Thermal flow sensor for high liquid flows.

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Introduction

Thermal mass flow metering for gases has been an established technique for decades.
The thermal measuring principle for mass flow metering found its success in the application for controlling gases for the semiconductor industry. But also, especially in Europe, the instrument is used in all kinds of applications in laboratories for measuring mass flow with high precision and very good reproducibility. For this market, a thermal mass flow sensor for liquids was developed some 10 years ago, but it was restricted to small flows, up to approximately 1 Kg/h [1]. To extend the flow ranges of the thermal mass flow instruments for gases, to very high flows, the bypass technique is used. For liquids the bypass measuring technique is unsuitable.
In this presentation, a thermal flow sensor with no bypass is presented for liquid flows from 1 Kg/h up to 25 Kg/h. In the flow meter, LIQUI-FLOW® L30, *see photograph*, a unique thin film thermopile sensor design is used for stable measurement of very small temperature signals.

Thermal mass flow metering.

A thermal mass flow meter measures mass flow instead of volume flow. So the flow meter is virtually independent of pressure and temperature. Another advantage of the mass flow meter is that it has no moving parts. Especially for small liquid flows this is an important feature.
In the thermal measuring principle the mass flow is detected by a shift in the thermal balance of the sensor. For all known variations of thermal mass flow sensors, the measuring principle is the same. The metering method is schematically explained in figure 1. Here, the fluid flows through a small capillary tube. On the tube a configuration of thermal sensors and heaters is placed. In the middle is a wire wound heater, and symmetrically just upstream and downstream of the heater two wire wound temperature sensors T_{up} and T_{down} are placed. Constant power is injected in the heater. The resulting temperature profile in the tube is plotted in the graph. The temperature profile is symmetrical at zero flow. At flow > 0, the temperature profile is a-symmetric. The resulting temperature difference between T_{up} and T_{down} is a measure for the mass flow, because the thermal shift is caused by the number of molecules passing the sensor.

This measuring principle is not restricted to gasses only, it can be applied for liquids too. The only restriction of the measuring method is that it is limited to relatively small mass flows [1]. Therefore, to overcome this limitation, most thermal mass flow meters make use of a bypass parallel to the sensor. Only a small fraction of the flow is lead through the sensor. For liquids, however, the bypass construction leads to severe problems, amongst others, attitude sensitivity due to internal flow caused by thermal siphoning, but also gas bubbles that can be trapped in the bypass construction.

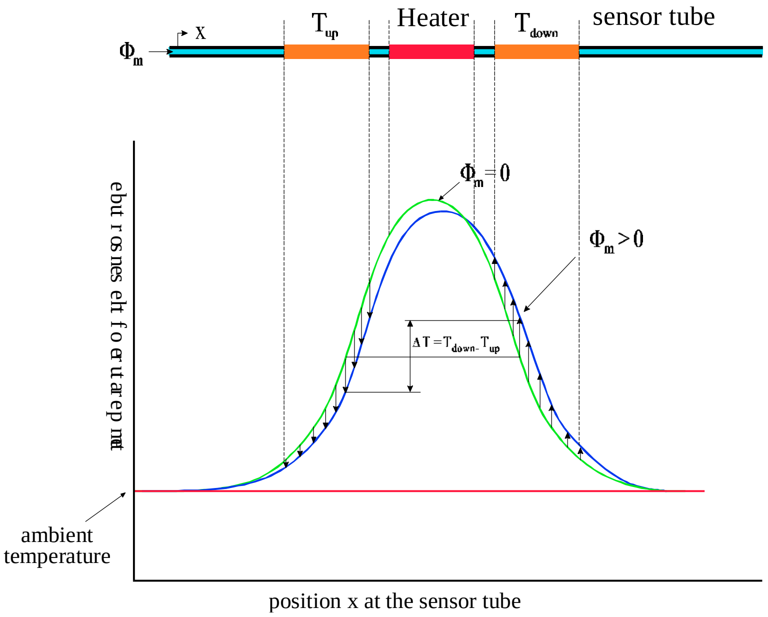


Figure 1. Temperature profile in thermal mass flow sensor. (745)

Theory of LIQUI-FLOW® L30.

With the measuring principle of the LIQUI-FLOW® L30 mass flow is detected and there are no moving parts in the sensor construction. The measuring principal is different from the method described above.
The layout of the sensor is shown in figure 2. The flow is lead through a straight pipe, on this pipe a configuration of sensors and heaters is placed. The heater temperature T_{heater} is maintained at a certain temperature above the incoming liquid, measured by T_{in}. The power needed to maintain this temperature rise while the fluid is flowing, is a measure for the flow. If the fluid is heated completely to the heater temperature, then the relation between power and mass flow is:

$$\text{Power} = K \cdot c_p \cdot \Phi_m \cdot (T_{heater} - T_{in}) \quad (1)$$

K = sensor constant.
c_p = the heat capacity of the fluid.
Φ_m = mass flow of the fluid.

So, contrary to the classical thermal mass flow sensing principle described above where the temperature difference is proportional to the mass flow, here the temperature difference is proportional to the inverse mass flow. This measuring principle is in fact a special form of a calorimetric thermal measuring principle [2].

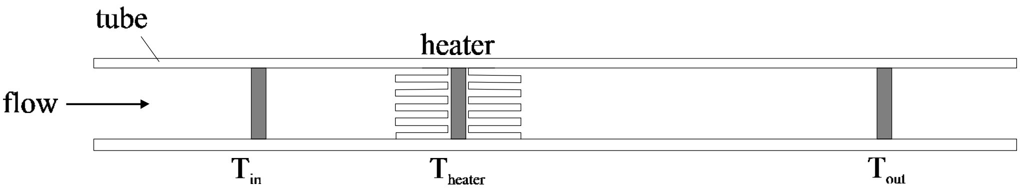


Figure 2. A schematic layout of the liquid mass flow sensor.

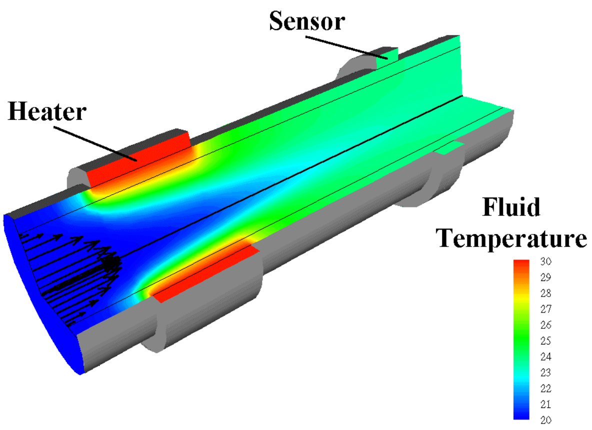


Figure 3. Simulation result of temp distribution in the fluid, flowing in a tube, heated by a heater. Simulationprogramm **"Wish 3D".** (1062)

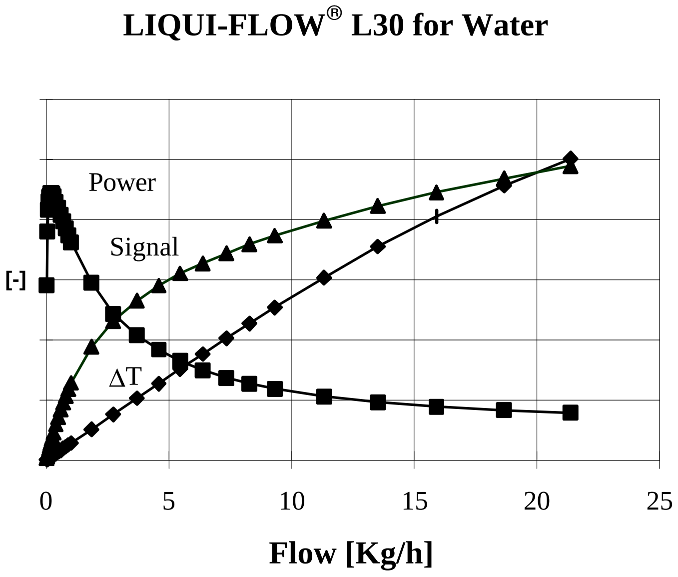
Only at very small flows, the fluid will be fully heated. At increasing flow, the mean cup temperature of the fluid will be smaller than the heater temperature. At a certain distance from T_{heater}, the fluid temperature will be homogeneous, by heat dispersion. If T_{out} is situated at this distance, it will measure the mean cup temperature of the fluid. See figure 3 for a simulation result of the temperature distribution of the flowing fluid; T_{out} is a measure for the temperature rise of the fluid due to the power injected at the heater. Although T_{heater} is kept constant, T_{out} will decrease at increasing flow. The power, needed to keep T_{heater} constant will increase parabolic with flow. See graph 1. (Graph of signals as a function of flow).

From formula 1 we can derive an output signal which is proportional to the mass flow.

$$\text{Signal output} = \frac{\text{Power}}{\Delta T} = K \cdot c_p \cdot \Phi_m \qquad (2)$$

From this formula, we can derive the conversion factor C_f . The conversion factor is very important for calibrating a sensor. The conversion factor is the relation between the mass flows of different fluids at the same output signal. The conversion factor for this flow meter is rather simple:

$$C_f = \frac{c_{p1}}{c_{p2}} \qquad (3)$$



Graph 1. Characteristic signals in the LIQUI-FLOW® L30 sensor.

Example: A flow meter is calibrated for 5 Kg/h water. This means that for a flow of 5 Kg/h, the output signal is 100%. If the flow meter is used for IPA (Isopropyl Alcohol), what will be the flow of IPA at 100% output signal?

From formula 1, the ratio between mass flow for water and for IPA is

$$C_f = \frac{c_{p\ \mathrm{water}}}{c_{p\ \mathrm{IPA}}} = \frac{4.18}{2.54}\ [\mathrm{KJ/Kg.K}] = 1.65.$$

So the IPA flow at 100 % will be 1.65 x 5 = 8.23 Kg/h.

$c_{p\ \mathrm{water}}$ = 4.18 [KJ/Kg.K]
$c_{p\ \mathrm{IPA}}$ = 2.54 [KJ/Kg.K]

Practical design of the L30 LIQUI-FLOW®.

The temperature differences T_{heater} - T_{in} and T_{out} - T_{in} are measured by a configuration of thermopiles. These thermopiles are a series of composite Copper-Constantan thermocouples. This is accomplished by an etching process of a thin Constantan layer on capton, which is partly covered by a Copper layer. See figure 4.
Also the heater is made of Constantan in the same layout. The power, injected in the fluid, is measured in an electronical control loop that maintains the heater temperature at a constant value. The use of the thermopile temperature sensing method allows us to only heat up the fluid to a few degrees above the incoming fluid. This is important for two reasons, raising the temperature of the fluid too much can damage the fluid (thermal disintegration), or it can start boiling. The second reason for keeping the heater temperature as low as possible is that at high flows, an increasing amount of power is needed. Example: If 20 Kg/h water has to be warmed up 5°C, more than 100 Watt is needed, which is unacceptable for a sensor.

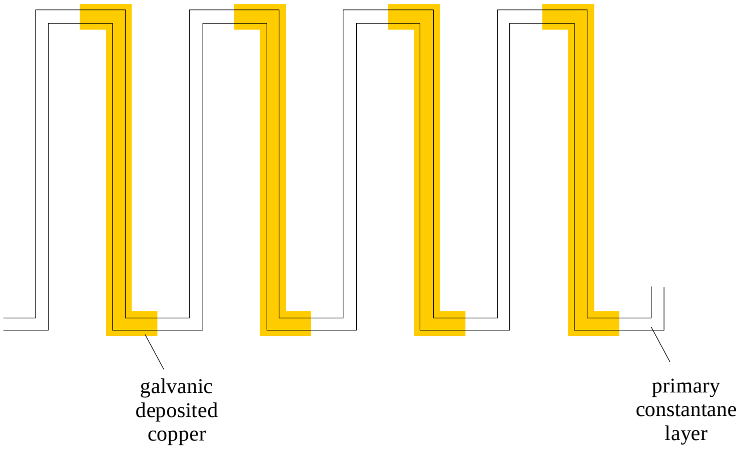


Figure 4. The thin film composite Copper-Constantan thermocouples in an array.

The place of T_{out} is critical for high flows. The boundary condition for this place is that the temperature of the fluid is homogeneous. This depends on the velocity (flow) of the fluid but also physical properties such as the thermal conductivity of the fluid plays a role. So, a sensor constructed for water is not optimal for other liquids like f.i. Iso-Propyl Alcohol (IPA). To find the optimal configuration of the heater and the temperature sensors, a thermal simulation program was used. See figure 3.
The mass flow meter has no elastomeric seals, the liquid is flowing through a straight pipe with no obstructions. The liquid is coming into contact with SS-316L only.

While the mechanical construction of the flow sensor is rather simple, the electronic processing of the signal is complex. To retrieve Power/ΔT, first an electronic multiplication has to be performed for the power, and in sequence, power has to be devided (multiplier) by the voltage of the thermopile. Analogue multipliers are severe sources for errors. Other functions of the electronic PC-board are linearisation, temperature compensation and a control circuit for flow control with a valve.

An important property of this measuring method is the dynamic behaviour of the sensor. This dynamic behaviour is important for flow control with a valve.
The dynamic response is dominated by the time lag between a heater change and the resulting temperature change of T_{out}. This time lag is caused by the time of travel of the liquid and therefore it depends on the flow rate. To overcome this problem, the feedback loop for the control valve anticipates on the response of the power input in the heater.
The behaviour of the sensor at flow = 0 is troublesome. The output signal is proportional to $1/T_{out}$, and at zero flow, T_{out} = zero, so the output signal is undefined here. There is a special circuit in the electronic design to zero the output at zero flow.

Conclusion

The calorimetric measuring principle is used to measure relatively large liquid flows. The mechanical design is simple, the instrument is robust, it has no moving parts, no obstructions, and is suited for pressures up to 100 bar.
The liquid mass flow meter LIQUI-FLOW® L30 was developed for a range of 20 Kg/h water, the power input is some 8 Watts maximum.
For smaller flows, the tube length can be smaller. The instrument has no has no elastomeric seals, the liquid is coming into contact with SS-316L only. Therefore, almost every liquid can be metered, including liquefied- and super-fluid gases.
Due to the use of thermopiles, small thermal signals can be used and thus the top temperature can be kept low. The electronics needed for this flow meter are rather complex especially due to analogue multipliers. The next generation of electronics will be a digital set-up, with a microprocessor.
In this (low) flow range, hardly any other mass flow sensors for liquids are known. Other measuring principles in this area measure volume flow like f.i. the turbine flow meter.
Some Applications of the LIQUI-FLOW® L30: Controlling Methanol for fuel cells and measuring pure water for generating combustion gasses to test catalysers. A special field of applications is where the Liquid Flow controller is used in combination with an evaporator, to deliver fluids in vapour phase [3]. This is applied for instance for $TiCl_4$ in a CVD process for hard, corrosion resistant thin layers on tools.

[1] H.J. Boer. A New Approach for Measuring (Very) Small Liquid Flows. Proceedings SENSOR 95. p.p. 97 - 102.

[2] Hohenstatt, M., Thermal Mass-Flow Meters, “SENSORS”, ed. W. Göpel, J. Hesse, J.N. Zemel Volume 4: “Thermal Sensors” Chapter 9. 1990, pp. 323-343. Published by VCH, Weinheim.

[3] H.J. Boer. “Mass Flow Controlled Evaporation System”, Journal De Physique IV, Colloque C5, supplement au Journal de Physique II, Volume 5, juin 1995. pp C5-961 - C5-966.