlab one.

V. CONCLUSION

A new concept of flat plate solar water collector highly building integrated was presented. The collector is made of several modules in serial position. The particularities of the collector are that it is integrated into a drainpipe and totally invisible from the ground level. It can be installed on both new and old buildings, and on individual or collective habitations. An experiment was implemented and promising first experimental results were presented. At low reduced temperature values, the thermal performances are close to conventional ones. However it is necessary to optimize the shape of this collector in order to improve the thermal insulation. Two thermal models have been developed and the obtained results are very close to the experimental ones which validates them. The next step will be to use these two models to optimize the performances of the solar collector.

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REFERENCE