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Thermal Modeling of a Solar Water Collector Highly Building Integrated

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Abstract: A European citizen uses 36 liters of 60°C hot water daily, with tendency for increase in future. Using solar collectors is a good and sustainable solution for heating water, but introducing innovative and environmentally positive solutions is difficult. The obstacles are numerous: financial, technical, psychological obstacles, or too conservative building standards [1].

A new concept of solar water collector, highly building integrated has been developed and patented. The collector is hidden into a drainpipe. The drainpipe keeps its water evacuation function. Each installation is composed of several modules serial connected. Using Comsol Multiphysics, we coupled the Heat transfer, and the Naviers Stokes modules. We used the Boussinesq approximation to model the natural convection. We also calculate all the surface-to-surface radiation transfers with a differentiation between the IR and UV radiations. We present a model with a high level of details. The main objective is to rebuild the design of this collector optimizing its total efficiency.

Keywords: Solar flat plate collector, Building integrated, natural convection, Boussinesq approximation, surface-to-surface radiation.

1. Introduction

The rapid increase of energy consumption in building sector is seen in many countries. In France, 30 million of housings use about 50% of final energy and produce 25% of green house gazes. The residential and tertiary sector is the first energy consumer in France with 69.4 Mtoe [2]. The percentage (43%) stays stable but the absolute value increases (+25% in 1973-2008). The energy needed to heat water is rising slightly, mostly because of the comfort level augmentation. In France, energy costs are mainly devoted to domestic heating (72%), followed by lighting and appliances (11%), hot water (11%) and cooking (6%) (Fig. 1) [3]. For Europe, 500 million inhabitants in 160 million housings consume energy in equivalent proportions.

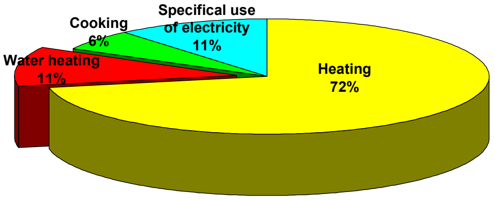

Fig. 1. Part of Energy (housing sector)

A European citizen uses 36 litres of 60°C hot water daily, on average. In older buildings, this part represents only 6% of overall energy consumption. In a modern housing, with reduced heating needs, mainly due to a better thermal insulation, the hot water production represents about 30% of the total energy consumption. Using solar collectors is a good and sustainable solution for heating water. An installation of 2m^2 provides 50-70% of the total hot water demand for a two persons standard house (located in southern France) [4], without fuel cost or pollution, and with minimal O&M expenses. The European Union's solar thermal market has clearly outstripped forecasts with 51.4% growth in 2008, or about 3 238.5 MWth installed. This represents a surface of over 4.6 million m^2, which is 1.6 million m^2 more than in 2007 [5]. 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 [1]. 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), with a large installation capacity and with an environmental positive solution. Our "basic" idea consists in making active the passive parts of building: earlier, a shutter was transformed into a solar air collector [6], now we develop a water collector integrated into a gutter, recovering rainwater and solar radiation. This 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 may also be used on north oriented walls, SWC being oriented south into the drainpipe (depending of the roof's shape). It is invisible from the ground level thanks to its integration (Fig.2). The drainpipe preserves its role of rainwater evacuation. The canalizations connecting the house to the SWC are hidden in the drainpipe. This is an important point, because there are still places where solar panels are forbidden by the law, in order to conserve the regional architecture [7].

An installation includes several serial connected modules. Each module is about 1 m length and 0.1 m in width (individual houses). The modules number depends on the drainpipe length. The employed technology is widespread. From top to bottom, a glass, an air space, a highly selective absorber and an insulation layer compose it. 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. Concerning the costs (in surface proportion), this collector is close to the commercial ones.

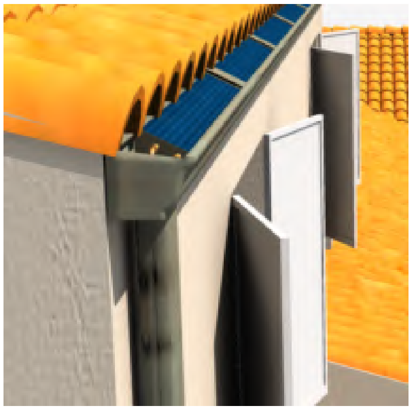

Figure 2. A H2OSS® module

2. COMSOL Multiphysics model

The aim of the presented thermal modeling is to improve the performances of the collector, mostly by reducing the thermal losses characterized by experimentation. A numerical model using an electrical analogy also was developed under Matlab® environment in order to determine all the convective coefficients and the thermal resistances of the collector. Due to the specificity of the shape of the collector, non-existent correlation was adaptable. We tested empirically, with the Matlab® model, various numerical values for these parameters trying to obtain a good accordance with the experimental results. The night also was modeled to calibrate the convection coefficients. In order to find the right coefficients, the root means square error (RMSE) Eq. (1-2) between experimental and numerical outside fluid temperature was calculated and minimized. The adjusted values of these parameters have been checked to be sure that they are physically acceptable. Then values founded using Matlab were set in the Comsol model.

$$RMSE_{abs} = \sqrt{\frac{\sum_{N_{steps}} \left(T_{num} - T_{\exp}\right)^2}{N_{steps}}} \quad (1)$$

$$RMSE_{rel} = \sqrt{\frac{\sum_{N_{steps}} \left(\frac{T_{num} - T_{\exp}}{T_{\exp}}\right)^2}{N_{steps}}} \quad (2)$$

We calculated the RMSE for the whole February month and the first half of March 2011 with capricious and fluctuating meteorological conditions and physical entries. The average RMSE is about 3 % (0.58°C), for the outside fluid temperature, and about 10% (1.57°C) for all the surface sensors (fig 14). Considering the disparity of the meteorological conditions and the accuracy of the used thermal sensors (close to 0.2°C), this result is considered sufficient, and the founded values are implemented in Comsol Multiphysics.

Comsol Multiphysics® allows a good and accurate visualization of the thermal phenomenon occurring inside the collector, for a given configuration. Comsol Multiphysics is used to test different designs and to choose which configuration gives best results. The concordance between the thermal results of the two models (Matlab and Comsol) has been checked and validated.

In this model, we consider isothermal finite elements, triangular shaped. We developed at the beginning of this study two models presented in Figure 3. The 3D one was developed in order to study the edges effects in the length direction. One important point is that we did not model the circulating fluid because it was consuming too much time and space memory. We focused on the collector itself.

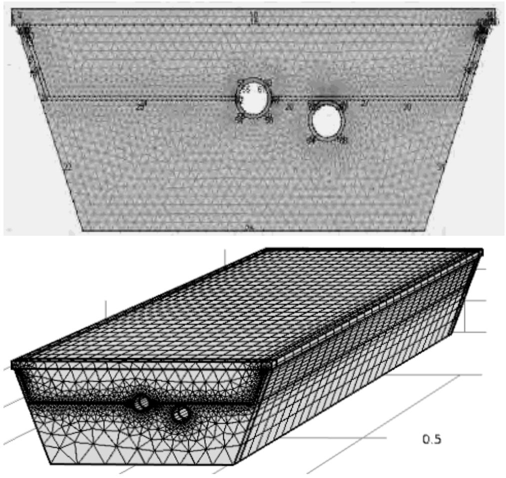

Figure 3. 2 and 3 Dimensions developed models

We used the heat transfer, surface to surface and the non-isothermal flow modules. The governing equations provided in Comsol Multiphysics have not been changed.

The surface-to-surface module is active only in the air layer where multi reflections occur. The non-isothermal flow module is used to model the natural convection inside the air layer using the Boussinesq approximation.

We set all the boundary layers as close as possible to their real conditions. This way, the glass layer of the collector is submitted to: incoming solar radiation, convection with the ambient, radiation losses to the sky, convection with the air layer, radiation exchanges with the absorber and of course conduction. We proceed the same way for the other boundaries.

The differentiation between the U.V and I.R radiations is done by setting the glass transparent to the incoming solar radiation but opaque for the radiations coming from the absorber.

Concerning the inside of the tubes, the thermal transfer between the collector and the fluid is done using a cooling convection transfer.

All the thermal properties are temperature dependent. We studied transient and stationary configurations. On the 3D model, despite there is an insulation part on both length side of the collector, edges effects exist, but are not so significant (fig.4). This justifies the exclusive utilization of a 2D-thermal.

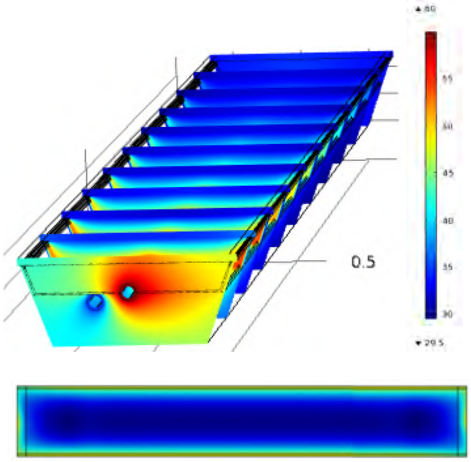

Figure 4. 3D model - Thermal repartition inside the collector: XY section and XZ section

3. Results

The aim of this study is to find the best design for this collector. Each configuration is characterized with the thermal losses occurring at the back and on the side of the collector, at the top of the collector and inside the tubes. In fact, the losses from the tubes represent the useful energy gained by the fluid. This is actually the main point. Under the same meteorological and experimental conditions, the configuration giving the highest power output (i.e. the total losses) can be considered as the best. We interpret the results using these losses from the back and from the front in order to fully understand the consequences of having changed the design. We will study three different configurations and the influence of the insulation layer at the back of the collector.

3.1 Choice of the designs

The experimentation showed some important thermal losses of the H2OSS collector. The aim is to decrease them as much as possible. There are different ways to accomplish that. The first one would be to increase the thermal insulation; the second one would be to decrease the operating temperature of the collector. The actual collector is shaped with one tube in the insulation layer and another tube in the absorber. In this paper we will present two more configurations:

- Two tubes in the insulation layer and one on the solar absorber
- One tube in the insulation layer and two on the solar absorber.

Figure 5. Every tested configuration

In each tested configuration (Fig.5) the insulation layer thickness is equal to 2.5cm. In order to keep valid our hypotheses of comparison, we consider the fluid at the same temperature wherever we consider the insulated tube or the irradiated one.

The third configuration with two tubes on the absorber should decrease the operating temperature by increasing the transfers to the fluid. Introducing more potential thermal losses, this configuration should be mostly efficient at low operating temperatures.

The second configuration with two tubes in the insulation layer should decrease the thermal losses from the back of the collector transferring them to the circulating fluid. The thermal losses should be less important at highest operating temperatures.

For the part regarding the influence of the insulation layer, we consider only the original design in this paper. The caused variation may be similar in all the studied cases. We kept the total high of the collector as a constant but we changed the thickness of the insulation layer. For a same collector high, when the insulation increases the air layer decreases in the same proportion, and inversely.

3.2. Choice of the meteorological conditions

To get the most representative and comprehensive study, we used the reduced temperature (Tr*) as variable. Tr* is expressed this way (Eq. 3) [8]:

$$Tr = \frac{T_m - T_{amb}}{\Phi} \qquad \text{(Eq.3)}$$

We work under standard conditions [9], resumed in the table 1. As the solar irradiation and the ambient temperature are imposed by the norm, the last variable parameter is the fluid temperature. The operating conditions of the solar flat plate collectors impose a study domain from Tr*=0.1 to Tr*=0.4 [10]. That means from Tm=27.5 to 57.5°C.

Parameter	**Value**
Ambient temperature	20 °C
Wind speed	2m/s
Solar irradiation	750 W.m-2
Flow rate	200 l.h-1

Table 1. Standard meteorological conditions

To resume, we tested 3 different configurations at different reduced temperatures and the influence of the insulation layer proportion. The configuration giving the highest output power and proportionally the less thermal losses will be chosen.

4. Results

4.1. Determination of the best configuration

The table 2 below shows a summary of the most significant result. The results corresponding to the config. 1 were really below under our attempts. This configuration, using two tubes in the solar absorber, increases the losses at the front of the collector but do not allowed to collect more solar irradiation. That means that the only tube of the solar absorber does not limit the thermal transfer from collector to the circulating fluid. Thus, the results regarding to this configuration are not presented.

		Tr*				
		0,01	0,02	0,03	0,04	0,05
Classical	**Total loses**	**46**	**64**	**83**	**102**	---
	- Convection	***26***	***38***	***51***	***63***	---
	- Front side	*7*	*10*	*14*	*17*	---
	- Backside	*19*	*28*	*37*	*46*	---
	- Radiation	***20***	***26***	***32***	***39***	---
	- Front side	*11*	*14*	*16*	*18*	---
	- Backside	*8*	*12*	*16*	*21*	---
Config. 2	**Fluid**	**183**	**139**	**99**	**53**	**35**
	- hot tube	181	136	94	46	27
	- cold tube	2	3	5	7	9
	Total loses	**92**	**146**	**190**	**235**	**274**
	- Convection	***59***	***98***	***127***	***157***	***181***
	- Front side	6	17	19	22	18
	- Backside	53	81	108	135	163
	- Radiation	***33***	***48***	***63***	***78***	***94***
	- Front side	11	12	15	17	19
	- Backside	23	35	48	61	75

Table 2. Dimensionless significant results of the study

Regarding the two remaining configurations, we can note that the lowest losses are obtained for the classical model. In both cases, the backside losses are not really influenced.

The table 3 below presents the influence of the insulation layer on the total losses of the classical configuration:

Insulation thickness (cm)		2	2,5	3	3,5	4
Total losses		65	64	62	61	60
Frontside	Radiation	14	14	13	13	13
	Convection	11	10	10	10	10
Backside	Radiation	13	12	12	11	11
	Convection	28	28	27	26	26

Table 3. Influence of the insulation layer (dimensionless)

This table shows that when the thickness of the insulation increases (i.e. the air layer thickness decreases), the thermal losses from the back are reduced while those from the front side remains almost unchanged.

5. Interpretation

The first point is that the obtained results are far below our attempts.

The configuration using two tubes in the solar absorber can be abandoned. The thermal losses from the front of the collector increased too much and the fraction of solar energy collected is not higher for the studied flow rate.

The configuration using two tubes in the insulation does not affect the behavior of the front of the collector. The results obtained with this configuration are less efficient that those from the classical design. However, the behavior of this collector is still interesting. We can see on table 2 that while the reduced temperature increases, the proportion of heat collected by the insulated tubes increases too. That was one of the topics of this study: to see how the insulated tubes could collect some thermal losses from the solar absorber.

The thermal losses found are still too high, but we can reduce the losses from the back increasing the insulation layer as shown in Table 3.

The next step of this study will consist in testing a better design for the configuration 2. The insulation layer will be increased to 4cm and the tubes will be positioned closer to the solar absorber. The goal is to limit the backside losses, to increase the heat transfer to the circulating fluid and do not increase the front side losses.

6. Conclusion

We developed a complex mathematical model in Matlab, using an electrical analogy to write all the thermal equations. This model has been used to calibrate all the unknown coefficient of the collector (specific heat transfers coefficients, thermal resistances…) and the results were implemented into Comsol Multiphysics.

The model represents all the thermal transfers occurring inside the collectors. It models the natural convection, the multi-optical reflection occurring between the glass and the solar absorber.

The aim of this work was to optimize a patented solar flat plate collector highly building integrated. Several configurations have been checked, but the obtained results were far below our attempts and worst than those obtained for the original design. However, the configuration 2, using two tubes in the insulation layer of the collector, shows an interesting way and will be study through a future work.

7. References

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8. Acknowledgements

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