Thermoelectric Cool-Film Shear Stress Sensor

Jonathon Oiler, *Student Member, IEEE*, Rui Tang, *Student Member, IEEE*,
Teng Ma, *Student Member, IEEE*, and Hongyu Yu, *Member, IEEE*

***Abstract*— Hot-wire anemometers, being a robust and highly sensitive method for measuring flow properties, can be limited in sensitivity where locally increasing the temperature may induce measurement inaccuracy such as when used in near-boiling fluids. In this environment, locally decreasing the temperature allows for a larger temperature difference between the sensor and the ambient environment, thereby increasing device sensitivity while maintaining single-phase convection heat transfer physics. In this letter, we present the new capability of using thermoelectrically cooled sensors to measure wall shear stress. The power required to maintain a constant sensor temperature was increased as the wall shear stress in the channel was increased, providing proof of concept.**

***Index Terms*— Shear stress sensor, flow sensor, thermoelectrics.**

I. Introduction

ONE OF THE main methods for measuring fluid shear stress using micro-sensors is thermal anemometry. The advantages of this sensing technique are simplicity in fabrication, robustness due to an absence of moving parts, high sensitivity, and the capability of measuring time-varying flows [1]. Typically, the operating principle is based on convective cooling of a heated temperature-sensing resistor as fluid flows over its surface. However, for heated sensing elements used in fluids at near-boiling temperatures that may vary in time, the heat energy generated by the resistor may periodically evaporate the liquid at the sensor surface, forming gas bubbles. When the bubbles form, the fluid becomes a two-phase mixture and the heat transfer physics change as the bubbles transport the latent heat of the phase change and increase convective heat transfer by agitating liquid near the sensor surface [2]. Bubble generation has been identified as one of the primary difficulties for operating hot-wire anemometers in liquid environments [3].

To prevent operation in both single-phase and two-phase heat transfer conditions, the temperature difference between the resistor and ambient environment would need to be severely limited in order to prevent boiling the fluid and thus decreasing measurement accuracy and in some conditions this may not even be possible. Reducing the temperature difference would decrease the measurement sensitivity. In addition, for *in-vivo* biomedical flow measurement applications, prolonged localized heating from a heated resistor may cause damage to cells or tissue [4]. Therefore, a cooled-film thermal anemometry idea has been developed and demonstrated in this letter which enables near-boiling temperature measurement and a reduction in bio-related risk in biomedical applications.

In near-boiling liquid environments, a sensor that measures flow properties through cooling rather than heating would ensure single-phase heat transfer physics and therefore maintain an accurate measurement of shear stress and allow for increased measurement sensitivity due to a larger possible temperature difference. In this case, the fluid can be actively cooled through use of thermoelectric cooling [5]. We present the physical explanation and experimental results from testing this new technique for measuring fluid shear stress using a micro temperature sensor and commercial thermoelectric cooler (TEC).

Thermoelectric cooling is governed by the Peltier effect to turn electrical energy into thermal energy by pumping heat from one area to another under a voltage differential. Thermoelectric coolers are inefficient and are best suited for cooling smaller objects to avoid a large consumption of power [6] and therefore are an ideal choice for this application. The thermoelectric cooling process is governed by:

$$q_1 = ST_c I - K\Delta T - \frac{1}{2} I R^2 \tag{1}$$

where q_1 is the heat energy transferred from the cold side per unit time, S is the Seebeck coefficient of the TEC, T_c is the temperature on the cold side of the TEC, I is the input current, K is the device thermal conductance, ΔT is the temperature difference between the hot and cold side of the TEC, and R is the electrical resistance of the TEC [7]. The first term in the equation represents the Peltier cooling, while the second term represents the negative effects of conduction from the hot side to the cold side of the TEC, and the third term represents the negative effects of joule heating in the device.

The single-phase heat transfer physics between the fluid and a surface are the same whether the fluid is actively heated or cooled. The temperature difference between the TEC cold surface and the ambient fluid drives the heat transfer. In a flowing fluid, convective heat transfer dominates [8] and is

Manuscript received March 19, 2014; revised April 9, 2014 and April 13, 2014; accepted April 24, 2014. Date of publication May 13, 2014; date of current version June 24, 2014. The review of this letter was arranged by Editor A. Flewitt.

J. Oiler was with the School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287 USA. He is now with Space and Naval Warfare Systems Center–Pacific, San Diego, CA 92152 USA (e-mail: joiler@asu.edu).

R. Tang and T. Ma are with the Fulton College of Engineering, Arizona State University, Tempe, AZ 85287 USA.

H. Yu is with the Fulton College of Engineering, Arizona State University, Tempe, AZ 85287 USA, and also with the School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287 USA.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2014.2320976

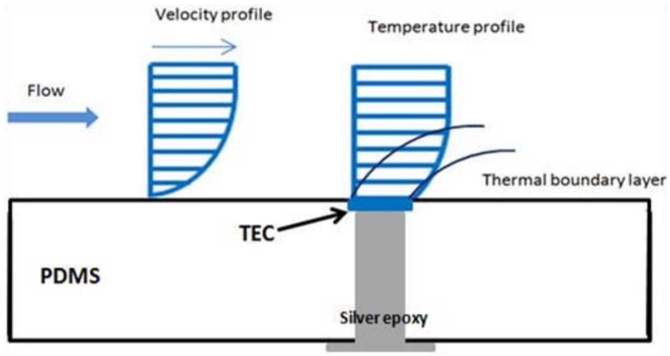

Fig. 1. Schematic diagram showing fluid moving across bottom of flow channel with exposed cold side of TEC. The velocity profile shows the shape of the velocity boundary layer and the thermal profile shows shape of the thermal boundary layer.

governed by:

$$q_2 = hA\Delta T \tag{2}$$

where q_2 is the heat energy transferred per unit time, h is the convective heat transfer coefficient, A is the surface area of the TEC, ΔT is the temperature difference between the bulk fluid and the TEC cold surface, which in this case is negative, indicating the direction of the heat transfer from the warmer fluid to the colder TEC. The convective heat transfer coefficient carries the information about the velocity of the flow and its equation is generally given as:

$$h = a + bv^c \tag{3}$$

where v is the velocity of the flow, and a, b, and c are ambient specific, empirically determined constants characterized through calibration. The flow velocity is proportional to the volumetric flow rate of the fluid and the flow rate through the rectangular calibration channel is related to wall shear stress by:

$$\tau = 6\mu \frac{Q}{L^3} \tag{4}$$

where τ is the wall shear stress, μ is the dynamic viscosity of fluid, Q is the volumetric flow rate and is proportional to the flow velocity, and L is the length of a side of the square cross-section flow channel [9].

II. Experiment

A 2.4 mm by 2.4 mm TEC (TE Technology) was embedded in a PDMS substrate used as the bottom of a flow channel such that the cold surface of the TEC was exposed to the flow at the bottom of the calibration channel. The hot surface of the TEC was inside the low thermal conductivity PDMS. A hole was bored through the backside of the PDMS substrate down to the TEC hot surface and filled with silver epoxy (Epoxy Technologies) to create a larger area heat sink to reduce joule heating at higher power operation (Fig. 1).

A micro resistance temperature detector (RTD) was bonded to the cold surface of the TEC using a thin thermally conductive epoxy (Epoxy Technologies) to monitor its temperature. The flexible RTD (fabrication described in [10]) is small (320 μm wide and 21 μm thick), relative to the size of the TEC in order to minimize disturbance of the flow and simulation verified the sensor disturbance was negligible. The sides and top of the flow channel are made of acrylic and bonded to the PDMS substrate such that the TEC is in the middle of the channel (1.1 cm wide by 1.1 cm height) and halfway down the length of the channel so that the laminar flow is ideally fully developed (Fig. 2).

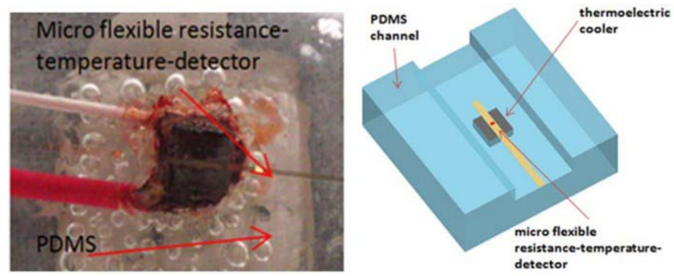

Fig. 2. (left) Image of the RTD sensing element on top of the TEC mounted in the PDMS. (right) Schematic depiction of flow channel setup (not to scale).

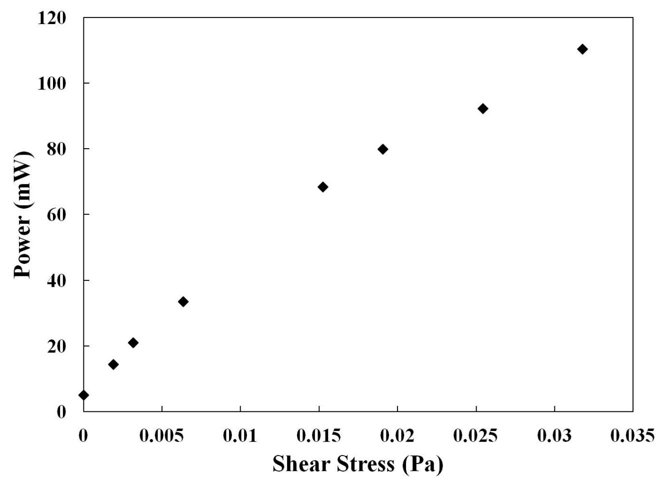

Fig. 3. At constant RTD temperature of 20 °C, an increase in the wall shear stress requires an increase in power to the thermoelectric cooler.

The thermoelectric cooler wires were connected to a variable power source and the RTD wires were connected to a high-precision multimeter. The flow rate through the channel was controlled by a variable speed peristaltic pump (Cole-Parmer). The PDMS substrate and acrylic channel were submerged in water for testing. The temperature coefficient of resistance for the micro RTD was determined through calibration so that resistance measurements from the multimeter could be converted to temperature.

III. Results

In the first test, the temperature of the TEC was maintained at 20 °C (approximately 4 °C below water temperature) using the variable power supply. As the shear stress over the TEC was increased from 0-0.035 Pa, the power needed to maintain a constant TEC surface temperature was increased from 5-110 mW. The data show an approximate linear response of power with increasing shear stress (Fig. 3).

In a second test, the power input to the TEC was maintained at a constant value of 47 mW. As the flow rate over the

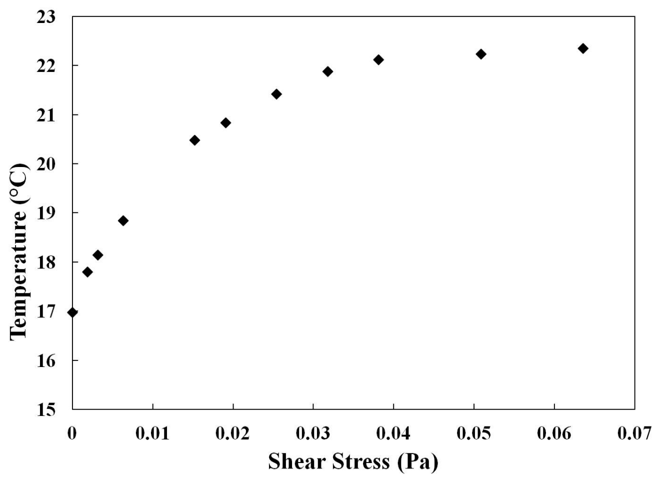

Fig. 4. At constant power input of 47 mW, in low shear stress domain, increasing the flow rate increases the temperature of the RTD linearly. At higher shear stress the slope of response gradually becomes flat.

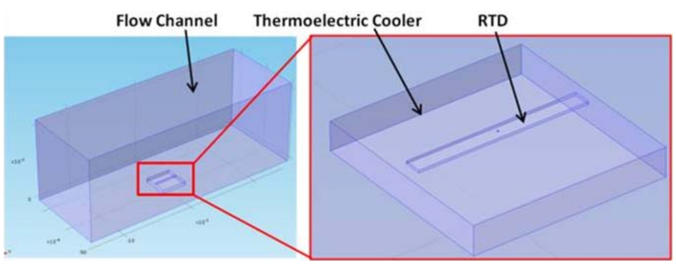

Fig. 5. Screenshot of Comsol 3D model of cooled RTD in flow channel. The RTD sits atop the TEC.

TEC was increased, the TEC temperature increased (Fig. 4). The measurement curve of this test shows saturation at higher wall shear stresses due to the TEC surface temperature approaching that of the water which decreases the thermal convection between the two surfaces and reduces sensitivity. The combined data show that wall shear stress can be measured using a thermoelectric cooler and temperature sensor mounted on the cold side surface. For implementation, the constant temperature technique will provide a more linear response and wider range of operation. However, for any TEC, continually increasing the electrical power will result in increased joule heating and back conduction from the hot side, eventually raising the temperature of the cold side and thus limit the dynamic range.

A 3D model of the experiment was created in Comsol Multiphysics to verify the proposed sensing mechanism (Fig. 5). The cooler was modeled as a ceramic box with a constant top surface temperature ∼10 °C cooler than the ambient fluid. The RTD was placed on top of the ceramic box and was modeled as a 20 μm thick polymer layer with a thin 1 μm thick platinum layer on top. A 1 μm thick thin-resistive-sheet was placed in between the RTD and cooler surface to model the epoxy bond.

Water (at 24 °C) was flowed over the RTD actively cooled from below. The RTD platinum temperature was monitored over different fluid velocities. The comparison between the experiment data at constant power and the model data (Fig. 6)

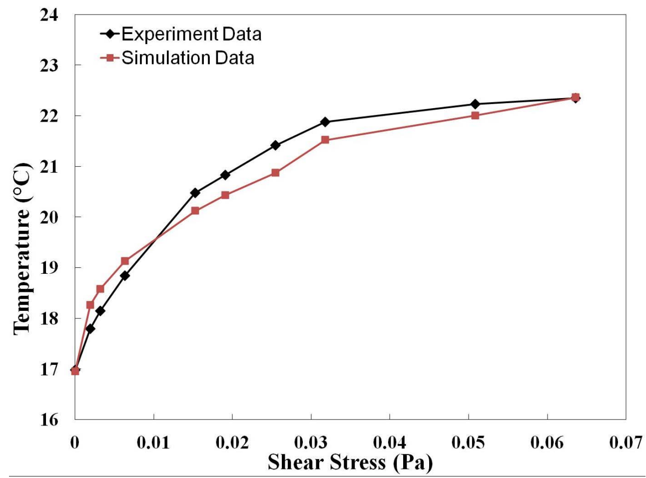

Fig. 6. Comparison between Comsol 3D simulation and experiment.

show relatively similar curve shapes. Differences between the experiment and model are attributed to slight differences in the simulation in terms of modeling the epoxy as a thin-resistive-sheet of no thickness and possible variations between the experimental flow in the channel relative to the ideal laminar flow conditions in the model.

IV. Conclusion

A thermoelectric-based shear stress measurement technique is important for operation in fluids at near-boiling temperatures or those that are sensitive to temperature increases. These results show that a thermoelectric cooler and associated temperature sensor can be used to monitor wall shear stress based on thermal convection principles. Channel size and flow rate were limited by the size of the TEC and peristaltic pump, respectively, so significantly higher shear stress measurements were not possible.

References

[1] Y. Xu *et al.*, "Micromachined thermal shear-stress sensor for underwater applications," *J. Microelectromech. Syst.*, vol. 14, no. 5, pp. 1023–1030, Oct. 2005.

[2] L. S. Tong and Y. S. Tang, *Boiling Heat Transfer and Two-Phase Flow*. Washington, DC, USA: Taylor & Francis, 1997.

[3] M. Melani *et al.*, "Hot wire anemometric MEMS sensor for water flow monitoring," in *Proc. Conf. Design, Autom. and Test Eur.*, Mar. 2008, pp. 342–347.

[4] M. Dewhirst *et al.*, "Basic principles of thermal dosimetry and thermal thresholds for tissue damage from hyperthermia," *Int. J. Hyperthermia*, vol. 19, no. 3, pp. 267–294, Jun. 2003.

[5] J. Oiler *et al.*, "Thermoelectric cool-film flow sensor," in *Proc. IEEE Sensors Conf.*, Oct. 2012, pp. 1–5.

[6] C. Hilbert *et al.*, "Thermoelectric MEMS coolers," in *Proc. 18th Int. Conf. Thermoelectr.*, 1999, pp. 117–122.

[7] G. J. Snyder *et al.*, "Hot spot cooling using embedded thermoelectric coolers," in *Proc. IEEE Semicond. Thermal Meas. and Manage. Symp.*, Mar. 2006, pp. 135–143.

[8] P. Hesketh, B. Gebhart, and J. N. Zemel, "Heat transfer model for the pyroelectric anemometer," *J. Appl. Phys.*, vol. 57, no. 11, pp. 4944–4949, Jun. 1985.

[9] M. G. Angelos *et al.*, "Dynamic adhesion of umbilical cord blood endothelial progenitor cells under laminar shear stress," *Biophys. J.*, vol. 99, no. 11, pp. 3545–3554, Dec. 2010.

[10] H. Yu *et al.*, "Flexible polymer sensors for in vivo intravascular shear stress analysis," *J. Microelectromech. Syst.*, vol. 17, no. 15, pp. 1178–1186, Oct. 2008.