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Performance of SDHW systems with fully mixed and stratified tank operation under radiative regimes with different degree of stability

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ABSTRACT

In this paper we investigate whether, and to what extent, the radiative regime has an influence on the performance of a solar domestic hot water system. We compared the results of two mathematical models (a more accurate model with stratification in the storage tank and a simple, less accurate, fully mixed model), simulating the dynamic behaviour of a system with two flat-plate solar collectors, under three commonly used tapping cycles. Four summer and four winter days with different radiative regimes have been selected for simulations. For the less stable winter day of 19 January (relative sunshine $\sigma = 0.4–0.7$), when the system operates with a constant working fluid flow rate of 0.01 kg/(s m^2) and hot water is extracted according to a medium consumption tapping cycle, the mean value predicted by the more accurate, stratification model, for the useful heat gain by the solar collector is 388.87 W. Using this value as a reference, the MBE and RMSE values of the results predicted by the less accurate model are 41.54 W and 293.28 W, respectively. This proves that approximation models may not be used successfully for simulation. For variable working fluid mass flow rate, depending on the level of incoming solar irradiation and collecting surface area, the simplified model accuracy increases with the increase of the radiative regime stability.

1. Introduction

Solar domestic hot water systems (SDHWS) are an alternative to classic fuels hot water systems. In practice, they work together with the classic systems, which are used as a backup supply when solar irradiance levels are too low and the solar system alone cannot provide the required energy. A particularly important aspect of SDHWS modelling is represented by the storage tank model. One-dimensional models are mostly used. These models include simple fully mixed approaches as well as more complex and accurate stratified models. Since fully mixed models require fewer resources, the tendency is to use them instead of the stratified ones. However, a compromise between accuracy and computation time should be found.

Several single node models have been previously proposed and comparisons between fully mixed models and models taking into account the water storage tank stratification have been performed. Kleinbach [1] tested various TRNSYS tank models against measured data in a wide range of conditions, in order to investigate the models accuracy. He recommended that the fully mixed tank model should never be used, since it underestimates both the energy input to the tank and the energy delivered to the user. The plug flow model with plume entrainment is suggested as an alternative to the multi-node models for a mean number of tank turnovers less than five. Campos Celador et al. [2] analysed three different tank model approaches: actual stratified model, ideal stratified model and fully mixed model. The analysis included a comparison between the three models in the same weather conditions by means of the TRNSYS simulation software. The system consists of a Combined Heat and Power production plant including a cylindrical hot water storage tank designed for residential urbanisation of 1000 dwellings. When comparing the actual stratified model with the fully mixed model, the authors concluded that stratification helps to increase the profitability of the plant, increasing the annual net savings by 6%. Ghaddar [3] presented the performance of a stratified solar water tank in different operation modes, both analytically and experimentally. When comparing the results with the fully mixed tank model [4] the author revealed an increase of up to 20%

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Nomenclature

a	thermal diffusivity, [m^2/s]
A_c	total collectors surface area, [m^2]
A_{ti}, A_{li}	cross-sectional and lateral area of the control volume, [m^2]
b_s	pitch, [m]
c_p	specific heat capacity [J/(kg K)]
$d_{ol,i}$	inner diameter of the solar coil, [m]
D	solar coil diameter, [m]
D_C	projected diameter of a winding, [m]
D_S	average diameter, [m]
g	9.81 [m/s^2], gravitational acceleration
G_t	global solar irradiance incident on the collector, [W/m^2]
h_c	convection heat transfer coefficient, [W/(m^2 K)]
K_i	heat loss coefficient from the tank to the environment, [W/(m^2 K)]
L_{ol}	tube length, [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n_c	number of turns
Nu_l	Nusselt number for the laminar flow regime
Nu_t	Nusselt number for the transient flow regime
Q	heat flux [W]
Ra	Rayleigh number
Re	Reynolds number
S	surface area, [m^2]
t	time, [s]
T_{amb}	ambient temperature, [°C]
T_{cons}	temperature of water delivered to consumer [°C]
T_{dif}	temperature difference between outlet from collectors and T_{cons} [°C]
T_i, T_{i+1}, T_{i-1}	temperature in, above, and below node i, respectively [°C]
T_{wb}	temperature of the first water layer which gets in contact with the solar coil [°C]
T_{wsi}, T_{wse}	temperature of the fluid at the solar coil inlet and outlet, respectively [°C]
v_{amb}	wind speed [m/s]

Greek letters

β	collectors tilt angle, [degrees]
β_v	volumetric thermal expansion coefficient, [1/K]
δ	thickness, [m]
Δx	distance between the centres of two adjacent control volumes, [m]
ε	emissivity
η	instantaneous system efficiency, [−]
η_0	collector optical efficiency, [%]
$\Delta\lambda$	destratification conductivity, [W/(m K)]
λ	thermal conductivity, [W/(m K)]
λ_b	tank water thermal conductivity, [W/(m K)]
μ_{ws}	dynamic viscosity of the fluid at solar coil wall temperature, [Pa s]
μ_m	dynamic viscosity at the fluid medium temperature, [Pa s]
ν	kinematic viscosity, [m^2/s]
σ_r	Stefan–Boltzmann constant [5.67 × 10^{-8} W m^{-2} K^{-4}]

Subscripts

ap	absorber plate
bp	metal back plate
co	copper pipe
is	back isolation
og	outer glass
sf	side frame
w	working fluid
ws	working fluid in the serpentine
wb	storage tank water

in efficiency of the stratified tank. Cadafalch [5] modeled a storage tank equipped with an immersed serpentine heat exchanger. The one dimensional model was validated against experimental data available in the literature, both for a mixed tank, obtained by using a single node, and for a multi-node stratified tank. The stratified model presented some deviations from experimental data, but the authors concluded that they are not significant and a modified, more accurate model would be too complex and expensive.

The above studies analysed the accuracy and performance of different storage tank models in various operation regimes. Though, none of them considered how much the accuracy of simple fully mixed models and stratified models depends on the stability of the radiative regime. This is the first objective of the present paper. Note that the performance of solar thermal systems is affected by the solar irradiance, ambient temperature and wind speed. There have been numerous studies on the influence of these three parameters. In this paper we analyze the influence of a fourth factor, namely radiative regime stability. The simultaneous analysis of all the four factors is complex and a study on the influence of temperature and wind speed is beyond the scope of the present paper.

A dynamic model based on several ordinary differential equations is developed to describe the SDHWS operation. The model takes into account the stratification in the tank storage. The fully mixed operation is a particular case of the general model. The model is validated against experimental data reported in literature. By using the dynamic model, we simulate the operation of SDHWS in real weather conditions, under three commonly used tapping cycles, corresponding to low, medium, and high consumption from the water tank, respectively, according with European standards. Meteorological and radiometric data measured at Timisoara (Romania, Eastern Europe) are used in this work. Summer and winter days belonging to different radiative regimes have been selected for analysis.

The performance of both photovoltaic (PV) systems and SDHW systems depend on the level of the incoming solar radiation. Since the weather conditions are variable, investigations regarding SDHWS performance require using dynamic analysis tools, which can describe more accurately the system response to fast variations of ambient conditions.

The influence of the magnitude of the solar irradiation level on SDHWS performance has been considered in many studies. However, there are days with the same irradiation level but different radiative regime stability. Previous research proved that the influence of the stability of the radiative regime on the PV systems performance is important [6]. The influence of the radiative regime stability on the performance of SDHWS has been rarely considered (see Ref. [7] where the focus is mainly on economic issues). In a previous paper [8] we have studied the thermal inertia of water heating solar collectors as a function of the stability of the radiative