IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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To cite this article: Julien Gambade *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1050** 012004

Modelling of "Water-in-glass" Solar Water Heaters Installation

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Abstract. As part of the ICaRE4Farms European project, a model of a solar water heater installation has been developed. This model is intended to estimate thermal performance of a specific arrangement of several "Water-in-Glass" solar collectors. In this solar field, the WiG collectors are arranged either in serial or in parallel, thus requiring the creation of two models. In this paper, the serial Evacuated Tubes collector's model is presented. The operational efficiency of a single in-series solar collector is expressed through a second-order expression in accordance with the ISO 9806-1. Its coefficients have been determined thanks to an optimization tool in order to compute thermal performance with reliability. In-situ data from a working installation were compared to simulated values. Two experimental sequences are presented: in May and in September 2021. Results showed that the model is reliable in terms of both collectors' temperature and energy balance.

1. Introduction

European Union is committed to reduce Greenhouse Gaz emissions and increase the share of renewable energies. Project ICaRE4Farms (I4F) intends to increase the use of solar thermal energy in farming in Northern and Western Europe. I4F Project aims to build 4 pilot sites to evaluate solar field's performance. A pre-study is set up in order to collect information needed to prepare pilot sites.

Solar thermal collectors are affordable solution to provide hot water. There are numerous types of solar collectors. They can be distributed in two groups: stationary and with sun-tracking. Among stationary collectors are Flat Plate (FP), Compound Parabolic Concentrating (CPC) and Evacuated tubes (ETC)[1].

Two different ETC exist: Heat-Pipe Evacuated Tubes Collectors (HP-ETC) and "Water-in-Glass" Evacuated Tubes Collector (Wig-ETC). Heat pipe is a thermal equipment which transports thermal energy received from solar irradiance to a working fluid. Regarding the WiG-ETC, the water directly circulates in the evacuated tubes from a storage tank, the water circulation is due to the thermosiphon effect. The heated water that moves to the top part of the tank is replaced by the cold one from the bottom part (figure 1). Those two types of ETC have been compared for domestic applications. Al-Jobbory investigated their thermal performances for three load configurations. Thermosiphon system performs well with no load and intermittent load at small removal quantities[2].

Thermal efficiency coefficients are essentials to develop a solar collector's numerical model. Bellos and Tzivanidis worked on different polynomial formula to calculate Parabolic through solar collector's efficiency[3]. Among observations, they found that second order polynomial equation defined in accordance with the ISO 9806-1 have a mean absolute percentage error of 0.43% for their numerical model.

The Solar Water Heater (SWH) studied is a combination of 30 Dewar type tubes connected to a horizontal cylindrical vessel. Alfaro-Ayala and al. worked on a computational fluid dynamics (CFD) model of a WiG-ETC[4]. They studied two different approaches to compute outlet temperature and thermal efficiency. CFD model has a good consistency when compared to experimental values.

Furthermore, Wig-ETC characteristics have been studied by Morrison, Budihardjo and Behnia. A numerical model of the heat conduction and thermosiphon flowrate inside an evacuated tube has been developed[5]. This work leads to the creation of a dynamic model of a SWH in Trnsys. Budihardjo and Morrison developed a transient model in order to simulate performance of WiG-ETC[6]. They elaborated a computation procedure to calculate natural circulation flowrate between tubes and storage tank This procedure has been adapted for the work presented in this paper.

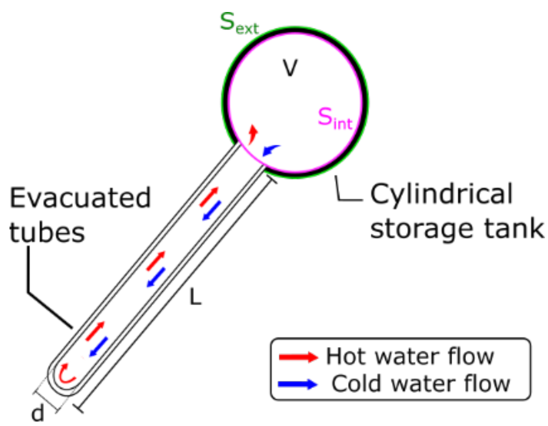

Figure 1. Natural circulation inside a WiG-ETC.

2. Materials and methods

Following sections provide information about the pre-audit site and its instrumentation. All sensors have been set up while the installation was in operation. Non-intrusive instruments had to be chosen in order to avoid any facility running discontinuity. Collected data are used to draw up energy balance as long as to validate the solar collector’s model.

2.1. Solar installation

The solar installation consists of 24 SWH divided into 2 rows (figure 2). Each row is made of 6 in series collectors followed by 6 in parallel collectors. Each solar collector has a gross area of 4m² and a water volume of 320L (241L stored in storage tank and 79L in evacuated tubes). Tanks are insulated with 60 mm of polyurethane.

Cold water is supplied from the town water network through a solenoid valve. Solar installation contributes to the needs of a calf farm. In order to prepare the food for their herd of 400 calves a large amount of water at 80°C is required.

In the course of a standard day, hot water is withdrawn twice a day to sustain the user’s needs. Only parallel collectors’ tanks are emptied whereas serial collector’s tanks remain full. A level probe located in an in-parallel collector triggers the solenoid valve connected to the town water. Given the hydraulic set-up, the filling of the row lasts for 7 to 8 hours. This slow flow rate enhances the thermal stratification in the storage tanks which improves the efficiency of the solar collectors [7].

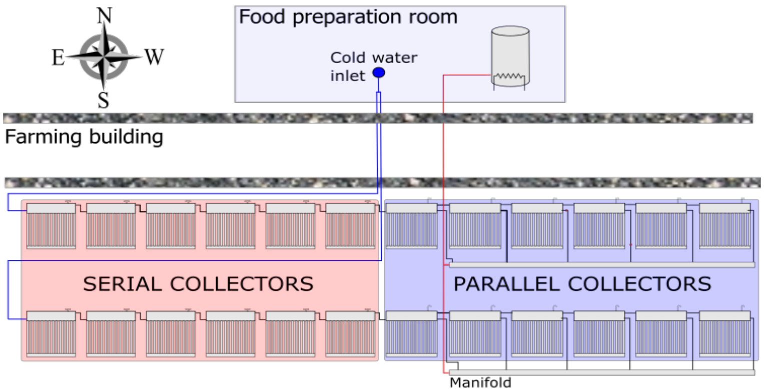

Figure 2. Pre-audit site.

2.2. Instrumentation

The solar field's instrumentation has been set-up in Summer 2020. One row out of two has been instrumented. Only sensors relevant for this paper are presented.

Five out of six serial collectors are instrumented with temperature sensors. K-Type thermocouples are inserted in the storage tanks upper part of collectors 1, 3, 4 and 6. Four identical sensors are put in place from the top at four different heights inside the collector 2 storage tank to evaluate thermal stratification. These temperatures are also used to calculate the average temperature $T_{ave,2}$. An on-site weather station measures the ambient temperature T_a, the relative humidity *RH* as well as the wind speed and direction. Global irradiance on horizontal plane (G_h) is measured by a pyranometer and an irradiance meter estimates global irradiance on the collector plane (G_{tilted}). A thermocouple and an ultrasonic flowmeter respectively determine the inlet flow rate (m_{inlet}) temperature (T_{inlet}) and flowrate (m_{inlet}). A scheme showing the solar installation probes location is given in figure 3:

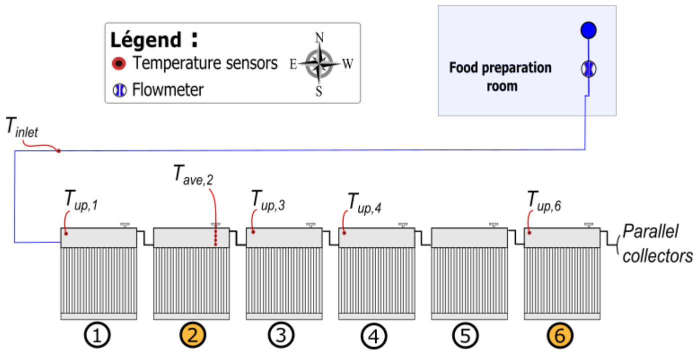

Figure 3. Solar field's instrumentation.

2.3. Validation tools

Data acquired are key to validate model. On one hand, temperatures measured from two serial collectors are compared to computed temperatures. Experimental and simulated values of $T_{ave,2}$ and $T_{up,6}$ are compared.

On the other hand, these measurements are used to determine the thermal energy to evaluate solar field's performance. The daily energy supplied by serial collectors (Q_{serial}) is calculated with the following equation 1:

$$Q_{serial} = \sum_0^{24h} \dot{m}_{inlet} . c_p . (T_{up,6} - T_{inlet}) \quad (1)$$

Where m_{inlet} is the mass inlet flowrate and c_p the specific heat. Integration is done over 24 hours starting at 23:00 to start with steady-state conditions (i.e. without any inlet or outlet flowrates nor solar irradiance).

Data presented in this paper are measurements from two different periods: from 20/05/2021 to 24/05/2021 and from 7/09/2021 to 12/09/2021. Global irradiance on horizontal plane and ambient temperature during the two periods are shown on figure 4 and 5:

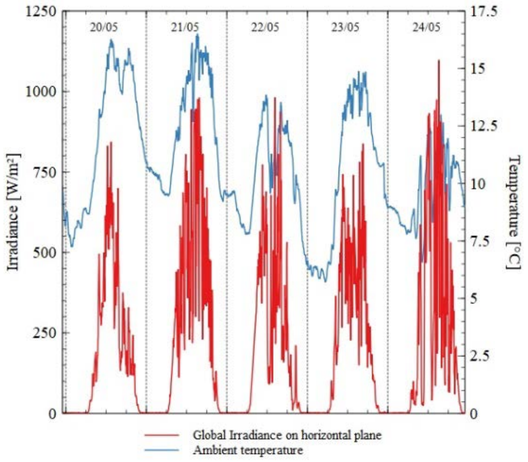

Figure 4. Weather conditions (May).

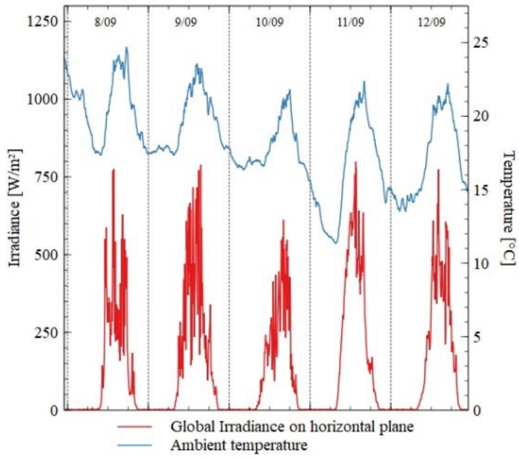

Figure 5. Weather conditions (September).

3. Model

The modelling of this SWH is carried out under Trnsys© software including TESS library which is dedicated to solar components. TRNSYS is a modular software based on "types" widely used to model and simulate the behaviour of transient thermal systems.

3.1. Model principles

Model of SWH consists of the combination of three existing types: Type71, Type533 and "Equation Type". Type71 models the behaviour of tubes. It computes outlet temperature and useful energy gain depending on external conditions such as irradiance and ambient temperature. Type533 is a horizontal and cylindrical storage tank type provided by Tess Library. It is divided into isothermal temperature nodes to model stratification in storage tanks. The natural circulation flow rate correlation (figure 6) is computed thanks to an Equation Type as presented in Budihardjo and al. (2005)[6].

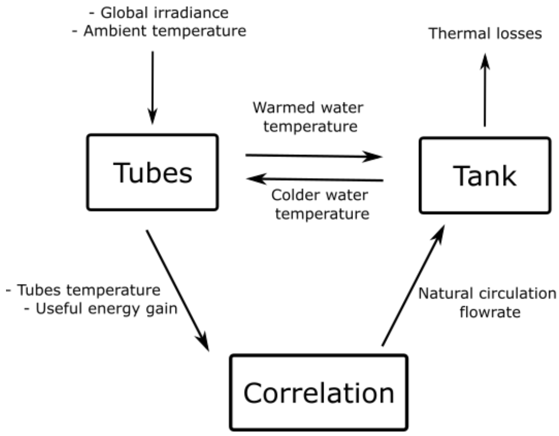

Figure 6. Model's principles.

3.2. Model optimization and validation

In order to calculate useful energy produced by a collector, three parameters need to be determined: Optical efficiency η_0, first order efficiency coefficient a_1 and second order efficiency coefficient a_2.

Optical efficiency is the fraction of the solar energy which is absorbed by heat-carrying fluid whereas first and second order efficiency coefficients represent thermal losses.

$$\eta = \eta_0 - a_1 \frac{T_c - T_a}{G_{tilted}} - a_2 \frac{(T_c - T_a)^2}{G_{tilted}} \quad (2)$$

Where T_c is the collector's average temperature.

Coefficients' identification is performed using TrnOpt tool from TESS library during the period of May. The cost function used is the PMAE (Percentage Mean Absolute Error). PMAE estimates the absolute deviation originating from the over-estimation and the under-estimation of collector's temperatures.

PMAE is calculated with the following equation as presented by Ayompe et al. [8]:

$$PMAE = \frac{100}{N} \sum_{i=1}^{N} \frac{|C_i - M_i|}{M_i} \quad (3)$$

Where N is the total number of iterations, C_i and M_i are respectively the computed and measured value at time step i.

Two identifications are performed with the measured value being either of $T_{ave,2}$ or $T_{up,6}$. Range of efficiencies coefficients are defined in order to have values consistent with literature. The optimization method is the "Particle Swarm Optimization with Inertia Weight".

Relative error (*RE*) is computed to assess the good determination of coefficients and the good performance of the model evaluates the difference between energies computed and measured. *RE* is calculated with the equation 4:

$$RE = \left| \frac{C - M}{M} \right| \quad (4)$$

Where C and M are respectively the values determined by simulation and measurement.

4. Results

4.1. Efficiency coefficients

Identifications have been processed and gave the following parameters respectively with the cost function calculated with $T_{ave,2}$ and $T_{up,6}$:

$$\eta_{T_{Ave,2}} = 0.59 - 0.56 \frac{T_c - T_a}{G_{tilted}} - 0.016 \frac{(T_c - T_a)^2}{G_{tilted}} \quad (5)$$

With a PMAE($T_{ave,2}$) equal to 9.3%

And:

$$\eta_{T_{up,6}} = 0.58 - 2.2 \frac{T_c - T_a}{G_{tilted}} - 0.011 \frac{(T_c - T_a)^2}{G_{tilted}} \quad (6)$$

With a PMAE($T_{up,6}$) equal to 5.0%.

Following results are computed using coefficients of equation 6.

4.2. Temperatures

Serial collector 2

Figures 7 and 8 show that average temperature computed of serial collector 2 behaves as the measured one. The PMAE calculated for May and September are respectively 11.9% and 7.6%.

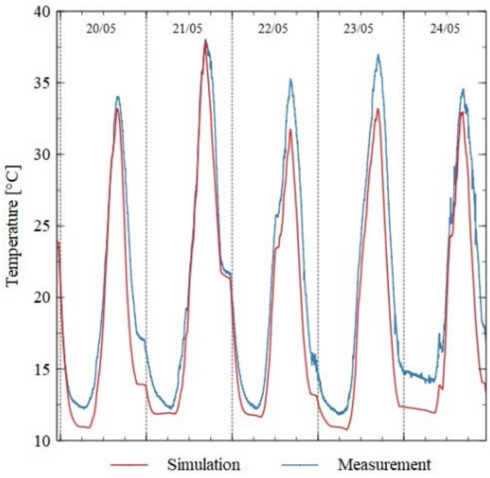

Figure 7. Average temperature of collector 2 (May).

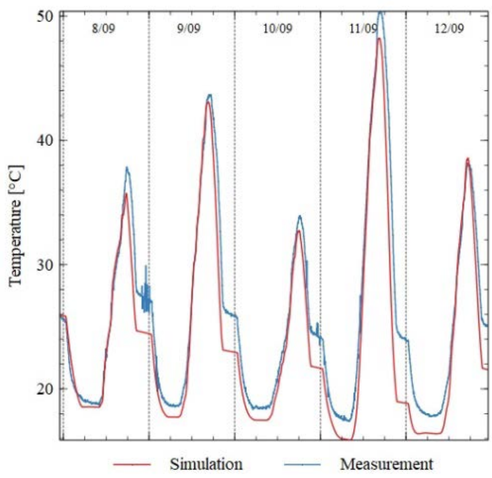

Figure 8. Average temperature of collector 2 (September).

Serial collector 6

Upper tank temperature of collector n°6 is well evaluated in both periods as shown on figures 9 and 10. However, an under-estimation is made for September. PMAE calculated for May is 5.0% and 5.9% for September.

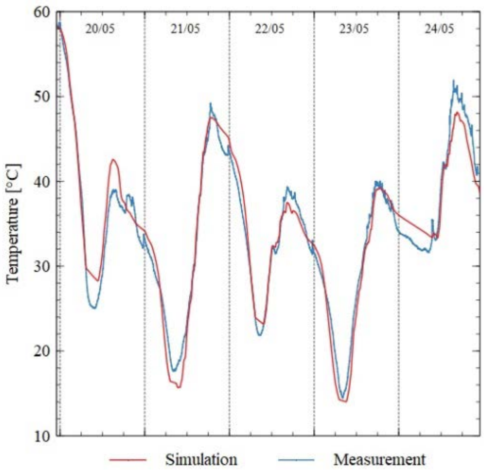

Figure 9. Upper tank temperature of collector 6 (May).

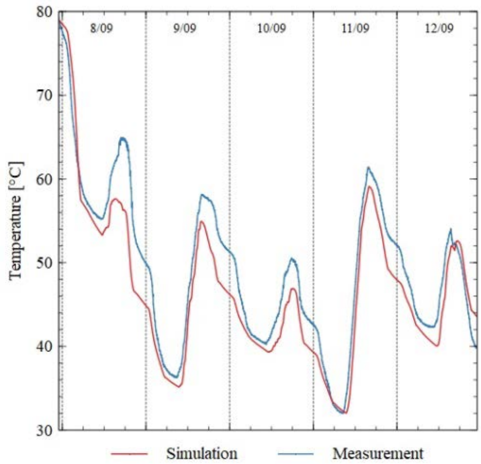

Figure 10. Upper tank temperature of collector 6 (September).

4.3. Energy supplied

Daily energy supplied for the presented periods are respectively illustrated in figures 11 and 12. For both sequences, the difference between daily energies supplied by serial collectors computed with the model and measured is close to zero. Table 1 presents the relative errors for May and September.

Table 1. Relative errors on energy supplied (May and September).

	Day 1	Day 2	Day 3	Day 4	Day 5
Relative error (May)	-7%	-6%	-2%	-5%	-16%
Relative error (September)	-1%	-7%	-7%	1%	3%

Relative errors for the entire period of May equals to -7% and to -2% for the whole period of September.

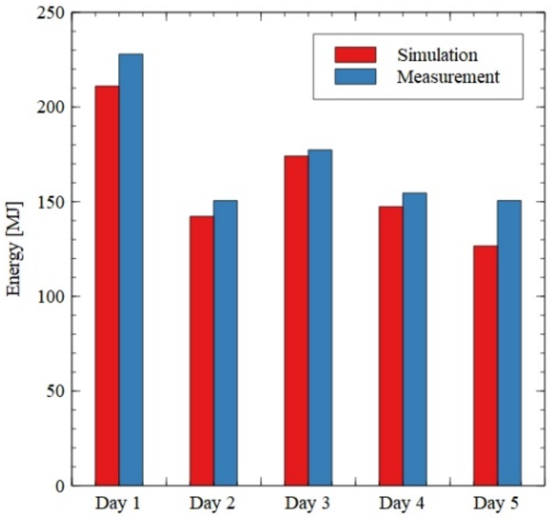

Figure 11. Daily energy supplied (May).

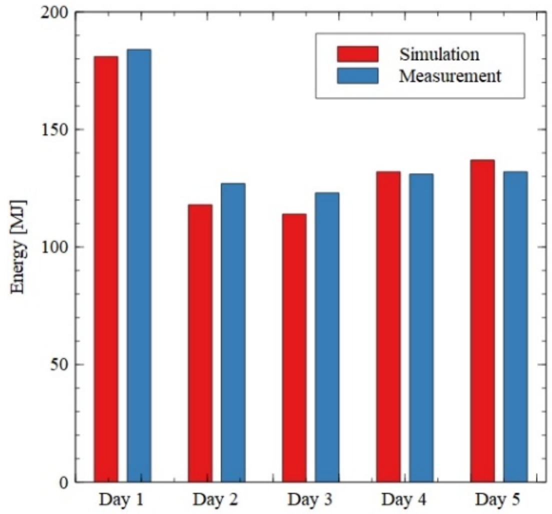

Figure 12. Daily energy supplied (September).

5. Conclusions

A Trnsys model was developed for a “Water-in-glass” evacuated tubes solar collector. The operational efficiency of a single in-series solar collector was expressed through a second-order expression. The efficiency coefficients η_0, a_1 and a_2 have been calculated from a spring experimental sequence thanks to optimization techniques under Trnsys software. The estimated values of these parameters are respectively 0.58, 2.2 and 0.011.

Simulations carried out on this spring test but also on another fall sequence showed a good agreement between simulated and experimental reference temperatures. The absolute deviations calculated were 11.9% and 5.0% for two serial collectors in May and 7.6% and 5.9% in September.

Furthermore, the model proved its capacity to predict satisfactorily the energy provided by six in-series solar collectors. In both five days experimental sequences, the relative error on energy production remains lower than 10%.

Future developments of this work will consist in modelling the second part of a row for this specific arrangement where solar collectors are assembled in-parallel. Ultimately, the model should be able to determine, under given weather conditions, the energy production of a solar installation made up of in-series collectors followed by in parallel solar collectors.

6. References

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Acknowledgments
This research was carried out in the framework of the ICaRE4Farms project, funded by the INTERREG North West Europe programme. Fengtech company made solar installation available for instrumentation and provided solar water heaters. Solar installation's specific arrangement is patented by Fengtech.