Temperature Based Determination of Volume Flow Rates in Pipes as a Low-Cost Option for Energy Measurements of Solar Thermal Systems

Abinson Paul Nedumparambil*, Manuel Joschka Seiz, Harald Drück and Dominik Bestenlehner

Solar and Heat Technology (SWT), Stuttgart (Germany)

Abstract

The aim of the scientific investigations presented here is the development of a new method for cost effective determination of volume flow rates in pipes, which can be used for energy measurement of solar thermal systems. The main advantage of this approach is that relatively expensive measurement technology for determining volume flows can be dispensed with. This newly developed method analyses the course of temperature propagation delay between two temperature profiles, when volume flow occurs in the hydraulic loop considered. This is achieved by installing a measurement track with two temperature sensors placed at a known distance apart in the hydraulic loops associated with the thermal system. Once the volume flow in each loop of the solar thermal system (i.e. solar collector loop, auxiliary loop, heating loop, domestic tap water) is determined by analyzing the temperature profiles recorded at the temperature sensors in the measurement track, the heat associated with the corresponding loop could also be determined. When it comes to small solar thermal systems, conventional heat meters are expensive, especially considering the total cost of the thermal plant. The new measurement method is very cheap, robust and achieves an accuracy of approx. ±10 % compared to the high-end measurement equipment. Hence, it can be easily integrated into the hydraulic loops of the thermal systems and now, failures and yield reductions can be detected. Thus, it is e. g. also possible to determine the useful solar heat supplied to the domestic hot water systems. This can create the prerequisite for yield-oriented promotion, especially for relatively small solar thermal systems.

Keywords: volume flow determination, solar thermal systems, energy measurement, heat meter

1. Introduction

Currently the energy balancing of solar thermal systems is carried out by installing heat meters in to each hydraulic loop of the thermal system. Installation of the heat meters are expensive compared to the total cost of the solar thermal system. Hence contribution of the solar energy in to small thermal systems are often neglected. Heat meters are expensive as they use expensive flow sensors to determine volume flow rate in pipes. This scientific work illustrates the development of a new cost-effective method to determine the volume flow rate within a pipe by analyzing the course of temperature propagation delay between two temperature sensors placed in the pipe at a known distance apart. Different algorithms are developed in the course of the project TeBwA (Temperature-based energetic balancing of thermo-technical systems) to determine the time propagation delay between the temperature profiles obtained by the two temperature sensors. For the development of the method, the temperature profiles were generated in a test rig especially designed to generate the temperature profiles characteristics of solar loop, domestic hot water loop, heating loop, and auxiliary loop. The test rig consists of a hydraulic pump capable to generate volume flow rates in the range of 60 to 1200 l/h, and an auxiliary heater to generate temperature profiles similar to the actual thermal cycles of a solar thermal system. The auxiliary heater is also needed and to be actuated in the hydraulic loops whenever natural temperature dynamics is not sufficient enough to be analyzed by the algorithms when fluid flows through the pipes.

A newly developed measurement track is also installed in the hydraulic loops of four solar thermal systems and data from these real systems are also evaluated using the algorithms developed. In addition to experimental data from the test rig and real data, synthetically generated data for different hydraulic loops of solar thermal systems simulations with TRNSYS18 (Klein 2017) are also used to evaluate the algorithms developed. This paper presents the newly developed algorithms and its results to the temperature-based determination of volume flow rates in pipes.

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2. Methodology

In order to achieve the objective of determining the volume flow in the pipes based on temperature measurements only, a measurement track was designed and build as shown in Fig.1 with a length of 480 mm and an inner diameter of 16 mm. If the volume flow rate in the hydraulic loop is very high for example above 1200 l/h the length of the measurement track is increased up to 1900 mm. This is because, when flow velocity is high a lead time is needed for obtaining identifiable temperature profiles at the second temperature sensor. High-volume flow rates will be usually observed in the auxiliary heating loop (pellet boiler, gas boiler) and domestic hot water loops of the solar thermal system. This length adjustable measurement track will be integrated to the actual hydraulic loops of the thermal system.

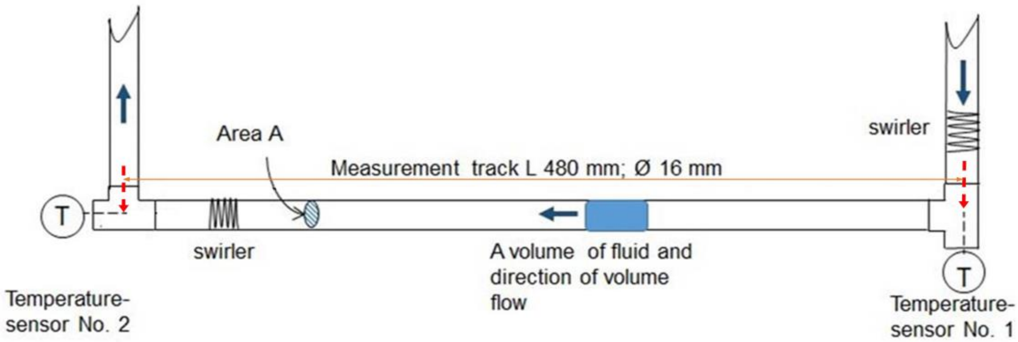

Fig. 1: Measurement track with temperature sensors

When water flows through the measurement track from sensor 1 to sensor 2 (shown in blue arrows) during operation of the test rig or the actual hydraulic loop, the temperature of the water is measured at two points with temperature sensors. The profiles of two temperatures measured with a resolution of 10 values per second can be seen in Fig. 1, which were inserted against the direction of flow in order to ensure optimum measurement quality of the respective temperatures of the flowing water. In order to ensure the temperature is distributed as homogeneously as possible across the cross-section of the pipe, swirlers were also inserted into the pipe immediately before the temperature sensors. The values of temperatures will be recorded continuously by the measurement system.

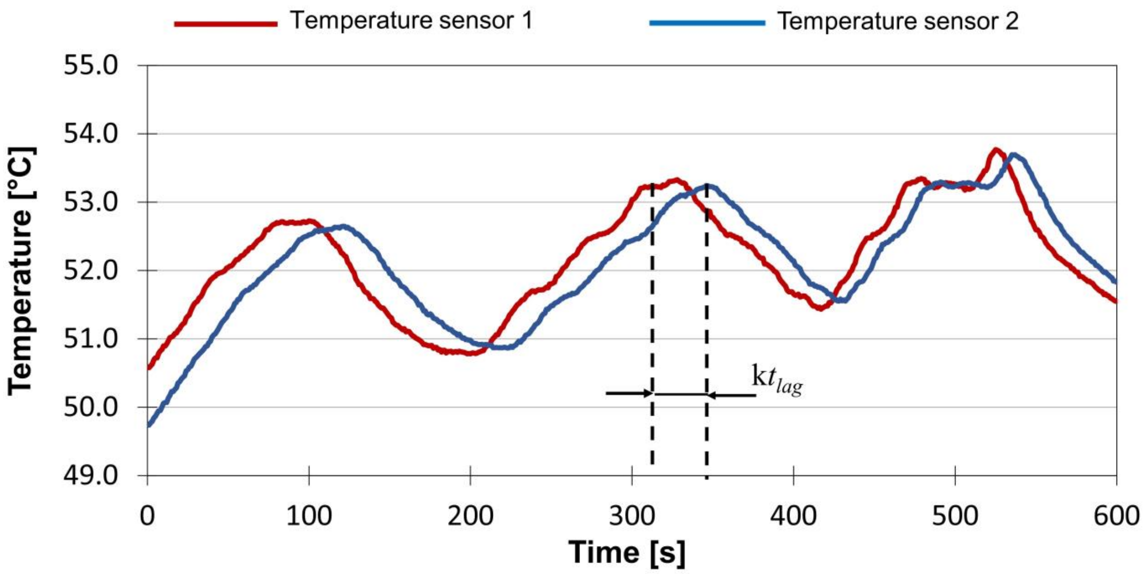

Fig. 2: Example of a temperature profile obtained by the measurement track

Fig. 2 shows an example of temperature profiles recorded at the two temperature sensors of the measurement track. It is obvious that the second temperature profile is lagging behind the first temperature profile by ‘kt_{lag}’ index positions. Index positions are the time of order of recording temperature values by the two temperature sensors. When volume flow is present, by analyzing two temperature profiles the propagation delay 'kt_{lag}' is find out using the algorithms developed as the second temperature profile is the replica of the first temperature profile with a time shift 'kt_{lag}'. Considering 'A' is the area of cross section of pipe and 'L' is the distance between the two temperature sensors installed, the volume flow rate '$\dot{V}$'s given by equation 1,

$$\dot{V} = \frac{A \cdot L}{kt_{lag}} \qquad \text{(eq. 1)}$$

using this principle volume flow is determined in the hydraulic loops of the thermal system. The above described measurement track will be implemented to each hydraulic loop of the solar thermal system as shown in Fig. 3.

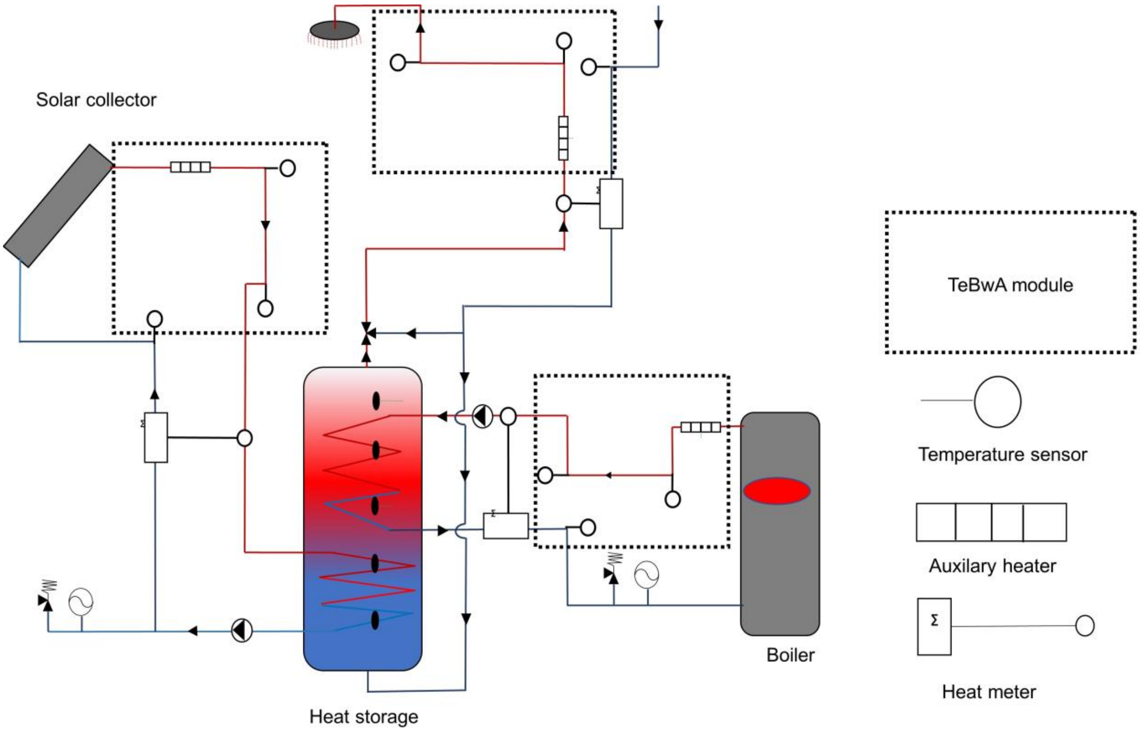

Fig. 3: Measurement track with temperature sensors (TeBwA module) installed in the hydraulic loops of the thermal system

To calculate the kt_{lag} between the temperature profile received at the measurement track of each hydraulic loop intelligent algorithms were developed, which is described in detail in the following section. To compare the results of the new method a heat meter is also attached to each hydraulic loops of the system. When the temperature dynamics in the hydraulic loop is not sufficient enough to determine the volume flow rate by using the algorithms developed, an auxiliary electric heater is also implemented and actuated in each hydraulic loop. Once volume flow rate occurring in each loop is find out the energy associated with the volume flow also be calculated. Thus, energy entering and leaving the thermal system is calculated which leads to complete energy balancing of the heat storage.

3. Algorithms developed

In the following the most promising algorithms for determining the time propagation delay 'kt_{lag}' between two temperature profiles with their results under investigation are described.

3.1 Euclidian distance method

This method works on the principle of finding the Euclidian distance (shortest length between two points) between the selected temperature points of the temperature profiles on two temperature sensors. A defined sector of the temperature curve (Ti^{in}) from the first temperature sensor is being considered by selecting ±m (number of elements chosen to define the sector) measured values from a chosen point in time, about which flow rate is to be determined as demonstrated in Frank 2001. The sector is shifted by time shift (t_{lag}) positions across the second temperature curve (Ti^{out}). For each of these offsets, the mathematical distance k (t_{lag}) is calculated represented by the following equation 2

$$k(t_{lag}) = \frac{1}{\sqrt{2m+1}} \sqrt{\sum_{i=-m}^{+m} (T_i^{in}(t - t_{lag}) - T_i^{out}(t))^2} \qquad \text{(eq. 2)}$$

The factor $(2m+1)^{-0.5}$ is a normalizing factor for k, which depends on the size of the number of elements chosen to define the sector (±m). The time shift (t_{lag}) will be equivalent to the occurrence of an index position of minimum value of k (t_{lag}). This 'kt_{lag}' is used to determine the fluid running time in the pipe.

3.2 Neighborhood approach

This method aims at comparing sequences of five measured temperature values each, which are recorded by the two temperature sensors of the measuring section.

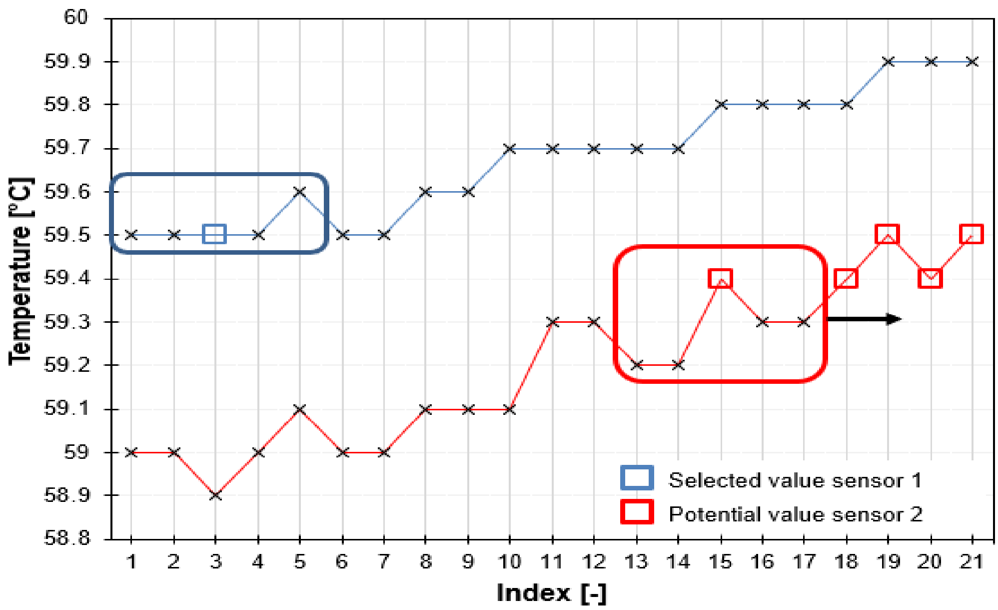

Fig. 4 Principle of neighborhood approach

For this purpose, first a measured value from temperature sensor 1 is randomly selected, see small blue square in Fig. 4. Then, all recorded temperature values of sensor 2 are searched for which lie within a certain tolerance range to the selected measured value of sensor 1. These readings from sensor 2 represent the points that can potentially be assigned to the value originally selected at sensor 1. In order to find out which of these potentially eligible values are actually the corresponding to the measured values of sensor 1, a more detailed analysis is then performed for these points. For this purpose, for each considered measured value additionally the two temporally preceding and the two temporally following measured values are consulted. This results in sequences of five measured values each. These sequences are then compared. A pairwise comparison of the upstream and downstream measured values of the sequences compared with each other is performed. This means that the first point considered in the sequence recorded by temperature sensor 1 is compared with the first point of the sequence belonging to temperature sensor 2. The same is done for the other four readings of the sequences. The aim of this comparison is to identify those two sequences of temperature values from the two temperature sensors whose temperature values have the highest possible agreement. To implement this, each sequence of measured values from sensor 1 is compared in succession with several successive sequences belonging to sensor 2.

A tolerance range is defined in which the temperature values of the respective sequences compared with each other must lie. If the differences of the compared pairs of temperature values lie within the tolerance range, then the two sequences are considered to belong to each other. In this comparison, the tolerance range is initially defined very narrowly and then gradually increased. The increase of the tolerance range is continued until a sequence of measured values at sensor 2 could be identified whose measured values each have a distance to the corresponding measured values of the respective sequence of sensor 1 that is within the defined tolerance. Should several sequences of sensor 2 be identified at the same time, whose measured values are within the defined tolerance range of the values of the sequence of sensor 1, the sum of the differences of the pairs of the measured values of the respective sequences to be compared with each other is calculated. The sequence of sensor 2 with the lowest value is assigned to the respective sequence of sensor 1. This results in five measured values at sensor 2 that lie within this tolerance range and thus represent the points in question. For these five measured values, a more detailed analysis is then carried out on the basis of the two temporally upstream and downstream measured values. After a sequence of measured values from sensor 2 could be assigned to a sequence of measured values from sensor 1, the temporal distance of these sequences is calculated. For this purpose, the index positions of the measured values are used. The index position of the third measured value of the sequence of sensor 1 is subtracted from the index position of the third measured value of the sequence of sensor 2. Since all measurements are carried out with a temporal resolution of ten measured values per second, the result of the subtraction is in the unit [0.1s].

3.3 Slope method

The Slope method is a statistical approach where the physical phenomenon of water flowing through the pipe is identified in terms of numbers. The statistical quantity determined by this method is used to determine the volume flow rate. When flow takes place, the statistical quantity obtained by this method describes the time delay between two temperature sensors. The average increase or the average decrease of the temperature of a certain number of measured values of sensor 1 is used. Accordingly, the average change in temperature over a certain period of time is used to calculate the volume flow. The mentioned time period is first estimated from the expected level of the volume flow to be calculated. This rough estimate is necessary to ensure that the fluid particles of the flow have sufficient time to travel from temperature sensor 1 to temperature sensor 2 within the time period considered. The amount of flow was assumed to be between 170 l/h and 1200 l/h and therefore 2.1 seconds was set as the maximum time period. The measurement technology implemented records ten measured values per second. This means that 21 temperature values of each sensor are used for the calculation during the period under consideration. These 21 values of each sensor are initially each stored in a field or array.

$$X_1 = \left[T_{1,1}; T_{1,2}; T_{1,3}; \dots; T_{1,21}\right] \qquad \text{(eq.3)}$$

$$X_2 = \left[T_{2,1}; T_{2,2}; T_{2,3}; \dots; T_{2,21}\right] \qquad \text{(eq. 4)}$$

Subsequently, the average temperature T_c is calculated from the 21 temperature values of the array X_1 belonging to sensor 1

$$T_c = \frac{\sum_{n=1}^{21} T_{1,n}}{21} \qquad \text{(eq. 5)}$$

Then, from the temperature values stored in array X_1, that value T_0 is determined which has the smallest deviation from T_c, so that applies:

$$T_c \approx T_0 \qquad \text{(eq. 6)}$$

Next, the slope S is calculated according to the following formula:

$$S = \frac{T_0 - T_{1,1}}{i_0 - i_{1,1}} \qquad \text{(eq. 7)}$$

Here, i_0 and $i_{1,1}$ stand for the index positions of the corresponding temperatures in array X_1 of sensor 1. Based on the gradient, the time delay kt_{lag} is calculated which the flow needs to cover the distance between the two sensors. For this purpose, the temperature difference of the first two temperature values of the arrays X_1 and X_2 is divided by the previously calculated temperature gradient S. Since the distance between the temperature sensors and the cross-sectional area of the pipe through which the flow passes are known, the volume flow can then be determined.

$$kt_{lag} = \frac{T_{1,1} - T_{2,1}}{S} \qquad \text{(eq. 8)}$$

After the volume flow has been calculated, the arrays X_1 and X_2 are filled with new temperature values according to the following method: The index positions of the temperature values increase by one value. This removes the first temperature value of the array and replaces it with a new value, which is placed at the last position of the respective array. Afterwards, all calculation steps are repeated.

3.4 Cosine method

In this approach the evaluation algorithms are developed based on the cosine similarity of two temperature profiles. Let ‘φ’ be the angle between the two temperature vectors, ‘a’ is the first temperature sensor vector array, ‘b’ is the second temperature sensor vector array and ‘n’ is the number of data points, The cosine similarity is given by equation 9,

$$\cos(\varphi) = \frac{\sum_{i=1}^{n} a_i\, b_i}{\sqrt{\sum_{i=1}^{n}(a_i)^2}\ \sqrt{\sum_{i=1}^{n}(b_i)^2}} \qquad \text{(eq. 9)}$$

4. Results and Discussion

The newly developed algorithms were applied to both synthetic and real data to calculate the volume flow rate using two temperature profiles obtained at the two temperature sensors. Synthetic temperature profiles of a pipe flow were generated using TRNSYS 18 simulation program. The actual data is obtained from test rig and implementing the TeBwA technology in to actual hydraulic loops of the solar thermal system. The following section explains the results obtained by the algorithms on different types of data.

4.1 Evaluation of algorithms Synthetic data

The TRNSYS 18 program was used to generate the raw data of a pipe flow. At first, water flowing through a pipe between two temperature sensors is simulated. The diameter of the pipe is 16mm, the distance between these temperature sensors was set to 5 m during the simulation. Fig. 5 shows the temperature profiles of the two temperature sensors located in the pipe flow as well as the associated volume flow rates.

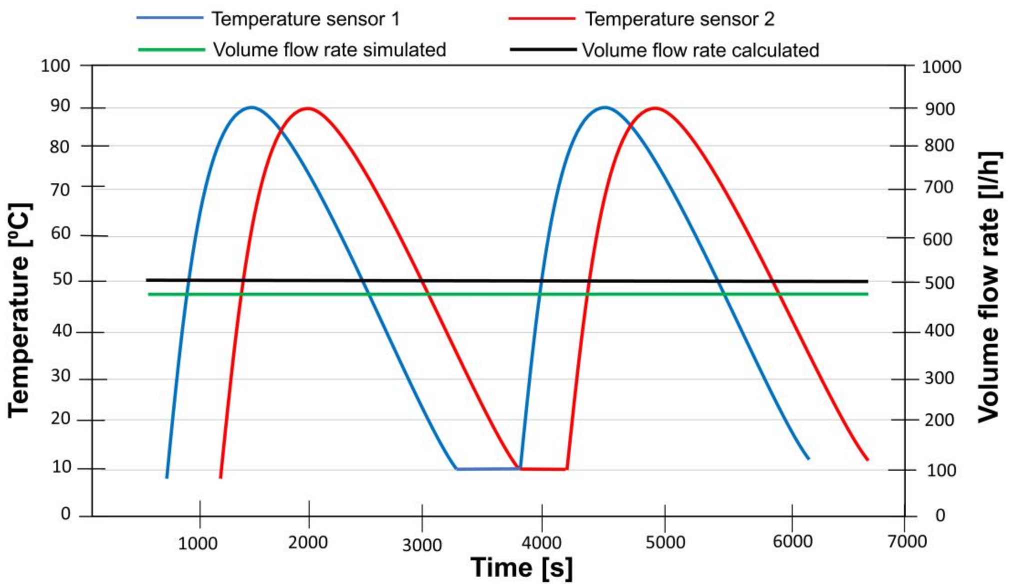

Fig. 5: Synthetically generated temperature profiles of a pipe flow using TRNSYS 18

With all approaches presented in section 3, the volume flow at 500 l/h could be calculated with high accuracy. The degree of deviation between the synthetical and calculated volume flow is primarily determined by the value of the heat transfer coefficient U specified for the pipe. If this is assumed to be 0 $W/(m^2 \cdot K)$, the deviation is less than 1 %. If the U-value is 12$W/(m^2 \cdot K)$, which is close to real conditions, then the deviation increases to about 3 %. In the second step, synthetically generated values were used, which originate from the simulation of a complete solar system for a day.

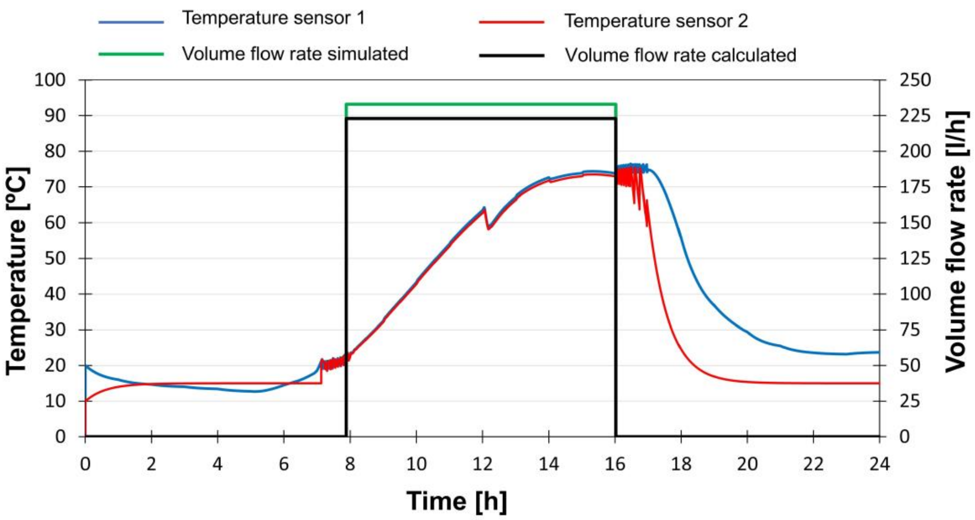

Fig. 6: Simulation of pipe flow in solar thermal system.

Here, the distance between collector outlet and storage inlet with a length of 10 m was considered. The diameter of the pipe in this case is again 16 mm and the heat transfer coefficient U was set to 12 $W/(m^2 \cdot K)$. Fig. 6 shows the resulting temperature profiles for the collector outlet temperature (blue) and the storage inlet temperature (red) as well as the corresponding synthetical volume flow (black) and the calculated volume flow (green), which is almost identical for the three approaches.

4.2 Evaluation of algorithms on experimental data

The three approaches presented in section 3 are suitable for volume flow calculation of synthetic data in a pipe flow. Then the algorithms were applied to experimentally generated data. These were generated by means of a test rig set up specifically for this purpose (see Fig. 7).

Fig. 7: Measurement test rig to generate actual temperature profiles as of the hydraulic loops of the thermal system

Fig. 7 shows the measurement track (1) with the two temperature sensors (2) and (3) installed. The tube of the measuring section has an inside diameter of 16 mm and the distance between the two temperature sensors is 0.46 m. During operation, the measuring section is provided with thermal insulation to keep heat losses between the temperature sensors to be low. The temperature sensors are ‘PT100’ sensors that have been fixed in the pipe by means of a compression fitting. This type of mounting puts the tips of the thermocouples in direct contact with the flowing water, allowing temperature changes in the flow to be detected immediately. Above the measuring section, two electric heating rods (4), (5) were installed in the pipe flow. With the help of these electric heaters thermal energy can be introduced into the system. The two heating rods having different electrical power. This helps the minimum level of electrical heating power to be determined experimentally, so that the temperature profiles generated still has sufficient accuracy to be calculated by the algorithms. In the actual implementation of the measurement track only one electric heater with an electric power of 1600W. In addition, the calibrated electromagnetic flow meter (6) can be seen. The flow rates measured with this flow meter serve as a reference value for assessing the accuracy of the flow rates calculated on the basis of the evaluation algorithms. The flow is generated with the aid of the pump (7). The pump and a regulating valve can also be used to vary the volume flow rate.

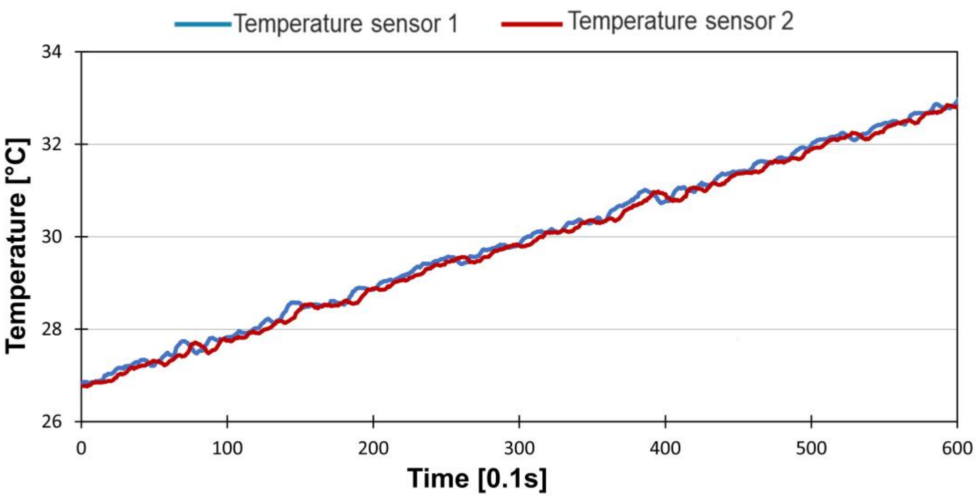

Fig. 8: Continuously rising temperature profile

Fig. 8 shows continuously rising temperature profiles. The temperature at the two sensors increases approximately linearly during the measurement. In order to generate such a rising profile, the heating element was switched on continuously, i.e., for the entire time interval of 60s.

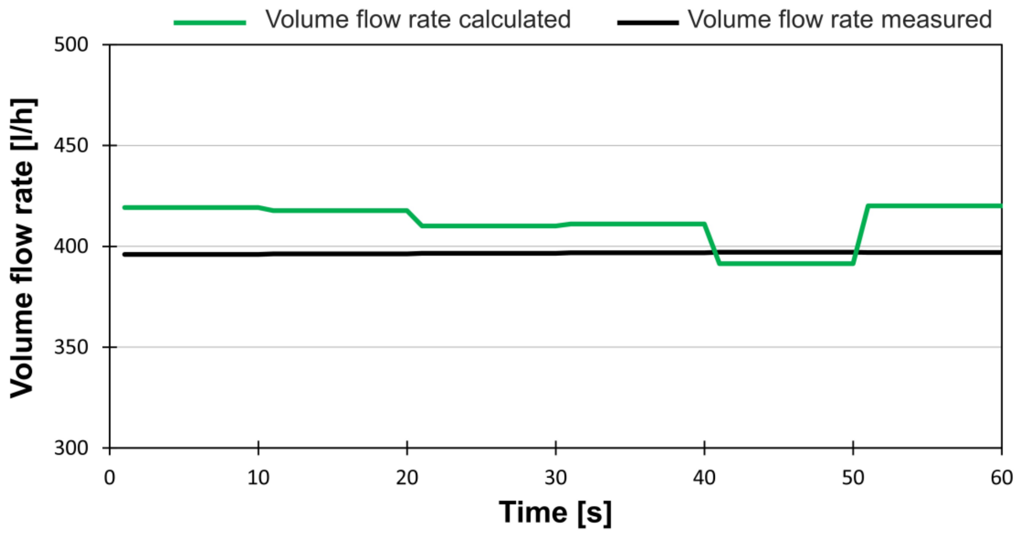

Fig. 9: Volume flow rate corresponding to the rising temperature profile

Fig. 9 shows the volume flow rate observed for the above temperature profile. The volume flow rate in the considered time interval is constant and amounts to 397 l/h. The volume flow rate is calculated for every 10s and it varies from 420 to 390 l/h. The average calculated volume flow rate for 60s by the methods are approx.413 l/h, which is about 4 % in deviation in accuracy with the measured volume flow rate. The temperature dynamics is about 0.17K/s during the calculation period.

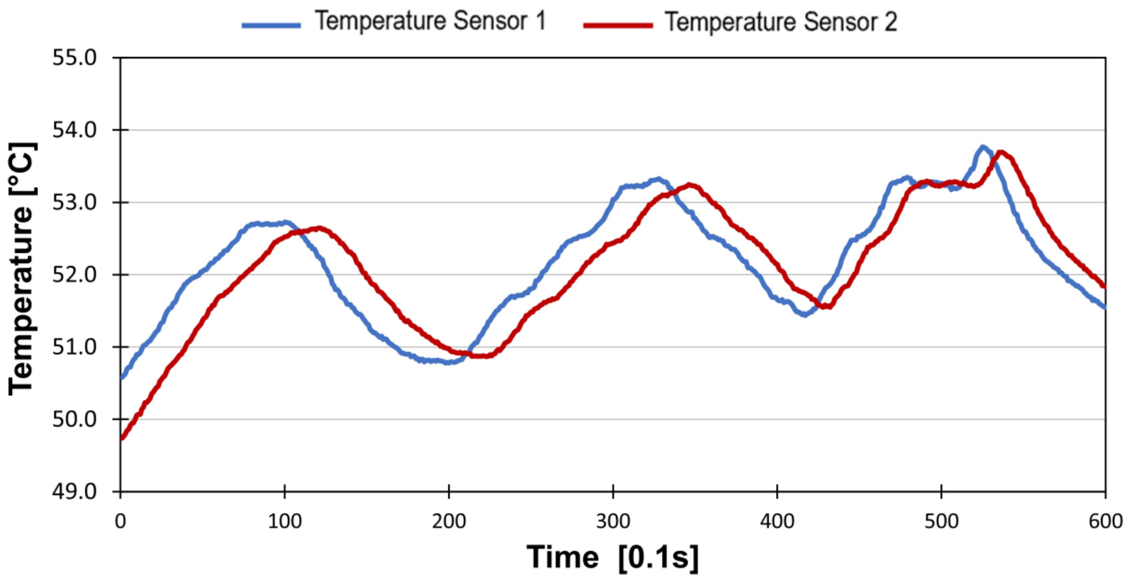

Fig. 10: Periodic temperature profile

Fig. 10 shows the temperature profiles with periodic nature. This is achieved by alternately switching the heater on for 15 seconds and off for 10 seconds. The volume flow rate varies between 174 l/h and 286 l/h. The calculated volume rate with the algorithms also has a very close agreement with the measured volume flow rate. The temperature dynamic in the pipe flow is about 0.2 K/s in the entire sequence.

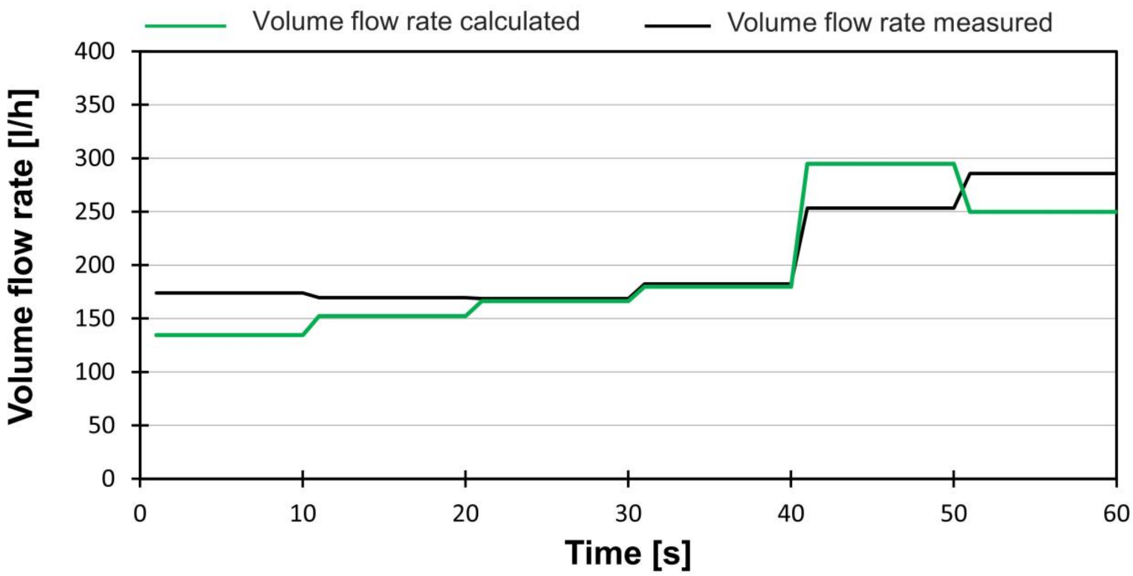

Fig. 11: Respective volume flow rate for the periodic temperature profile

4.3 Evaluation of algorithms on insitu data

The measurement track is also implemented in to actual hydraulic loops of the thermal system. For this very purpose four solar thermal systems were selected in Stuttgart, Germany including solar combi systems. Fig. 12 shows an example of a temperature profile obtained from an actual solar thermal system.

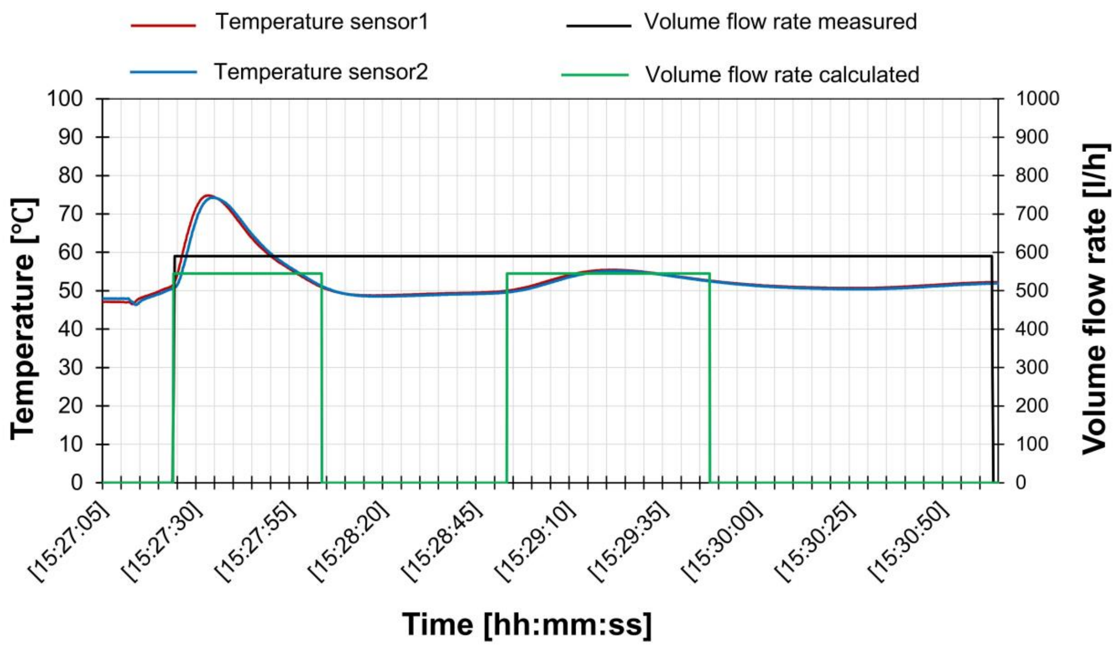

Fig. 12 Temperature profiles obtained and volume flow rate calculated for an actual solar loop

The green line shows the calculated volume flow rates by analyzing the course of temperature profiles of a solar loop. The calculated and measured volume flow rate is 550 l/h and 590 l/h respectively, which is approx. -9 % deviation in accuracy. For comparing the calculated volume flow rate by the algorithms, heat meters are installed in to each hydraulic loop of the thermal system. The flow rate measured by the heat meters serve as the reference for comparison. Volume flow rates in the actual hydraulic loops of thermal systems can be determined with a deviation in accuracy of approx. ±10 % with the newly developed algorithms. In the real operation of thermo-technical plants, periods occur in some hydraulic circuits in which the temperature dynamics of the flowing fluid is so low that no reliable calculation of the volume flow can be guaranteed. The evaluation algorithms developed in the TeBwA project are able to detect such periods and exclude them from the calculation. To implement this, the temperature dynamics are determined simultaneously during the calculation of the volume flow. If this is below a certain limit value in the period under consideration, no volume flow is calculated for the period in question. In a next development step, it is planned to make the algorithms more intelligent such that the auxiliary heater is able to be activated automatically for a short time, if the temperature dynamic falls below the limit value in order to ensure sufficiently high temperature dynamics.

The following table 1 summarizes the above-mentioned evaluation algorithms mentioned for determining the volume flow rates in the pipes together with characteristic values for the accuracy deviation.

Tab. 1: Result of different evaluation algorithm for the temperature-based determination of volume flow rates in pipe

Type of temperature profile	Algorithm 1: Euclidian distance method	Algorithm 2: Neighbourhood method	Algorithm 3: Slope method	Algorithm 4: Cosine method
Synthetic data for increasing, decreasing temperature for water flow in pipes generated by TRNSYS simulations	±3 to ±5 %	±3 to ±5 %	±3 to ±5 %	±3 to ±5 %
Synthetic data of solar loop generated by TRNSYS simulations	< ±5 %	< ±5 %	< ±5 %	< ±5 %
Exp. data & real plant data– Continuously increasing temperature profile	< ±9 %	< ±5 %	< ±5 %	< ±9 %
Exp. data & real plant data– temperatures created using alternatively activating the auxiliary heater	< ±5 %	±6 to ±10 %	±6 to ±10 %	±2 to ±5 %
Exp. data & real plant data– Continuously decreasing temperature profile	< ±9 %	< ±10 %	< ±10 %	< ± 9 %

To prove the accuracy and reliability of the newly developed algorithms, experimentally generated data and real data from solar loop, boiler loop, space heating loop and domestic hot water loop of the thermal systems were used. For the actual thermal systems, heat meters are installed in each hydraulic loop, which serve as reference for comparison.

5. Conclusion and inference

This paper presents newly developed algorithms for determining the volume flow in pipes by analyzing temperature profiles. The methods developed (Euclidian distance method, Neighborhood method, Slope method and Cosine method) are suitable for determining the volume flow rates in pipes with deviation in accuracy of approx. ± 10 %. Algorithms are evaluated using experimental data, synthetic data and real data from the hydraulic loops of solar thermal systems. Considering the actual implementation of the measurement system into the hydraulic loops further development is needed. First aspect of this development is to identify the presence of water flow in the pipe. Second aspect is related to an economically feasible actuation of the auxiliary heater in the measurement system.

In principle, the approach is a cost-effective method, since only one measurement pipe, two temperatures sensors and an auxiliary heater are required. The measurement system can be easily integrated in actual hydraulic loops of thermal systems. Once the measurement system described in this paper is integrated into actual hydraulic loops of solar thermal systems, energy transport in each hydraulic loop could be determined, especially the contribution of the solar loop. Definitely, this creates the prerequisite for yield-oriented promotion, for relatively small solar thermal systems.

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