INTEGRATED MULTI-PARAMETER FLOW MEASUREMENT SYSTEM

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ABSTRACT

We have designed and realized an integrated multi-parameter flow measurement system, consisting of an integrated Coriolis and thermal flow sensor, and a pressure sensor. The integrated system enables on-chip measurement, analysis and determination of flow and several physical properties of both gases and liquids. With the system, we demonstrated the feasibility to measure the flow rate, density, viscosity, specific heat capacity and thermal conductivity of hydrogen, helium, nitrogen, air, argon, water and IPA.

INTRODUCTION

Knowledge of both the flow rate and its composition is essential in medical infusion pumps, especially in neonatology, where a newborn baby should receive both the right and the right amount of medicine and/or nutrient. Since the flow rates involved are extremely small, typically in the range of 0.1 - 1 ml/h, it is important to have a very compact single chip integrated system rather than a system composed of separate devices, to maximally reduce the internal volume of the system. Other examples of applications are flow chemistry for the production of specialty drugs, production of the right mix of gases for medical purposes, and measurement of the composition of fuel gas to determine its energy content.


Up to now, no systems have been reported in which different types of sensor principles are integrated to measure the flow rate and several physical properties of both gases and liquids.

SYSTEM STRUCTURE

The basic structure of the integrated multi-parameter flow measurement system is shown in figure 1. The system consists of an integrated Coriolis and thermal flow sensor, and an additional differential pressure sensor. Fluid flow enters the system at the inlet, passes through the Coriolis and the thermal flow sensor, and leaves the system at the outlet. The differential pressure between the inlet and outlet is measured by the pressure sensor.

OPERATING PRINCIPLE

The output signal of the thermal flow sensor is a measure for the flow rate, the pressure is measured by the pressure sensor. The output signal of the Coriolis mass flow sensor provides both the mass flow and information about the density of the medium [4, 5].

As shown in figure 2, the other parameters can be obtained from the output signals via a calculation model. By comparing the output signals of the Coriolis flow sensor and the pressure sensor, and taking the density into account, the viscosity of the medium can be calculated. By comparing the output signals of the thermal and the Coriolis flow sensors at low flows, the heat capacity of the medium can be calculated. The thermal conductivity can be determined by comparing the output signals of the thermal and Coriolis flow sensors at higher flows.

Figure 1: Basic structure of the integrated multi-parameter flow measurement system
MODELLING

In this section, it is explained how the different physical parameters are derived from the sensor signals.

Density

The resonance frequency of the Coriolis flow tube is dependent on and therefore a measure for the density of the medium that is inside the tube \([4, 5]\). The equation is shown in figure 2.

Specific Heat Capacity

When the output signal of the thermal flow sensor is plotted against the output signal of the Coriolis flow sensor, the slope of the curve at low flows is a measure for the heat capacity of the medium that is inside both sensors.

The resulting curve can be described by a third order polynomial function:

\[
S = C_1 y^3 + C_2 y^2 + C_3 y + C_4
\]

where the constants \(C_{1-4}\) are medium independent sensor parameters, their value is determined with air as reference medium, \(y\) is the output signal of the Coriolis flow sensor, and \(S\) the output signal of the thermal flow sensor.

When another medium is present in the system, we can solve equation (1) for a certain value of \(S\). The ratio of the solved value for \(y\) and the measured value for \(y\), multiplied with the value of the specific heat capacity of the reference medium air, provides the value of the specific heat capacity of the actual medium.

Viscosity

When the output of the Coriolis flow sensor is plotted against the output of the pressure sensor, the slope of the curve is a measure for the viscosity of the medium that is inside both sensors.

The viscosity can be calculated with the following equation \([6]\):

\[
\eta = \frac{\Delta P}{\Phi_m R_0} = \frac{\Delta P \rho}{\Phi_m R_0}
\]

(2)

The medium independent hydraulic resistance \(R_0\) is determined by using air as reference medium. The mass flow \(\Phi_m\) and the density \(\rho\) are measured by the Coriolis sensor, the pressure drop \(\Delta P\) is measured by the pressure sensor. For gases, we have to correct the measured density for the compressibility of the gas.

Thermal Conductivity

When the output signal of the thermal flow sensor is plotted against the output signal of the Coriolis flow sensor, the slope of the curve at higher flows is a measure for the thermal conductivity of the medium that is inside both sensors.

The resulting curve can be described by \([7]\)

\[
V = S_0 c_p \Phi_m \left(1 - \frac{5\lambda}{2} c_p \Phi_m - S_0 c_p \Phi_m \right)
\]

(3)

where \(V\) is the output signal of the thermal flow sensor, \(S_0\) are medium independent sensor constants, \(c_p\) is the specific heat capacity, \(\Phi_m\) the mass flow and \(\lambda\) the thermal conductivity. It should be noted that \(\lambda\) is determined from equation (3) by curve fitting, so no direct analytical relation can be provided, and therefore equation (3) is not shown in figure 2.

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FABRICATION
A detailed description of the fabrication process can be found in [8]. A picture of the fabricated system is shown in figure 3.

Figure 3: Fabricated system, showing the thermal (left) and Coriolis (right) flow sensors

MEASUREMENT SET-UP
For the gas flows, a pressurised vessel was used to generate air, hydrogen, helium, argon and nitrogen flows in the range of 1 up to 20 mL/min. For the liquid flows, a syringe pump system was used to generate water and IPA flows in the range of 1 up to 35 mg/h through the system. Pressures in the range of 1 through 7 bar were provided to the system. A photograph of the measurement set-up is shown in figure 4.

Figure 4: Measurement set-up

During the measurements the output signals of the pressure, thermal flow and Coriolis flow sensor were recorded simultaneously, together with the output signals of the reference instruments.

MEASUREMENT RESULTS
In figure 5, the relation between the output of the thermal flow sensor and the Coriolis flow sensor is shown, which is a measure for the heat capacity of the medium. All via equation (1) derived heat capacities were within 5% of their value as found in literature.

Figure 5: Relation between the output of the thermal flow sensor and the output of the Coriolis flow sensor for several gases (liquids not shown). According to the modelling, this represents the heat capacity of the medium, as shown in the smaller graph.

Figure 6: Relation between the output of the Coriolis flow sensor and the output of the pressure sensor for several gases (liquids not shown). According to the modelling, this represents the viscosity of the medium, as shown in the smaller graph.

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In figure 6, the relation between the output of the Coriolis flow sensor and the pressure sensor is shown, which is a measure for the viscosity of the medium. All via equation (2) derived viscosities were within 10% of their value as found in literature. The biggest deviations occur for hydrogen and helium, as it is difficult to fill the system with these gases, and a mixture between hydrogen or helium and air is likely to occur.

In figure 7, the values for the thermal conductivity of the measured gases are given. All via curve fitting of equation (3) found values are within 10% of their value as found in literature, except for helium, which is within 20% of the literature value.

**CONCLUSIONS**

We have designed and realised an integrated multi-parameter flow measurement system, consisting of an integrated Coriolis and thermal flow sensor, and an additional pressure sensor. The integrated system enables on-chip measurement, analysis and determination of flow and several physical properties of both gases and liquids. With the system, we demonstrated the feasibility to measure the flow rate, density, viscosity, specific heat capacity and thermal conductivity of hydrogen, helium, nitrogen, air, argon, water and IPA. Future research will focus on improving the accuracy of the measured parameters and integration of further functionalities in the system.

**ACKNOWLEDGMENTS**

This research was partly financed by the Dutch NanoNexNL program. The authors would like to thank the industrial partners in this project for their in-kind contributions and many fruitful discussions.

**REFERENCES**


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