Optical Flow Sensor Based on Thermal Time Constant Measurement

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Abstract— **This contribution presents a novel all-dielectric, all-optical microfluidic flow sensor based on thermal time constant measurement. The proposed sensor utilizes a single optical fiber positioned perpendicular to the flow in a glass capillary. A Vanadium-Doped Fiber was utilized, in combination with Fiber Bragg grating to measure the thermal time constant of the fiber. The fiber was heated periodically with a laser source. The temperature change of the fiber was observed, and the system's thermal time constant calculated simultaneously. The thermal time constant of the system correlates directly with the flow of the fluid. When the fiber was placed in a glass capillary with an inner diameter of 650 µm, flow rate measurement in the range from 0 ml/h to 300 ml/h was achievable. Furthermore, as shown in this contribution, the sensor was not sensitive to losses in the lead-in optical fiber or optical source power fluctuations, which is rarely the case with optical fiber sensors utilizing an optical fiber heater.**

Keywords—optical fiber sensor; thermal time constant; flow measurement.

I. INTRODUCTION

Flow rate measurement is an essential procedure in a variety of applications. Ranging from the process, biomedical, microfluidic, petrochemical, and other industries, various principles have been employed; some have been tailored specifically for a given metering application. Conventional mechanical principles are well proven, and used in many industrial applications; however, they lack the potential for miniaturization. Therefore, a variety of thermal principles have been developed in the past which enable miniaturization. The majority of the anemometric or calorimetric sensors depend on electrical heating and sensing, which disables the application of such systems in electromagnetically polluted areas, at high temperatures and/or chemically aggressive environments. Many researchers have recently proposed using optical fiber setups for thermal flow metering, using various principles[1]–[12]. Cobalt or Vanadium-Doped Fibers (VDF) have been used [1]–[9][11][12] in calorimetric or anemometric setups because their use enables fast and controllable heating. Cobalt or vanadium doped fibers act as a heater. A standard pump diode is usually used as a photon supply for the Vanadium and Cobalt doped fibers, absorbing the light and transforming it to heat. However, anemometric and calorimetric principles are very sensitive to changes in the heating power delivered to the fiber, which is an issue that many optical fiber sensors cannot mitigate. Losses in connectors, fibers, and fluctuations of the source's optical output power are difficult to control, and usually demand complex and expensive compensation systems, making them non-competitive on the market. Matjasec and Donlagic[13] have shown that this issue can be avoided if the appropriate control technique is used in a thermal conductivity measurement setup. Instead of a constant power or constant temperature approach, a sinusoidally modulated heating source was employed, which overcame unavoidable fluctuations of heating power. Measurement of thermal time constant was used in their case to determine the thermal conductivity of the measured liquid. In this paper, this principle has been extended to measure flow rate. Measured thermal time constant is highly dependent on the flow velocity of the liquid surrounding the sensor, as is shown in the following sections.

One of the possible approaches that could mitigate the drawbacks mentioned above and simultaneously offer a reliable and straightforward design capable of flow measurement could be via the measurement of thermal time constant of a structure submerged in a flow. In this principle a time varying heat source is submerged in the fluids flow and thermal time constant is measured. Nusselt number (ratio of convective heat transfer and conductive heat transfer) increases with the increase of flow velocity around the sensor due to forced convection introduced with the flow. Such a system also enables implementation in a microfluidic environment if optical fiber technology is applied to measure the thermal constant. Simultaneously, optical fiber technology enables the use of the proposed measurement system in areas that present an unavoidable obstacle for classic electrical sensors, such as high temperatures, chemically harsh, or/and radiation polluted environments. Furthermore, simple construction and low-cost optical fibers enable the use of the proposed system in various applications, especially for lab-on-a-chip applications, where flow measurement is needed during the operation, and later the chip is discarded.

In this paper, we present an all silica, all-optical, all-dielectric, microfluidic flow sensor based on thermal time constant measurement. The proposed sensor cultivates principles from two sensors previously designed by our research group[10][13]. The proposed sensor is based on a single Vanadium-Doped Fiber with inscribed Fiber Bragg grating (FBG), which acts as a dynamic temperature sensor. FBG is a periodic change of the refractive index in the fiber core, which generates a wavelength specific dielectric mirror. With temperature increase of the FBG, the reflected wavelength increases accordingly. This setup enables measurement of the heat discharge from the heated surface, which correlates with the velocity of the fluid. The proposed sensor is highly insensitive to the variations or the changes of the heating power, which is rarely the case with other flow sensors based on thermal principles. Moreover, due to its all-silica design, it possesses all the advantages of optical fiber sensors, for example, application in electromagnetically polluted areas, in high temperatures or chemically harsh environments. The remainder of the paper is organised as follows. Section 2 presents sensor's design; Section 3 presents the manufacturing method and experimental setup for the measurements. Section 4 presents the Results. Conclusions are made in the last, Section 5.

II. SENSOR DESIGN

The presented sensor is a redesign from the previous work of Matjasec and Donlagic[13]. Their sensor is redesigned to employ FBG instead of the Fabry-Perot sensing cavity. Redesign allows the sensor to be shorter and inserted in a capillary with an inner diameter of 650 µm. It also enables the use of commercially available high-speed FBG interrogators.

The addition of small amounts of Vanadium to the core of silica optical fibers has been found to increase absorption of light with wavelengths lower than 1000 nm [14][15]. The VDF was initially drawn to 125 µm diameter with a core diameter of about 9 µm. A Medium Power Laser Diode(MPLD) was used, with a central wavelength of 980 nm. Such diodes are usually used as pumping sources for Erbium fiber amplifiers. MPLD is modulated sinusoidally, which causes the VDF to heat up and cool down in the fluid flow. To decrease the natural time constant of the system, the sensing fiber was etched to a diameter of 35 µm. This also decreases the drag in the channel, which correlates with fluid velocity. The sensing fiber was positioned perpendicularly to the flow direction, in the middle of the flow channel. The sensor assembly is shown in Fig. 1, and the manufactured sensor is shown in Fig. 2.

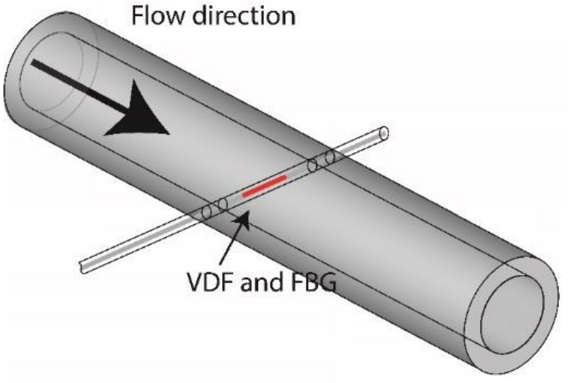

Figure 1. Schematic view of the proposed sensor

The heating segment was a 250 µm long piece positioned in the middle of the flow channel. It was spliced to an HI 1060 fiber which served as the lead-in fiber. The Vanadium-Doped Fiber was custom made and is described in [16]. The fiber used in this work can be found as fiber 3 in Table 2 of [16]. The fiber's initial diameter was 125 µm with a core diameter of 9 µm, which was later etched as described further below. The Fiber Bragg Grating was inscribed in the section of the VDF which enabled thermal time constant measurement. The proposed sensor was positioned in a glass capillary with an inner diameter of 650 µm and an outer diameter of 1000 µm.

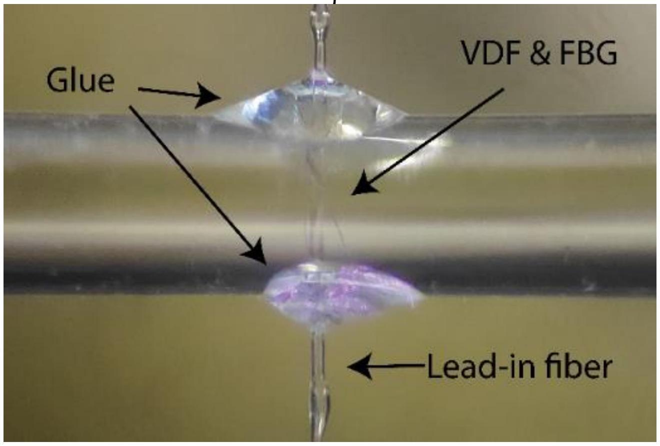

Figure 2. Photograph of the manufactured sensor

III. MANUFACTURING PROCEDURE AND EXPERIMETNAL SETUP

The manufacturing process of the sensing fiber consisted of a simple cleave and splice sequence. As shown in Fig. 3a, a cleaved piece of VDF was spliced to the lead-in single mode HI-1060 fiber. This was accomplished in a standard arc fusion splicer. The VDF was then cleaved at the length of 250 µm from the splice, under an optical microscope to ensure the correct length of the VDF. The remaining fiber was spliced to the lead-out coreless fiber, as seen in Fig. 3b, which was cleaved at a length about 1 mm away from the VDF. The FBG was inscribed using a femtosecond laser and positioning system as shown in Fig. 3c. The desired length, reflectivity, and Bragg wavelength of the FBG can be selected with such a system. With a desired length of 250 µm, we achieved reflectivity of about 10% at Bragg wavelength 1543 nm. The sensing fiber was then etched in a 40% HF solution for about 50 minutes to decrease its diameter from 125 µm to about 35 µm, as shown in Fig. 3d. Fiber diameter reduction shortens the thermal response time and, consequently, enables the use of higher modulation frequencies. The same femtosecond laser system was used to drill holes with diameter of about 45 µm in the glass capillary, which served as a flow channel (Fig. 3e). Drilled holes were oversized to enable easier insertion of the etched fiber. High laser power was used to ablate the material. Lastly, the fiber was inserted into the capillary by hand, under an optical microscope. To determine the axial position of the FBG in the fiber, a red laser pointer was coupled in the fiber produced by the above-mentioned method, and the position of the FBG was clearly visible with the eye due to diffraction of the red light on imperfections caused by the manufacturing method. This supported flawless positioning of the sensing fiber in the middle of the flow channel. High viscosity 2-component epoxy glue was used to seal off the holes in the capillary. A fully assembled sensor is depicted in Fig. 2 under an optical microscope.

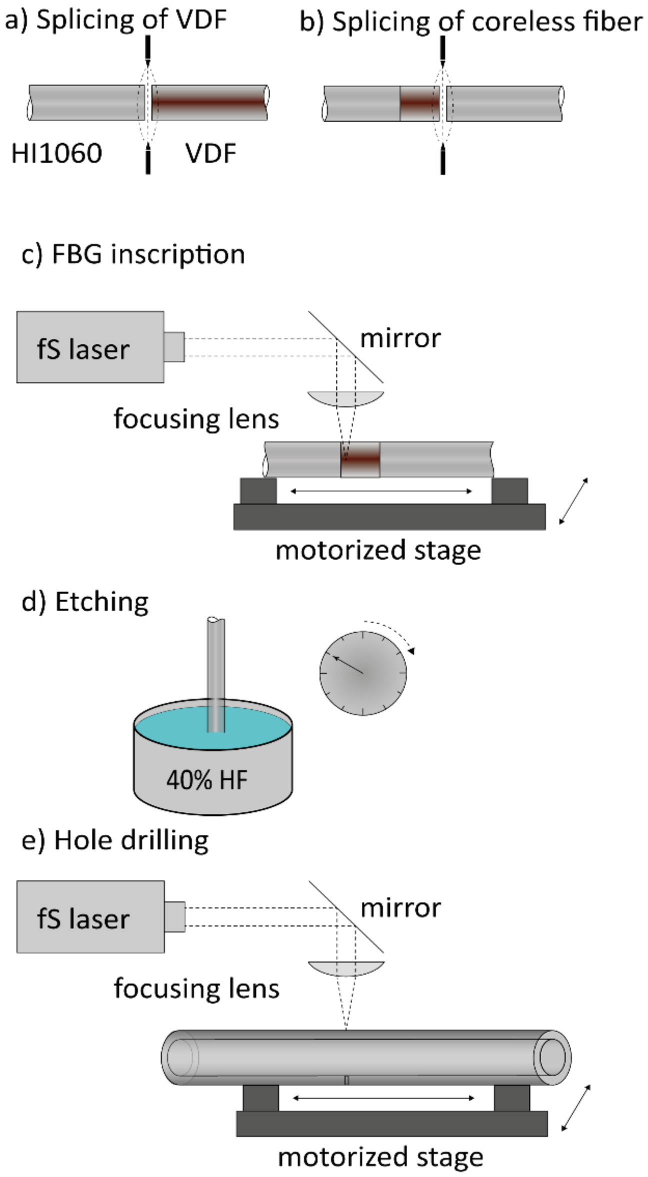

Figure 3. Manufacturing procedure

Two interconnected subsystems were used for thermal time constant measurement: A heating power delivery subsystem and dynamic temperature measurement and processing subsystem. Both subsystems are depicted in Fig. 4. The heating power delivery subsystem consisted of a medium power laser diode (MPLD) with central wavelength of 980 nm, which was connected to an appropriate driver. The driver was controlled with a programmable sine function generator. The programmable sine generator enabled control over the frequency and amplitude of the modulation. The dynamic temperature measurement subsystem consisted of a high speed FBG interrogator (FAZ I4E). The Bragg wavelength data were transferred in real time to a PC using LabVIEW. The sensing fiber was connected to both subsystems with a Wavelength Division Multiplexer (WDM), which enables coupling of the light from the MPLD and FBG interrogator.

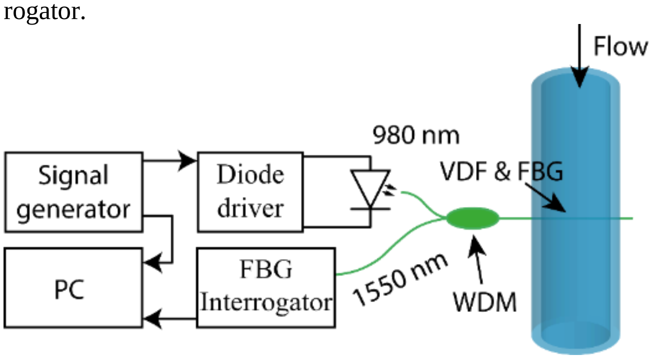

Figure 4. Interrogation setup

IV. SENSOR OPERATION AND THEROY

Two principles could be used to measure flow rate with the presented setup: a) Measurement of the total/accumulative change of the heated object's temperature due to the application of the known heating power, and b) Measurement of the thermal time constant of the heated object. While the first approach offers more simple interrogation software, it requires that the delivered heating power is known and constant. This is a drawback of many optical fiber sensors, because losses in the optical systems are unpredictable and are hard to evaluate. Therefore, we decided to employ the second technique, where the thermal time constant of the heated fiber is measured. The MPLD was driven by a current that was modulated with a raised sine function, which resulted in further raised-sine modulation of the output optical power. This sine-modulated optical power was then delivered to the optical sensor inserted in the fluid flow. The VDF absorbed the optical power, which resulted in a sinusoidal time-dependent variolation of the VDF's temperature. This time-dependent temperature variation was then determined with the use of FBG and a high-speed interrogator. Bragg wavelength variation followed MPLD sine modulation but was delayed/lagged in time to the modulation signal. A lag/phase difference $\Delta\varphi$ between the MPLD sine modulation and FBG's wavelength (temperature) change was correlated to the heated fiber's thermal time constant τ as:

$$\tau = -tg(\Delta\varphi) / 2\pi f \; ; \; -\pi < \Delta\varphi < \pi \qquad (1)$$

Where f represents the frequency of the MPLD modulation and $\Delta\varphi$ representes the measured phase delay between the modulation and temperature signal. The fiber's (sensor's) thermal time constant τ and the thermal conductivity k_f are related through the following expression [16]:

$$\tau = p_s \, c_s \, b^2 / k_f \, Nu \qquad (2)$$

where p_s represents silica specific density, c_s silica specific heat, b fiber radius and Nu the Nusselt number. Silica specific density, silica specific heat and fiber radius were, in our case, constant. The Nusselt number, however, is a fluido-dynamic parameter, which represents the ratio between convective to conductive heat transfer at a boundary in a fluid. We can conclude that, when the flow rate around the sensor increases, the Nusselt number increases accordingly, due to forced convection, consequently changing the thermal time constant.

V. MEASUREMENT RESULTS

The proposed and experimentally produced sensor was configured and tested in a liquid flow control system. We used a calibrated syringe pump, which provided the possibility to set abslotue flow rates over a broad range of flow rate values. Connections between the syringe, sensor and waste beaker were made with silicone tubing with an inner diameter of 1mm. In the first set of experiments the sensor`s response for flow ranging from 0 to 300 ml/h is shown. Isopropyl alcohol was used for all experiments. The heating peak-to-peak power amplitude corresponded to 34 mW, and the frequency was set to 20 Hz. This frequency was selected because the sensor`s natural time constant (no-flow condition) corresponded to around 5 ms. To establish a continuous flow rate measurement through the sensor, the phase difference between the FBG's temperature signals and modulation signal was measured continuously over time. This was accomplished by performing a Fast Fourier Transformation (FFT) continuously on the FBG temperature versus time and heating power versus time signals acquired within 1 s long time intervals. The phase difference between both signals was then obtained by subtracting the phases of the components in the FFT that correspond to the excitation frequency. This provided a robust and noise-tolerant calculation of the phase difference between both signals. The phase difference between both signals was converted to a time constant, using Eq.1. An example of measured time constant versus flow rate, using IPA and the above-mentioned excitation parameters, is shown in Fig. 5. for the flow rate between 0 and 300 ml/h.

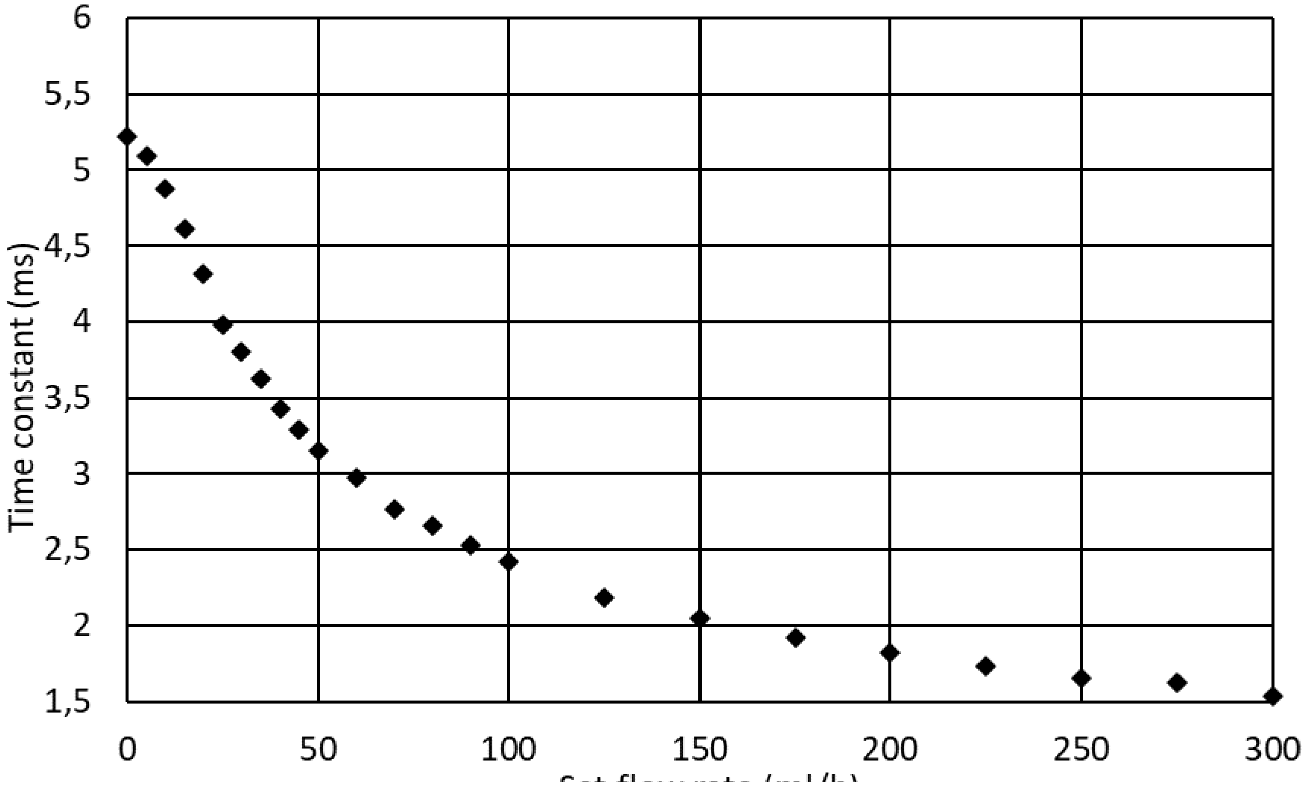

Figure 5. Graph of measured time constants versus given flow rates

As seen in Fig. 5, the flow rate and measured thermal time constant are proportionally inverse, as predicted by Equation 2.

Most thermo-optic fiber-based flow sensors reported in the literature [1][4][5][12][17] assume that the delivered heating optical power is known and constant. Deviation from this assumption usually translates directly into the increased measurement uncertainty. The proposed sensor is, however, due to the application of the thermal time constant measurment principle, highly tolerant to the variations in delivered heating power, as demonstrated by Fig. 6. Figure 6 shows the experiment where the flow rate was measured at three substantially different amplitudes of sinusoidal modulation optical power. The results in Fig. 6 demonstrate that there is no correlation between total delivered optical power to the Vanadium-Doped Fiber and the measured thermal time constant. However, it should also be stressed that, at lower flow velocities, the delivered power shall be limited to prevent reaching the fluid's boiling point, as this disturbs the flow and affects measurement. On the other hand, very low optical powers lead to the degradation of signal amplitude, and, thus, to reduced signal to noise ratio, which is reflected further in degradation of the measurement resolution.

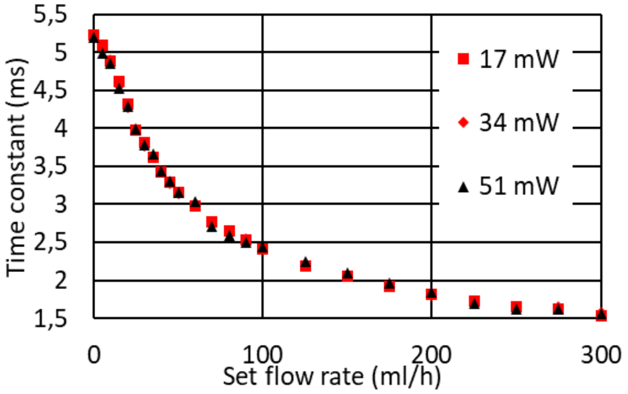

Figure 6. Dependency of measured result from heating power

The last set of performed experiments was devoted to experimental investigation of the proposed sensor's measurement resolution. The sensor`s resolution was demonstrated at different flows using a siphoning effect to enable a pulsation free and stable fluid flow. Known and predetermined amounts of liquid were added to the upper beaker at approximately 20 s intervals. The flow rate was verified using a scale by weighting the change of mass of the liquid in time. An example of the sensor`s resolution demonstration is, thus, presented in Figs. 7 and 8 at initial flow rates of around 25 ml/h and 210 ml/h, respectively.

By comparing the sensor's output change with the measurement of noise levels in Figs. 7 and 8 we concluded that the sensor`s resolution was about 0.81 ml/h for flow rates around 25 ml/h, and 3.1 ml/h for flow rates around 200 ml/h. Altogether, we can conclude that the proposed sensor's overall resolution was 3.1ml/h for the flow range from 0 to 300 ml/h, which corresponded to about 1.03% of the full scale resolution.

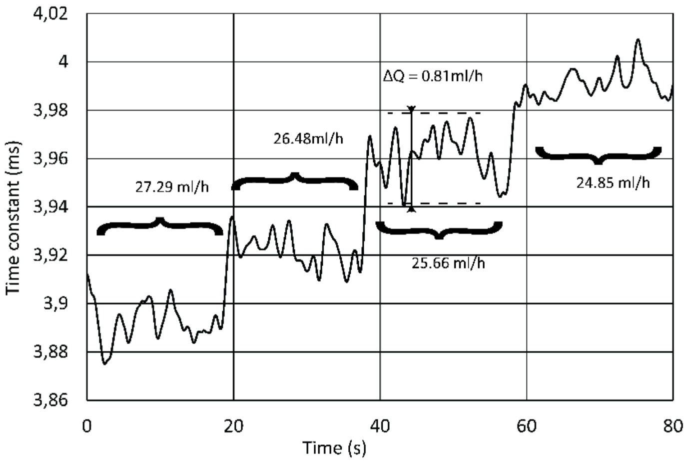

Figure 7. Demonstration of sensor resolution and time response at low flow rates

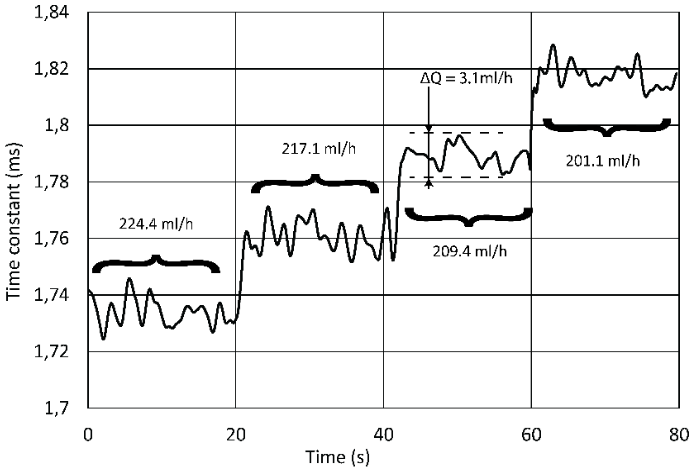

Figure 8. Demonstration of sensor resolution and time response at low flow rates

VI. CONCLUSIONS

An all-fiber, all-silica microfluidic flow sensor based on thermal time constant measurement was presented in this paper. The sensor was based on a short section of Vanadium-Doped Fiber with inscribed Fiber Bragg Grating. The sensor was heated optically and periodically in time by a laser diode, while the temperature change was observed, and the phase difference calculated between the modulated and measured temperature signal. This phase difference was used to calculate the thermal time constant of the sensor, which, in accord with the presented theoretical background, decreased when the flow of the fluid was introduced around the sensor. The sensor was packaged in a glass capillary with an inner diameter of 650 µm, and tested for different flow rates using IPA. The proposed sensor was simple to construct and interrogate. It offers two distinct advantages over other optical fiber flow sensors. Firstly, it's very simple, single fiber design offers the possibility in microfluidic applications where space is limited. Secondly, its immunity to varying losses in optical fibers offers the possibility to use it in rugged areas with minimal maintenance and human interference during its lifetime. The experimental version of the sensor was demonstrated for flow rate measurement from 0 to 300 ml/h with a full-scale resolution of around 1%. All the experiments were conducted with IPA, and calibration of the sensor would be needed in a commercial application for the given fluid. However, with measurement of the time constant of the liquid when there is no flow presented in the channel, an in-situ calibration is possible. The sensor is sensitive to debris presented in the liquid, especially microfibers, which clog the flow channel and interfere with the time constant measurement. Moreover, any two-phase flow (gas and liquid) would also interfere with the measurement and render it unreliable. The proposed sensor also possesses all the advantages associated with fiber-optic sensors, such as, for example, dielectric and chemically inert design, electrical passivity, immunity to electromagnetic interference, small size, and biocompatibility. The proposed sensor can measure the flow velocities of aggressive fluids and enables use of long lead-in fibers to measure flow in remote locations separated from the optoelectronic interrogation unit. Moreover, the authors believe that the sensor's upscaling and downscaling without degradation of properties is possible. While other flow measurement solutions might offer better dynamic range and resolution, the proposed sensors' simple and low-cost design enables use in single-use lab-on-a-chip applications and biomedical applications.

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