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Quasi-continuous flow rate determination based on analyzing temperature courses

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Abstract

The aim of the investigations presented was the development of a new method that enables a continuous flow rate detection in the collector circuit of solar thermal systems on the basis of analyzing temperature courses. To verify the so-called distance method that is introduced in this paper regarding its accuracy and the opportunity of application, the method has been tested on measured data. On five days with characteristic irradiance profiles an almost continuous flow rate detection was possible with a mean error of 2 % up to 4 % compared to the measured reference flow rate of an oscillating piston flowmeter. However, in cases of little changing temperature courses a reliable and accurate flow rate detection by using the distance method is possible only for a small fraction of the pump operating time.
In order to verify the distance method for different operating conditions and parameter settings, it has been additionally applied to data generated by TRNSYS simulations. Essentially, the results were showing that with greater influence of heat losses and capacity effects the fraction of the pump operating time is reduced for which a reliable flow rate determination is possible, whereas more distinct and steep temperature fluctuations, i.e. due to irradiance changes, increase the accuracy of the distance method.

1. INTRODUCTION

At present, solar domestic hot water systems are gaining more acceptance and currency. To encourage this development, reliable functional tests of solar thermal systems are required in particular. An important quantity that has to be known not just for the detection of system faults but also for the survey of the heat flow is the volume flow rate in the collector circuit. However, especially for smaller solar systems the installation of a flow meter is rather expensive compared to the total investment so that in this case inexpensive solutions would be helpful.

A possible solution could be the flow rate determination on the basis of temperature steps. For this the temperature courses measured at two temperature sensors in the collector outlet duct are compared (see figure 1). With the time difference in which a temperature step passes these two sensors the running time Δt of the fluid can be determined which leads – with knowledge of the pipe cross-section A and the distance ΔS between the sensors – to the flow rate following equation (1):

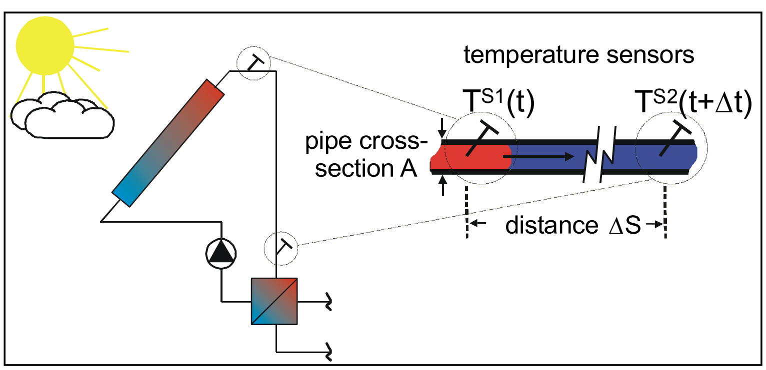

Figure 1: Schematic principle of the flow rate measurement on the basis of analyzing temperature steps

$$\dot{V} = A \cdot \frac{\Delta S}{\Delta t} \qquad (1)$$

Some procedures for such a simplified volume flow measurement have been described in the specialized literature so far, i.e. Kaufmann (1999) and Altgeld (1999); however, they all have in common that for the generation of a temperature step which is suitable for the application of the respective method a short-term stop of the circulation pump is necessary. On the one hand this leads to an uncertainty whether the volume flow rate during the start-up of the pump is representative of its normal operation. On the other hand the volume flow rate is just being examined in a snapshot by this. Therefore, these methods do not provide a continuous functional testing or a measurement of the amount of heat during the whole operating time of the pump.
With the investigations described in this paper a new method is presented which uses naturally occurring temperature steps caused by irradiance or consumption fluctuations. Due to this, a quasi-continuous flow rate determination is possible. After presenting the concept as well as some applications in chapter 2, the results will be summarized in chapter 3.

2. THE DISTANCE METHOD

The basic concept how a continuous flow rate detection without using flow meters should be possible with the new method is described in chapter 2.1. Though, additional theoretical considerations had to be made about the influence of thermal losses and capacity effects that can lead to a modification of the temperature courses at the two sensors T^{S1} and T^{S2} as well as to an extension of the running time (described in chapter 2.2). The development of the concept which is described in chapter 2.1 is based on the evaluation of data measured with the system described in chapter 2.3 when some applications of the method on measured data as well as on data generated by TRNSYS simulations will be described.

2.1. The concept

As already mentioned, the distance method also determines the running time Δt of the temperature information from one sensor to another. However, unlike other known methods this concept is able to evaluate naturally occurring temperature fluctuations caused by irradiance or consumption. To illustrate the idea of the concept, in Figure 2 a temperature step is outlined that moved from the first to the second sensor on the basis of which the four different steps of the concept are presented.

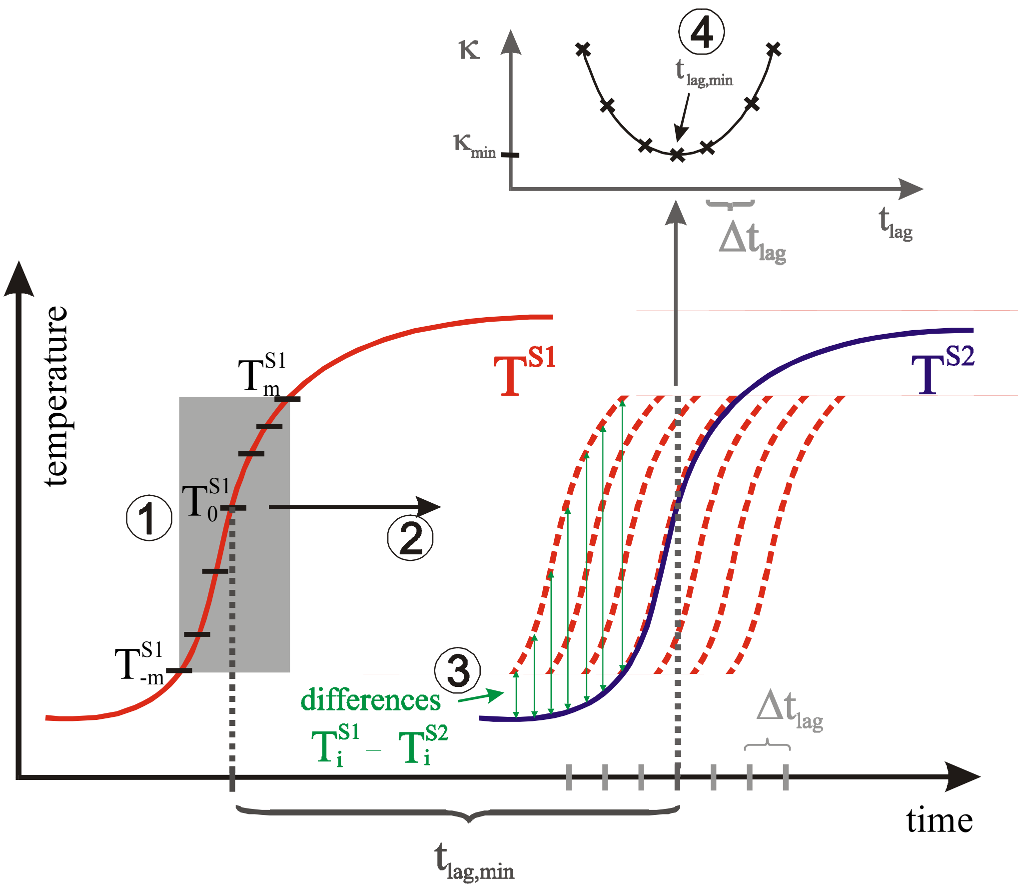

Figure 2: Outline of the concept of the distance method. For better understanding, a temperature step is shown exemplary that is measured first at the sensor T^{S1} and, with a time delay, at the sensor T^{S2}. The discrete time shifts of a window (1) that is cut out of the first temperature curve are plotted as broken lines (2), and an assumed gradient of the distances (3) corresponding to the respective time shifts is outlined in the κ diagram on top (4). The shift that is almost completely hidden behind the second temperature curve is the one with the smallest distance κ_{min}. Thus, its offset is the demanded running time $t_{lag,min}$. As indicated by the slight changes of the temperature curve from T^{S1} to T^{S2}, the peaks and the gradient of the temperature curves are reduced due to heat losses and capacity effects.

To find Δt with the distance method, in a first step a sector of the temperature curve measured at T^{S1} is being cut out by selecting ±m measured values around that point in time for which the flow rate should be determined. In a second step, this sector is shifted by defined time intervals Δt_{lag} across the temperature curve measured at T^{S2}. Thirdly, for each of these offsets the mathematical distance $\kappa(t_{lag})$ between the shifted sector and the corresponding sector of the temperature curve measured at T^{S2} is calculated by the Euclidian metric represented by equation (2):

$$\kappa(t_{lag}) = \frac{1}{\sqrt{2m+1}} \sqrt{\sum_{i=-m}^{+m} \left(T_i^{S1}(t - t_{lag}) - T_i^{S2}(t) \right)^2} \qquad (2)$$

The factor $(2m+1)^{-0.5}$ is a normalizing factor providing that κ is commensurable for different m if a smaller or bigger sector is chosen or if there are more measuring points within the sector. If the time interval Δt_{lag} is smaller than the time resolution of the measured data, a linear interpolation of the temperature between the two related measuring points is used.

In fourth place, the minimum $\kappa_{min} = \kappa(t_{lag,min})$ of the mathematical distance of the chosen sector to the measured T^{S2} curve has to be found. This time shift $t_{lag,min}$ now is equivalent to the demanded fluid running time Δt that can be used to get the flow rate following equation (1).

2.2. Additional considerations

Theoretically, a continuous flow rate determination should be possible by using the distance method if the time steps Δt_{lag} between the shifts of the curve window is small enough and if there is any temperature fluctuation within the shifted curve window. However, difficulties for the application of this method are on the one hand changes in the form of the temperature curve from the detection at T^{S1} to T^{S2} due to heat losses and capacity effects and on the other hand particular small and flat temperature steps.
Especially when longer running times of the temperature information between the two sensors occur, the heat losses to the surroundings lead to a reduction of the temperature measured at the second sensor. Furthermore, due to the finite heat transfer between the fluid and the tube wall the temperature peaks are reduced from one sensor to the other; in case of temperature steps this effect becomes apparent by a smaller gradient of the temperature curve.
In addition, the influence of the tube wall capacity causes that the tube wall itself is being heated up with increasing temperatures of the fluid flowing through the pipe. By this, heat energy is transferred from the fluid to the tube wall which leads to an extension of the detected running time. In case of decreasing temperature of the flowing fluid the warmer tube wall is heating up the fluid so that the temperature information which passes the first sensor also is delayed passing the second sensor. Thus, to calculate the flow rate with the detected running time, a correction factor had to be introduced that compensates this effect, cf. Frank (2000).
First applications of the distance method on measured data showed that for some parts of the pump operating time the determined flow rate was very accurate whereas for some other parts the discrepancy was about 15 %. Therefore, a reliability criterion has been developed that is based on the evaluation of how marked the distance minimum κ_{min} of the respective curve parts is. To get a measure for this, the difference δ of the minimum and a number of n values right and left of it is formed by equation (3):

$$\delta = \kappa(t_{lag,min} \pm n \cdot \Delta t_{lag}) - \kappa(t_{lag,min}) \quad (3)$$

Here, n has to be chosen practically depending on the resolution of the measured data. Furthermore, a quantity κ_{limit} has been introduced, and by comparing δ with a value of κ_{limit} that has been made up empirically for the specific system the flow rates determined by the distance method can be identified as more or less reliable. Especially plane and little marked temperature courses that in some cases do not lead to a unique value of κ_{min} at all can be classified as less reliable in this way. Finally, using this criterion only those parts of the pump operation time are evaluated by the distance method that lead to a reliable flow rate.
The applications described in chapter 2.3 show that indeed those values that are identified as less reliable are values that would lead to greater deviations from the measured flow rate at the same time. Nevertheless, still some cases occur when a marked minimum of the distance is leading to a wrong value of the flow rate. These systematical difficulties of the method have been scrutinized in Frank (2000) with the conclusion that more distinct and steep temperature curves are leading to more accurate and reliable flow rate determinations whereas the applicability of the method is reduced with increasing influence of thermal losses and capacity effects.

2.3. Application of the Distance Method

The development of the distance method is based on the analysis of measured data from the collector circuit of a 50m² solar thermal system in Marburg (Germany) that is being examined in detail since 1996, cf. i.e. Ratka (1998) or Uecker (1998). The data are one minute mean values and cover five days with different irradiance profiles. To measure the temperatures, PT 100 sensors were used that have been installed with a distance of ΔS=24.2m between the collector and the heat exchanger (see figure 3). The installed copper pipes have an inside diameter of 25mm and an outside diameter of 28mm. As reference the flow rate $\dot{V}_{ref}$ has been measured by an oscillating piston flowmeter.

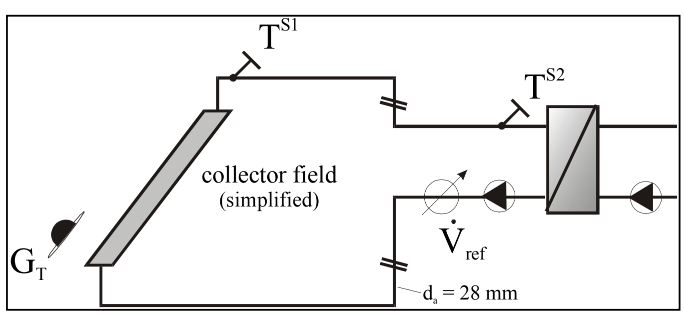

Figure 3: Sketch of the collector circuit with the relevant measuring points.

As described in the previous chapter, the introduced reliability criterion excludes some of the flow rate values

$\dot{V}_{dist}$ determined by the distance method from the evaluated pump operating time. Due to this, a compromise has to be found between120
the accuracy of the determined flow rates and the fraction of the pump operating time for that a flow rate determination is possible after using the reliability criterion. To find out which κ_{limit} (for n = 3) is leading to results that are accurate enough without reducing the number of determined flow rates too much, the deviations between $\dot{V}_{ref}$ and $\dot{V}_{dist}$ have been ascertained by calculating the mean value and variance of the quotient $\dot{V}_{dist}/\dot{V}_{ref}$ depending on κ_{limit}. For the described system and different irradiance profiles, a useful κ_{limit} of 0.05 K could have been read; for one of the investigated days this is leading to results for the flow rate determination shown in figure 4.

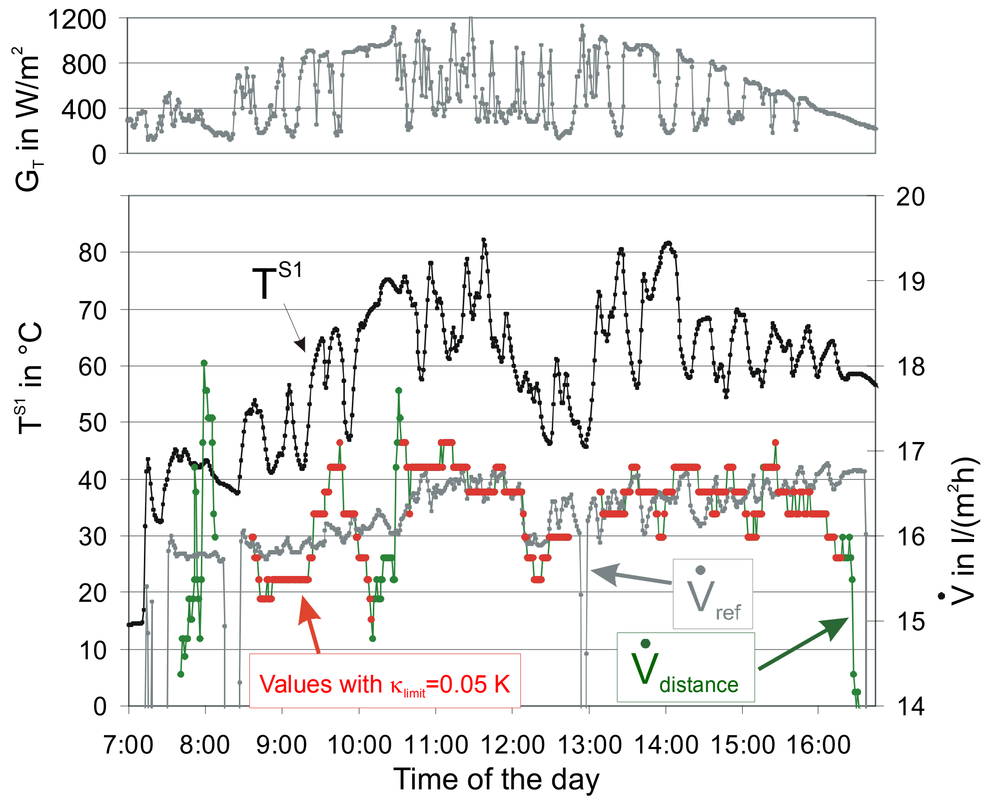

Figure 4: Application of the distance method on measured data from June 6, 1998. The diagram shows for a changeable day the global irradiance G_T in the collector plane and the inlet temperature into the pipe section measured at the sensor T^{S1} on the left axis. The outlet temperature of the pipe section measured at the sensor T^{S2} are not plotted because the T^{S2} curve is very close to the T^{S1} curve. On the right axis, the measured reference flow rate (grey) and the flow rate which is determined by the distance method (green) are represented. Those values that are still valid after the application of the reliability criterion with κ_{limit} = 0.05 K (for n = 3) are emphasized (red).

With the settings described above (κ_{limit} = 0.05 K and n = 3), on the exemplary day shown in figure 4 a flow rate determination for 75 % of the pump operation is identified as reliable with a deviation of 0.03 ± 0.36 l(m²h) which corresponds to a relative variance to the measured value of 2.4 %. Though, the distinct changes of the irradiance and therefore the temperatures are providing good conditions for the application of the distance method on this day so that the reliability criterion κ_{limit} might have been chosen different leading to a bigger number of reliable values with similar errors. However, in periods with very little changes of irradiance and temperatures in the collector circuit (like very clear days and no consumption) κ_{limit} = 0.05 K turned out to be useful as well.

In order to check the applicability of the distance method for different and frequently occurring weather conditions, five days with representative irradiance profiles have been examined. With κ_{limit} = 0.05 K the relative

error was between 2.4 % under good conditions (above all distinct and steep temperature curves) and 4.8 % under difficult conditions (like little changing irradiance and temperature curves, many stops of the pump) with a fraction of flow rate determinations compared to the pump operating time between 75 % and 41 %.
To analyze the appropriate choice of the parameters connected with the application of the distance method (like n or κ_{limit}, m, Δt_{lag}), the distance method has also been applied to data generated by TRNSYS simulations. Furthermore, different operating conditions like the distance of the sensors, the pipe diameter or the required demand interval of the measurements could have been examined whose modifications in measurements of installed systems would be a great effort in some cases. Essentially, the results were showing that with greater influence of heat losses and capacity effects on the form changes of the temperature courses from one sensor to the other, i.e. due to low flow rates or high heat loss coefficients in the pipe section, the number of points in time is reduced for which a reliable flow rate determination is possible.

3. RESULTS

Depending on the course of irradiance, the distance method combined with a useful chosen reliability criterion was able to evaluate between 41% and 75% of the daily measured data within the operation time of the pump for an accurate flow rate determination. Under difficult conditions for the use of this method (no or very small and little steep temperature steps) the flow rate was determined with a relative error of 4.8% compared to the measured flow rate, whereas in the best case (distinct temperature course changes e.g. because of high and quickly changing irradiance) a relative error of 2.4% occurred. As a result, a quasi-continuous flow rate determination by the presented distance method leads to satisfactory results keeping in mind that marked and steep temperature changes increase the accuracy whereas the applicability of the method is restricted by growing influences of thermal losses and capacity effects on the temperature course. Thus, mindful of the potential of possible development the distance method can be regarded as a reasonable and promising alternative to conventional flow meters without moving into gear with the collector circuit of the solar thermal system.

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