

# Development of clamp-on type thermal mass flow meter using near infrared absorption method for micro flow applications

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## Abstract

We have developed a portable device, based on this infrared absorption method, that can measure in-situ micro flow rates from 0.2 to 20 mL/min using a simple diode laser and a photo detector. A 1450 nm laser absorbed in water was irradiated to form a hot spot and the temperature was measured upstream and downstream of the hot spot. Two diode lasers and two photodetectors were used to measure the water temperature in the tube upstream and downstream of the hot spot. The amount of laser diode light from 1550 nm to 1650 nm wavelength absorbed by the water varied with the temperature of the water. The flow rate was measured by the temperature difference obtained by the diode laser absorption upstream and downstream of the hot spot. The temperature difference measured upstream and downstream decreased exponentially with increasing flow rate. Thus, it was confirmed that the flow rate can be measured through the temperature difference gauged using a simple diode laser set. This method is used for various applications including biomedical and chemical processing without causing any contamination owing to the flow meter installation.

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## 1. Introduction

The measurement and control of liquid micro flow rates is important in several processes, such as medical drug injection, semiconductor manufacturing processes, and chemical processes. Recently, many researchers have developed various methods for measuring micro flow rates. Coriolis flowmeters and thermal mass flowmeters are typically used for measuring micro flow rates. Coriolis flowmeters measure extremely low flow rates (maximum flow rate: 5 g/h) with extremely high accuracy ( $\pm 0.2\%$ ). However, they exhibit a few limitations, such as high cost and pressure resistance. Thermal mass flowmeters have relatively low flow measurement accuracy (10%). Despite these drawbacks, Coriolis flowmeters and thermal mass flowmeters are widely used in industry [1].

In addition, there is an increasing demand in the industry for approaches that allow in-situ flow rates to be measured without pipeline cutting and fluid contamination. As coriolis flowmeters and thermal mass flowmeters cannot measure in-situ flow rates, techniques for measuring the flow rate in-situ without cutting the piping are being developed, such as the use of ultrasonic waves. Ultrasonic

flowmeters use the clamp on type method to measure the flow rate by irradiating ultrasonic waves outside of a pipe for in situ measurement. However, measuring low flow rates with ultrasonic flowmeters is challenging because the signal intensity reduces as the flow velocity reduces.

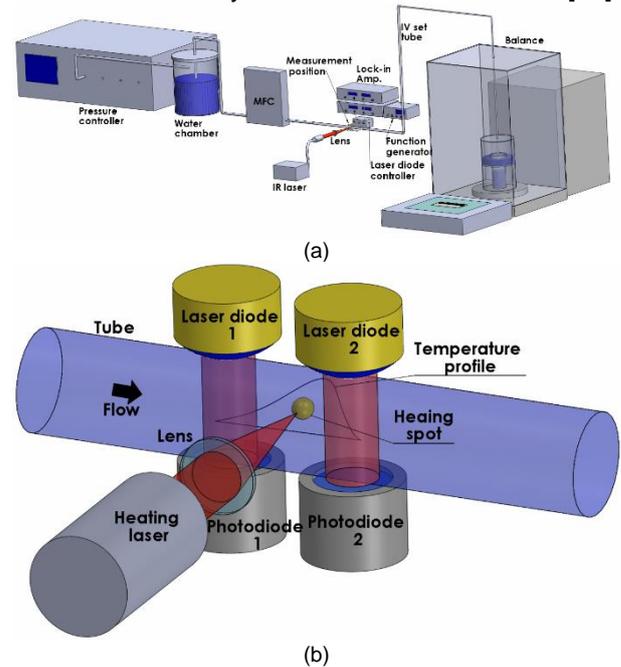
Laser-based techniques for the measurement of flow rates have several advantages, such as remote, nonintrusive, in situ, spatial, and temporally precise measurement[2-5]. Laser Doppler velocimetry (LDV) uses the Doppler shift in a laser beam to measure the velocity of particle seeded fluid flows[6; 7]. Particle image velocimetry (PIV) measures the flow velocity field by capturing two images of seeding particles in the fluid with a time gap. Although several LDV and PIV have been applied to measure flow velocity, they require particle seeding. Recently, techniques for measuring the flow field without the seeding of particles were developed by using fluorescence and Raman scattering [3; 4; 8]. To overcome the disadvantages associated with using particles for measuring flow, different dyes were used as markers [9]. A non-intrusive measurement technique based on spontaneous Raman imaging was proposed to investigate microscale flow structures[8] and spray flow[3].

Specifically, near-infrared (NIR) spectroscopy is a conventional method for measuring the molecular composition of a substance using a vibrational molecular band [12]. Water exhibits several absorption bands in the NIR region, and the spectral shape of each band varies with respect to temperature. The absorption band of water (O-H band,  $\nu_1+\nu_3$ ) shifts to a shorter wavelength with increases in temperature [13]. Additionally, NIR spectroscopy is used for water temperature measurement in channels with sizes in the range of micrometers [10]. The water temperature in a microchannel was visualized by using the NIR absorption method with a high resolution (0.2 K) [11]. The NIR absorption method exhibits high potential in terms of measuring the flow rate. Recently, the technique was proposed for measuring micro flow rates by our group [12]. The flow rate is measured by irradiating water with an IR laser to heat it, and then measuring the water temperature by using FTNIR (Fourier transform near infrared). However, the FTNIR used to measure the near infrared absorption spectrum in that study was bulky and expensive, which would have made its application to industrial sites challenging. There is a need for an in-situ micro flowmeter that can be applied to industrial fields. Moreover, the development of low cost, small, and stable laser diodes has made it possible to simplify the infrared absorption technique. Studies have been performed to measure the flow velocity using tunable diode laser absorption spectroscopy, but this can only be applied to high speed flow [13]. However, no studies have been performed to measure micro flow rates using diode lasers.

In this study, a new technique for measuring micro flow rates using small chip diode lasers was developed. The NIR laser heats a tiny spot in a transparent polymer tube through a lens. The water temperatures upstream and the downstream of the heated point were measured by the laser diode absorption method. The theoretical heat transfer was analyzed through a simulation of the temperature profile for different flow rates. The temperature difference measured by the laser diode upstream and downstream of the heated point was used to measure the micro flow rate. The micro flow rate measurement accuracy and measurement range were determined according to the laser's energy and temperature measurement positions. The calibration curve for the temperature difference and the reference flow rate were obtained with a flow rate in the range of 0.2–20 mL/h. Thus, we confirmed that the laser diode absorption method can measure micro flow rates in the 0.2–20 mL/h range in-situ with high accuracy.

## 2. Experiment

Figures 1 (a) and (b) show the experimental setup for the laser diode (LD)-based thermal mass flowmeter and a magnification of the measurement position, respectively. The deionized (DI) water was sent to the LD flowmeter and the balance through an IV set tube commonly used in the hospital. The internal diameter of the IV set tube was 3 mm, and an optical transparency of 0.3  $\mu\text{m}$  to 3  $\mu\text{m}$  in the near infrared region. The flow was generated by air pressure using a pressure controller (Elve flow, OB1) and controlled from 0.2 to 20 mL/h using a mass flow controller (MFC, Bronkhorst M12). The reference flow rate was obtained using a micro balance (Mettler-Toledo, XPE 206 DR) with an evaporation trap. To obtain the reference flow rate using the balance, we calculated the measurement uncertainty of the balance with respect to buoyancy, evaporation, and accuracy of the balance. The detailed uncertainty calculation can be found in [14].



**Figure 1:** (a) Experimental setup for the laser diode-based micro flowmeter; (b) magnification of the measurement position shown in Fig. 1 (a)

The LD flowmeter consists of a heating laser (CNI, 1450 nm  $\pm$ 15 nm), two diode lasers (Thorlabs, LED1600L) for emitting light, and two photodetectors (Roithner Laser Technik, LAPD-1-09-17-TO46) for receiving light. The light emitted by the heating laser with a 1450 nm wavelength was absorbed by the water owing to the vibration ( $\nu_{\text{OH}}$ ) [15]. The heating laser was focused on the center of the IV set tube through a lens (50 mm focal length). The water was heated at a tiny spot region

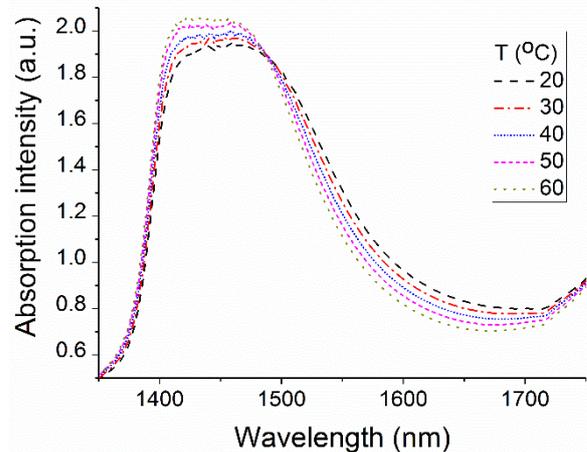
by the focused laser with a spot diameter of 12.5  $\mu\text{m}$ . To measure the temperature of water upstream and downstream of the heated spot, two diode lasers emitting light at a wavelength of 1550 nm to 1650 nm, and two photodetectors measuring light at 900 nm to 1700 nm were used. Near infrared light was collimated through a lens in front of the laser diode, and the light absorbed by the water in the tube was measured with a photodetector. Two lock-in amplifiers (SR530, Stanford Research Systems) were used to amplify the water absorption signal of the laser diode. The noise of the absorption signal was minimized by synchronizing the laser diode and photodetector with the signal generated by the function generator. The distance between the two laser diodes and photodetector pairs was 10 mm. The distance between the optimized upstream measurement point and the heated spot was 1 mm.

### 3. Results

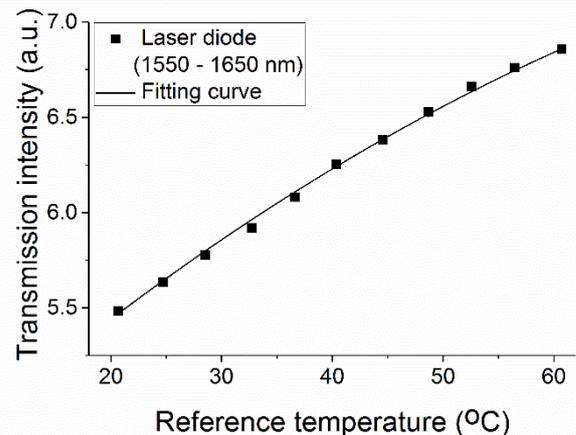
#### 2.1 Temperature measurement using the NIR absorption method

In this study, the flow rate was measured using the temperature difference upstream and downstream of the heated spot by measuring the temperature under in-situ conditions. The principle of measuring the temperature under in-situ conditions was based on the fact that the absorption spectrum of NIR changes according to the temperature [11]. Figure 2 shows the absorption spectra according to the temperature (20, 30, 40, 50, and 60 oC) measured with Fourier transform near infrared (FTNIR) spectroscopy. When the temperature of water increases, the absorption intensity at wavelengths from 1400 nm to 1450 nm increases, and the absorption at wavelengths from 1500 nm to 1700 nm decreases. If we obtain the absorption intensity from 1500 nm to 1700 nm, we can measure the temperature of water under in-situ conditions. Therefore, we irradiated the light from 1550 to 1650 nm with a laser diode on the tube, and measured the light transmittance using a photodetector on the other side. Figure 3 shows the transmission intensity signal from the laser diode with various reference temperatures. When the reference temperature increases, the transmission intensity increases as shown in Fig. 3. This is because, as the temperature increases, the amount of light absorbed by the water decreases, thereby increasing the amount of light transmitted. The relationship between the reference temperature and the transmission intensity is a quadratic function, which depends on the characteristics of the measurement sensor. Using this temperature calibration curve, a quantitative temperature can be

obtained under in-situ conditions through a laser diode



**Figure 2:** Absorption spectra according to the temperature (20, 30, 40, 50, and 60 °C) measured with FTNIR.

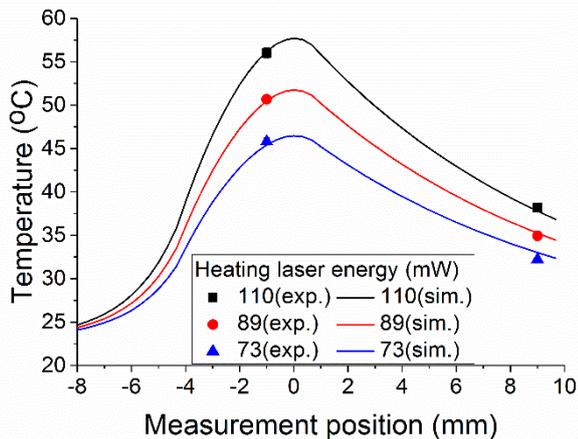


**Figure 3:** Variation in the transmission intensity signal from the laser diode with reference temperature

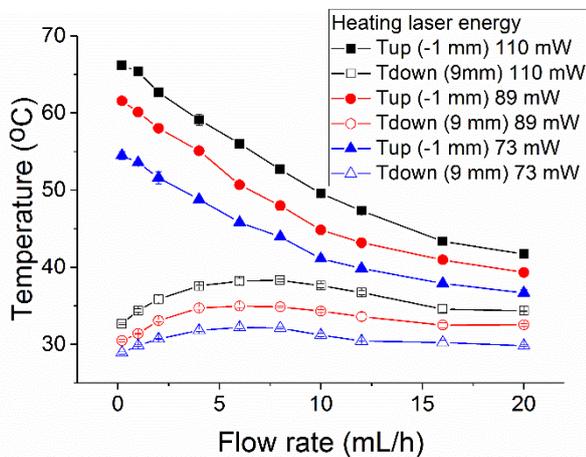
#### 3.2 Analysis of the laser diode flowmeter for different heating laser energies

The energy of the heating laser is one of the important parameters of the laser diode-based micro flowmeter. Therefore, we changed the heating laser's energy to analyze how the laser energy affects the flow measurement in this study. Figure 4 shows a comparison of temperature profiles between the experimental and simulation results of the 73, 89, and 110 mW heating laser energy cases at a 6 mL/h flow rate. This figure shows that the simulation results were well matched with the experimental results. When the heating laser energy increases, the maximum temperature increases up to more than 55 °C. The maximum temperature difference between the laser energy of

73 mW and 110 mW is about 10 °C. Upstream of the heated spot, the slope of the curve between the temperature and the measurement positions increases with increasing heating laser energy, and downstream of the heated spot, the slope of the curve is almost constant for different heating laser energies.



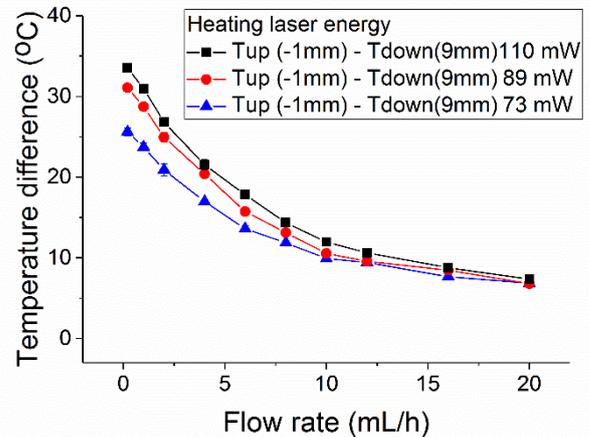
**Figure 4:** Comparison of temperature profiles between the experimental and simulation results of 73, 89, and 110 mW heating laser energy cases at 6 mL/h flow rate.



**Figure 5:** Temperatures at two measuring positions (upstream : -1 mm, downstream : 9 mm) according to the flow rates for different heating laser energies (73, 89, and 110 mW)

Figure 5 shows the temperatures at two measuring positions (upstream : -1 mm, downstream : 9 mm) according to the flow rates for different heating laser energies (73, 89, and 110 mW). When the flow rate increases, the temperature upstream of the heated spot decreases, and there is little change in the temperature downstream of the heated spot for each of the heating laser energy cases. As the heating laser energy decreases, the temperature curve according to the flow rate at each position is shifted downward. Therefore, the measured temperatures upstream and downstream of the

heated spot do not overlap when the flow rate is high.



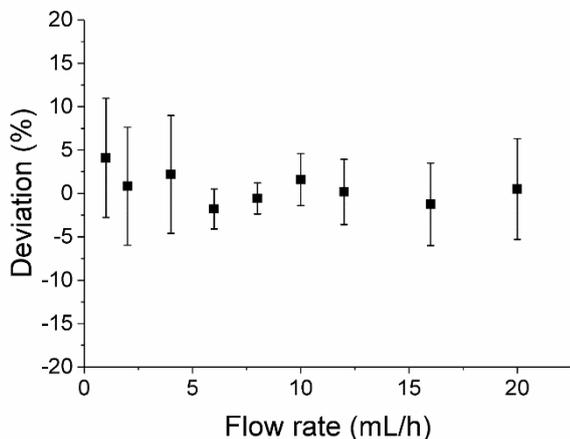
**Figure 6:** Temperatures difference according to the flow rates for different heating laser energies (73, 89, and 110 mW)

Figure 6 shows the temperature difference according to the flow rates for different heating laser energies (73, 89, and 110 mW). The temperature difference decreases exponentially as the flow rate increases. Moreover, as the heating laser energy decreases, the slope of the temperature curve decreases. This means that the higher the heating laser energy, the better the accuracy of the flow measurement. However, at low heating laser energies (73 mW), the temperature difference is maintained at a high flow rate range even though the accuracy of the flow measurement is low. Furthermore, the low heating laser energy (73 mW) has an operating temperature that is about 10 °C lower than that of the high heating laser energy (110 mW), which may be advantageous for applications involving biofluids that are easily destroyed by heat. The lowest flow rate measured in this study is 0.2 mL/h, but if the laser energy is controlled, lower flow rates can be measured in the future. As the accuracy of the flow measurement is drastically improved as the flow rate is lowered, the flowmeter can be used for accurate micro flow measurement.

#### 4. Uncertainty analysis

The Figure 7 shows the deviations in the LD flowmeter readings according to the flow rate with measurement uncertainty. When the flow rate increases, the deviation approaches zero. However, the measurement uncertainty decreases as the flow rate increases and then increases again. This is because the slope of the temperature difference according to the flow rate is lowered at a high flow rate, and the measurement accuracy is lowered.

Thus, the maximum measurement uncertainty was 6.8% at a 1 mL/h flow rate, and the minimum measurement uncertainty was 1.78% at 8 mL/h. However, these values vary with the measurement positions and the energies of the heating laser used to determine the optimal flow rate range. The performance of the LD flowmeter developed in this study was confirmed to be close to that of a commercial thermal mass flowmeter (10%, full scale). Using the laser diode-based flowmeter developed in this study, it is possible to measure flow rate in-situ without injecting contaminants such as particles for measurement without cutting piping. In addition, it can be manufactured in a miniaturized form at a low cost, and thus, it can be used for multi-drug infusion analysis, and semiconductor process monitoring, etc.



**Figure 7:** Deviations in laser diode-based flowmeter according to the flow rate with measurement uncertainty

## 5. Conclusion

We have developed a laser diode-based flowmeter based on this infrared absorption method that can measure in-situ micro flow rates from 0.2 to 20 mL/min using a simple diode laser and a photo detector. The amount of laser diode light from 1550 nm to 1650 nm absorbed by the water varied with the temperature of the water. The calibration curve of the infrared light transmission intensity through the water at various temperatures of the water was obtained. A 1450 nm laser absorbed in water was irradiated to form a heated spot at 0 mm, and the temperature was measured upstream and downstream of the heated spot. Two diode lasers and two photodetectors were used to measure the water temperature in the tube upstream and downstream of the heated spot. The flow rate was measured by the temperature difference obtained by two diode lasers and photodetectors upstream

and downstream of the heated spot. We measured the temperature profile of the flow rate by changing the heating laser energy upstream and downstream of the heated spot, and compared the obtained values with the simulation results. As the flow rate increased, the temperature profile shifted downstream, and the measured temperature upstream and downstream were analyzed according to the flow rate. The temperature difference measured upstream and downstream decreased exponentially with increasing flow rate, and it was confirmed that quantitative measurement could be made using this calibration curve. Increasing the energy of the heating laser also improved the measurement accuracy in the lower flow range. The developed flowmeter was calibrated by the gravimetric method, and the maximum measurement uncertainty was 6.8%, which is similar to that of the conventional commercial contact thermal mass flowmeter. The lowest flow measurement uncertainty was 1.78% at a flow rate of 8 mL/h. Thus, it was confirmed that the flow rate can be measured through the temperature difference gauged using a simple diode laser set. The diode laser-based flowmeter developed in this study has the following advantages:

1. The flow rate can be measured non-contact without the need to inject additional particles.
  2. We can measure the flow rate in-situ without cutting the pipe.
  3. We can set the flow measurement range by adjusting the heating laser energy and the measuring position.
  4. It is possible to measure the flow rate with high flow measurement accuracy in the low flow rate range.
  5. It can be manufactured in a small size at low price; thus, it is easy to mass produce.
- Owing to these advantages, this method can be used in various processes, including biomedical and chemical processes, without causing any contamination owing to the flowmeter installation.

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