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An optical fiber based on sensor for measurement of both flow rate and temperature in the pipeline

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ABSTRACT

An optical fiber sensor was studied for the simultaneous measurement of flow rate and temperature. It includes a capillary steel tube, an adjustable target and two Fiber Bragg gratings (FBGs). The two fiber Bragg gratings were fixed in the tube by glue, they could be protected very well. One end of the tube was assembled in the protective shell, the other end was connected to target. Flow rate and temperature would both cause the wavelength shifts of Fiber Bragg gratings (FBGs). The flow sensitivity of the proposed sensor adjusted by only assembling a properly designed target. The sensor was fabricated and realized the simultaneous measurement of flow rate and temperature, which was verified by experiments. Due to the limitation of experiment system, the flow rate accuracy was up to 2.30% in the range of 5–20 m3/h, and the temperature accuracy was under ± 1 °C in the range of 25-90 °C. With advantages of compact size, high sensitivity, wide measurement range and small pressure loss, it has a great potential application in so many areas.

Keywords: Optical fiber sensor, Flow rate, Temperature, Pipeline.

INTRODUCTION

Fibre Optics 2020 It is focusing on "Changing the World by Exploring Newer and Sustainable Technologies in Optics, Fibre Optics and Communication Systems" to develop and explore knowledge among Optics community and to launch new businesses and swapping ideas. Providing the right stage to present thought-provoking Keynote talks, Plenary sessions, Discussion Panels, Optics engineering 2020 foresees over 200 participants from 7 continents with revolutionary subjects, discussions and expositions. This will be a marvelous viability for the researchers, students and the delegates from Universities and Institutes to intermingle with the world class Scientists, speakers, technicians and laser Practitioners and Industry Professionals working in the field of lasers, Optics and communication system.

One of the industry's largest tradeshows dedicated to photonic technologies, which is held at the Moscone Convention Center in San Francisco. In Corning's Booth No. 2027, the company will feature demonstrations and new products that are enabling major emerging trends, such as augmented reality, 5G, and next-generation semiconductor manufacturing including. This full metrology system will run live demos to show precise surface form measurements on 300mm wafers. Wave Optics Augmented Reality Headset. This wearable waveguide device features Corning's high-index glass and enables a 40-degree field of view. This newly launched optical fiber is the first reduced-clad fiber compatible for G.657 and G.652. In addition to this new fiber,

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Corning will showcase a new Fiber Array Unit (FAU) with improved density and footprint capabilities enabled by the RCBI fiber. Corning will also emphasize its full range of capabilities and solutions for semiconductor manufacturing applications and how they are enabling the next generation of consumer electronics through high-quality materials, full optical systems, and world-class manufacturing platforms. “We look forward to showing a variety of Corning’s capabilities at Photonics West this year,”

“From high-quality, optical materials to precision and inspection equipment, our diverse range of products and design expertise meets our customer’s needs at all steps of the semiconductor manufacturing process. We are proud of our well-established proficiency in this area and look forward to connecting with our industry colleagues at the show.”Corning Advanced Optics leverages Corning’s experience in glass science and optical physics to solve its customers’ optical challenges through customized design and cutting-edge optical materials and full-systems. Those capabilities include high-quality materials such as Corning ULE® and HPFS® as well as metrology capabilities, automated laser glass-cutting, and optical design expertise.

Caution concerning forward looking statements

This press release contains “forward-looking statements” (within the meaning of the Private Securities Litigation Reform Act of 1995), which are based on current expectations and assumptions about Corning’s financial results and business operations, that involve substantial risks and uncertainties that could cause actual results to differ materially. These risks and uncertainties include: the effects of acquisitions, dispositions and other similar transactions by the Company, the effect of global business, financial, economic and political conditions; tariffs and import duties; currency fluctuations between the U.S. dollar and other currencies, primarily the Japanese yen, New Taiwan dollar, euro, Chinese yuan, and South Korean won; product demand and industry capacity; competitive products and pricing; availability and costs of critical components and materials; new product development and commercialization; order activity and demand from major customers; the amount and timing of our cash flows and earnings and other conditions, which may affect our ability to pay our quarterly dividend at the planned level or to repurchase shares at planned levels; possible disruption in commercial activities due to terrorist activity, cyber-attack, armed conflict, political or financial instability, natural disasters, or major health concerns; unanticipated disruption to equipment, facilities, IT systems or operations; effect of regulatory and legal developments; ability to pace capital spending to anticipated levels of customer demand; rate of technology change; ability to enforce patents and protect intellectual property and trade secrets; adverse litigation; product and components performance issues; retention of key personnel; customer ability, most notably in the Display Technologies segment, to maintain profitable operations and obtain financing to fund their ongoing operations and manufacturing expansions and pay their receivables when due; loss of significant customers; changes in tax laws and regulations including the Tax Cuts and Jobs Act of 2017; and the potential impact of legislation, government regulations, and other government action and investigations. Flow rate and temperature are very important parameters to pipeline transportation which can reflect the operation condition of the pipeline. The effective measurement of those parameters is significant in many industry areas, such as medical treatment, chemical engineering [1–3]. Now many kinds of flow meter sensors have been proposed, such as electromagnetic flow meter [4], ultrasonic flow meter [5] and differential pressure type flow meter [6], they are not good to meet the requirements in some special occasions. With some features of optical fiber technique, such as corrosion resistance, multiplex capability, electromagnetic immunity and compact size [7, 8], optical fiber sensors are widely concerned as a promising technology, target-type-based fiber flow sensor [9, 10], optical fiber thermal gas flow meter [11, 12], optical turbine flow meter [13, 14]. FBG is a widely applied in the optical fiber sensors because it is a low fabrication cost, stable characteristic and multiplex capability [15]. Many of the optical fiber flow rate sensors were proposed based on the principle that FBG was sensitive to strain. However, its temperature- sensitive property, which would influence the measurement precision of strain or flow rate, should be also focused on. present a flow rate sensor on the basis of Karman vortex [16], two cantilevers are applied to measure the frequency of the vertex which can ignore the temperature effect. The sensor can achieve a liquid flow rate measurement between 0 and 1 m^3/h whose measurement range was limited in practical application. proposed a target-type flow sensor for simultaneous measurement of flow-rate/temperature, and the sensor had a good performance. But its triangle cantilever caused a relatively large pressure loss, which restricted its measurement range, only from 1.40 to 8.0 m^3 /h. A hot-wired flow meter with a resolution of 1.00 m/s which fully utilize the FBG's temperature characteristic [17].

However, the sensor structure is too vulnerable to apply for the pipeline fluid measurement, and the liquid has relatively high thermal conduction which is not suitable for the application of hot-wired sensor. The capillary steel tube with the target was proposed to increase the sensitivity of flow rate to adapt to the application and achieve the temperature measurement at the same time. A pair of FBGs were fixed in the capillary steel tube which worked as a protector. By fixing a target on the free end of the capillary, the flow rate sensitivity of the sensor was improved apparently. By the way, the temperature could be obtained by the shift of central wavelength between the resonance wavelengths of the two FBGs. Meanwhile, with the compact sensing probe, the proposed sensor would produce a low pressure-loss in actual measurement. An **optical fibre** is a thin **fiber** of glass or plastic that can carry light from one end to the other. The study of **optical fibers** is called **fiber optics**, which is part of applied science and engineering. An **optical fiber** is a cylindrical dielectric waveguide (non-conducting waveguide) that transmits light along its axis, by the process of total internal reflection. The **fiber** consists of a core surrounded by a cladding layer, both of which are made of dielectric materials.

Light travels down a **fiber optic** cable by bouncing off the walls of the cable repeatedly. Each light particle (photon) bounces down the pipe with continued internal mirror-like reflection. The light beam travels down the core of the cable. There are three **types** of **fiber optic** cable commonly used: single mode, multimode and plastic **optical fiber** (POF). Transparent glass or plastic **fibers** which allow light to be guided from one end to the other with minimal loss. A **fiber optic cable** is a network **cable** that contains strands of glass **fibers** inside an insulated casing. They're designed for long distance, high-performance data networking, and telecommunications. Compared to wired **cables**, **fiber optic cables** provide higher bandwidth and can transmit data over longer distances. An **optical fiber** is a cylindrical dielectric waveguide (non-conducting waveguide) that transmits light along its axis, by the process of total internal reflection. The **fiber** consists of a core surrounded by a cladding layer, both of which are made of dielectric materials. **Fiber optic** cables have a much greater bandwidth than metal cables. The amount of information that can be transmitted per unit time of **fiber** over other transmission media is its most significant **advantage**. An **optical fiber** offers low power loss, which allows for longer transmission distances. They are widely **used** in lighting, both in the interior and exterior of vehicles. Because of its ability to conserve space and provide superior lighting, **fibre optics** is **used** in more vehicles every day. Also, **Fibre optic** cables can transmit signals between different parts of the vehicle at lightning speed. **Optical signal** is an electromagnetic **signal**. It has electric and magnetic fields that are orthogonal to each other. Typically, the frequency of this EM wave is extremely high (in the order of THz). Therefore, it is more convenient to measure it in terms of wavelength. A **technology** that uses glass (or plastic) threads (**fibers**) to transmit data. **fiber** optic cable consists of a bundle of glass threads, each of which is capable of transmitting messages modulated onto light waves.

Fiber optic cables have a much greater bandwidth than metal cables. An **optical**

transmitter is one half of a communications system, where the other half would be an **optical** receiver. Generating an **optical** signal is the job of the **optical transmitter**, which encodes the information to be transmitted on the light that it generates. **Optical** Fibres **used** for Broadcasting These cables are **used** to transmit high definition television signals which has a greater bandwidth and speed. **Optical Fibre** is cheaper compared to same quantity of copper wires. Broadcasting companies use **optical** fibres for wiring HDTV, CATV, video-on demand and many **applications**. At distances up to3 km, single mode **fiber** will deliver data rates up to Gbps with a **bandwidth** of Ghz. Its operating wavelengths are nm and nm. 1920s: Englishman John Logie Baird and American Clarence W. Hansell patented the idea of using arrays of transparent rods to transmit images for television and facsimiles respectively. 1930: German medical student Heinrich Lamm was the first person to assemble a bundle of **optical fibers** to carry an image. An **optical fiber** is a cylindrical dielectric waveguide (no conducting waveguide) that transmits light along its axis, by the process of total internal reflection. The **fiber** consists of a core surrounded by a cladding layer, both of which are made of dielectric materials.

Sensor structure and measurement principle

The sensing structure is composed of a section of pipe with flanges, a target, a capillary steel tube, a pair of FBGs, and a protective casing, which is shown in bellow figure Fig. 1.

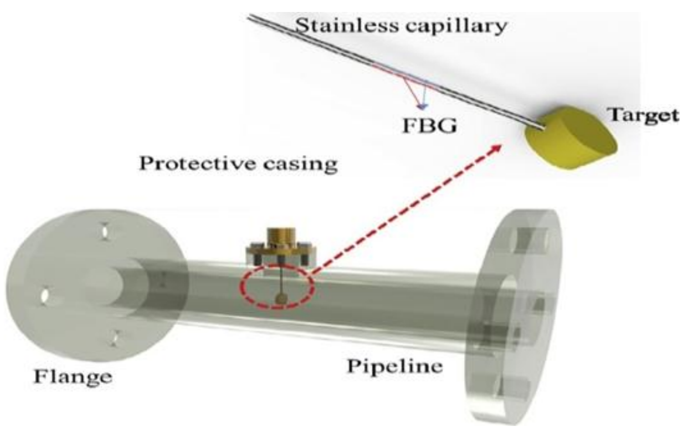

Fig. 1. The sensing structure of the proposed sensor.

The pipe with flanges makes the installation of the sensor easier. The target is placed in the center of the pipeline, and the plane of the target is perpendicular to the flow direction. The free end of the capillary is inserted into the target, and the other end is fixed in the protective casing. The protect casing prevents the fluid from flowing out of the pipe and fixes the capillary steel tube. Besides, the two FBGs were put through the capillary steel cantilever and stuck symmetrically along its inner wall. Meanwhile, the plane of the two FBGs is parallel to the direction of the fluid. The capillary by the impact force of the flow, while the strain is transferred to the two FBGs. Consequently, the resonance wavelengths of FBGs shift with the change of fluid. The FBG with longer resonance wavelength shift to the red side and the other FBG shift to the blue side. The relations between the deformation and the flow rate are calculated by using the finite element analyze (FEA) method. Stainless steel was selected as the material of the capillary for its good mechanical characteristic. The target’s diameter was set to 10 mm. The inner diameter and the outer diameter of capillary were 0.5 mm and 1 mm, respectively. The capillary’s length was 30 mm, and 10 mm length of the capillary was inserted into the target to hold the target. Pure water was selected as the fluid. To reduce the calculation consumption and increase the computation efficiency, half of real part was adopted as the model. Fig. 2 showed the simulation result of the model.

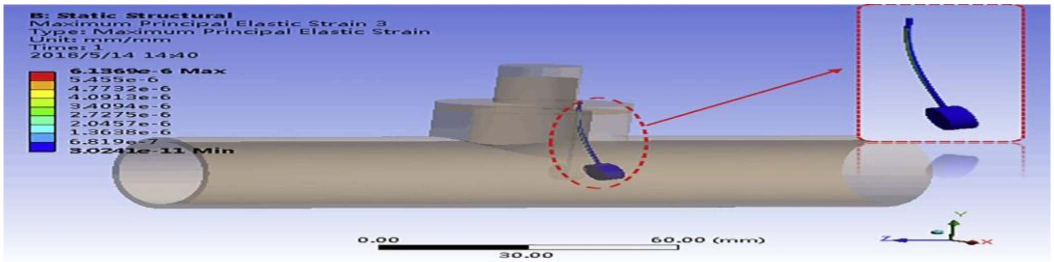

Fig. 2. The simulation result of the sensor

Then, one end of the capillary beam was fixed and the other end was free. The two FBGs stuck on the inner wall of the capillary steel tube, sense the positive and negative strain respectively. The strain on the lines of the inner wall along the assembled positions of two FBGs was calculated. The strain under different flow rates is shown in Fig. 3. The reason that the strain fluctuates up and down is because of the grid limitation, but it basically reflects the strain because it is consist with the coarser mesh. As the previous mentions, the plane formed by the two gratings is parallel to the flow direction. According to the knowledge of elastic mechanical, the two line sense the negative and positive strain separately, and the magnitude of the strain on the two FBGs was the same. The position of x = 30 mm around was chosen to place the FBGs. The reason why choose here is that the strain in there was relatively big, and the FBG has a little distance to the ending of the capillary which the FBG cannot be easily damaged. The relationship between the strain and the flow rate at x = 30 mm was plot in Fig. 4.

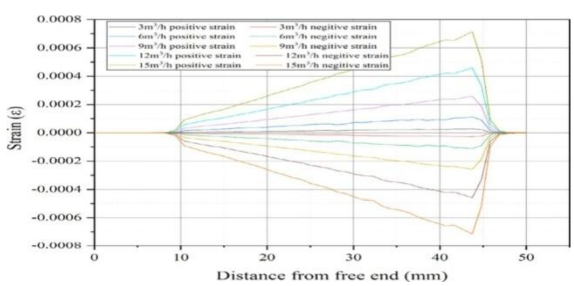

Fig. 3. The theoretical strain on the capillary Under different flow rate.

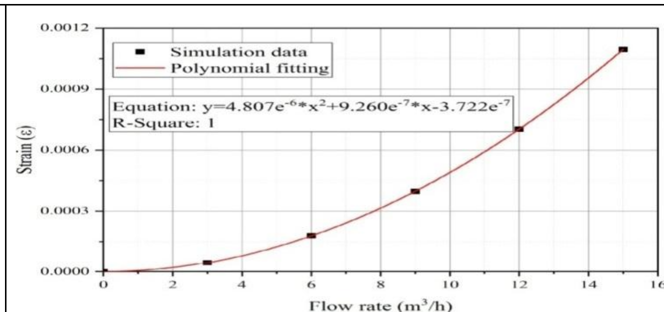

Fig. 4. The theoretical relationship between deformation and flow rate.

The relationship between the strain on the capillary and the flow was quadratic. According to the fiber grating strain measurement formula:

$\Delta\lambda B / \lambda B=(1-Pe).\varepsilon$ (1)

Where ε is the strain on the capillary, and Pe is the effective photo- elastic coefficient of fiber. The relation can be established between the flow rate and the wavelength shift (assuming that the resonance wavelength of the FBG is 1550 nm):

$y = 0.0058x2 + 0.0011x-0.0004$ (2)

Where x represents the flow rate in the pipeline, and y stands for the FBG wavelength drift at different flow rate.

The sensor can realize the simultaneous measurement of temperature and flow rate because the two FBGs are located in essentially the same temperature field.

Experimental setup

The experiment system which provide liquid at different flow rate and temperature was built. As shown in Fig. 5, it includes a pump, a standard magnetic flowmeter, a standard temperature sensor, a standard pressure sensor, a water tank, a heating rod, a control box and our proposed sensor. The flow rate and water temperature were controlled by the control box.

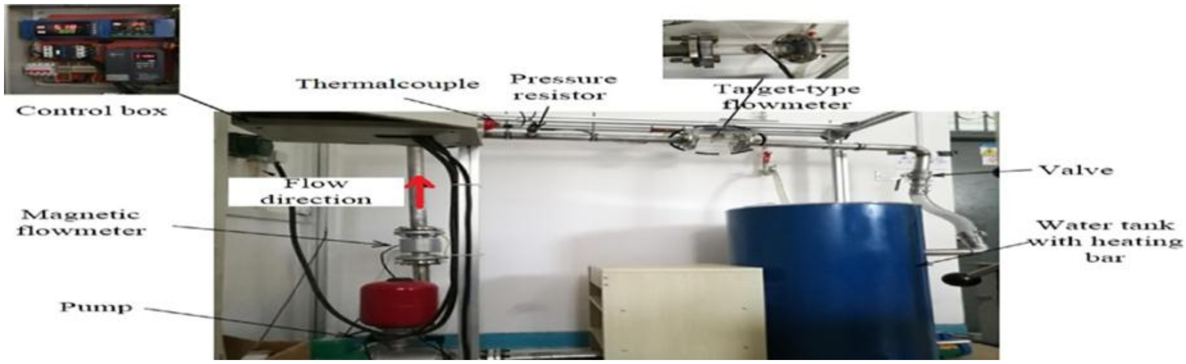

Fig. 5. The experiment system to provide liquid with different flow rate and temperature

The standard magnetic flowmeter (a product of Be-I, Fe-I Automation Instrument with accuracy of 0.3% in the range of 2–20 m3/h, and its operating temperature range is −20 °C to 60 °C) was applied as the calibrate instrumentation for the flow measurement of the proposed optical fiber sensor. The temperature sensor is applied to correct the temperature characteristic of the proposed sensor. The sensor was fabricated according to the previous description. And the fixture of the FBGs is the focus of sensor production. Make sure that the two FBGs are not wrapped in the capillary tube. The central reflection wavelengths of the two FBGs were 1554.216 nm and 1558.110 nm respectively at room temperature, which is aimed to achieve the differential measurement. Their grating lengths were 5 mm.

Global fibre optics industry

The shifting dynamics supporting this growth makes it critical for businesses in this space to keep abreast of the changing pulse of the market. Poised to reach over US$4.9 Billion by the year 2025, Single mode will bring in healthy gains adding significant momentum to global growth. Representing the developed world, the United States will maintain a 8.3% growth momentum. Within Europe, which continues to remain an important element in the world economy, Germany will add over US$133.3 Million to the region's size and clout in the next 5 to 6 years. Over US$108.8 Million worth of projected demand in the region will come from Rest of Europe markets. In Japan, Single mode will reach a market size of US$266 Million by the close of the analysis period. As the world's second largest economy and the new game changer in global markets, China exhibits the potential to grow at 12.4% over the next couple of years and add approximately US$787.3 Million in terms of addressable opportunity for the picking by aspiring businesses and their astute leaders. Presented in visually rich graphics are these and many more need-to-know quantitative data important in ensuring quality of strategy decisions, be it entry into new markets or allocation of resources within a portfolio. Several macroeconomic factors and internal market forces will shape growth and development of demand patterns in emerging countries in Asia-Pacific, Latin America and the Middle East. All research viewpoints presented are based on validated engagements from influencers in the market, whose opinions supersede all other research methodologies.

RESULTS AND DISCUSSION

Temperature sensing property

Firstly, the sensor's temperature characteristic was analyzed by the experiment. The temperature calibration was carried in an insulation cup which has the merit of slow temperature change. TFX430 Precision Thermometer (Ebro) with the accuracy of ± 0.05 °C in the range of −100 °C to 500 °C was applied in the experiment. The temperature response curves of FBGs were shown in Fig. 6. The temperature sensitivities of FBG1 and FBG2 were 0.02750 nm/°C and 0.02600 nm/°C respectively, and their fitting degrees were more than 1.00000. The temperature sensitivity of the sensor is higher than that of the bare FBG because the stainless steel tube reducing the grating plays a role in sensitization. The stainless steel tube has a high thermal expansion which is larger than that of fiber, then it can stretch the FBG when the temperature changes. The temperature sensitivities of the two FBGs are theoretically the same. However, they are not consistent for that the manufacture condition have difference and the characteristics of the two FBGs are not identical. In order to make the sensor have a better performance, temperature compensation was adopted. Temperature compensation is achieved by multiplying the temperature sensitivity of a FBG by a factor such that the temperature sensitivity of the two gratings is the same. A comparison of temperature compensation and no temperature compensation is given in Fig. 7. We can see that the wavelength shift will reach 70 pm without temperature compensation, which will have an influence on the measurement of flow rate.

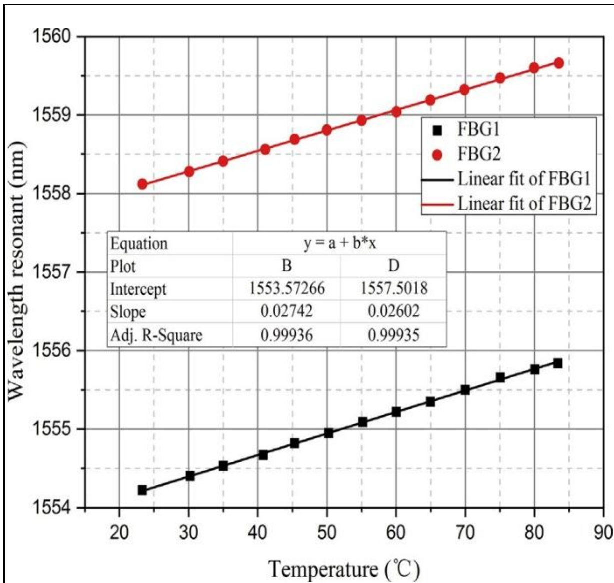

Fig.6.Temperature characteristics of the two FBGs. at

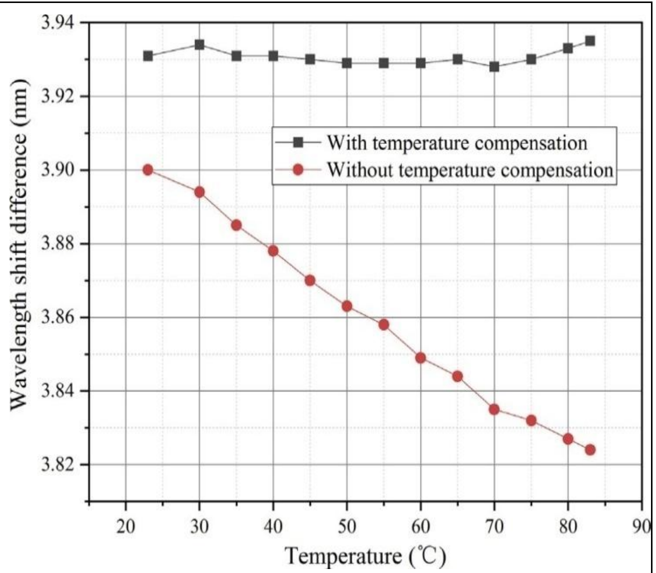

Fig.7.The response curves under different temperature with or without temperature at compensation at zero flow rate.

Flow rate sensing property

Then the flow rate sensing response curves were obtained by the experiment system. The proposed sensor was tested at the temperature of 20 °C. The frequency transformer was adopted to change the rotating speed of the pump, then the flow rate changed with the pump speed changing. By adjusting the frequency of the pump, the measurement range of proposed sensor could be up to 20 m3/h. With the increase of flow rate, the reflected wavelength of FBG1 shifted to the blue side, and that of FBG2 shifted to the red side. The relationship between resonance wavelengths and the flow rate was shown in Fig. 8. The lowest flow rate is about 5 m3/h because the flow sensor was installed horizontally and the fluid cannot fully developed under 5 m3/h. The total wavelength shift difference was up to 1 nm for the total range of 5–20 m3/h with the calibration according to the results of Fig. 9.

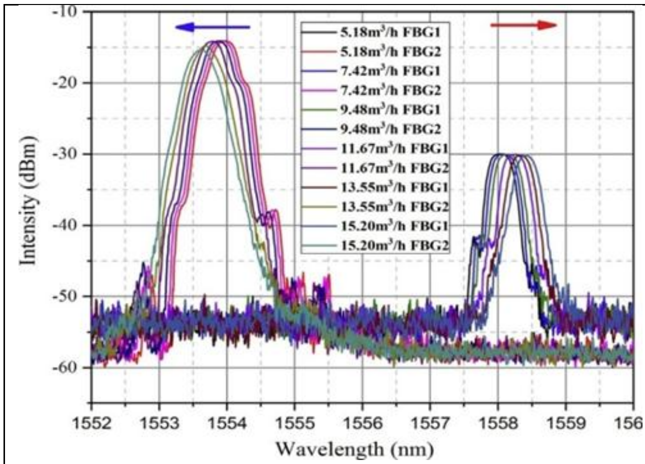

Fig. 8. Spectral shift diagram with different flow rate. resonance wavelength

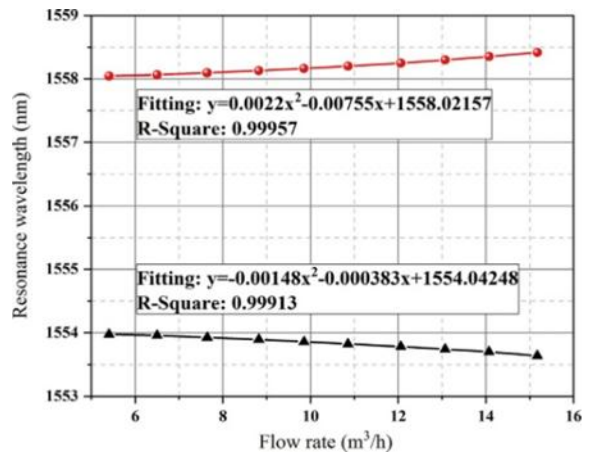

Fig. 9. The response curves of and flow rate.

Although there were some differences between experimental results and theoretical results, the relationship was mainly consistent with the theoretical result. The actual response sensitivity was less than that of theoretical results. The material of coating layer which protect the FBGs has a good toughness. Thus, the coating layer consumed part of strain in the transferring process. The negative strain grating is further away from the Capillary tube wall so that the strain sensitivity is lower than that of the positive strain grating. We tried to design a capillary with two holes for a better fixing of FBG, but the fabrication accuracy cannot meet the demand of it. Therefore, the fluid force in the experiment might be smaller than that in theory.

Repeatability experiment

After acquiring the target-type flow meter's characteristics of flow rate and temperature, the performance test was taken place. In order to examine the temperature decoupling effect of the sensor, the test experiments of flow measurement were carried out at different temperatures. The measurement range was from 15 °C to 60 °C. The performance of the sensor at different temperatures as shown in Fig. 10. The distribution of the flow rate deviation errors is shown in Fig. 11. The absolute deviation errors of flow measurement were less than0.25 m3/h in the measurement range of 5–20m3/h. The accuracy of the sensor is 2.25% according to the testing results, we can know that the flow rate repeatability of the sensor was good. Temperature measurement experiment was also carried out at 8 m3/ h by controlling the heating time of the heating rod, and the testing result is shown in Fig. 12. The upper temperature was 60 °C because of the limitation of the standard flowmeter's maximum operating temperature. As shown in Fig. 13, the measurement error is under ± 1 °C in the range of 25-90 o C.

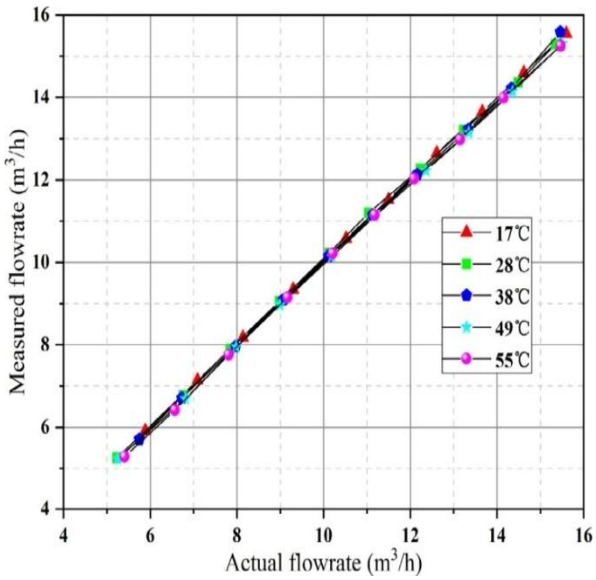

Fig. 10. The performance of flow measurement at different temperatures.

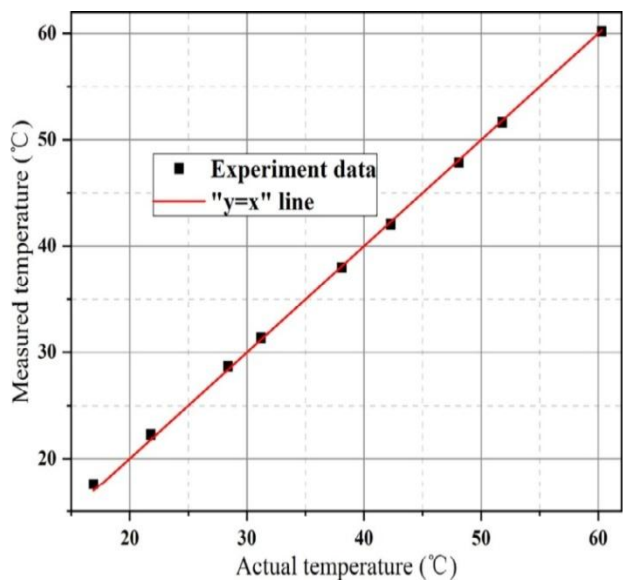

Fig. 11. The comparison of actual temperature and measured.

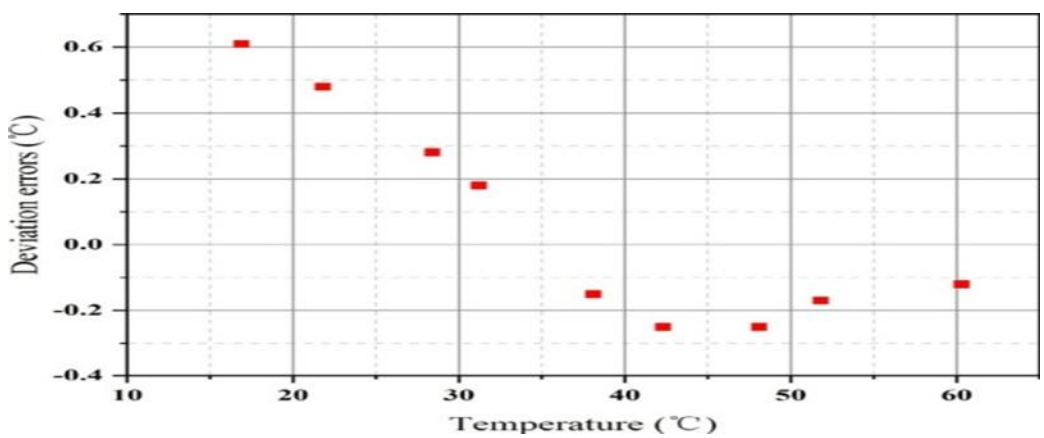

Fig. 12. The deviation errors of the measured temperature

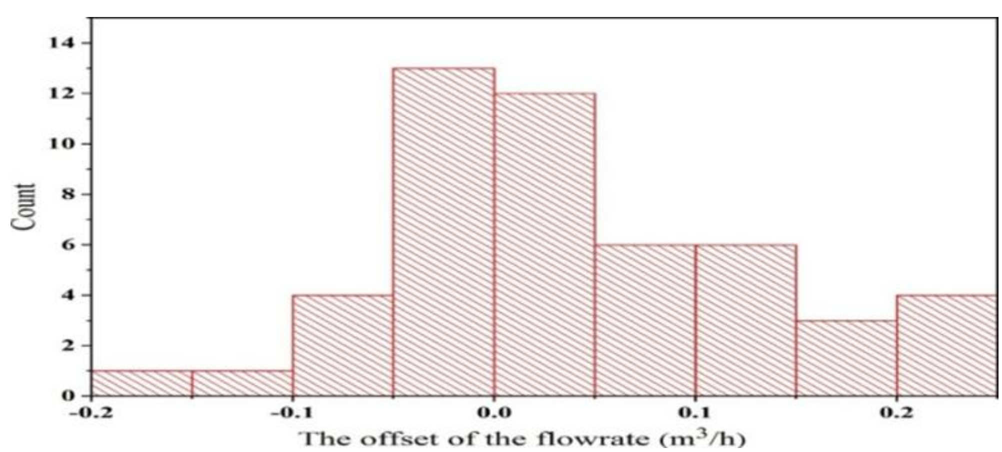

Fig. 13. The distribution of the flow rate deviation errors.

CONCLUSION

An optical fiber sensor which realized simultaneous measurement of flow rate and the temperature was developed; the flow rate and the temperature were measured by the shift of the wavelength. The capillary steel tube cantilever with a small target was more sensitive than that the sensor in last achievement. The FBGs which were applied for the measurement were fixed on the inner wall of the tube, and were protected effectively. The proposed flow meter could be applied to measure the flow rate from 5 m3/h to 20 m3/ h with the accuracy of 2.30%, and the temperature precision was under ± 1 °C in the range of 25–90 °C. Moreover, the proposed sensor has merits of small size, low-pressure loss, easy fabrication and steady structure, and it can be applied to some situations where the flow rate is required such as oil pipeline and chemical industry of the industry's largest tradeshows dedicated to photonic technologies. In Corning's Booth No. 2027, the company will feature demonstrations and new products that are enabling major emerging trends, such as augmented reality, 5G, and next-generation semiconductor manufacturing including. "We look forward to showing a variety of Corning's capabilities at Photonics West this year," "From high-quality, optical materials to precision and inspection equipment, our diverse range of products and design expertise meets our customer's needs at all steps of the semiconductor manufacturing process. We are proud of our well-established proficiency in this area and look forward to connecting with our industry colleagues at the show."

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