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1. Introduction

Measuring flow of heat transfer fluids on CSP facilities is extremely important because of it takes part on the evaluation of the Energy/Power gained by the HTF

$Q = \dot{m}\Delta H$ where \dot{m} is the HTF flow and ΔH is the enthalpy change.

And, consequently for evaluating the efficiency of such kind of systems.

$\eta = \frac{Q}{P_i}$ Where P_i is the incident power of the system.

This deliverable presents possible methods in order to measure the flow measurements for CSP facilities.

Calibration of flowmeters is not performed on working conditions (in most of the cases): sensors are calibrated using water a 20°C, and even using density corrections, flow measurement is not correct. This issue is more relevant if HTF is hot air (around 150-200°C) were differences between real and measured flow can reach 20-30%.

The first chapter is derived from the chapter included in SFERA deliverable R12.4 **Guidelines for Testing of CSP components**, but with additional precisions. Reading other chapters from R12.4 such as the metrology introduction should be of interest to the reader.

Several ISO, EN and ANSI norms are also listed in the Literature section.

It should be noted that calibration of mass flowmeters for HTF fluid in CSP facilities is among the activities planned in the upcoming SFERA II, WP15.

2. Flow measurement: different technologies

Any evaluation of receiver, collector or (sub)system performance or efficiency based on heat balances necessarily requires measuring the flow rate of a heat transfer medium. Typically, flow rates are measured at the cold inlet of the system under investigation.

Different measurement principles and sensors can be used to determine flow rates in CSP testing. Measurement principles and instruments are chosen according to the heat transfer fluid, flow rates, pipe diameter and specific uncertainty requirements as well as cost aspects.

Two families of flowmeters exist:

- Volumetric flowmeters: the device determines the volume of fluid passing.
- Mass flowmeters: the device determines the quantity of fluid passing.

Volumetric flowmeters require the calculation of the quantity of fluid passing by determining the density of the fluid which can change due to change of temperature (dilatation) or change of the chemical composition (oxidation, slurries...).

Large scale parabolic trough applications commonly use ultrasonic and vortex volumetric flowmeters whereas smaller units may use coriolis mass meters. Tower related applications often use vortex meters or pressure drop based devices depending on the heat transfer medium.

For installation and handling, Performance Test Code PTC 19.5 norm must be followed, as well as indications of PTC 19.1 norm.

3. Ultrasonic flowmeters

Ultrasonic flowmeters are based on measuring the travel time difference between ultrasonic signals travelling upstream or downstream. To this end, signals are created by a transmitter injected diagonally into the pipe or onto its surface, pass through the HTF (with or without reflection on the pipe walls) and are picked up by a receiver. When subtracting travel times of signals travelling downstream from those travelling upstream, the speed of sound in the HTF cancels out. The travel time difference is directly proportional to the HTF mean speed: it is a **volumetric** measurement.

Sensors are bidirectional and can measure positive and negative flows (an arrow on the sensor marks positive direction). They are composed by the sensor itself and the signal converter must be installed far from the sensor to prevent high temperatures on the converter when used with HTF.

There are two different kinds of sensor based on the installation: inserted directly on the pipe by means of a welded or flanged roll; or Clamp-on type mounted outside in the pipe.

Accuracy of these sensors is 1% or lower.

Table 1: Advantages and disadvantages of ultrasonic flowmeters

| Advantages | Disadvantages |
|---|---|
| No additional pressure drops on the pipes | High cost |
| Suitable for corrosive and dirty fluids | Weak signal for low flows rates |
| Portable models available | Not suitable for two-phase flows |
| Measure in both directions | Volumetric method, fluid density required |
| Signal Linearity | |



Ultrasonic flowmeters can be installed out of the pipe, allowing on site inspection at different location with the same instrument

4. Vortex flowmeters

This measuring method is based on Von Kármán vortex street: a fluid passing through an internal tube element that partially blocks the pipe generates alternating vortex to both sides of the blocking element with opposite directions. The frequency of the wake vortex is proportional to the **volumetric flow rate** ($f=k \cdot Q_v$), where the k factor depends only on the geometry of the equipment and is independent from fluid speed, viscosity or density.

Vortex flowmeters have **no moving components**, reducing the maintenance of the equipment.

There are different types of bluff bodies such as wafer, lug or flanged.

Capacitive transducers are the main technology used, due to the robust behavior when submitted to thermal changes and tube vibration.

The accuracy of these sensors is 1.5% or lower.

Table 2: Advantages and disadvantages of vortex flowmeters

| Advantages | Disadvantages |
|---------------------------------------|--|
| No moving parts | Not suitable for laminar flows and high viscosity fluids |
| Suitable for liquids, gases and steam | Reynolds number > 10000 |
| Acceptable pressure drops | Pipe vibrations largely influence measurements |
| Low maintenance | Volumetric method, fluid density required |



Vortex flowmeter principle: counting vortices due to an obstacle in the flow.

[Figure from Efunda].

5. Coriolis flowmeters

This measuring principle is based on generating a controlled coriolis force into the sensor: these forces appear when longitudinal and rotational movements are superposed. The magnitude of the coriolis force and resulting phase difference in vibration are **proportional to the mass of the fluid** that flows through the sensor and accordingly, to the mass flow rate of the fluid.

The effect is **independent from temperature, pressure, viscosity, conductivity and flow** profile. Some additional corrections of sensor temperature and pressure may be done to compensate changes of the instrument characteristics with these conditions.

Coriolis flowmeters measure directly mass flow and no density corrections are needed. Sensor must be inserted in the pipes using flanged or welds.

Accuracy of these sensors is 0.5% or lower.

Table 3 shows the advantages and disadvantages of Coriolis flowmeters.

Table 3: Advantages and disadvantages of Coriolis flowmeters

| Advantages | Disadvantages |
|---------------------------------------|---------------------------------------|
| High accuracy | High cost |
| Direct measurement of mass flow rate | High pressure drops |
| Suitable for liquids, gases and steam | Not suitable for large pipe diameters |
| Wide measurement ranges | |

6. Pressure drop flowmeters

Pressure drop flowmeters measure the pressure drop across a nozzle or orifice plate inserted in the fluid flow in terms of differential pressure. The flow rate is correlated with the differential pressure measured thanks to Bernoulli's principle according to:

$$\dot{Q}_v = K \cdot \sqrt{\Delta p}$$

\dot{Q}_v volumetric flow rate (m³/s)

K calibration coefficient depending on the sensor and the fluid properties

Δp measured pressure drop (Pa)

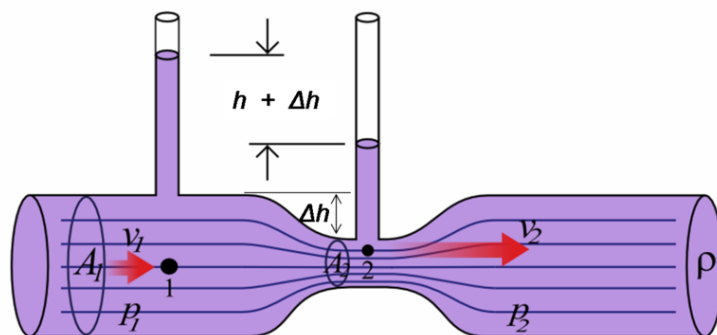
Pressure drops flowmeters are volumetric sensors.

Accuracy of these sensors is 2.0% or lower.

Table 4 shows advantages and disadvantages of "pressure drop" flowmeters

Table 4: Advantages and disadvantages of "pressure drop" flowmeters

| Advantages | Disadvantages |
|---------------------------------------|---|
| Low cost | Accuracy depends on fluids conditions |
| Simplicity | High pressure drops |
| Suitable for liquids, gases and steam | Not suitable for high viscosity fluids |
| | Broad measurement ranges |
| | Volumetric method, fluid density required |



Example of pressure drop flowmeter: Venturi flowmeter. A restriction on the path of the fluid leads to a change of speed of the fluid, therefore a change of pressure (Bernoulli's principle).

[illustration from Wikipedia]

7. Selection criteria

Most adequate flowmeters for CSP applications below 400°C are ultrasonic and vortex ones. Coriolis is the best selection for small size pipes if both higher price and larger external size can be afforded. Above 500°C, pressure drop flowmeters are typically the easiest technology to use.

Parameters to have in mind in the selection of the adequate equipment are: accuracy, measurement range, pressure drops, cost, corrosion, maintenance, etc.

8. Sensor calibration issues

All flow sensors require regular (re)calibration, preferably at operating conditions. Standard commercial calibrations are carried out using water at ambient temperature, however. The effect of such deviating operation conditions on the sensor performance depends on the individual measurement principle and characteristic behavior of the sensor and needs to be considered individually. Typical calibrations involve a fluid loop with reference flowmeters or a precise measurement of the volume that passes through the meter during a certain period of time.

9. Main error sources and expected precision

All methods for volumetric flow rate measurement described above are based on the assumption of a fully developed flow profile at or rather just before the location of the sensor and no important upstream disturbances. This implies the need for sufficient unimpeded piping length upstream of the sensors. Should this assumption be violated important errors will occur when deducing the flow rate from the signal.

Furthermore, temperature and density information is required in order to calculate the mass flow rate from measurements of volumetric flow rate. Possible errors much depend on the quality of this information.

10. Recommendations

A) For any flowmeter

To avoid measurement errors, it is necessary to keep straight distances before and after the sensor (indicated by the manufacturer and guidelines to assure fully developed flow profiles). Usually 10 and 5 pipe diameters upstream and downstream respectively (50 and 15 diameters respectively for small size pipes between 1 and 3 inches). Required unimpeded lengths depend on upstream and downstream obstacles and need to be carefully checked for every application individually.

Orientation can be horizontal or vertical with rising flow. Pipes must be filled completely without air inside to prevent signal losses or poor flow measurements. To avoid air in pipes, following considerations have to be in mind:

- Do not install sensors in pipe's high point.
- Install sensor in upward slope horizontal pipes.
- Guarantee a minimum flow speed to avoid air in pipes.
- Do not install sensors in vertical pipes with downwards flows because full pipes cannot be guaranteed.

B) Additional recommendations for Vortex flowmeters

These sensors are highly affected by pipe vibrations and thus, these must be avoided in order to obtain correct flow readings. At the same time, the flow profile must be stable to improve precision.

In case of installation of temperature and pressure sensors to convert volumetric flow to mass flow; they must be installed far away from the sensor in order not to affect generated vortex.

C) Additional recommendations for Coriolis flowmeters

These flowmeters do not require long straight pipe distance upstream in order to measure correctly and valves, elbow joints, etc. do not affect measurement process.

To prevent cavitation inside sensor pipes, it is necessary to maintain an over pressure in the sensor. For this reason, coriolis sensors must be installed in the impeller pipe of the pumps or in the lower vertical pipes points.

11. Proposal of calibration loop for measuring air flowmeters

The proposal consists on installing a closed-loop for check air flowmeters calibration with different methods. The loop will be equipped with an electric heater to increase air temperature up to 200°C. After heated the air pass through a pressure drop flowmeter (orifice-plate type) that serves as reference flowmeter. Air temperature and pressure must be measured before and after the plate. After this reference flowmeter, a removable pipe with flanges is installed to attach the different flowmeters for testing/calibrating. The loop is closed by a water cooler to cold down the air before entering again the heater. Air pressure and temperature is also measured at the inlet and outlet of the water cooler. And also water flow and temperature is monitored on the loop.

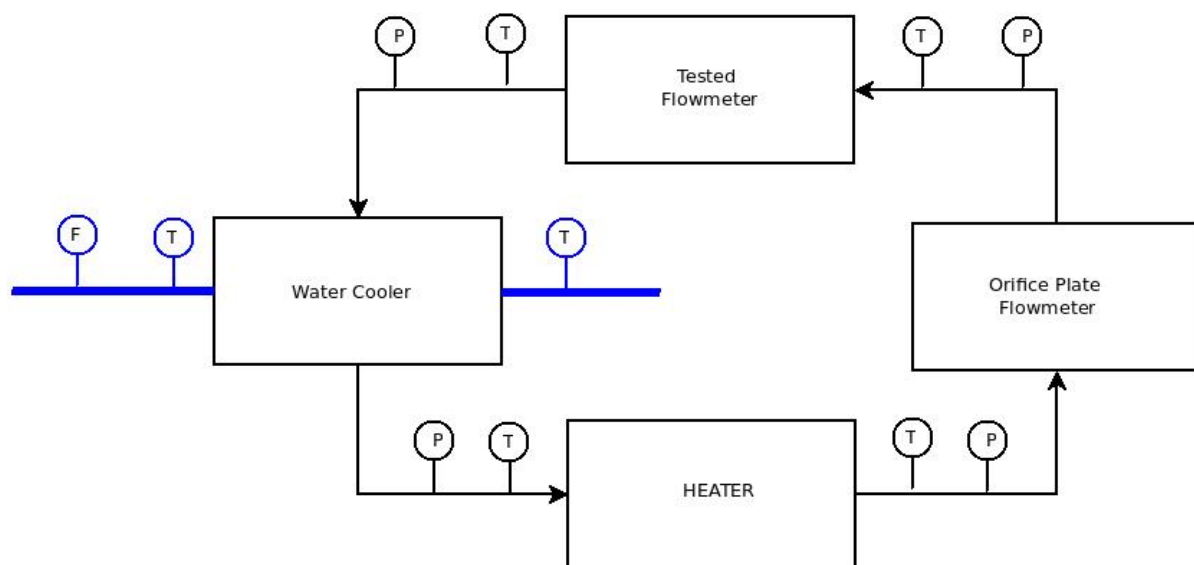


Diagram of the proposed loop for testing air flowmeters

On this way, air mass flow can be determined by means of:

- The electric power consumption of the heater, that will be directly proportional to the air mass flow:

$$\dot{m} = P_{electric} / \Delta H_{air}$$

- In the water cooler, considering the power gained by the water is the same to the power loosed by the air, then air mass flow can be determined as follows:

$$\dot{m}_{air} = \dot{m}_{water} \Delta H_{water} / \Delta H_{air}$$

Converting mass to volumetric flow (dividing by density) this two measurements can be compared with the reference flowmeter and with the flow measured by the flowmeter under calibration/testing.

12. Literature

International normative applicable to mass flow measurement are:

- ISO 5167:2003 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 1: General principles and requirements.
- ASME PTC 19.5-2004. Flow Measurement.
- ASME PTC 19.1-2005. Test Uncertainty.
- EMI/RFI "Susceptibility of Electronic Equipment Standard".
- EN60079-10: 2004. Electrical Apparatus for Explosive Gas Atmospheres General Requirement.
- IEC 60529. Grados de protección proporcionados por Envolverte (código IP) 2004.
- IEC 61000. Electromagnetic compatibility for industrial process measurement and control equipment.
- EN IEC 61010-1 first and second edition (safety requirements for electrical equipment for measurement, control and laboratory use part 1).
- IEC 61000-4-2 - Electrostatic Discharge Requirements.
- IEC 61000-4-3 - 2002 Electromagnetic compatibility (EMC). Part 4-3: Testing and Measurement Techniques-Radiated, Radio-Frequency, Electromagnetic Field Immunity Test.
- Pressure equipment directive (Module H of 97/23/EC, full quality assurance).
- ANSI B 16.5. Pipe flanges and flange fitting, 1988.
- ANSI B 16.25. Butt Welding Ends.
- ANSI/ASME B1.20.1. Pipe Threads, General Purpose (Inch).