Cost-Effective Energy Balancing of Thermal Systems Based on Temperature Measurements Only

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Abstract

Usually, thermal systems, especially small solar thermal systems, are not energetically balanced for financial reasons. To overcome this problem, low cost but accurate measuring equipment is required. This paper describes a method to determine the volume flow rate in a pipe and hence the thermal energy transfer through a hydraulic circuit, with the exclusive use of low-cost temperature sensors. Evaluations based on experimentally measured data show, that the method is able to calculate a volume flow rate in a range of 130 and 910 l/h with a deviation of less than ±10% compared to values measured by conventional flow meters or heat meters respectively. The calculated volume flow rate is subsequently used to perform an energy balancing of a thermal system. Hereby the heat input and output of the hydraulic circuits into and out of the central hot water store is considered to perform this energy balancing. The accuracy of the calculation of the heat quantities varies depending on the type of circuit, e.g. if it is a circuit for space heating or domestic hot water preparation. However, the results on a monthly basis consistently show a deviation of less than ±10.8% compared to the results of conventional heat meters.

Keywords: Energy Balancing, Volume Flow Determination, Cost Efficiency, Thermal Systems, Temperature Profiles, Heat Meter

1. Introduction

Currently, the energy balancing of thermal systems, e.g. solar thermal systems, is based on the measurement of the temperatures in the hot and in the cold side, as well as the volume flow rate of the heat transfer fluid in the circuit under consideration. With these quantities, the heat input e.g. of a solar circuit into a hot water store can be determined by integrating the thermal power over time. The heat meters required for this lead often to considerable costs, which represent a significant share of the total investment, especially for small solar thermal systems. For this reason, the energy balancing of such small systems is often omitted, which makes a reliable surveillance of the system impossible. The aim of the project TeBwA (Temperaturbasierte energetische Bilanzierung wärmetechnischer Anlagen / Temperature-based Energy Balancing of Thermal Systems), which is funded by the German Federal Ministry for Economic Affairs and Climate Action, is to develop a technology that allows for energy balancing at significantly lower costs than energy balancing based on conventional heat meters.

Fig. 1 exemplary illustrates the setup for an energy balancing of a solar thermal domestic hot water system using three conventional heat meters that measure the volume flow rate and the temperatures in the hot and in the cold side of each hydraulic circuit attached to the central hot water store.

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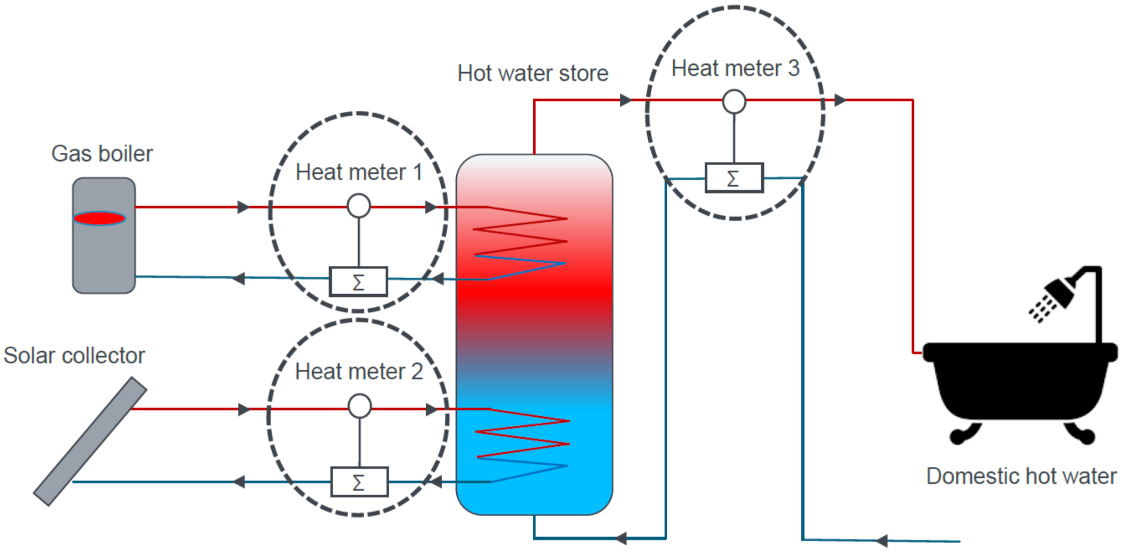

Fig. 1: Solar thermal domestic hot water system with a central hot water store and three attached hydraulic circuits equipped with three conventional heat meters that are required for energy balancing

The newly developed TeBwA method is based on the calculation of the volume flow rate derived from the temporal propagation of a temperature gradient in the fluid. To identify the propagation of a temperature gradient, the temperature of the heat transfer fluid in the pipe must be measured at two points. The initial work based on this approach is described by Frank (2000). To calculate the heat flux, a third temperature sensor is required in the second pipe, which is located on the other side of the hydraulic circuit under consideration. Fig. 2 shows the principle positioning of the three required temperature sensors for the developed TeBwA method.

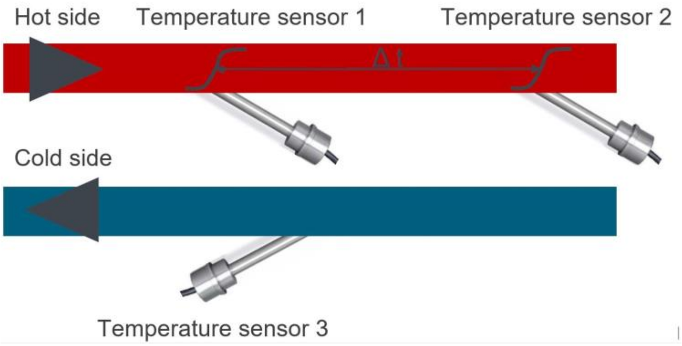

Fig. 2: Principal temperature sensors positioning in the hot side and in the cold side of a single hydraulic circuit

As Fig. 2 shows, in total only three low-cost temperature sensors and no flow meter are required for each hydraulic circuit. This makes the determination and recording of thermal energy much more favorable from a financial point of view.

The TeBwA project and the method developed in the project were already described by Nedumparambil (2021) and Seiz (2021). In the publications mentioned, the basic principle of the developed method is explained. In addition, the approaches followed at that time for calculating the volume flow rate within a pipe are explained and initial calculation results based on synthetically and experimentally generated measurement values are presented. In this context it is shown that, when using the TeBwA method, the volume flow rate within a pipe can principally be calculated with a deviation of less than ±10% compared to the value measured by means of a conventional flow meter being part of a heat meter.

The article at hand presents the current status and latest results of the development of the TeBwA method. Among others, it describes the approach chosen for calculating the volume flow rate within a pipe and the accuracy that can be achieved at different temperature levels and at different volume flow rates within the pipe. In addition, the present article reports about the results of the energy balancing of four field test systems, which are equipped with measurement technology. The energy balancing was carried out both, on the basis of the TeBwA method and by means of conventional heat meters. On this basis the accuracy with which an energy balancing of thermal systems can be carried out using the TeBwA method is presented. Hereby four different types of hydraulic circuits of the field test systems are considered. Finally, the article gives an overview of the plans regarding the further development of the TeBwA method and the market implementation strategy of the resulting product.

2. Basic principle of the method

2.1 Principle of temperature-based volume flow determination

As stated above, the newly developed TeBwA method allows for the calculation of the volume flow rate within a pipe based on temperature measurements at two points inside the pipe. The two temporal temperature profiles created on basis of the values supplied by the two temperature sensors are compared with each other in order to calculate the time which the flow requires to cover the distance between the two temperature sensors. Once this time is determined, the corresponding volume flow rate can be calculated if the distance between the temperature sensors and the pipe cross-section are known. A prerequisite for the successful implementation of this method is the presence of sufficiently high temperature dynamics. Fig. 3 shows exemplary temporal temperature profiles generated on basis of temperature values of the two temperature sensors of the measurement track of a test rig. For a detailed description of the test rig see Seiz (2021).

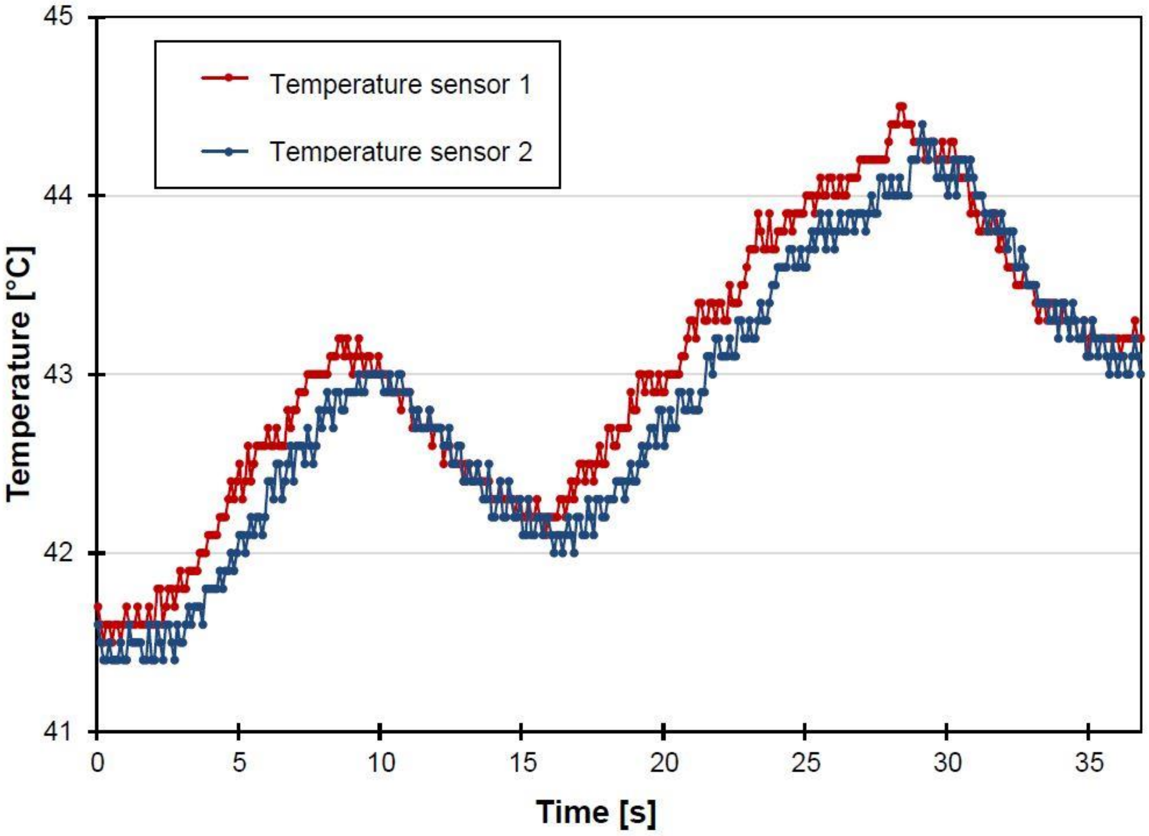

Fig. 3: Measurement values of two temperature sensors in the measurement track of a test rig - temporal temperature profiles

As Fig. 3 shows, the temperature profile of temperature sensor 1 can be approximately transformed into the temperature profile of temperature sensor 2 by a horizontal shift. This shift along the time axis corresponds to the time interval required by the flow to cover the distance between the two temperature sensors.

For a detailed description of the basic principle of the developed method see Seiz (2021) and Nedumparambil (2021). Both publications describe different approaches and each presents initial results for calculating the volume flow rate in a pipe on the basis of temperature measurements. Seiz (2022) describes further developed approaches and results for the calculation of the volume flow rate.

2.2 Principle of temperature-based energy balancing

In the following, starting from the temperature-based volume flow determination, this chapter explains how an energy balancing of a thermal system can be carried out. For a more detailed description of this procedure and for a detailed description of the technical components used in the four field test systems equipped with measurement technology, see Seiz (2021).

In order to carry out an energy balancing of a thermal system, first the volume flow rates in the hydraulic circuits connected to the central hot water store of the system must be determined. This is done on the basis of the temperature-based volume flow determination described in section 2.1. In order to be able to perform this successfully, measurement tracks (see Fig. 4) are installed in the hot side of each of the hydraulic circuits attached to the central hot water store. Two temperature sensors are located in each of the measurement tracks. The temperatures recorded by these sensors are primarily used to calculate the respective volume flow rate. In addition, an electrical heating element with a thermal output of 1.6 kW is installed in each measurement track. At times, when the temperature dynamics of a hydraulic circuit concerned are too low for a temperature-based volume flow determination, sufficient temperature dynamics can be ensured by activating the electrical heating element. For the actual energy balancing, the temperatures in the hot side and in the cold side of each hydraulic circuit must also be measured. The temperature sensors, which are required for the calculation of the volume flow rate, also serve this energy balancing, as one of the two measured values is included in the energy balancing as temperature value of the hot side of the respective hydraulic circuit. To enable energy balancing, a temperature sensor is also installed in the cold side of each hydraulic circuit in order to record the temperatures occurring there. In addition, for a complete energy balancing of the entire system, the temperatures inside the hot water store must also be determined. For this purpose, temperature sensors are installed on the outside of the metal wall of the hot water store, beneath the thermal insulation. In addition to the described technical components, which are required for the temperature-based energy balancing, conventional heat meters are installed in each hydraulic circuit. The values provided by these conventional heat meters were used to carry out a second energy balancing of the entire system. The result of this second energy balancing serves as a reference value for the energy balancing based on the newly developed TeBwA method. Fig. 4 shows one of the measurement tracks described, which, together with temperature sensors and an electrical heating element, is installed in one of the hydraulic circuits of a field test system. The actual measurement track is located between the two temperature sensors. Arrows in Fig. 4 mark the flow direction.

In order to keep the occurring heat losses as low as possible, the measurement tracks were well thermally insulated, following the creation of the photograph.

Fig. 4: Measurement track (a) with temperature sensors (b) and electrical heating element (c); Note: Shown without thermal insulation for better clarity

3. Temperature-based volume flow calculation

During the development of the method, the authors were investigating various approaches for determining the similarity of the compared temperature profiles and respectively the transit time of the fluid with regard to their suitability for calculating the volume flow rate within a pipe. Seiz (2021) gives a detailed description of these approaches.

The verification of the suitability of the different approaches was based on the accuracy with which the occurring volume flow rates could be calculated under different conditions. For this purpose, the authors used synthetically generated data, i.e. calculated with the simulation program TRNSYS, and experimentally measured data, produced with the test rig, that was set up for this purpose. In one of the approaches investigated in this context, cosine similarity is used as a similarity indicator. This approach achieved the best results over a large number of calculations performed. The cosine similarity κ is calculated according to eq. 1:

$$\kappa = 1 - \frac{a \bullet b}{||a||\ ||b||} = 1 - \frac{\sum_{i=1}^{n} a_i\, b_i}{\sqrt{\sum_{i=1}^{n}(a_i)^2} \bullet \sqrt{\sum_{i=1}^{n}(b_i)^2}} \qquad \text{(eq. 1)}$$

With:

a	vector a, segment with values of temperature sensor 1 [-]
b	vector b, segment with values of temperature sensor 2 [-]
n	dimension of vectors, number of temperature values per segment [-]

After the crucial choice of an appropriate similarity indicator and the development of the evaluation algorithms based on this approach, the authors focused on the procedure for shifting the segments of the temperature values of temperature sensor 1 and temperature sensor 2 to be compared with each other (see Fig. 5). This shifting process also has a major influence on the achievable accuracy of the calculation of a present volume flow rate. Therefore, a suitable procedure for the shifting process was developed. Chapter 3.1. contains detailed explanation on the procedure of this shifting process.

Subsequently, chapter 3.2 presents result of the evaluation of experimentally generated data. In the evaluations carried out, the cosine similarity as a similarity indicator was combined with the developed procedure for the shifting of the temperature segments.

3.1 Shifting of the temperature segments

The first logical step in the newly developed algorithm is the calculation-based estimation of the time, required by the flow to cover the distance between the two temperature sensors. This is based on empirical values for the occurring volume flows, the measured distance between the two temperature sensors and the pipe cross-section. Then, the algorithm selects a segment of the temperature values from temperature sensor 1 that lies in the time range in which the volume flow rate should be calculated. After this the algorithm determines the segment of temperature values of temperature sensor 2 whose temperature values were measured at the same times as those of the segment previously selected for temperature sensor 1. Subsequently the algorithm calculates the similarity of the two segments according to eq. 1. After that, the actual shifting of the segments takes place. Hereby, the algorithm shifts the segment of temperature sensor 1 by one index position against the time axis and at the same time the segment of temperature sensor 2 by one index position along the time axis. At the same time the algorithm shortens the temperature segment of temperature sensor 1 by the last included temperature value and the temperature segment of temperature sensor 2 by the first included temperature value. Afterwards the algorithm again determines the similarity of the resulting segments of temperature sensor 1 and temperature sensor 2, followed by a new shift and shortening. Fig. 5 schematically shows the described shifting process.

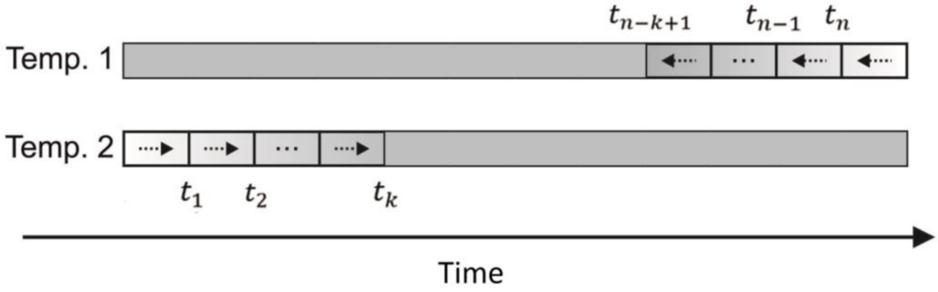

Fig. 5: Schematic illustration of the shifting process

The shifting of the two segments continues until the initially estimated maximum time required for the flow to cover the distance between the two temperature sensors is reached. In Fig. 5, the length of the gray horizontal bars, denoted by the letter n, represents the original length of the segments of temperature sensor 1 and of temperature sensor 2. The designation t_k stands for the assumed maximum time required by the flow to cover the distance between the two temperature sensors in the measurement track. In this context, the index k stands for the corresponding number of shifting steps. When using the cosine similarity as a method for determining the runtime or the similarity of two segments, a minimum of the similarity indicator Kappa (see eq. 1) stands for a maximum similarity between the two temperature segments compared with each other. Fig. 6 shows the resulting values for the similarity indicator Kappa for a comparison of two temperature segments.

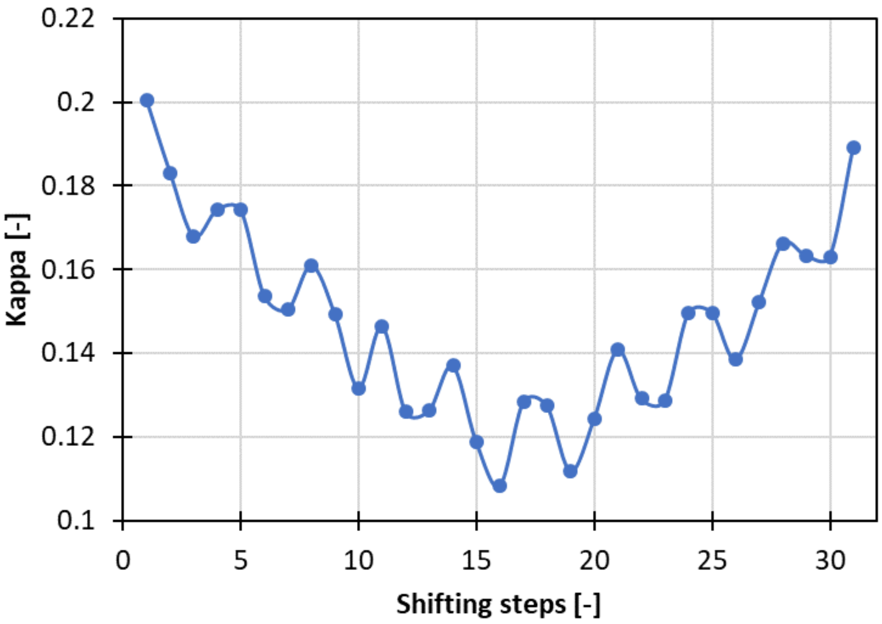

Fig. 6: Similarity indicator Kappa between two temperature segments at stepwise shifting

Fig. 6 shows a minimum of the similarity indicator Kappa at shifting step 16. Based on the number of shifting steps, the time required for the flow to cover the distance between the two temperature sensors can be derived. Afterwards the calculation of the magnitude of the volume flow rate can be executed.

3.2 Achievable accuracy - experimentally generated data

To investigate the suitability of the combination of the developed shifting process and the cosine similarity based approach, the authors generated data sets with different boundary conditions using the test rig developed in the project. In data set 1 medium-sized volume flow rates are considered. In data set 2, discussed further below, relatively large volume flow rates are considered and in data set 3, discussed even further below, relatively small volume flow rates are considered.

Fig 7 shows measured and calculated values of data set 1. The temperature profile shown in Fig. 7 was created by simultaneously using two electrical heating elements installed in the test rig. The temperature range considered extends from 40 to 80 °C and thus essentially corresponds to the temperature range that can also be expected in the regular operation of solar thermal systems. Hereby the primary electrical heating element, with an electrical power of 2 kW, was permanently activated in order to generate the basically increasing temperature profile and to cover an as large as possible temperature range. In addition, the secondary electrical heating element, with an electrical power of 1.6 kW, was periodically activated for 4.5 seconds and deactivated for 6.0 seconds, which resulted in the temperature fluctuations that can be seen in Fig. 7. Unfortunately, the activation of the secondary electrical heating element lead to a temporary drop of the supply voltage of the pump, which is installed in the test rig in order to create the fluid flow. This drop of the supply voltage of the pump resulted in the fluctuations in the measured volume flow rate that can be recognized in Fig. 7.

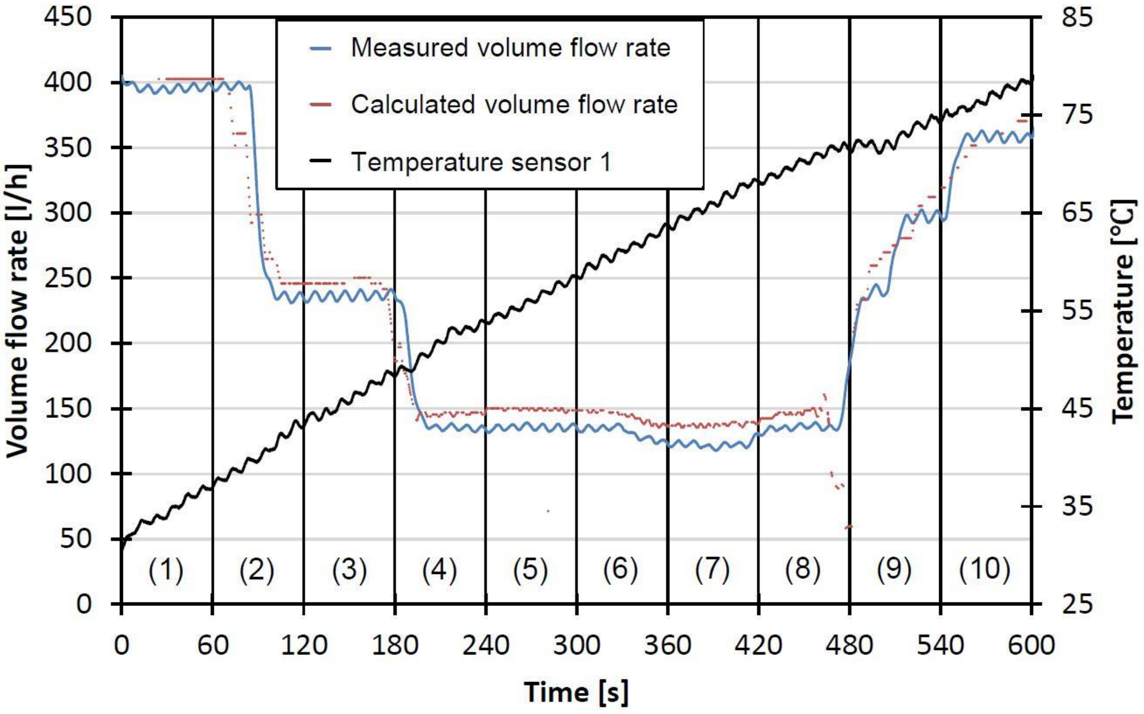

Fig. 7: Measured and calculated volume flow rate within sections (1) to (10) from data set 1

Fig. 7 shows the temperature of the volume flow entering the measurement track at temperature sensor 1 for data set 1. Fig. 7 does not show the temperature of the volume flow at temperature sensor 2, because this temperature is almost identical to the temperature at temperature sensor 1. Fig. 7 also shows the volume flow rate that was calculated using the newly developed method and the volume flow rate measured using an electromagnetic flow meter. The measured volume flow rate lay in a range between 130 and 400 l/h. Tab. 1 lists the calculated volume flow rate and the measured volume flow rate based on minutely average values for data set 1 as well as the deviation between the two values.

Tab. 1: Calculated and measured volume flow rate as well as deviation between both with the use of minutely average values - for data set 1

Section of data set 1 (According to Fig. 7)	**Calculated volume flow rate [l/h]**	**Measured volume flow rate [l/h]**	**Deviation [%]**
1	393.44	396.24	-0.71
2	252.11	250.44	0.67
3	210.36	213.53	-1.49
4	147.62	135.16	9.22
5	147.92	135.31	9.32
6	139.13	126.55	9.94
7	140.63	127.21	10.55
8	175.93	176.89	-0.54
9	305.05	308.29	-1.05
10	358.91	371.49	-3.39

Tab. 1 shows that the deviation between the calculated and measured volume flow rate is within ±10%, except for section 7. The evaluation of data set 1 could therefore demonstrate the suitability of the developed method for the calculation of volume flow rates in the afore mentioned volume flow range on the basis of experimentally generated measurement values. The developed algorithm removed individual outliers in the calculation of the volume flow rate. The identification of these outliers is based on the degree of similarity between the two temperature segments of temperature sensor 1 and temperature sensor 2 which are compared with each other; see Fig. 6. If the distance between the time indices of the two smallest values of Kappa was less than 5 time steps or 0.5 seconds respectively, the algorithm used the mean value of the two time indices to calculate the corresponding volume flow rate. Otherwise, the algorithm considered the value as an outlier and excluded the value in question from the calculation process. After the removal of the outliers, calculated values for the volume flow rate remained available for approx. 47% of the operating time.

In order to test the suitability of the method also in a higher range of the volume flow rate, the volume flow rate was increased for the creation of data set 2 to a range between 400 and 910 l/h. The temperature ranged from approximately 54 to 64 °C. Due to limited available space this paper does not show the temperature and volume flow curves for data set 2. Tab. 2 lists the calculated volume flow rate and the measured volume flow rate based on minutely average values for data set 2 as well as the deviation between the two values.

Tab. 2: Calculated and measured volume flow rate as well as deviation between both with the use of minutely average values - for data set 2

Section of data set 2	Calculated volume flow rate [l/h]	Measured volume flow rate [l/h]	Deviation [%]
1	455.45	426.44	6.80
2	488.30	436.85	11.78
3	524.20	500.52	4.73
4	538.51	515.07	4.55
5	570.10	544.09	4.78
6	616.43	595.06	3.59
7	627.52	667.38	-5.97
8	683.59	698.23	-2.10
9	717.45	736.38	-2.57
10	750.87	761.48	-1.39
11	830.55	807.26	2.88
12	958.01	912.54	4.98

Tab. 2 shows that for data set 2, with the exception of section 2, the deviation between the calculated and the measured volume flow rate is within ±7%. The evaluation of data set 2 could therefore also demonstrate the suitability of the developed method for the calculation of large volume flow rates on the basis of experimentally generated measurement values.

When calculating small volume flow rates, a lower limit value must be defined. Otherwise the segment lengths of the temperature values of temperature sensor 1 and temperature sensor 2, which have to be compared with each other, would become very large. This would result in an unacceptable computational effort for the calculation of the volume flow rate. For the evaluation of data set 3, the lower limit value of the volume flow rate was set to 58 l/h based on experimental investigations. When data set 3 was created, the measured volume flow rate was between 35 and 65 l/h. The temperature ranged from approximately 58 to 74 °C. Due to limited available space this paper also does not show the temperature and volume flow curves for data set 3. Tab. 3 lists the calculated volume flow rate and the measured volume flow rate based on minutely average values for data set 3 and the deviation between the two values.

Tab. 3: Calculated and measured volume flow rate as well as deviation between both with the use of minutely average values - for data set 3

Section of data set 3	Calculated volume flow rate [l/h]	Measured volume flow rate [l/h]	Deviation [%]
1	61.29	50.37	21.67
2	58.96	46.54	26.69
3	60.63	46.17	31.33
4	70.08	62.66	11.83
5	72.49	63.32	14.49
6	102.94	49.86	106.47
7	58.30	35.21	65.55
8	58.25	36.89	57.91

Tab. 3 shows that the values of the calculated volume flow rate in parts deviate significantly from the values of the measured volume flow rate. These partly large deviations are the result of the necessarily determined lower limit value. The lower limit value of 58 l/h had the effect, that the algorithm could not determine volume flow rates with less than 58 l/h. Since there are also individual measured volume flow rates in data set 3 that are lower than the limit value mentioned, the calculated volume flow rate was overestimated. Therefore Tab. 3 shows significant relative deviations between the measured volume flow rate and the calculated volume flow rate in most of the sections of data set 3. However, while the relative deviations are high when comparing the minutely average values, the absolute deviations are small in most cases. Setting the lower limit to a lower value does increase the accuracy with which small volume flow rates can be calculated. But unfortunately this has the consequence that the accuracy with which medium and large volume flow rates can be calculated decreases. In addition, a decrease in the lower limit value is accompanied by an exponential increase in computational effort.

The authors assume, that the effect of this high relative but low absolute deviations in the calculation of volume flow rates in the low volume flow range is not significant when performing an energy balancing of a thermal system. To verify this assumption, the authors are currently carrying out corresponding investigations. It seems unambiguous, that the successful performance of an accurate energy balancing of a thermal system depends on a precise calculation of occurring volume flow rates in the medium and in the high volume flow range. The evaluations of data set 1 and of data set 2 proofed the suitability of the newly developed method for calculating volume flow rates in these volume flow ranges on the basis of experimentally generated data. Nevertheless, the evaluation algorithms developed so far are currently being improved in order to increase the accuracy with which small volume flow rates can be calculated. In addition, a modified measurement track is currently being developed and tested, that is expected to lead, in combination with an adapted calculation procedure, to more accurate results, especially for small volume flow rates.

4. Temperature-based energy balancing

This chapter reports about the achievable accuracy when using the TeBwA method to perform a temperature-based energy balancing of thermal systems. Hereby the thermal energy was considered, that was transferred within one month in four different types of hydraulic circuits of thermal systems. In order to receive the measurement values required to perform the necessary calculations, four field test systems were equipped with the necessary measurement technology; see section 2.2.

The four types of hydraulic circuits considered are the following:

- solar circuit,
- boiler circuit,
- heating circuit,
- domestic hot water circuit.

For the evaluation, the monthly transferred thermal energy determined using the TeBwA method was compared with the corresponding values measured by conventional heat meters as reference values.

Fig. 8 exemplary shows the accumulated thermal energy transferred within the month of June 2022 from the solar circuit of a solar thermal domestic hot water system to the central hot water store. These curves of accumulated transferred thermal energy are based on the one hand on the recorded values of a conventional heat meter and on the other hand on the values calculated on the basis of the TeBwA method.

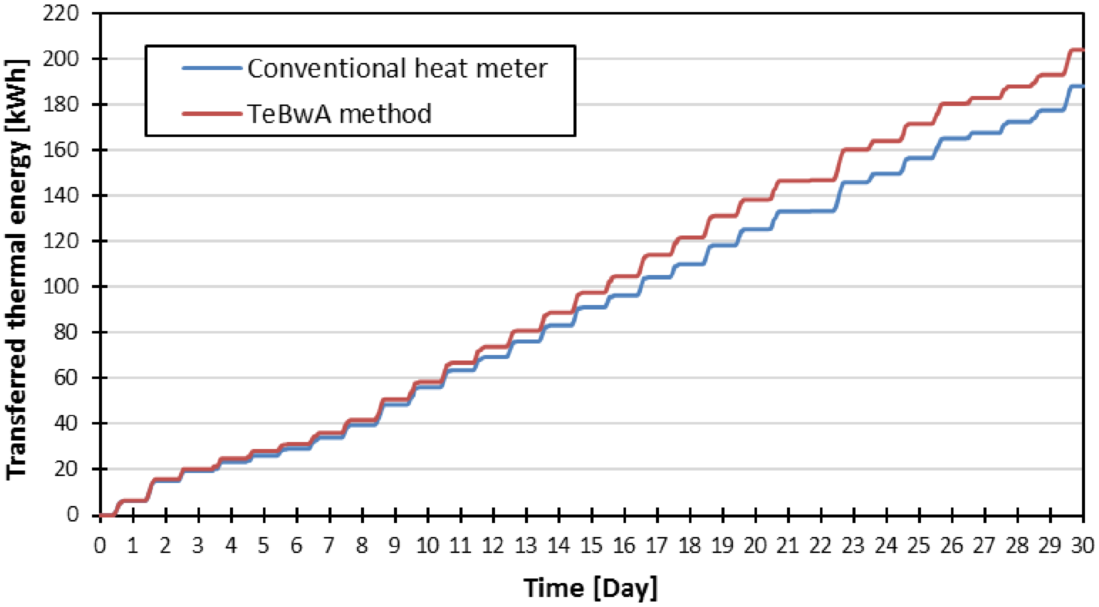

Fig. 8: Accumulated transferred thermal energy of the solar circuit of a solar thermal domestic hot water system in the month of June 2022

As Fig. 8 indicates, the thermal energy transferred, calculated on basis of the TeBwA method, amounts to approx. 204 kWh. The corresponding value determined with a conventional heat meter is approx. 188 kWh. Thus, there is a relative deviation of about +8.4%. The overestimation of the transferred thermal energy in solar circuits mainly occurs during periods of solar thermal stagnation. In periods of solar thermal stagnation, no volume flow exists in the solar circuit while the temperatures of the heat transfer fluid continuously rise up to certain, relatively high temperatures. The evaluation algorithms currently in use sometimes incorrectly detect the presence of a volume flow in the solar circuit during stagnation conditions. This incorrect detection of a volume flow, when actually there is none, can lead to the described overestimation of the transferred thermal energy. This effect occurred in the second half of June 2022. As can be seen in Fig. 8, this led to an increase in the daily deviations between the values determined using the TeBwA method and those based on a conventional heat meter. The algorithms used at present are currently under improvement, to address the stagnation problem described.

Due to limited available space, curves of the accumulated thermal energy transferred within one month for the other three types of hydraulic circuits are not shown. Tab. 4 lists the monthly transferred thermal energy for each of the hydraulic circuits based on the calculations performed by conventional heat meters and by the TeBwA method, as well as the relative deviation between both.

Tab. 4: Conventional and temperature-based energy balancing (TeBwA method) as well as deviation between both for the month of October 2021 for various solar thermal systems investigated

Field test system with corresponding hydraulic circuit		**Conventional energy balancing by means of a heat meter [kWh]**	**Temperature-based energy balancing with TeBwA-method [kWh]**	**Deviation [%]**
System 1*	Solar circuit	0.0	0.1	-
	Boiler circuit	467.0	503.5	+7.82
	Heating circuit	1,398.0	1,304.0	-6.72
System 2	Solar circuit	114.0	121.6	+6.70
	Boiler circuit	97.0	105.9	+9.18
	Domestic hot water circuit	57.0	60.5	+6.19

System 3[**]	Solar circuit	173.0	177.0	+2.36
	Boiler circuit	2,337.0	2,500.9	+7.01
	Heating circuit	2,024.0	2,015.0	-0.44
System 4[***]	Boiler circuit	872.0	943.5	+8.20
	Domestic hot water circuit	654.0	621.7	-4.94

[*] The solar circuit of field test system 1 was out of service in October 2021 due to technical problems with the controller.

[**] For field test system 3, a temporary problem occurred in October 2021 with the programs used for data acquisition. Therefore, only 25 days are included for the values shown in Tab. 4

[***] Field test system 4 experienced temporary problems with the temperature sensors used in the boiler circuit in October 2021. In addition, modification work was carried out on the boiler. Therefore, for the boiler circuit only 23 days could be considered for the values presented in Tab. 4. For the domestic hot water circuit of field test system 4 only 28 days could be considered in Tab. 4 due to technical problems. As the solar collectors are damaged, the solar circuit of field test systems 4 is currently not in operation.

Since the solar yield in the month of October 2021 was relatively low due to a small number of sunny days, Tab. 5 shows supplementary results of the solar circuits of the field test systems for the month of June 2022.

Tab. 5 Conventional and temperature-based energy balancing (TeBwA method) as well as deviation between both for the month of June 2022 for various solar thermal systems investigated

Field test system with corresponding hydraulic circuit		Conventional energy balancing by means of a heat meter [kWh]	Temperature-based energy balancing with TeBwA-method [kWh]	Deviation [%]
System 1	Solar circuit	376.4	349.3	-7.20
System 2	Solar circuit	188.1	203.9	+8.41
System 3[*]	Solar circuit	582.3	519.5	-10.78
System 4[**]	Solar circuit	-	-	-

[*] For field test system 3, the measurement track of the solar circuit was temporarily removed to be modified. Therefore, only 26 days are included for the values given in Tab. 5.

[**] As the solar collectors are damaged, the solar circuit of field test system 4 is currently not in operation.

Tab. 4 and Tab. 5 show, that the monthly transferred thermal energy in the different types of hydraulic circuits can be calculated with high precision when using the newly developed TeBwA method for the temperature-based energy balancing of thermal systems. The calculation results deviate within a range of ±10.8% compared to the results of conventional heat meters. A precise energy balancing of thermal systems, using only low-cost temperature sensors, is therefore principally possible. It should be noted however, that the use of the electrical heating elements installed in the hydraulic circuits was deliberately omitted. This was done in order to determine the performance of the TeBwA method under regular operation of the systems and to avoid additional consumption of electricity. If the electrical heating elements were used, the achievable precision would even be higher.

When assessing the results presented in Tab. 4 and Tab. 5, it should also be taken into account that the comparison is based on monthly values. The deviations occurring for individual days are sometimes significantly greater than ±10%. Future work will therefore, among others, focus on further improving the temperature-based energy balancing algorithms developed so far.

5. Further Action

The next steps with regard to the further development of the TeBwA method for the temperature-based energy balancing of thermal systems are mentioned in the following.

The evaluation algorithms to reliably detect the presence of an occurring volume flow within a pipe and the evaluation algorithms to subsequently calculate the volume flow rate with high precision will be improved to further increase the accuracy of the TeBwA method.

Investigations will be performed how to increase the accuracy with which small volume flow rates can be calculated by using three, instead of two temperature sensors in a measurement track. By an appropriate placement of the three temperature sensors in the measurement track, two partial sections with different lengths can be realized. This allows a flexible reaction to volume flow changes in the hydraulic circuit under consideration.

Also, investigations will be performed regarding a targeted increase in the temperature dynamics of the pipe flows under consideration. This should enable more precise temperature-based volume flow calculation even if the temperature dynamics during regular operation of the hydraulic circuit are temporarily insufficient. Therefore, the use of electrical heating elements installed in the measurement tracks will be investigated. One important challenge here lies in the development of an activation strategy that leads only to a minimal additional use of electrical energy.

Additionally, it will be examined to what extent the temporal resolution with which the temperatures in the measurement track are recorded can be reduced, without leading to a significant influence on the calculated volume flow rates. This approach is intended to reduce the demands on the measurement technology used. This would allow for the use of cheaper components and thus reduce the overall costs of the TeBwA method.

Another aspect that is being investigated lies in a general abandonment of the measurement tracks currently in use. As an alternative the required temperature sensors are inserted at a defined distance apart from each other directly into the water-bearing pipes. The sections between the temperature sensors act as quasi measurement tracks. The abandonment of the presently used measurement tracks would result in a further reduction in costs and also the intervention in the hydraulic circuits of the thermal systems would be reduced.

In the medium term, the authors are intending to commercialize the newly developed TeBwA method for the temperature-based energy balancing of thermal systems. For this purpose, a partner from industry is sought at present. In cooperation with this partner, the future design of the technical components will be developed.

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7. References

Frank, E., 2000. Untersuchungen zur Bestimmung von Kollektorkreis-Volumenströmen durch Auswertung von Temperaturflanken. State examination thesis, Philipps-Universität Marburg.

Nedumparambil, A.; Seiz, M.; Drück, H.; Bestenlehner, D., 2021. Temperature based determination of volume flow rates in pipes as a low-cost option for energy measurements of solar thermal systems, in: Proceedings of the Solar World Congress, 25.-29.10.2021, online, International Solar Energy Society, Freiburg, ISBN 978-3-9820408-7-5, pp. 608-619, viewed 12 September, 2022, http://proceedings.ises.org/swc2021/swc2021-proceedings.pdf.

Seiz, M.; Lang, X., Drück, H., Bestenlehner, D., 2022. Kostengünstige energetische Bilanzierung wärmetechnischer Anlagen durch eine temperaturbasierte Volumenstrombestimmung, in: Proceedings of the Symposium Solarthermie und innovative Wärmesysteme, 03.-05.05.2022, Bad Staffelstein, Conexio GmbH, Pforzheim, ISBN 978-3-948176-17-4, pp. 211-230, viewed 12 August, 2022, https://www.solarthermie-symposium.de/konferenz/tagungsunterlagen.

Seiz, M.; Nedumparambil, A.; Drück, H.; Bestenlehner, D., 2021. Kostengünstige Volumenstrombestimmung von Rohrströmungen mittels Temperaturmessungen, in: Proceedings of the Symposium Solarthermie und innovative Wärmesysteme, 27.-30.04.2021, online, Conexio GmbH, Pforzheim, ISBN 978-3-948176-13-6, pp. 352-368, viewed 12 August, 2022, https://www.solarthermie-symposium.de/konferenz/tagungsunterlagen.