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FLUID FLOW CONTROL IN DOMESTIC HOT WATER SYSTEMS DURING DAYS WITH DIFFERENT RADIATIVE STABILITY LEVELS

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Abstract

This paper presents models / strategies for optimum performance of solar collector in closed loop systems. These models aim to maximize the obtained energy by thermal conversion of solar energy. The mass flow rate of the fluid from the primary circuit of the system is the control parameter. The semi empirical models and optimal control methods are in brief presented. The volume of the storage tank is important and the ratio V_s/A_c between this volume and area of the collectors is a key factor in appropriate sizing of the DHW system. Therefore, the paper establishes a relationship between this ratio and the mass flow rate of the fluid in the collector This paper also analyses the variation of the energetic performance (useful heat flux transferred to the storage tank, heat flux transferred to the water, water temperature in the storage tank) with the volume of the storage tank. Analysis was performed on an extensive set of meteorological data from Timisoara, Romania, with instantaneous data (measured at 15 seconds) for summer days, from July 2009, with different relative sunshine values, σ. Important differences have been observed between days with different stability levels - days more or less stable.

1. Introduction

From the specific literature are known models / strategies for good performance of solar collector working in closed loop systems. These models aim to maximize the energy (useful heat flux transferred to the storage tank, heat flux transferred to the domestic hot water) resulted by thermal conversion of solar energy. The control parameter is the mass flow rate of the fluid from the primary circuit of the system. The empirical numerical models assume the mass flow as constant (depending on the solar global irradiance and on the area of solar collector) [1], [2] or variable, depending on the variation of temperature ΔT (between water's temperature at the collector outlet and water temperature in the storage tank) [1], [3]. Models based on the optimal control of the mass flow rate as control parameter [2], [4], [5] are based on Pontryagin's principle of maximum. Starting from a maximal value of the flow given by the empirical control relations, an optimum mass flow rate is calculating by maximization of the objective function. That function is the net useful heat stored in the water tank. The best empirical control strategy uses information regarding solar radiation as input data [5]. These models to calculate the mass flow rate in DHW systems are centralized in Table 1.

A solar domestic hot water (DHW) system consisting in solar collectors with surface area Ac, a storage tank with volume Vs, a mass flow rate $\dot{m}_1$ with $T_{f,in}$ temperature in the collectors inlet and $T_{f,out}$ temperature at the collector outlet, like in figure 1, was considered. The performance of solar domestic hot water system is dependent on the solar irradiance and on σ - the relative sunshine. This paper show how the mass flow rate in the primary circuit depends on the stability of the radiative regime and establish the relationship between $\dot{m}_1$ and V_s / A_c, in the purpose to obtain the optimum mass flow rate in the primary circuit. The ratio V_s / A_c may be used as a design parameter in solar hot water systems, since it contains the most important key components: the volume of storage tank and the area of solar collectors. A similar analysis was made in [6], but only for a summer day.
This article extends the study to a longer time, including summer days with different relative sunshine values, σ, and relative stability.

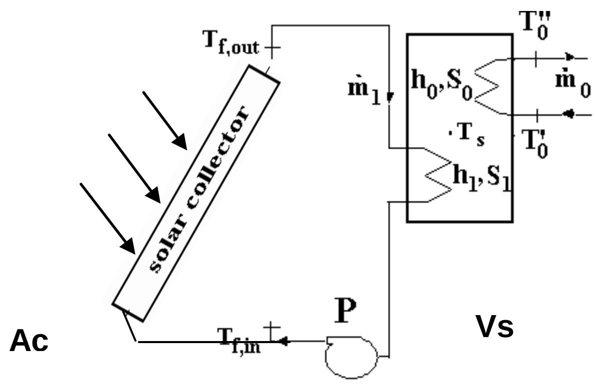


Fig. 1. Solar DHW system in closed loop primary circuit and serpentine in storage tank. $T_{f,in}$, $T_{f,out}$-fluid temperature at inlet/outlet of the collector, ho, h1-heat transfer coefficient of serpentine in secondary and primary circuit, S_0, S_1-heat transfer surface of serpentine, m_0', m_1'-mass flow rate in secondary and primary circuit, P-pump, Vs-volume of the storage tank, Ac -area of the collector, T_0', T_0"-fresh and warm water temperature to the user.

The optimum mass flow rate for a solar DHW system $\dot{m}_1$ can be calculated with different models from the literature (Table 1). Present paper establishes a relationship / coefficient between this ratio V_s / A_c and the mass flow rate of the fluid in the collector:

$$\dot{m}_1 = 0.0014356 \cdot \frac{V_s}{A_c}. \tag{1}$$

This relationship may be added to the strategies known in the literature (Table 1).

Table 1. Strategies to calculate the mass flow rate

Relationship	Comment
$\dot{m}_1 = 0.000167\sqrt{G} \cdot A_c$	First strategy in [1] Obs. Not for cloudy days with σ = 0.
$\dot{m}_1 = 0.000417\left(T_{f,out} - T_s\right) \cdot A_c$	Second strategy in [1]
$\dot{m}_1 = 0.000833\left(T_{f,out} - T_s\right) \cdot A_c$	Second strategy in [1], as corrected in [2]
$\dot{m}_1 = 0.014 \cdot A_c$	Strategy in [3]
$\dot{m}_1 = 0.0014356 \cdot \frac{V_s}{A_c}$	Strategy in present paper

Note that stagnation threshold temperature is obviously faster reached if the storage tank volume is lower. Therefore, the present paper covers functional situations that are not considering stagnation.

The paper also analyses the variation of the energetic performances (useful heat Qu, heat transferred to the water Q_{out}, fluid temperature at collector outlet, $T_{f,out}$) with the volume of the storage tank. Analysis was performed on an extensive set of meteorological data from Timisoara, Romania, with practically instantaneous data (measured at 15 seconds) from July 2009, with different relative sunshine values σ and taking into account of the radiative regime. Important differences have been observed between days with different stability of the radiative regime (i.e. days more or less stable). It was found that Qu increases with relative sunshine, σ, but remains almost constant when increasing the volume of the storage tank. The heat flux extracted by the user from the storage tank, Q_{out} slightly decreases with V_s and the outlet temperature $T_{f,out}$ also decreases with increasing V_s. Some of these results were confirmed by previously papers [3, 4, 6]. In this paper one used the optimal strategy for fluid flow control, developed in [4]. The useful heat flux Q_u provided by the collectors was defined in [7]. The heat flux delivered Q_{out} from the storage tank to the user has been estimated also in [8, 9, 10]. In the optimal control model is defined the objective function namely the net useful heat collected during a day. Using a maximum value of the flow from the empirical control relations, an optimum mass flow rate is calculated by derivation of the objective function. Time integrated values of: (i) the optimal mass flow rate for different volume of the storage tank, (ii) the useful heat flux collected by the solar energy conversion area, Q_u, (iii) the heat flux extracted by the user from the storage tank, Q_{out} and (iv) the $T_{f,out}$ temperature at collector outlet were computed. These are the parameters of interest when the daily performance of a solar DHW system is analyzed. The methodology has been validated by comparison with results obtained with [11].

2. System Setup

The solar DHW system analyzed (Figure 1) consists of collectors with surface area A_c = 9 m^2. Four different size storage tanks are considered. They have the same inner diameter 0.69 m while their height H_s is 0.4, 0.8, 1.2 and 1.6 m, respectively (their volume V_s is 150, 300, 450 and 600 L).

Weather database measurements performed in the Romanian town of Timisoara (latitude 45°46'N, longitude, 21°25'E and 85 m altitude above mean sea level) are used in this study. Air temperature and global and diffuse solar irradiance are recorded on a horizontal surface and calculated for a tilted surface at 30°. Measurements are performed on time intervals of 15 s. Data from July 2009 are used in this analysis (see Table 2); the six summer days analyzed have different relative sunshine σ and radiative regime (stable or less stable days).

3. Results for Optimum Mass Flow Rate

A linear relation of the form

$$\dot{m}_1 = a \cdot (\frac{V_s}{A_c}) \tag{2}$$

have been obtained by fitting results for more than three thousand points, like in figure 2a) and figure 2b) with TableCurve2 software [12]. "a" is the regression coefficient and "r2" is the coefficient of determination. For each of the six summer days were performed such fittings and were obtained regression coefficients, function of the relative sunshine and radiative regime. For overcast sky days (σ=0), this coefficient is a=0.0020; for stable sunny days, (σ=0.8-1), one may use a=0.0012. The coefficient "a" increases with the decrease of σ. Values are given in Table 2 and variation of the coefficient "a" can be seen for all summer days analyzed. Figure 2a) presents these coefficients for days with σ=0.4-0.7, with a great slope for a less stable day (12 July) and a lower slope for a more stable day (3 July). In figure 2b) there are other two days with relative sunshine σ=0.8-0.1 (i.e. a stable day (15 July) and a less stable day (26 July)). In conclusion for the summer season, the control of the fluid flow can be made using the relation:

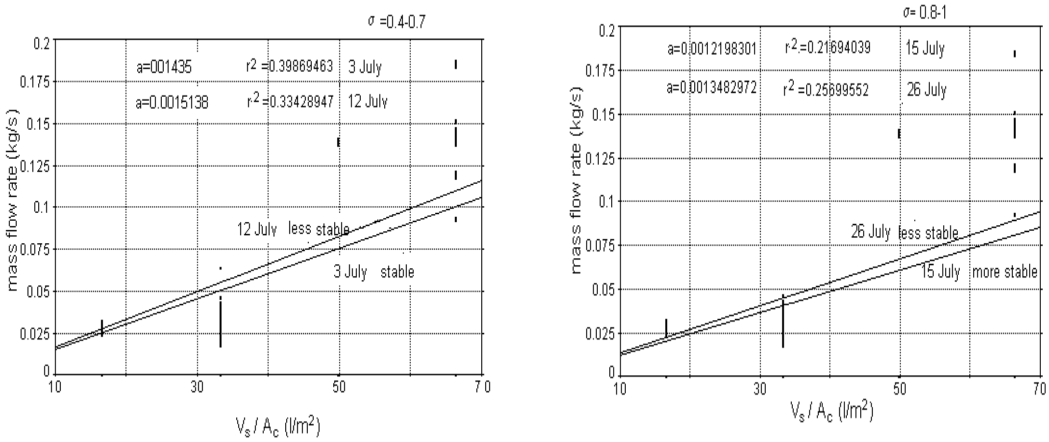
$$\dot{m}_1 = 0.0014 \cdot \frac{V_s}{A_c} \cdot \tag{3}$$

The coefficient "a" in equation (3) represents the average for the warm season. The mean value for summer season is almost identical to that of a stable day with σ=0.4-0.7.

Table 2. The regression coefficient „*a*" to find optimum mass flow rate function of V_s/A_c for summer days

	Sunshine class σ	Radiative regime	Summer day	Coefficient for mass flow rate control "a"
Overcast sky day	0	stable	July, 11	0.0020
High cloudiness	0-0.3	less stable	NA	-
		stable	July,2	0.0017
Medium cloudiness	0.4-0.7	less stable	July, 12	0.0015
		stable	July,3	0.0014
Low cloudiness	0.8-1	less stable	July, 26	0.0013
		stable	July, 15	0.0012
Clear sky	1	stable	NA	-
Average for summer days	0-1	stable and less stable	July	0.0014

This paper proposes numerical coefficient a = 0.0014 to properly sizing DHW systems regarding the storage tank volume and collectors' area, to maximize the energetic performance (see section 4).



a) b)

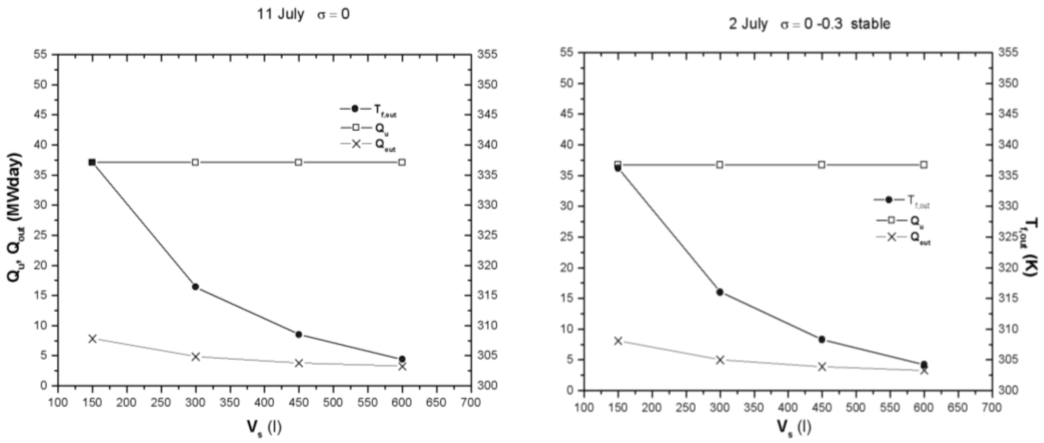
Fig 1. Relationship between mass flow rate and V_s/A_c for different relative sunshine and radiative regime, a) in summer days with σ=0.4-0.7; b) other summer days with σ=0.8-1

4. Results regarding the Energetic Performance

In this section were analyzed the variation of the energetic performance (useful heat Qu, heat transferred to the water Q_{out}, outlet fluid temperature $T_{f,out}$) when the volume of the storage tank Vs increases. The variation of these parameters is presented in figures 3, 4 and 5, for days with different relative sunshine σ and different radiative regime (stable or less stable days).

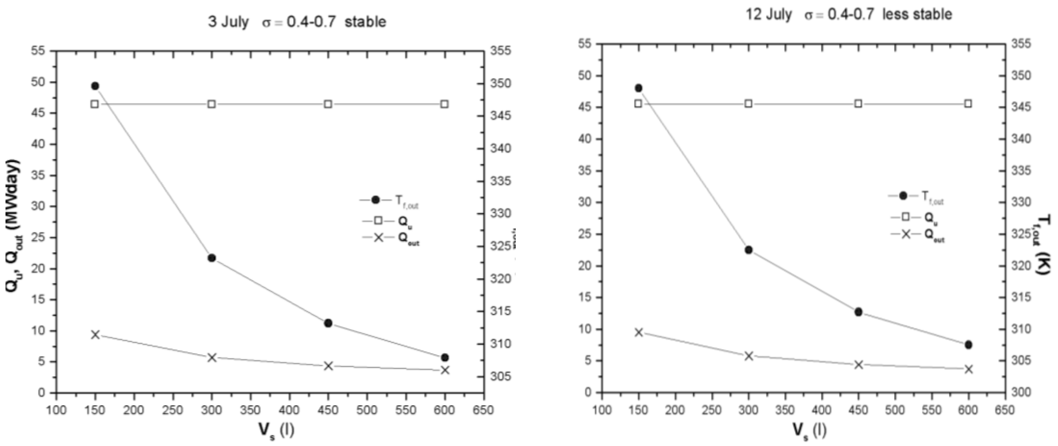
It was found that Q_u increase with increasing relative sunshine, σ, but remains almost constant with increasing the volume of the storage tank. The heat flux extracted by the user from the storage tank, Q_{out} slightly decreases with increasing V_s. The outlet temperature $T_{f,out}$ decreases with increasing V_s. Some of these results were confirmed by previously papers [3],[4].

Regarding the stability of the radiative volume, values for σ=0.4-0.7 are close for stable or less stable days (compare figure 4a) with figure 4b)), but for a low cloudiness day, σ=0.8-1, the energetic performances for a less stable day (26 July) are better compared with those of a more stable day (15 July) (see figure 5a) and figure 5b)). The energetic performances for an overcast sky day (11 July) are worst.



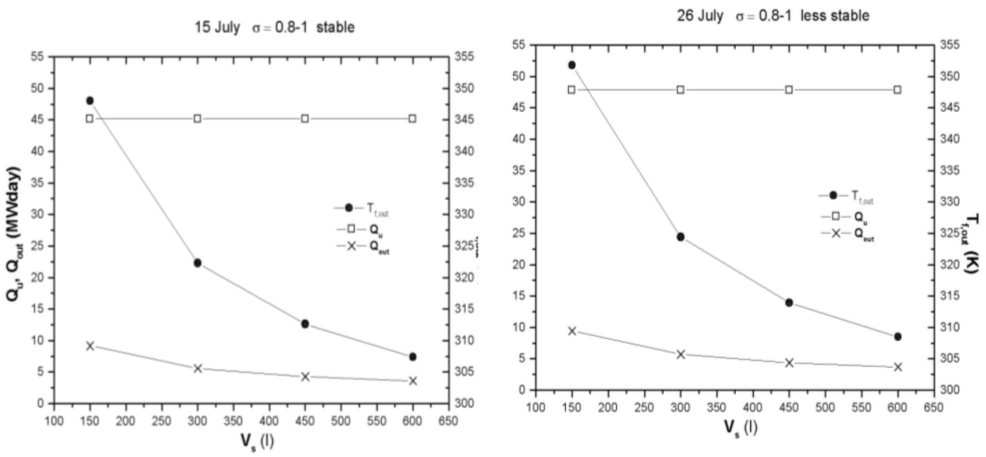
a) b)

Fig 2. Variation of Q_u, Q_{out} and T_{fout} with the storage tank volume for an overcast sky day, σ=0; b) for a high cloudiness stable day σ=0-0.3



a) b)

Fig 3.Variation of Q_u, Q_{out} and T_{fout} with the storage tank volume a) for a medium cloudiness day, σ=0.4-0.7; b) for a medium cloudiness less stable day σ=0.4-0.7



a) b)

Fig 4. Variation of Q_u, Q_{out} and T_{fout} with the storage tank volume a) for a low cloudiness day, σ=0.8-1; b) for a low cloudiness less stable day σ=0.8-1

5. Conclusion

Starting from the strategy of optimal control for mass flow rate in a solar DHW system, this paper proposes the new relationship equation (3) between the mass flow rate and the volume of the storage tank. Equation (3) can be used for correct sizing the solar DHW systems.

Regarding the energetic performances, Qu increase with increasing relative sunshine, σ, but remains almost constant when the volume of the storage tank increases. The heat flux extracted by the user from the storage tank, Q_{out} , slightly decreases with V_s increasing and the outlet temperature $T_{f,out}$ decreases with V_s increasing.

The performances of solar DHW systems depend on the relative sunshine σ and the stability of the radiative regime. Significant differences have been observed between days with different levels of the stability of the radiative regime.

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