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1993 Meas. Sci. Technol. 4 158

(http://iopscience.iop.org/0957-0233/4/2/004)

Meas. Sci. Technol. 4 (1993) 158–163. Printed in the UK

Utilization of the Peltier effect for measuring a fluid property. Application for designing new sensors

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Received 6 August 1992, accepted for publication 2 October 1992

Abstract. This paper describes a prototype thermoelectric sensor system which makes use of the Peltier emf in an array of thermocouples to sense properties of flowing fluids. The sensor is made of a thin continuous metallic strip of low conductivity, covered at regular intervals with numerous highly conducting electroplated patches of copper. Since the Peltier EMF is influenced by the heat transmission characteristic of the fluid, a first appliction is to measure the thermal conductivity of a fluid from a calibration curve. Consequently, liquids and gases may be analysed for purity by sensing the change in the Peltier EMF. When placing the circuit in a tube conducting a fluid flow, the Peltier EMF is dependent on the mass flow rate and can be used to measure it. Since the Peltier EMF depends mainly on the heat transmission characteristic of the fluid there is no need (as with a classical thermal mass flowmeter) to maintain the sensor at a given temperature above that of the fluid. Experimental tests show that temperature-compensated sensors based on the Peltier effect are sensitive devices, convenient for measuring low fluid flows independently of pressure and temperature changes.

1. Introduction

The hot wire anemometer has been used for many years as a research tool in fluid mechanics [1]. A hot wire anemometer usually refers to the use of a small electrically heated element placed in a fluid with the aim of measuring a property of that medium. Normally, the property being measured is the velocity. Since these elements are sensitive to heat transfer between the element and its environment, temperature and composition changes can also be measured. Film type sensors have been used for a great variety of measurements such as turbulent levels in a wind tunnel, flow patterns around models, etc. Monolithic silicon thermal flow sensors for measuring the velocity of gas or liquid have appeared in the literature [2] and can be used as the hot wire for mass flow measurements in a pipe. In this paper a new sensor based on the Peltier [3, 4] effect is presented which is particularly useful for the purpose of measuring the average heat transmission characteristic of fluids (liquids and gases) over its length. It is also applied to mass flow measurements in a pipe or to thermal conductivity measurements of the fluid when there is no flow.

2. Operating principle

The sensing element is basically a thermopile (figure 1) comprising a thin continuous strip foil of low conductivity overlaid with numerous electroplated patches of copper coatings of high conductivity. It has been recognized [6] that when the plated portions are located in a temperature gradient between a heat source region and a heat sink region a number of thermocouple junctions operating at the coating boundaries are interconnected in series. If such a thermopile, immersed in a fluid, is operating without electric current flowing through it, the junction points are kept at the fluid temperature. If the fluid temperature is uniformly distributed in space, the temperature difference between each couple of junctions points is equal to zero and so is the output voltage measured between the ends of the continuous foil strip.

Let us now assume that a very low current has been flowing through the circuit, generating the Joule effect for a sufficiently long time to reach thermal equilibrium. On account of the difference between the conductivities of the superimposed metallic materials most of the current will pass through the electrodes placed in parallel with the poorly conducting support. Since the part of the current that enters and leaves the poorly conducting continuous foil strip passes near the junction points and near the electrode ends, heating and cooling effects by the Peltier effect (as low as 12 μW for a current of 1 mA) alternately localized at the junction points take place.

At the initiation of the electric current, temperature differences ΔT are then developed between each couple

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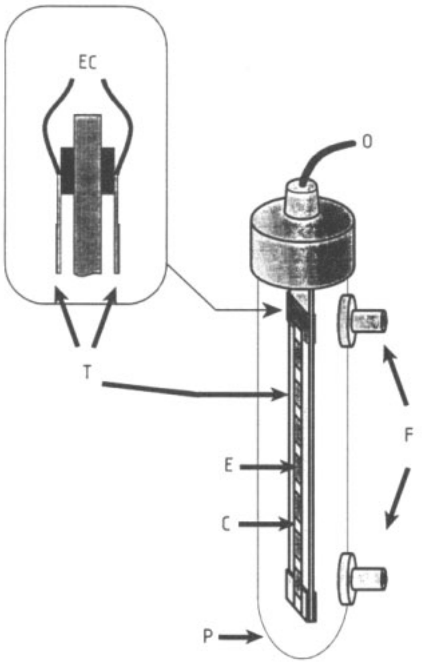

Figure 1. Schematic view of the cell used for thermal conductivity measurements. O, output coaxial cable; F, fluid supply/discharge tubes; P, Pyrex tube; C, continuous constantan support; E, plated electrode; T, folded thermoelectric strip; EC, electrical connections.

of junction points giving thus a Peltier EMF depending directly on the thermal resistance between the junction points. Consequently, any change in the thermal resistance between the junction points is directly converted into a proportional change in the Peltier voltage. Since the thermal resistance between two consecutive junction points is directly influenced by the fluid acting in parallel with the thermopile material, any change in the fluid heat transmission characteristic will be directly converted into electric voltage which may be used to measure it. To perform measurements based on the Peltier effect, it is essential that any change in the heat transmission characteristic of the fluid can operate a change in the part of Peltier heat conducted in the thermopile material from the hot to the cold junction. In other words, any decrease in the heat transmission characteristic of the fluid will decrease the part of Peltier heat removed through convection into the fluid from the junction points. Moreover, since heat generation by the Peltier effect at the junction points is maintained at a constant rate, a greater part of Peltier heat is conducted from the hot to the cold junction in the thermopile materials, thus developing a greater Peltier voltage.

Conversely, any increase in the fluid heat transmission characteristic will decrease the part of Peltier heat conducted through the thermopile materials and thus give a proportional decrease in the Peltier voltage generated around the thermopile circuit.

In order to obtain high sensitivity to the fluid heat transmission characteristic, which may be increased or decreased around a reference value, it is desirable to select the dimensions and shape factor of the plated electrodes in such a way that the part of Peltier heat conducted from the hot to the cold junction through the thermopile is nearly equal to the part removed through conduction and convection into the fluid in its reference state. Under such circumstances, the thermal resistance of the thermopile between two consecutive junction points is matched to that of the fluid between the same points.

The problem then remaining is to find a method to measure the Peltier voltage occurring in the circuit. When current I flows through the circuit, the actual output voltage is equal to the sum of the ohmic drop due to the circuit electric resistance plus the Peltier voltage.

On account of the electrical resistance temperature dependance, the ohmic drop $R\hat{e}I$ is a random voltage controlled by changes in the average temperature of the circuit. The magnitude of these ohmic drop changes, which are in fact one or two orders of magnitude above the Peltier voltage to be measured, renders its direct extraction from the output voltage quite impossible.

The simplest way to measure the small Peltier voltage independently of the ohmic drop influenced by the temperature of the circuit is to remove the current I suddenly and to measure under open circuit conditions the initial value of the voltage delivered by the thermopile. Since the temperature difference between the junction points cannot change its value instantaneously, this output voltage is equal to the Peltier voltage which was superimposed to the ohmic drop just before the circuit was opened.

A block diagram of the electronic circuit which was used for the operation of the sensor was described previously [3] and is used

(i) to pass an electric current through the sensor in order to generate quasi-steady temperature differences between the electrode ends, and

(ii) to cancel that current and connect the measuring circuit to the sensor in order to measure rapidly the output voltage just after the current is off.

A sequence of data points, which represents the Peltier voltage, is thus obtained. It is the sum of the temperature differences taking place on the bimetallic sensor as it varies with time. The problem that remains now is to relate that Peltier voltage to a heat transmission characteristic of the fluid, that is to the thermal conductivity for a fluid at rest and to the mass flow rate for a fluid flow.

The theory governing such a thermal sensor is complex and only a numerical solution of the equations may be obtained. Since the present paper deals with application of the sensor, our investigation will be limited to explaining the physical principles of operation.

3. Application for measuring the thermal conductivity of a fluid

There are many methods available for the measurement of the thermal conductivity of a fluid. In the case of gases this is usually accomplished by passing the gas through a cell containing fine wire grids through which an electric current is passed. The grid is made of a metal which exhibits a specific temperature/resistance characteristic. Since each gas has its own thermal conductivity, changing the gas in the cell will change the grid temperature slightly, thereby causing a change in the grid resistance. In the case of a liquid, the transient hot wire technique has become the most widely used technique for determining the thermal conductivity [5]. It involves electrical heating of a thin wire immersed in the liquid and the determination of the thermal conductivity from the temperature rise of the wire (which is usually determined from its resistance). In all thermal sensors the goal is to measure heat losses depending on the fluid thermal conductivity and it is the temperature of a thermally sensitive resistor that yields the response. It may be noted that if the temperature of the fluid (liquid or gas) changes, the zero point of the resistor changes.

On the other hand, when using a Peltier sensor (i.e. a thin wire covered with numerous plated electrodes), positive and negative heat losses are supplied in the fluid medium by the thermoelectric heater whose average temperature is maintained equal to that of the fluid. The important difference with usual thermal sensors is that any change in the fluid thermal conductivity, directly related to the heat losses into the fluid is not measured from the average temperature of the circuit. As a result, when a Peltier sensor is dipped into a given fluid there is no change in the output voltage when its average temperature varies. In the first series of measurements, two Peltier sensors (labelled 1 and 2 in figure 2) were immersed in several liquids and gases taken as references for their thermal conductivities (nitrogen, carbon dioxide, helium, trichloroethylene, methyl alcohol) given in table 1. The measured data are shown in figure 2 plotted against the fluids' thermal conductivity. The current through the sensors was maintained at 20 mA. From the data curve it clearly appears that any change in Peltier voltage corresponds to a change in the fluid thermal conductivity and can be used to measure it when the calibration curve is known. Whatever the electrical current intensity in the range 0–100 mA, the ratio of Peltier voltage to current intensity was found to be constant. The value from which the thermal conductivity is determined is not affected by Joule heating of the sensor. Because of the high thermal sensitivity of such thin thermoelectric circuits, the input energy can be very small. When operating the sensor at constant current, the dissipated power was as low as 10 mW and the measured average temperature rise of the sensor less than 0.1 °C.

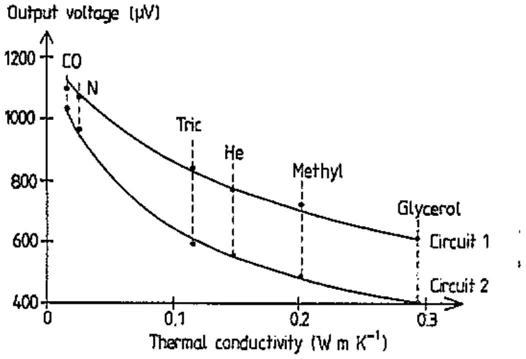

Figure 2. Calibration curves giving the output voltage against the fluid thermal conductivity for a given current of 20 mA through the thermopile. For the Peltier element labelled 1, the constantan thickness was 7.8 μm, the electrode thickness 1.25 μm, the electrode length 1.45 mm, the spacing between them 1 mm, the width 0.63 mm. For the Peltier element labelled 2, the constantan thickness was 10 μm, the electrode thickness 1.8 μm, the electrode length 2.95 mm, the electrode spacing 2 mm, the width 0.55 mm. Curves show calculated results, full circles are experimental results. Tric, trichloroethylene; methyl, methyl alcohol.

Despite the low-power requirement, the Peltier sensor has an extraordinarily wide measurement range. The measurements ranging from 0.016 W mK^{-1} to over 0.3 W mK^{-1} could be obtained with only one sensor and its calibration curve. As we can see on the calibration curve the same sensor may be used for measurements in liquids as well as in gases. The lower limit was set by the reference gas and not by any intrinsic limit of the device. It has the widest range of any thermal device described up to now. It should be noted that such a Peltier sensor has a very low electrical resistance and gives a good signal-to-noise ratio (SNR). The overall observed RMS noise level did not exceed 1% of the output voltage at any thermal conductivity.

The purpose of varying the number of elements, the plated coated length, and the metallic layer thickness, while maintaining constant the thermopile length at 174 mm and input power at 10 mW, was to show the interest of determining optimized dimensions of the thermoelectric circuit in order to match the thermal resistance of the circuit to that of the fluid. From the comparison of the data obtained with circuits labelled 1 and 2, it clearly appears that a greater sensitivity to the change in thermal conductivity in the range (0.05–0.15 W mK^{-1}) was obtained by using circuit 2.

In practice, the thermoelectric strip was protected with a non-metallic coating on its lateral surface for use in corrosive fluids and mounted in a Pyrex tube containing the fluid. To avoid thermocouple effects as much as possible, the constantan output connections welded to the output copper wires were maintained at the same temperature by thermal contact with a highly thermal conducting plate.

Folding the thermopile strips into two equal parts along the axial direction of the tube gives a symmetrical configuration having the advantage of cancelling Seebeck voltages generated by temperature differences occurring in the axial direction of the fluid (and thereby allowing measurements even if the fluid temperature is not uniform).

3.1. Specific temperature effect

Since positive and negative heat losses are generated around the average temperature of the sensor which is equal to that of the fluid, there must be no change in the output voltage when the sensor is immersed in a fluid whose temperature varies. In fact, there is a small temperature dependence of the Peltier heat generation and its temperature compensation is of importance when measuring a change in thermal conductivity in a fluid whose temperature varies.

The simplest approach for temperature correction is to measure the circuit temperature separately and correct the data by referring to a family of calibration curves taken at different temperatures for a given fluid. On account of the small temperature dependence of the copper–constantan thermocouple, corrections are generally small. The measured change in output voltage as a function of temperature was observed to be linear and does not depend on the thermal conductivity of the surrounding fluid.

Since the output voltage delivered by a Peltier sensor depends mainly on the thermal conductivity of the surrounding fluid and slightly on the temperature, the simplest approach for temperature compensation consists in associating another Peltier element of very low sensitivity to the fluid conductivity, comprising, for example, platings of reduced length. This second device is used to regulate the current in the measuring Peltier element whose output is highly influenced by the fluid conductivity.

For such a compensation, the current in the element of low sensitivity is maintained constant and the current through the measuring device is controlled by an electronic circuit which equalizes the Peltier voltages at the terminals of the two Peltier elements. Therefore, any change in the fluid conductivity decreases the output voltage and is immediately corrected by an increase or decrease in the current through the sensitive element. The output of the regulated system is the voltage which is required to drive the necessary current through the element of high sensitivity. Since the output voltage generated by the Peltier element of low sensitivity is dependent on temperature, as is Peltier heat generation, the feedback makes the temperature compensation automatic. Calibration curves with temperature as the parameter are therefore not needed for thermal conductivity measurements.

When compensating the temperature dependence of the sensor it was observed that previous calibration curves were not dependent on fluid temperature in the range 20–70 °C.

Table 1. Thermal conductivity of fluids at 25°C.

Fluids	λ (W mK^{-1}) (20 °C)	Output voltage (μV)			
		Circuit 1		Circuit 2	
		Exp.	Calc.	Exp.	Calc.
Carbon dioxide	0.0159	1101	1126	1036	1024
Nitrogen	0.0255	1072	1080	966	947
Trichloroethylene	0.116	832	830	596	608
Helium	0.149	767	773	555	549
Methyl alcohol	0.202	716	701	488	481
Glycerol	0.294	610	609	402	403

4. Application for measuring mass flow

From the previous results it can be seen that sensors based on the Peltier effect are sensitive devices and are ideal for measuring small changes in thermal conductivity. These initial results were sufficiently promising for additional studies to be undertaken to explore the influence of a flow on the Peltier sensor response. Since the fluid flow influences the fluid heat transfer characteristic, a change depending on the flow is expected in the sensor response. For such an application, the thermoelectric circuit was mounted on the centre of a rectangular flow tube (figure 3). As previously shown in the absence of fluid flow, the output voltage V_0 takes a reference value (zero flow value) depending only on the fluid thermal conductivity. When a flow is induced, there is a spatial change in the convective heat flow from the lateral surface which depends on the thermal boundary condition on the lateral surface. Thus a change in the temperature difference between the junction points gives a change in Peltier voltage. By measuring the variation $\Delta V = V_0 - V$, a measure of the mass flow can be obtained. The laminar or turbulent character of the flow is thus an important factor in evaluating the response of flow device. On account of the fluid properties used for experiments (nitrogen, air, carbon dioxide, helium) and the hydraulic diameter of the pipe, turbulent flow was barely reached in the flow measurements.

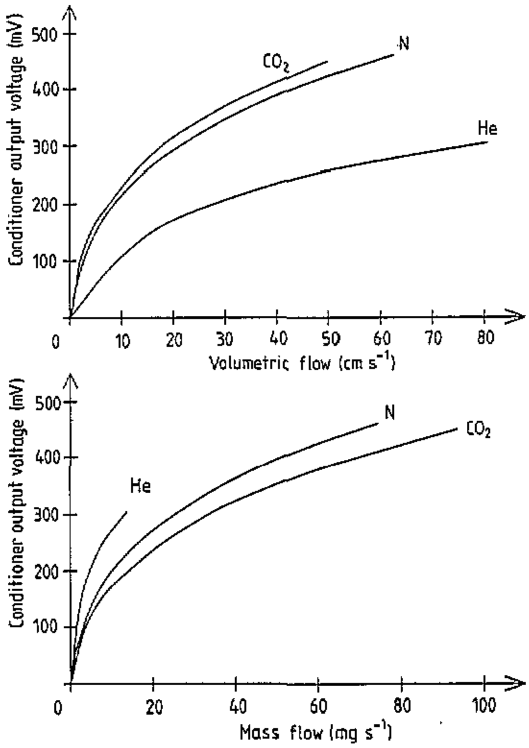

Figure 3. Calibration curves in several gases at constant temperature. $I = 20$ mA, $T = 21$ °C.

4.1. Typical calibration characteristics

A first consideration that might affect the response is the orientation of the device in the tube. The turbulence caused by the device not being aligned with the flow lines could change the response slightly. A simple way to obtain a response depending on the total flow in the tube, that is, on the flow velocity averaged on the cross sectional area, is to incline the Peltier element in the form of a V shape in the direction of the flow. A second consideration that might also influence the response is the joule heating of the sensor. Since the heat transfer from the sensor surface to the flow is largest at the upstream side where the flow first encounters the surface, a small temperature gradient is induced over the sensor length giving a small Seebeck EMF which is then superimposed on the Peltier response. However, since that small additional flow-induced EMF is sensitive to the flow direction (it changes in polarity when the flow is reversed) it will be cancelled in a sensor configurated in the form of a V. Consequently no matter how the sensor is positioned in the flow pipe, the Peltier element will give a response which is not sensitive to the flow direction.

In the first series of measurements at constant temperature, the Peltier sensor was mounted in a 0.3 cm^2 cross sectional rectangular pipe that was connected to a reference flowmeter. The reference volumetric flow-rate was measured by a soap film burette of appropriate size which is the best known primary standard for gas flow measurements [6]. The data points for the corresponding mass flows were obtained by multiplying the volumetric flow by the gas specific gravity at the operating temperature.

Before measuring the flow response, the zero flow output voltage was measured. The difference between that reference voltage and the actually measured output voltage in the presence of flow was offset to zero electronically and used to draw the calibration curves.

Figure 4 shows typical flow rate calibration curves for a Peltier sensor of type labelled 2 in the previous section with a current of 20 mA flowing through it. The calibration curves are nonlinear with maximum sensitivities at low flow rates decreasing towards high flow rates. Very small flow rates can then be measured with high accuracy with the advantage, as compared with capillaries commonly employed, of having a very low-pressure drop between the ends of the pipe (of the order of a few millbar). A significant advantage of the nonlinear output characteristic is the ability to make measurements over a wide range of flow rates while maintaining a nearly constant 'percentage of reading' accuracy. By changing the gas pressure in the sensor over the range (0.01–1 bar) while maintaining constant the flow rate measured by the reference flowmeter, it was shown that the output as well as the calibration curves were interchanged and not dependent on the gas pressure. Because of the large changes in volumetric flow induced by the pressure variations, it clearly appears that the fundamental measured variable is the mass flow rate. The volumetric flow may also be obtained whenever density is constant.

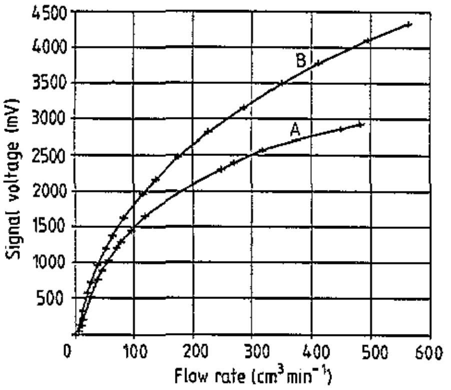

Figure 4. Effect of the compensating circuitry on the calibration curve. Curve A, the current is maintained constant in the flow sensitive Peltier element; Curve B, the current is maintained constant in the Peltier element of very low sensitivity.

This result may be interpreted from the available results on gas properties, since the heat transmission characteristic of fluid exhibits a very small pressure dependence in the range (0.01–1 bar). From this result, such a Peltier sensor is ideal for measuring a mass flow independently of pressure and temperature changes.

From experimental results it has been shown, as in thermal conductivity measurements, that electrode dimensions can be calculated to obtain high sensitivity in a given range of flow around a reference value (zero flow value).

To make an optimized sensor, that is to obtain a wide flow range with a given device, electrodes of differing lengths may be associated on the same continuous support.

To compare the new Peltier sensor with other mass flow sensors we use sensitive elements in the form of thin wires of 0.025 mm in diameter covered with electrodes of 3 mm in length and with a spacing of 1 mm between them. Such a sensitive element of 170 mm in length is mounted in a V shape in a cylindrical flow tube, together with a similar element of much lower sensitivity for temperature compensation.

4.2. Control circuit

Since Peltier elements must be controlled with an electronic circuit the basic performance parameters depend on its function and operation. The temperature compensation system used two sensors as described in the previous part. Two differing calibration curves can be obtained when a current is maintained constant through the Peltier element of low sensitivity or through the flow sensitive Peltier element.

Let us first consider the case where the current is maintained constant through the flow sensitive element. As the fluid velocity through the device increases, the terminal Peltier voltage tends to decrease. Since with the feedback control, the output voltage of the two Peltier elements are maintained equal, any increase in the fluid velocity will be immediately corrected by a decrease in the current through the Peltier element of low sensitivity. The output is then the voltage which is required to decrease the current through that reference sensor and the calibration curve obtained against flow rate is labelled A in figure 4. In the high-flow range, as the velocity increases the Peltier elements tend to cool with a resulting decrease in the Peltier heat generation. Since the negative feedback which is required for temperature compensation decreases when the flow is increased the major drawback of that system is decreasing sensitivity toward the high flow rates.

The system with a constant current through the Peltier element of low sensitivity overcomes the disadvantage mentioned above. As the flow velocity over the Peltier element increases, the output voltage generated by the flow sensitive element tends to decrease. Therefore, with the feedback control any decrease in Peltier voltage will be immediately adjusted by an increase in the current through the Peltier element sensitive to the flow. The output is the voltage required to drive the current in that Peltier element. With that regulating system the negative feedback proportional to the current flowing through the sensitive element is increased in the high flow range and results in a sensitivity increase in the high flow range (curve labelled B in figure 4). Moreover, since the cooling induced in the high flow range tends to decrease the temperature change produced by the current increases in the sensitive element, such a system can be regarded as a self-regulating system. Consequently, when comparing the two types of control system, it appears that maintaining constant the current through a low-sensitivity Peltier element is a more practical approach for mass flow rate measurement.

Despite the low power requirements as discussed above, such a Peltier system has a very wide measurement range. The measurements in the 0.3 cm^2 cross sectional area tube showed an air–gas flow ranging to well over 0.5 l min^{-1} could be obtained. The overall observed RMS sensor noise level in the low-flow range (lower than 0.2 l min^{-1}) did not exceed 0.5% at any flow level. With the onset of turbulence in the higher flow range the noise slightly increased. These instabilities appear to be a result of fluctuation in the flow itself. The reproducibility at any given flow level was well within the precision of the TSI model 2231 which could be used as a reference standard.

5. Dynamic response

Another important characteristic of a flow sensor is its dynamic response. This was measured using a system in which the gas flow could be controlled so that the flow originally equal to zero was then abruptly established through the Peltier sensor. The response time defined as the time to reach full scale is approximately 25 ms. Since electronic circuitry time response was lower than 1 ms, this suggested that the measured response was due to the sensor. The inherent speed of a Peltier element is very high since it responds to changes in heat transmission characteristic of the fluid and not to temperature itself.

6. Conclusion

This study demonstrates that the Peltier sensor is a very sensitive and versatile flow sensor, giving a zero flow output depending on the fluid thermal conductivity. The fact that different geometries generate substantially identical flow curves is an attractive aspect of this type of flow sensor. It suggests that the prospect for highly reproducible manufacture of this device is good. The reproducible at any given flow level suggests that the Peltier sensor has interesting applications as a transfer standard in the detailed calibration of flow sensor against a well defined standard.

References

[1] Bruun H H, Khan M A, Al Kaijien H H and Fardad A A 1988 Velocity calibration relationships for hot wire anemometry *J. Phys. E: Sci. Instrum.* **21** 225–32

[2] Oudheusden B W 1990 Silicon thermal flow sensor with a two dimensional direction sensitivity *Meas. Sci. Technol.* **1** 565–75

[3] Leclercq D, Wattiau F and Thery P 1989 Procédé et dispositif utilisant les effets thermoélectriques pour la mesure d'une grandeur physique dont la variation est apte à modifier les propriétés thermophysiques d'un milieu *French Patent* 8916809

[4] Leclercq D 1991 Contribution à l'étude de l'effet Peltier dans les circuits bimétalliques à électrodes plaquées. Application à la conception de nouveaux capteurs. *Thèse de Doctorat* Université de Lille

[5] Herin P and Thery P 1992 Measurements on the thermoelectric properties of thin layers of two metals in electrical contact. Application for designing new heat flow sensors *Meas. Sci. Technol.* **3** 495–500

[6] Knibbe P G 1987 An accurate instrument for fast thermal conductivity and thermal diffusivity measurements at elevated temperature and pressure *J. Phys. E: Sci. Instrum.* **20** 1205–11

[7] Hobbs J M 1987 Variable area and pressure difference flowmeters *J. Phys. E: Sci. Instrum.* **20** 10–7