Overview of the state of the art heat measurement technologies for larger solar thermal systems

Overview of the state of the art heat measurement technologies for larger solar thermal systems 1

Introduction 3
Objectives 3
Definitions 3

Basic Principles of Heat Measurement 4

Basic Principles of Heat Measurement 4
Principle 4
Main measurement parameters 5
Flow meters 5
  Principle of the electromagnetic flowmeter 6
  Principle of the ultrasonic flowmeter 7
  Principle of vortex flowmeter 8
  Flowmeter with rotating impeller 9
Temperature sensors 9
  Resistance temperature detector 10
  Thermocouple thermometer 11
Calculator 11

Accuracy of Heat Measurement Systems 12
Introduction into accuracy requirements 12
  Technical accuracy (measurement system related) 12
  Non technical accuracy and errors 12
Accuracy of heat measurement in solar thermal 13

System costs 13
Cost benefit ratio 15

References 16
Scientific sources and papers 16
Product specific resources 16

Introduction

Objectives

This report provides an overview of the state of the art of measuring heat delivery in larger solar systems, looking also at the costs and accuracy of the measuring systems.

The present document was produced within the framework of the Intelligent Energy-Europe project Key Issues for Renewable Heat in Europe (K4RES-H)[1]. The project looks at providing guidelines for best practice policies to support renewable heating and cooling (RES-H) technologies.

Definitions

K4RES-H addresses the total amount of produced renewable and useful heat. This definition comprises the following specifications:

- The heat is measured directly after the conversion which means that all storage and transfer issues are neglected. Biomass is measured after the combustion, solar thermal after the collector and geothermal after the heat exchanger (direct system) or after the heat pump
- Auxiliary energy supply within the conversion process is only considered when being a considerable amount (suggestion for more than 5 %). It is expected that only Heat Pumps will find consideration as auxiliary systems.
- The energy used to produce and transport biomass shall not be considered

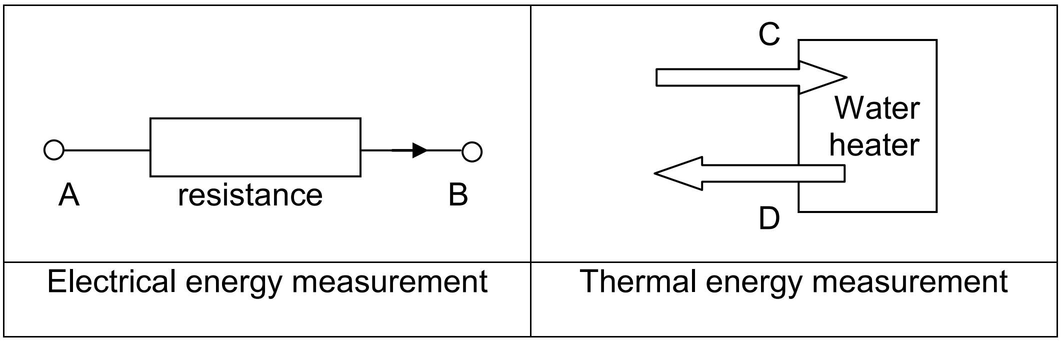
---

[1] The K4RES-H homepage can be found at: http://www.erec-renewables.org/projects/proj_K4_RES-H_homepage.htm

Basic Principles of Heat Measurement

Principle

The measurement of a flow of thermal energy is based on the measurement of two physical properties: flow rate and temperature difference. The analogy with the measurement of electrical energy is illustrated in the figures below.



Electrical energy measurement

Thermal energy measurement

Figure 1: Measurement of electricity and of heat

The electrical energy [Wh] consumed in the resistance is calculated from the potential difference [V] measured between point A and B, and the flow of electrons, current [A]. The equivalent to consumed thermal energy is calculated from the temperature difference between point C and D [degree C] and the flow of water [m^3/s].

The measurement of thermal energy is in principle similar to electrical energy, however due to the physical differences, like dimension of water pipes, complexity of installations it is in practice more difficult than electrical energy measurement. The accuracy of the measurements depends not only on the sensors and instruments used but also on the correct place where the sensors are positioned.

There are different types of parameters which have to be measured for calculating the quantity of heat produced:

- the flow rate F [m^3/s]
- the temperature:
    - the in temperature tin [K]
    - the out temperature tout [K]
- the time t [s]

Those parameters allow calculating the heat power P [kW]:

$P = \rho * c_p * V * (t_{in} - t_{out})$

With :

- ρ : the density [kg/m^{33}]
- c_p : the specific heat capacity [J/(kg*K)]

The density and the specific heat capacity depend on the type and temperature of the fluid used (and if the fluid is a gas also on the pressure). For example, if the water contents glycol in a certain percentage, it is necessary to adapt the cp. If the fluid is a gas and the pressure varies, it is also necessary to measure the pressure.

The following definitions are required:
Specific heat capacity: The quantity of energy needed to increase the temperature of one unit of mass by one degree. [GIECK, 1997]

With the power, it is possible to calculate the quantity of heat energy Q [kJ]:

$Q = P * t$

Main measurement parameters

Heat counters, from the smallest domestic appliances to the largest industrial equipment with far more than 10 MW ratings, consist of three basic components:

1. Flow meter (water is used almost exclusively as heat transfer medium)
2. Temperature sensors (to measure the temperature difference)
3. Processor (often also called integrator)

Technological specifications for all three components are given in the following.

Flow meters

Various principles to measure the flow rate exist. The most prominent flowmeters are:

- electromagnetic flowmeter (used for conductive liquid: e.g. water, water with glycol)
- ultrasonic flowmeter
- vortex flowmeter
- flowmeter with rotating impeller

- (coreolis mass flow meter - normally only for laboratory/calibration use – very expensive – not relevant for field measurements)

Principle of the electromagnetic flowmeter

Faraday's law of induction states that a conductor moving in a magnetic field induces an electrical voltage. With a magmeter, the flowing fluid is the moving conductor. The constant-strength magnetic field is generated by two field coils, one on either side of the measuring tube. Two measuring electrodes on the inside wall of the tube are at right angles to the coils and detect the voltage induced by the fluid flowing through the magnetic field. The induced voltage is proportional to flow velocity and thus to volume flow.

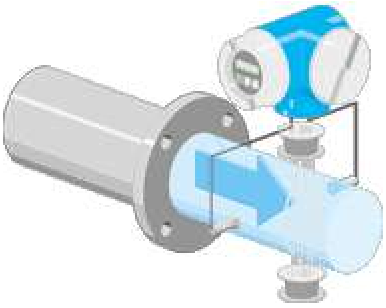


Figure 2: Electromagnetic flowmeter (source: www.endress.com)

The magnetic field is generated by a pulsed direct current with alternating polarity. This ensures a stable zero point, and makes the measurement insensitive to influences from multi-phase or inhomogeneous liquids or low conductivity.

Advantages of electromagnetic flowmeter

- The principle is virtually independent of pressure, density, temperature and viscosity
- Even fluids with entrained solids can be metered (e.g. ore slurry, cellulose pulp)
- Large nominal-diameter range available (DN 2...2000)
- Free pipe cross-section (CIP/SIP cleaning, piggable)
- No moving parts
- Minimum outlay for maintenance and upkeep
- No pressure losses
- Very high turndown, up to 1000:1
- High degree of measuring dependability and reproducibility, good long-term stability

Principle of the ultrasonic flowmeter

Swimming against the flow requires more power and more time than swimming with the flow. Ultrasonic flow measurement is based on this elementary transit time difference effect. Two sensors mounted on the pipe simultaneously send and receive ultrasonic pulses. At zero flow, both sensors receive the transmitted ultrasonic wave at the same time, i.e. without transit time delay. When the fluid is in motion, however, the waves of ultrasonic sound do not reach the two sensors at the same time. This measured "transit time difference" is directly proportional to the flow velocity and therefore to flow volume.

Advantages of ultrasonic flowmeter

- Non-contact measurement from outside. Ideal for measuring highly aggressive liquids or fluids under high pressure
- With homogeneous fluids, the principle is independent of pressure, temperature, conductivity and viscosity
- Usable for a wide range of nominal diameters (DN 15...4000)
- Direct meter installation on existing pipes. Retrofitting is also possible
- Commissioning without process interruption
- Non-invasive measurement
- No pipe constrictions, no pressure losses
- No moving parts. Minimum outlay for maintenance and upkeep
- High life expectancy (no abrasion or corrosion by the fluid)

Doppler ultrasonic flowmeters operate on the Doppler shift principal, whereby the transmitted frequency is altered linearly by being reflected from particles and bubbles in the fluid. The net result is a frequency shift between transmitter and receiver frequencies that can be directly related to the flow velocity. If the pipe internal diameter is known, the volumetric flow rate can be calculated. Doppler meters require a minimum amount of solid particles or air in the line to achieve measurements. Within the Time Meter Measurement Principle are made by sending bursts of signals through a pipe. The measurement of flow is based on the principle that sound waves travelling in the direction of flow of the fluid require less time than when travelling in the opposite direction. At zero velocity, the transit time or delta T is zero. If we know the diameter of the pipe, the pipe wall thickness and the pipe wall material the angle of refraction can be calculated automatically and we will know how far apart to space our transducers. The difference in transit times of the ultrasonic signals is an indication for the flow rate of the fluid. Since ultrasonic signals can also penetrate solid materials, the transducers can be mounted onto the outside of the pipe. Fast Digital Signal Processors and signal analysis guarantee reliable measuring results even under difficult conditions where previously ultrasonic flowmeters have failed.

Thermal Mass Flow Meters are based on an operational principle that states that the rate of heat absorbed by a flow stream is directly proportional to its mass flow. As molecules of a moving gas/liquid come into contact with a heat source, they absorb heat and thereby cool the source. At increased flow rates, more molecules come into contact with the heat source, absorbing even more heat. The amount of heat dissipated from the heat source in this manner is proportional to the number of molecules of a particular gas/liquid (its mass), the thermal characteristics of the gas/liquid, and its flow characteristics.

Principle of vortex flowmeter

This measuring principle is based on the fact that vortices are formed downstream of an obstacle in a fluid flow, e.g. behind a bridge pillar. This phenomenon is commonly known as the Kármán vortex street. When the fluid flows past a bluff body in the measuring tube, vortices are alternately formed on each side of this body. The frequency of vortex shedding down each side of the bluff body is directly proportional to mean flow velocity and therefore to volume flow. As they shed in the downstream flow, each of the alternating vortices creates a local low pressure area in the measuring tube. This is detected by a capacitive sensor and fed to the electronic processor as a primary, digitized, linear signal.

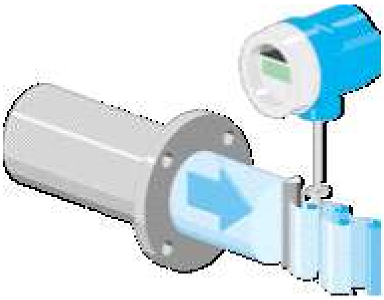


Figure 3: Vortex flowmeter (source: www.endress.com)

The measuring signal is not subject to drift. Consequently, vortex meters can operate an entire life long without recalibration.

Capacitive sensors with integrated temperature measurement can directly register the mass flow of saturated steam as well, for example.

Advantages of vortex flowmeter

- Universally suitable for measuring liquids, gases and steam
- Largely unaffected by changes in pressure, temperature and viscosity

- High long-term stability (lifetime K factor), no zero-point drift
- No moving parts
- Marginal pressure loss
- Easy to install and commission
- Large turndown of typically 10:1 to 30:1 for gas/steam or 40:1 for liquids
- Large temperature range from -200...+400 °C

Flowmeter with rotating impeller

This measuring instrument determines the flow with the rotation velocity of the impeller. After flow of a specific volume, the flowmeter sends an impulse to the calorimeter.

Figure 4: Flowmeter with irradiation impeller (source: www.resol.de)

Temperature sensors

Sensors and instruments are available on the market that perform the same measurement but vary significantly in accuracy and precision. To measure temperatures in a flow of water, usually thermocouples or platinum resistance (PT-) sensors are used. Thermocouple sensors are available for different temperature ranges each with its own accuracy. A PT100 temperature sensor can have a higher precision than a thermocouple. Note that the quality of the instruments and sensors are not related to the measurement itself. A PT100 temperature sensor can be measured in different ways (2-, 3- or 4-wires) with different accuracies.

2 types of temperature sensor can be used in this application:

- the resistance temperature detector
- the thermocouple thermometer

Resistance temperature detector

A Resistance Temperature Detector (RTD) is a temperature responsive device based on a predictable resistance change in the sensing element. The EN 60751 standard specifies requirements for industrial Platinum resistance sensors and covers the PT 100 thermometers.
The PT 100 sensing element has a resistance of 100 Ω at 0°C.
According to EN standard and most common industrial applications, the PT 100 type sensors are used for temperature measurement and control in the range from -50°C to 400°C or -200°C to 600°C.

Advantages of RTDs:

- high accuracy
- excellent long-term stability
- high signal output level which allows transmission over long distances without ancillary equipment.

Basic construction of Platinum resistance elements cannot be used directly in contact with process environments, hence the complete thermometers are built as assemblies which can withstand light, medium and heavy duty industrial conditions.
In general, the sensor assembly includes three components:

- the resistance thermometer inset
- the protecting tube (thermowell)
- the terminal housing.

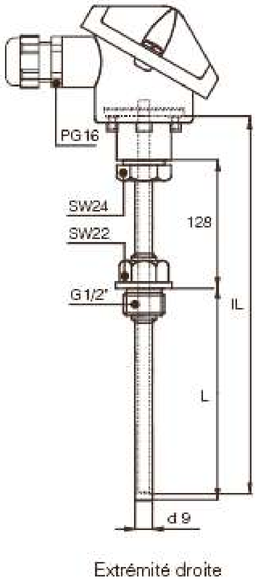


Figure 5: Resistance temperature detector RTD PT 100

Thermocouple thermometer

A thermocouple (TC) consists of two wires of different conductive material, connected each other by means of two junctions forming an electrical circuit. If one junction is at temperature T1 and the other at T2, then an electromotive force is generated in the circuit, and it depends on the materials and temperatures T1 and T2 (Seebeck effect). In an industrial TC thermometer one junction is the measuring joint, and the other is a reference one which is usually located in correspondence of the conversion electronics (transmitter).

According to EN/ANSI standards and most common industrial applications, the thermocouple sensors are used for temperature measurement and control in the range from -40°C to 1800°C.

Advantages of thermocouples

- Good accuracy
- excellent response time
- wide measuring range.

Basic construction of thermocouple sensing elements cannot be used directly in contact with process environments, hence the complete thermometers are built as assemblies which can withstand light, medium and heavy duty industrial conditions. In general, the sensor assembly includes three components:

- the thermocouple inset
- the protecting tube (thermowell)
- the terminal housing

Calculator

With the flow rate and temperature sensors, the parameters are measured. It is now necessary to calculate the thermal power and the thermal energy with a calculator/processor, using (temperature dependent) values of density and specific heat capacity of the circulating fluid.

Accuracy of Heat Measurement Systems

Introduction into accuracy requirements

In the accuracy of Heat Measurement Systems the technical accuracy and non-technical mistakes are to be differentiated.

Technical accuracy (measurement system related)

In principle one may recognize three main sources for errors related to reported results. These errors are identified by the origin of it in the overall process to assess reporting data from physical observations.

The three main sources of errors are due to:
1. The instruments and sensors applied for the measurements
2. The measurement of physical parameters itself
3. The numerical analysis of obtained results to assess a desired parameter

The assessment of the technical accuracy of heat measurement systems can be based on the settings of the EU Directive 2004/22/EC on measuring instruments. This Directive defines the following accuracy classes:

Class	$E = E_f + E_t + E_c$ total Error of **heat meter**	E_{min}
1		~ 2%
2		~3%
3		~4%

Example: class 2 instruments are allowed to show a total error of 3%.

Recommendations for accuracy in solar thermal systems:

Systems with more than 1.000 m^2 collector area:	2% (Class 1)
Systems with more than 500 m^2 collector area:	3% (Class 2)
Systems with more than 100 m^2 collector area:	4% (Class 3)
Systems with more than 50 m^2 collector area:	5%
Systems with more than 10 m^2 collector area:	10%

Non technical accuracy and errors

Errors due to installation, dimensioning of the application or operating conditions are often more problematic than the errors on the hard-/software side of the measurement system.
Example: for solar thermal the varying density of the glycol in the collector circuit has a significant effect on the energy measured.

Accuracy of heat measurement in solar thermal

For solar thermal the non-technical issues are most determined for the measurement accuracy, as they are often more problematic than the errors on the hardware side. These items should be discussed in the fields of:

- Installation
- Dimensioning
- Operation conditions

Attention is here drawn to one specific operating condition: The fluid circulating in the solar collector loop. To protect against freezing solar thermal systems often use anti-freeze fluid; typically based on a mixture of water and propylene glycol. Using normal heat meters for water in a solar loop with a typical glycol mixture of 30-40% will lead to an over-estimation of the delivered energy of approx. 5%.

Simple correction can be made using a constant correction factor to be multiplied to the value determined by the “water” heat meter. The factor depends on the propylene glycol mixture-%:

Glycol mixture %	Correction factor
10	1.00
20	0.99
30	0.97
40	0.94
50	0.91

Some uncertainty is introduced using this simple correction as the anti-freeze fluid is seldom pure propylene glycol – and the fluid data is depending on the temperature level; but normally this correction will be true within ± 2%.

The calculator/processor converting flow rate and temperature into thermal power and energy should use correct temperature dependent data for the actual fluid when high accuracy is required (very large systems).

System costs

The costs of one specific system can be very different (calculation tax excluded). Based on concrete configurations of different existing products, the following example calculations were produced:

Measuring systems based on a **flowmeter with impeller**:

- 1 flowmeter with impeller (DN 20: 147 € - DN 32 : 315 €)
- 2 resistance temperature detector PT1000 (14 € * 2 = 38 €)
- 1 calculator (136 €)

Total costs: 320 – 490 €

Measuring systems based on an **ultrasonic flowmeter** (verified to accuracy classes: 2-3):

- 1 ultrasonic flowmeter (DN 20 - DN 50)
- 2 resistance temperature detector PT500
- 1 calculator (based on water data)

Total costs: 450 – 1090 €

Measuring systems based on an **ultrasonic flowmeter**:

- 1 electromagnetic flowmeter (DN 50: 1 711 € - DN 200: 3 062 €)
- 2 resistance temperature detector PT100 (2*237 €)
- 1 calculator (726 €)

Total costs: 2910 – 4260 €

The first two systems would be typically used in practical field applications, whereas the third one is targeted at industrial and scientific applications.

Investment for heat meters
Examples of costs of heat meters are given above; installation costs can be estimated to 0,5-1 hour: approx.: 50 €; extra price for a calculator programmed to water/glycol depends very much on the size of the market (80 € corresponding to a substantial market is included in the Figure 6).

It is immediately seen that adding a heat meter to a small thermo siphon solar system with a cost of approx. 1000 € will increase the price more than 33%.

For pumped systems the costs for the heat meter is compared with the costs of the solar system in Figure 6. The figure is based on prices of Kamstrup and Resol heat meters and the system price is estimated using the rather rough price equation:

Costs/collector area = 800 € - 80 € * ln(Collector area) (ex. VAT)

From Figure 6 it is seen that for small systems the heat meter adds significantly to the solar system costs, but for larger systems >70 kW (100 m²) the relative costs of a heat meter is below 2% of the solar system costs.
Adding investment costs (approx. 150 €) for remote reading service (M-bus and modem / radio) has significant influence only on the investment cost ratio for small systems.

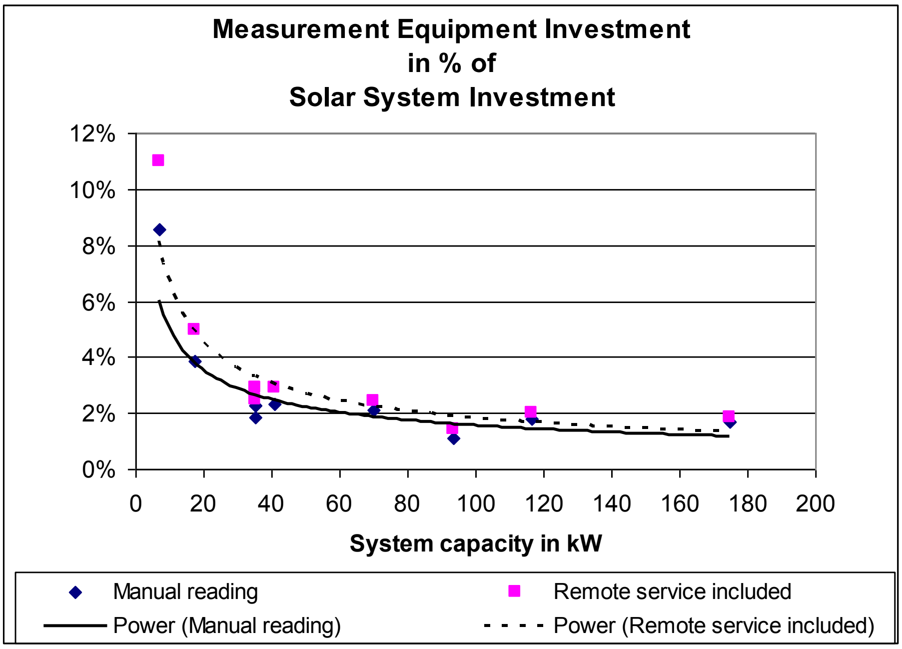


Figure 6: Heat meter investment costs (with and without remote reading service) compared to solar system costs

Operating costs

Simple/manual operation: The heat meter should be read and recorded at least once a year (negligible costs in comparison with larger solar thermal systems)
Remote monitoring/reading: Depends very much on number of systems and degree of details wanted: 5-50 € per year and per meter.
For initial verified meters the accuracy is normally defined for a period of time. To keep this guaranteed accuracy calibration is necessary every 3-6 years, each time approx. 100 € + de- and re-installation

System life expectation

Estimated expected technical life time is approx.10-15 years, depending on the actual measurement principle and system used. Calibration should be done according to recommendations from the manufacturer of the heat meter

Cost benefit ratio

Small systems below 50-100 m^2 are seldom metered due to the relative high cost of metering for small systems.

References

Scientific sources and papers

BERA F. (April 2006), personal communication. Professor in the “technologie des industries agroalimentaire”, Faculté des sciences agronomiques de Gembloux, Belgium
GIECK K. + R. (1997) Formulaire technique. Gieck Verlag, D-82110 Germering

Product specific resources

RESOL Elektronische Regelungen Gmbh (www.resol.com, April 2006)
Endress+Hauser (www.endress.com, April 2006)