33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

A vapor pressure thermometer for use in muscle microcalorimetry

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***Abstract*—Measurement of the energy consumption of isolated cardiac trabeculae requires highly sensitive temperature sensors. In this paper we describe and characterize an initial prototype of a vapor pressure thermometer being designed and built for application to muscle microcalorimetry. The device exploits the change in vapor pressure with temperature of a solvent and the change in pressure with volume of a gas. The sensor achieves a sensitivity of 86 µm/K and a resolution of 3.6 µK. Predictions from a finite element model of the expected displacement compare favorably with the tests performed.**

I. Introduction

Cardiac muscle liberates heat as it performs work due to imperfect chemo-mechanical energy conversion. Measurement of the heat liberation, combined with measurements of mechanical properties, provides valuable insight into the thermodynamics of muscle contraction.

The Auckland Bioengineering Institute has produced a micromechanocalorimeter that allows simultaneous measurement of thermal and mechanical events. The temperature increase of a fluid flowing over the muscle is measured and used to infer the heat output. Experiments are performed on rat right-ventricular trabeculae (≈2 mm long × 200 µm in diameter) as their small diameter allows sufficient oxygen to be obtained from diffusion alone [1]. The trabeculae's small size means that the rate of heat production is small (≈10 µW), as is the resulting temperature change of the fluid (≈1.6 mK) [2].

Currently, thermopiles are used to measure the temperature change. These thermopiles have a temperature resolution of 5 µK [2]. It is of interest to improve the ability to infer energy consumption, and so a thermometer with a higher resolution is desired. A novel thermometer that operates on the principle that a change in temperature of a solvent changes its vapor pressure is to be created

This article reports on an initial prototype that has been designed and constructed, pictured in Fig. 1. This device is a single-sided sensor that uses a multispecies gas phase to transduce temperature.

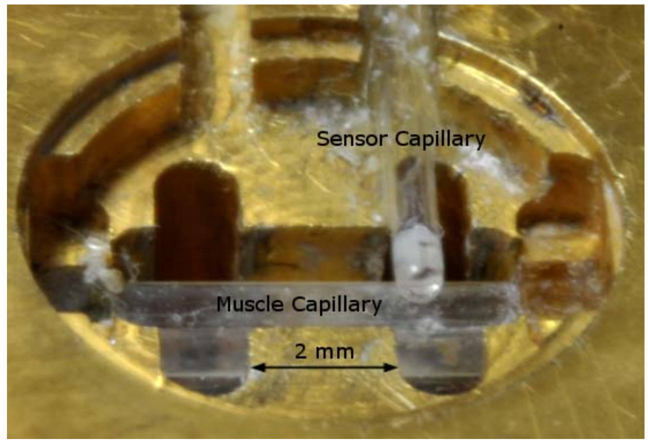

Fig. 1. Vapour pressure sensor integrated into the muscle micromechanocalorimeter.

II. Vapor Pressure

The *modus operandi* of the thermometer exploits the change in vapor pressure of a solvent with temperature. The vapor pressure of a substance is the partial pressure of the gas phase when the system is in equilibrium – i.e., when the rate of evaporation (a function of temperature) equals the rate of condensation (a function of pressure) [3]. This allows temperature to be inferred from measurements of pressure.

The relationship between pressure and temperature corresponds to the liquid-vapor coexistence curve on a phase diagram. The gradient of this curve may be described by the Clausius-Clapeyron relation (1), where P is the pressure; T is the temperature; Δh is the difference in enthalpy between the states and R is the ideal gas constant [3].

$$dP/dT = P\Delta h(T,P)/T^2R \quad (1)$$

Equation (1) is not used in practice, due to difficulties integrating it. Instead, equations formulated experimentally are used. Reference [4] gives the Korea thermophysical properties data bank (KDB) correlation equation, (2). A, B, C and D are material-dependent constants.

$$\ln(P) = A\ln(T) + B/T + C + DT^2 \quad (2)$$

The sensitivity of any vapor pressure thermometer depends on the change in pressure with temperature of the

Manuscript received April 14, 2011. This work was supported by the University of Auckland FRDF and VCSDF funds.

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978-1-4244-4122-8/11/$26.00 ©2011 IEEE

solvent used. There are four requirements for the substance. It must:

1. be solid or liquid at operating temperature (25 °C);
2. have a large change in pressure with temperature in the range of interest; and
3. have a low specific heat.

It is also preferable that the substance is safe to work with. Examination of Fig. 2 gives an indication of gradient (requirement #2). The four substances that are liquid at room temperature and have the highest gradients are dichloromethane, chloroform, methyl formate and diethyl ether.

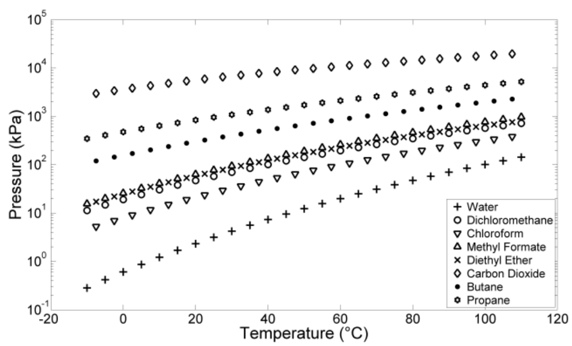

Fig. 2. Vapor pressure versus temperature for a range of substances.

The gradient for each of the four substances was calculated at 25 °C. The gradient, the specific heat, the ratio between the two, and the safety rating are shown in table 1 (4). Dichloromethane has been chosen for use in our sensor as it has the highest ratio of gradient to specific heat in addition to the lowest hazard level.

TABLE I
COMPARISON OF SOLVENTS

Substance	Gradient (kPa/K)	Specific Heat (kJ/(kg.K))	Ratio (Pa.kg/J)	Hazard Level
Dichloromethane	1.96	1.21	1.62	Moderate
Chloroform	0.95	0.98	0.97	High
Methyl Formate	2.63	2.06	1.27	Extreme
Diethyl Ether	2.34	2.32	1.01	Extreme

III. Design and Methods

Our thermometer (Fig. 3) comprises a 12 mm long, circular, borosilicate glass tube with an internal diameter of 0.6 mm. One end of the glass tube is sealed using an Arizona Hydrogen Flame Generator.

The glass tube is mounted on the microcalorimeter. The tube is then filled using a Hamilton syringe. Approximately 1 µl of dichloromethane liquid is injected first. Water is then injected 2 mm from the dichloromethane to 0.5 mm from the tip of the tube. The water serves to isolate the dichloromethane and enclose the gas layer. Oil (3-in-one lubricant oil) is then injected at the surface of the water to the very end of the tube. The oil acts as a reflective surface for the laser interferometer, as well as preventing evaporation of water. Oil must be prevented from coming in direct contact with the dichloromethane section as the two are miscible. When filling, it must be ensured that no gas bubbles are present between the water and oil segments.

Fig. 3. Sensor showing its different segments (not to scale).

Displacement of the meniscus of the oil segment is measured using a laser interferometer (Agilent 5517D). Focusing of the laser beam onto the meniscus was performed using a Nikon 4×, infinity-corrected objective lens mounted on a Linos three-axis, microbench stage.

Data were acquired and analyzed using software written in National Instruments LabVIEW 2009. Further analysis was performed using MATLAB R2009a.

Characterization was performed using a heater element (1 kΩ surface mount resistor) placed in the middle of the glass tube where the muscle would normally be located. Heat is produced as a result of a signal from a waveform generator (Agilent 33220A).

A combination of equations and finite element modeling was used to gain an improved understanding of the system and to predict the characteristics of the sensor. A model of the muscle tube, the heater, the sensor tube and the heat-sink compound thermally connecting them, as well as the dichloromethane liquid phase, was created in SolidWorks 2009. The model was imported into ANSYS and transient thermal analysis was performed. This model allowed the thermal impact and the expected temperature change at the dichloromethane liquid-vapour interface to be estimated. This, combined with analytical equations, provided a prediction of the expected movement of the oil meniscus for different heat pulses or filling volumes.

IV. Results

To characterize the temperature sensor, the muscle tube was filled with water. The heater element was placed within the center of this tube. This heater element was driven by a 1 mW square wave with a period of 40 s.

A. Thermal Impact

The thermal impact of the sensor was assessed through modeling. Heat was produced within the heater unit. The final temperature of the heater unit was then compared with and without the sensor present. The thermal impact was found to be negligible; the temperature reached differed by only 0.62% when the sensor was present.

The difference in temperature distribution can be seen in Fig. 4. Examination of Fig. 4 shows the distribution of temperature is similar with differences occurring only directly below the sensor.

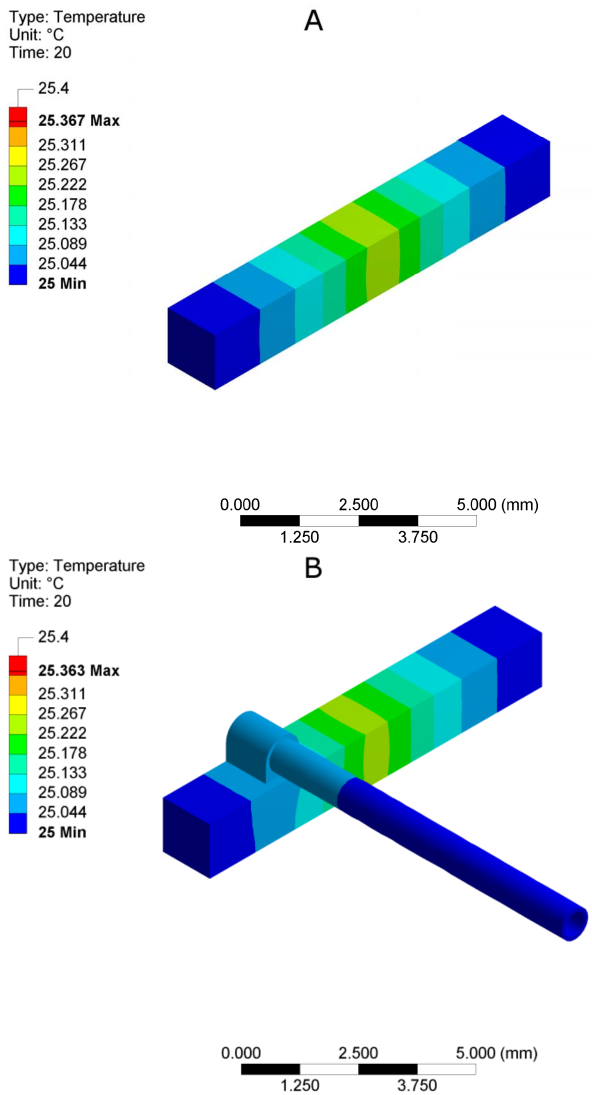

Fig. 4. Finite element model of the temperature distribution without a sensor present (A), and with a sensor present (B).

B. Displacement Modeling

Finite element modeling was used to predict the change in temperature of the dichloromethane liquid-vapour interface. A 1 mW rate of heat production over 20 s led to a change in temperature of 0.258 K at the surface of the dichloromethane liquid.

Combining (2) with the ideal gas law, and knowing the size of capillary tube, allows the change in meniscus position to be predicted resulting from a change in temperature. This gives (3) where Δd is the change in meniscus position in metres and l is the initial length of the vapour segment in metres.

$$\Delta d = \Delta T(0.0572l - 7 \times 10^{-12}) \quad (3)$$

This change of temperature gives an expected displacement of 39.1 µm. However this does not take into account the oil, which is located at the tip of the tube. The effective radius is the external diameter of the tube (0.84 mm). The expected displacement is therefore multiplied by the square of the ratio of inner diameter to outer diameter (0.549). The expected displacement is thus 21.5 µm.

C. Sensitivity and Resolution Measurements

A 1 mW square wave with a 40 s period was the input to the heater element. There was no fluid flow so heat accumulated within the system. A high-pass filter with a cut-off frequency of 0.3 mHz was used in LabVIEW to remove the effect of heat accumulation. Fig 5 shows the resulting output.

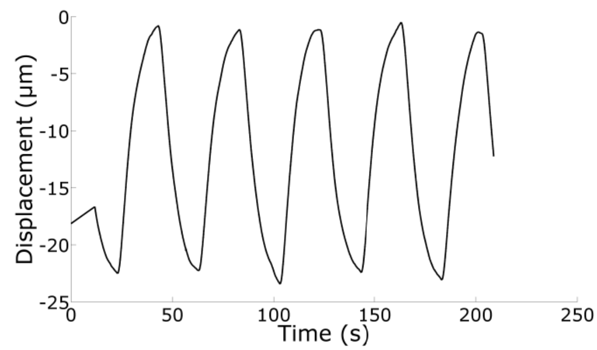

Fig. 5. Displacement of oil meniscus over time with 1 mW, 40 s period square wave input.

The displacement resulting from a 20 mJ heat pulse is approximately 22.2 µm; the heat sensitivity is thus 1.1 mm/J. The change in temperature at the surface of dichoromethane is 0.258 K (as found from modeling). The temperature sensitivity is thus 86 µm/K.

The resolution of the heterodyne interferometer used was 0.31 nm. The heat and temperature resolution are 0.28 µJ and 3.6 µK, respectively.

The position noise of the interferometer was measured over 10 minutes and found to have a standard deviation of 3.8 nm over a 1 Hz bandwidth. The position noise limits the minimum resolvable heat and temperature measurement. The noise-equivalent heat and noise-equivalent temperature resolutions with the hood lowered are 3.5 µJ and 44 µK, respectively.

V. Discussion

Modeling and measurement have been undertaken for the case where there is no flow in the muscle capillary. Modeling without flow has been found to enable accurate prediction of the expected displacement (within 3.2%). Prior to application to the working microcalorimeter, tests of the sensitivity and noise levels must be performed in the presence of flowing fluid.

In comparison to the thermopiles currently employed in our calorimeters, this sensor has a poorer effective resolution due to the noise present in the system. The thermal impact of the sensor design is also greater. The thermopiles are not in contact with the muscle capillary; thus they have negligible thermal impact [6].

VI. CONCLUSION

A temperature sensor with negligible thermal impact has been created. The sensor transduces temperature via its effect on vapor pressure. Modeling accurately predicts the expected movement of a meniscus resulting from a temperature change.

The current device uses multiple chemical species; work is currently proceeding on development of a single-species device with an improved noise-equivalent temperature.

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