ABSTRACT
A new concept of flat plate solar collector is presented: its originality comes from its remarkable shape and from its integration into a rainwater gutter. The complete solar collector consists in several short modules connected serially. After a brief presentation of the building energy problem, the new patented solar collector is described and the two thermal experimentations are shown. A numerical model is developed in Matlab® 15 environment using a finite difference model and an electrical analogy. At last, the thermal model is validated from experimental data under various meteorological situations. The adequacy of the model with the experimental data is shown for various temperatures inside the solar collector and for the water temperatures.

KEY WORDS
Thermal solar collector; building-integration; modelling; experimentation.

1. Introduction

There’s no doubt that the fossil energy resources of our Earth are being decreasing and that the strong economical development of the developing countries as China or India will increase the resources drop. In the other hand, it appears that the massive utilization of fossil fuels (and nuclear ones) endangers our Environment.

The statistics show that building (residential and tertiary), today, accounts for more than one third of the world final energy; for developing countries, this part exceeds 40%. It is a key sector where real, relevant and sustainable solutions of energy management can and must be developed. The rapid increase in energy consumption by the building sector is observed in many countries around the world. For Europe, 500 millions of inhabitants in 60 millions of housings consume also half the energy.

The residential and tertiary sector is the first energy consumer in France (Fig. 1) with 69 MTOE of primary energy [1] i.e. 42.75 % of the total primary energy and 64.5 MTOE of final energy in 2008 [2] and it produces 25% of green house gazes. The part of the residential and tertiary sector stay stable (around 41-44%) but in absolute value, the energy consumed in this sector increases. From 1973 to 2010, the residential-tertiary sector increased of 21%.

The total energy consumption of the building sector increased of about 50% during these twenty last years with a high penetration of electricity (+130%) which covers 40% of all the needs whose 50% for captive use as lighting, domestic appliances, etc ….

The repartition of the consumption by type of use for residential and tertiary sector from 1990 to 2009 is shown in Fig.2. In France, the energy consumption is mainly devoted to domestic heating (69%), followed by lighting and appliances (15%), 67 hot water (10%) and cooking (5%) [2]. The heating represents 15% of household expenditure devoted to housing, or 3.7% of their total expenditure [2-3]. In 2006, the household heating expenditures reached 21.3 G€ [3].

Figure 1. Primary energy consumption by sector in France [1].
Figure 2. Final Energy Consumption in the tertiary and residential sector [2]

Figure 3. Final energy consumption by sector and sources in 2010 in France [4]

Fig. 3. illustrates the repartition of the various energy sources in the final energy consumption [4]. The part of renewable energies in the residential and tertiary sector is about 14% today.

An European citizen uses 36 litres of 60 °C hot water daily with tendency for increase in future [5]. 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 can represent 30% of energy consumption in a modern housing. A solar collector is a good and sustainable solution for heating water and can efficiently provide up to 80% of the hot water needs, without fuel cost or pollution and with minimal O&M expense. The following observations explain the researches renewal in view to improve and conceive new thermal collectors:

- the increase of the water heating part in the housing consumption;
- the development of new sustainable solutions for reducing the building consumption;
- the strong growth of the solar thermal market;

Builders recognize more and more that build high energy efficient housings is a sensible, ethical, ecological idea and workable at medium and long-term. A lot of them think that innovation is an essential component of their job. But, if we observe the majority of recent or in process buildings, we note easily that the previous considerations are not taken into account when arrive the moment to concept or to build the house. To be an innovator it’s to know how to put into practice or how to give concrete expression of its creativity. Introduce innovating and environmentally positive solutions is a difficult work. The obstacles are numerous: financial, technical and psychological obstacles, incompetent professionals or building standards too conservatives [6].

Thus, it is necessary to find an innovative concept of heating system easily building integrated for reducing the visual impact (psychological obstacle), easy to install in both new and old houses (technical obstacle), not too costly to install (financial obstacle) and having no negative impact on the indoor and outdoor environment (environmental positive solution). In other words, the integration into buildings is the marriage of aesthetics and sustainability. Our —basic idea consists in making actives passive parts of building; with this vision, we developed, few years ago, a solar air collector integrated into a shutter [7] and we present, in this paper, a new concept of water collector inserted into a gutter, recovering rainwater and solar radiation.

2. The concept

The new concept of solar water collector (SWC) is patented [8] and named H2OSS®; it 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. 4). The drainpipe preserves its role of rainwater evacuation. The canalisations connecting the house to the SWC are hidden in the vertical drainpipe. An installation consists in several connected modules. One module is about 1 m length and 0.1 m in width (individual houses), larger modules can be developed for buildings. The number of modules depends on the drainpipe length.

From top to bottom, a thermal module is composed by a
glass, an air layer, a highly selective absorber and an insulation layer (Fig. 5). 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.

Figure 4. The solar gutter H2OSS®.

Figure 5. The thermal solar module structure.

3. The experimentations

The objectives of the two experiments (Fig. 6) are to test the thermal behaviour, to validate the thermal model and to improve the performances by some parameters adjustments. The two experimentations are located on the laboratory site situated in the gulf of Ajaccio (latitude: 41°55’ N; longitude: 8°55’ E) at about 200 m from the Mediterranean sea and at an altitude of 70 m. The first experiment consists in 18 serial modules (about 2m²) arranged in two rows on a South-West-faced wall in view to operate in similar conditions to those met in an individual housing but not optimal from a performance point of view. The second one allows to operate closer to the European Standard EN 12975-1 [9]: 4 rows of 4 thermal modules (1.8 m²), connected in serial or parallel, are fixed on a solar tracker for a better control of the solar intensity and direction.

Figure 6. The two experiments a) SE-faced wall b) Solar tracker

The solar modules are connected to a thermal loop which regulates the input fluid temperature heating the fluid if it is too cold and cooling it in the other case using a air cooler (Fig. 7)

Figure 7. The thermal loop

Every minute are collected: solar irradiance on the collector plane (measured by a Kipp & Zonen (CM11) pyranometer), 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 m³.h⁻¹ Fig. 8 shows an example of measured data during a summer day: inlet and outlet collector temperatures Tout and Tin, ambient temperature, wind speed, solar irradiance and instantaneous efficiency η defined by:

\[
\eta = \frac{\rho Q C_p (T_{\text{fluid, output}} - T_{\text{fluid, input}})}{(\phi S)}
\]

Where ρ is the water density, Q the volume flow rate, Cp the thermal capacity, φ the solar irradiance on the collector with a surface area S.

Figure 8. Experimental results for the H2OSS® collector.

The maximum gap between inlet and outlet fluid temperatures is about 9°C. The inlet fluid temperature has not been taken constant in this experiment. The instantaneous efficiency, up to 60% at the steady-state, decreases rapidly after noon (Fig. 8). In fact, the wall is south-east oriented and the absorbed solar irradiance is different the morning and the afternoon influencing the parameters as absorptivity and transmittivity. It is particularly for this reason that a new experimentation with a solar tracker has been implemented. We observed the temperature evolution along the thermal line on the tracker. For these measures (sensors located in A, B, C, D, E and F), the input temperature was taken to 40.3°C (Fig. 9). We note that the profile is linear and the maximal useful length
has not been reached. The temperature continues to increase, thus we can install efficiently more than 16 serial modules. If there was stabilization of the temperature then there would be a need to use a parallel configuration. In the input tube located into the insulation (AB), the fluid temperature increases by 0.7°C for 16 m length before entering in the absorber.

Figure 9 – Evolution of the output fluid temperature versus the length of the thermal line.

4. Thermal model implementation

The particular geometry of the solar thermal collector which has lateral faces much wider than a conventional collector relatively to its collecting surface, generates a specific thermal behaviour.

We present a bi-dimensional model with thermal transfers composed of a serial assembling of one-dimensional elementary models. The domain is broken up into elementary isotherm volumes, and for each node, we write a thermal balance equation using an electrical analogy where temperatures, flows, flow sources and imposed temperatures are assimilated to potentials, currents, current generators and voltage generators.

In most numerical models encountered in literature, the number of nodes is reduced because only the overall performances of the solar collector are studied. The aim of this work is to characterize the heat distribution inside the solar collector H2OSS®. Thus, we use in our models a very large number of nodes (97 nodes) (see Fig. 10).

We tried to get as close as possible to the exact shape of the solar collector in view to obtain the maximum resolution and accuracy of results while maintaining an affordable number of elements. The average error on the solar module size remains below 2% and the maximum error on one mesh element reaches 15% i.e. 1 mm.

Figure 10. – Electrical analogy of the solar thermal collector.

All parameters of this model can be easily changed as module length, number of modules, physical properties of materials, geometry, convective coefficients, contact resistances, … in such a way that we can estimate the influence of future changes on the thermal performances of solar module.

The model is based on the following assumptions:
- the thermo-physical properties in solids and fluids are constant;
- the temperature is homogeneous in each unit of volume;
- the conductive transfers are neglected compared to the convective and radiative exchanges in the air layer;
- in the water layer of the collector, the conductive and radiative transfers are neglected with regard to the convective ones;
- the effects of the gutter has been modelled: its temperature was previously calculated on the basis of a heat balance; radiative and convective exchanges between the solar thermal collector and the gutter are taken into account; the temperature of the air between the gutter and the solar collector was considered equal to the ambient temperature;
- the modelling is in 2-D;
- the optical properties of glass are different with respect to the solar radiation and IR radiation from the absorber;
- the radiative exchange between the nodes are located in the center of the element when they should be held between the surfaces of each element but the thickness of the elements is small and this assumption is acceptable.

The input variables of this model are: solar irradiance $\phi$, ambient temperature $T_{\text{amb}}$, air speed $v$, ground and sky temperatures and cold fluid temperature. It is impossible to write here all the equations, but the thermal balance for the elementary model corresponding to the node 4 (Figure 10) in glass, is detailed in Eq. (2).

$$
\rho_{\text{glass}}C_{\text{glass}}V_4 \frac{dT_4}{dt} = \phi_4 S_{\text{glass}} (\dot{m} \rho_4 c_4 (T_4 - T_{\text{amb}}) + (\dot{m} \rho_4 c_4) \sum_{n=1}^{N} \frac{T_n - T_4}{R_{\text{cond}} + R_{\text{conv}}}) + \frac{T_{\text{amb}} - T_4}{R_{\text{cond}} + R_{\text{conv}}} + \frac{T_1 - T_2 + T_3 - T_4}{R_{\text{cond}}} + \frac{\sum_{n=1}^{N} \frac{T_n - T_4}{R_{\text{cond}} + R_{\text{conv}}}}{g} + \frac{\sum_{n=1}^{N} \frac{T_n - T_4}{R_{\text{cond}} + R_{\text{conv}}}}{g}$$

(2)
n is the number of surfaces involved in the multiple reflections in the air layer; f the view factor, A the area, α the absorption coefficient, ε the emissivity coefficient, f geometrical factor, T temperature and R thermal resistance.

The convective heat transfer flux between the fluid and the tube is given by:

\[ \dot{m}_c P_f \left( T_{\text{fluid,input}} - T_{\text{fluid,output}} \right) = \dot{m}_c A T_{\text{tube}} \left( T_{\text{fluid}} - T_{\text{tube}} \right) \]

(3)

with \( T_{\text{fluid,input}} \) and \( T_{\text{fluid,output}} \) the fluid temperature in the inlet and outlet of the tube, \( T_{\text{fluid}} \) the average temperature of the fluid, \( T_{\text{tube}} \), the temperature of the tube and \( \dot{m}_c \) the flow rate of the heating fluid (m\(^3\).s\(^{-1}\)).

To solve Eq. (13), the output fluid temperature \( T_{\text{fluid,output}} \) is calculated on the basis of the temperature profile of a fluid flowing inside a tube with an area \( S_{\text{tube}} \) and an homogeneous temperature \( T_{\text{tube}} \) using the NTU equation [10] in steady-state conditions.

\[ T_{\text{fluid,output}} = T_{\text{tube}} + \left( T_{\text{fluid,input}} - T_{\text{tube}} \right) \exp(-NTU) \]

(4)

NTU (Number of Transfer Units) is given by:

\[ NTU = \left( \frac{1}{h_{\text{fluid}}/S_{\text{tube}}} \right) \frac{\dot{m}_c P_f}{T_{\text{tube}}} \]

(5)

Thus, it is possible to calculate the output fluid temperature from the tube temperature and the input fluid temperature. We obtain a system of \( n \) differential equations in time and in space. All the energy balances can be written in the guise of a differential matrix equation:

\[ [C] \frac{d\bar{T}(t)}{dt} = [M] \bar{T}(t) + [S] \bar{E}(t) \]

\( \bar{T}(t) \) is a vector containing the temperatures of the solar collector at the 97 nodes of the mesh, \([C]\) is a diagonal matrix (dimension 97) with all the values of the thermal capacities, \([M]\) is a matrix (dimension 97) with all the heat exchange coefficients between the elements of the mesh, \([S]\) is a matrix (dimension 97 x 4) which joins together the four input physical parameters expressed by the vector \( \bar{E}(t) \) (\( \phi, T_{\text{amb}}, T_{\text{sky}}, T_{\text{gutter}} \)) and 97 elements of the mesh.

By solving the equations of this analogical model, we get directly the temperature for each node of the mesh. This equation system is solved by the Runge Kutta Merson’s method. The input data are measured each minute and the sky temperature is calculated using the formula given by Bernard [11].

\[ T_{\text{ciel}} = 0.0552 T_{\text{amb}}^{1.5} \]

(7)

In the next paragraph, we will validate this model not only from the output water temperature but also from some temperatures inside the solar collectors.

5. Experimental validation

The thermal model being implemented, we validated this model from experimental data collected with the second experiment (with solar tracker).

A thermal solar module has been specially instrumented with 9 thermal sensors (type PT100 class B) measuring the surface temperature in 9 specific points (Fig. 11):

1. on the glass;
2. on the right blade;
3. on the left blade;
4. on the right absorber;
5. on the left absorber;
6. in the right insulation;
7. in the left insulation;
8. on the right side;
9. on the rear face;

The solar thermal modules are connected in parallel with a water flow rate equal to 450 L.h\(^{-1}\); in these conditions the increase in the temperature of the water is small but the gradient of temperature inside the module is more visible.

An experimental verification was realized during one year and we show, in Fig. 12, the results of this validation for three days successively with clear, partially cloudy and cloudy skies for the nine temperatures inside the instrumented solar collector.
Figure 12 – Experimental verification of the thermal model – a) meteorological conditions – b) and c) experimental and modelled temperatures inside the solar thermal module.

We note a good accuracy between modelled and experimental temperatures. We calculated the absolute and relative Root Mean Square Errors (RMSE and RRMSE) for the totality of the experimental period over the four seasons (about 100 days). The values of RMSE and RRMSE for the nine temperatures calculated from Equations (8) and (9) are given in Table 1.

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_{\text{sim},i} - X_{\text{exp},i})^2}
\]

\[
RRMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left[\frac{X_{\text{sim},i} - X_{\text{exp},i}}{X_{\text{sim},i}}\right]^2}
\]

\(n\) is the number of data, \(X_{\text{sim},i}\) and \(X_{\text{exp},i}\) are respectively the simulated and experimental data.

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Table 1 – Accuracy of the thermal model for the nine temperatures inside the solar module.

We note that the adequacy between simulated and experimental temperatures is correct. Similarly, we simulated the output water temperature in the following conditions: serial connexion of the thermal module, water flow rate equal to 140 L.h⁻¹. We chose these conditions in view to be in the conditions which are the most similar to the real operating conditions.

We drew the result of the simulation for some days during two periods (summer and winter) in Fig. 13.
We computed the RMSE and RRMSE for the output water temperature for the four seasons (using about 90 days) and we obtained the following values: RMSE = 1.4 °C and RRMSE = 5.2%. These errors are fully acceptable. These two validations allow to certificate that the model has a sufficient adequacy to be used in a future work to study the influence of material change, structure modification or other possible modifications.

6. Conclusion

The aesthetic of solar thermal collectors can be an obstacle to their development and limits the growth of the market. The integration of solar collectors in buildings allows to make them invisible from the ground. We presented a new patented concept of solar collector totally integrated into a gutter. His specific and original form makes its thermal modeling interesting.

We developed a two-dimensional thermal model using a finite difference method and an electrical analogy and considering 97 elementary volumes. The model was implemented and the numerical results were validated from experimental data: a thermal solar module was specially instrumented with 9 thermal sensors measuring temperatures into the solar collector and the water output and input temperatures were also recorded.

The experimental validation shows that the developed model has a good accuracy with the measured data: the relative root mean square errors are around 5% for the water temperatures and from 4.6% to 10% for the internal ones. The main advantage of this model is to be able to modify easily the characteristics and the form of the used materials. Thus, it will be possible to study in a future work the influence of any change in material and structure on the performances of the solar collector. Then, this thermal solar collector model will be coupled with a water tank model in view to model the global thermal system behaviour.

References