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A novel wind sensor concept based on thermal image measurement using a temperature sensor array

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Abstract

This paper presents a novel concept of designing wind sensors without moving parts. The measurement concept is based on the evaluation of the thermal image around a circular heater. Forced convection, caused by the wind, modulates this thermal image, which reveals information about both flow velocity and flow direction. The new concept uses an array of temperature sensors to capture the thermal image. Temperature data are transferred to a computer or a micro controller by a multiplexer. A program running on the computer extracts the values of speed and direction from the thermal image. The paper discusses different evaluation algorithms and compares their results. Three-point-estimators such as Gaussian estimator, peak centroid estimator, and parabolic estimator are used to improve the resolution of the direction measurement. The result of velocity measurement is also presented.

Keywords: Wind sensor; Direction sensor; Thermal flow sensor; Thermal imager

1. Introduction

Commercially available wind sensors are mainly based on a mechanical concept. These sensors measure the wind speed and the wind direction separately. Both, the speed sensor and the direction sensor, utilize drag force of the wind as the sensing principle. Thus the sensor design involves moving parts, which are large and may require frequent maintenance.

Other conventional sensors such as Pitot probes, hot-films, and hot-wires are only capable to measure point velocities [1]. Wind direction needs to be evaluated separately. Optical methods, such as laser doppler anemometry (LDA) and particle image velocimetry (PIV) need extensive measurement set-ups, which are not suitable for rough out-door applications [2,3].

Recently, a silicon-based thermal wind sensor was developed [4–8]. The sensor consists of four heaters and four thermoelectric sensors, which are integrated with evaluation electronics in a single silicon chip. This concept uses two sensor pairs for sensing orthogonal components of the flow velocity. The flow direction is evaluated from the arctangent function of these components.

The wind sensor concept presented in this paper is also based on the thermal principle. However, the sensor consists of a single heater and an array of temperature sensors. There are no moving parts involved in this concept allowing small sizes and robust operation. A similar approach using an array of integrated hot-wires for measuring the shear stress image on a surface is presented in [9].

The novelty of our concept is the evaluation method of the flow direction. The concept works for all flow ranges and does not depend on the accuracy of the velocity measurement. Instead of measuring a single temperature value, the sensor collects a large number of values, the thermal image, which is evaluated by corresponding algorithms to extract the desired variables such as velocity and direction. Modern micro controllers and signal processors are capable to process such algorithms in real time. The thermal image can be evaluated and recognized without extensive calibration. And that in turn could make robust operation possible.

2. Measurement concepts

2.1. Wind direction measurement

The new wind sensor concept is based on the fact that the peripheral temperature distribution around a circular heater

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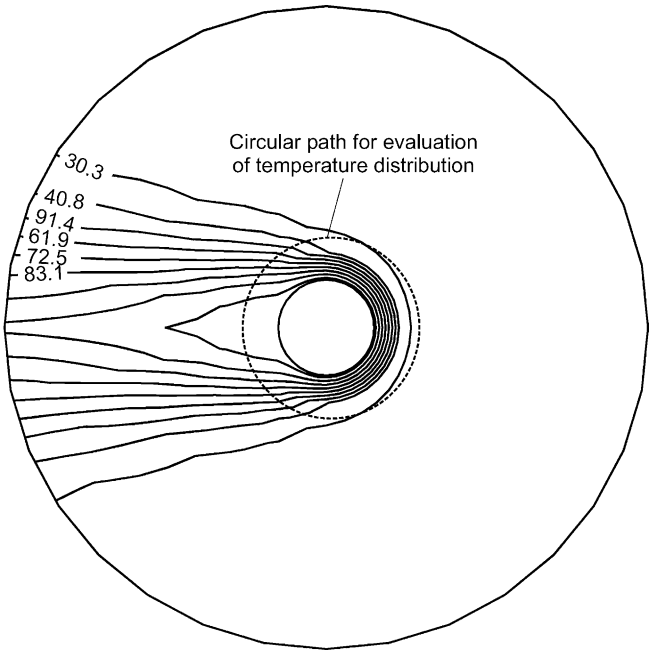

Fig. 1. Simulated temperature distribution around a circular heater (heater temperature: 120 °C, ambient temperature: 20 °C, flow velocity: 50 mm/s, direction: 180°). The circular path for the temperature distribution shown on Fig. 2 is indicated.

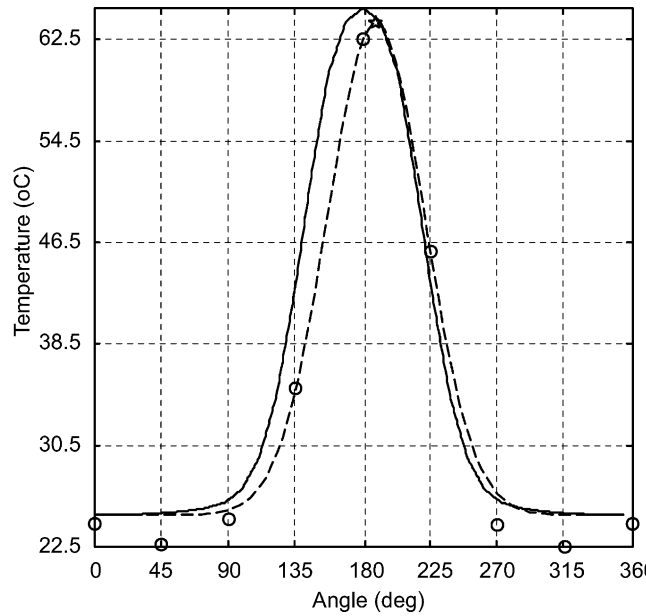

Fig. 2. Comparison between the simulated temperature profile (—), the fitting Gaussian function (- - -), and the measurement results (○).

under forced convection is similar to a Gaussian distribution function. Fig. 1 shows the simulated temperature distribution around a circular heater. The heater has a diameter of 1 cm, the heater temperature is fixed at a constant temperature of 120 °C. A constant air velocity of 50 mm/s under a flow direction of 180° was applied for this simulation.

Fig. 2 compares the results of the temperature distribution along the evaluation path as depicted in Fig. 1. This circular path has a diameter of 1.9 cm. The circles represent experimental results obtained under the same conditions as for the numerical simulation. The temperature sensors are fixed on the path at an angular spacing of 45°. More details on the measurement are given later in Section 3. By detecting the maximum temperature $T_{\max}$ of the profile shown in Fig. 2, the flow direction can be determined. The resolution of this method is limited by the angular spacing of 45°. However, if we assume a fitting function for the measured profile, the temperature peak can be estimated and the direction results can be refined to better than 45°. The difference between the measured temperature T_n of sensor n and the ambient temperature T_0:

$$\Delta T_n = T_n - T_0 \tag{1}$$

is considered for estimating the direction angle. With the direction angle θ, the fitting function $\Delta T(\theta)$ along the circular path around the heater can be described as a Gaussian distribution function:

$$\Delta T(\theta) = \Delta T_{\max} \exp\left[-\frac{(\theta - \theta_{\max})^2}{2\sigma^2}\right] \tag{2}$$

where $\Delta T_{\max}$, $\theta_{\max}$ and σ are the peak value, the corresponding direction angle at the peak, and the variance, respectively. With assumption (2) and three known measured points $(\theta_1, \Delta T_1)$, $(\theta_2, \Delta T_2)$ and $(\theta_3, \Delta T_3)$, the direction angle at the peak can be estimated as:

$$\theta_{\max} = \frac{(\theta_2^2 - \theta_1^2)\ln(\Delta T_2/\Delta T_3) - (\theta_3^2 - \theta_2^2)\ln(\Delta T_1/\Delta T_2)}{2[(\theta_2 - \theta_1)\ln(\Delta T_2/\Delta T_3) - (\theta_3 - \theta_2)\ln(\Delta T_1/\Delta T_2)} \tag{3}$$

ΔT_2 is the largest value of the three measured points. The variance σ and subsequently the maximum temperature difference $\Delta T_{\max}$ can be estimated as

$$\sigma = \sqrt{\frac{(\theta_1 + \theta_2 - 2\theta_{\max})(\theta_2 - \theta_1)}{2\ln(\Delta T_1/\Delta T_2)}} \tag{4}$$

$$\Delta T_{\max} = \frac{\Delta T_1}{\exp[-(\theta_1 - \theta_{\max})^2/2\sigma^2]} \tag{5}$$

The star in Fig. 2 represents the estimated temperature peak after refining with the above estimation method. This concept yields a resolution better than the geometric resolution of 45° of the actual measurement.

The Gaussian estimator described above was borrowed from conventional PIV-techniques, where it is used for achieving sub-pixel resolutions [10]. According to PIV, simpler fitting algorithms such as peak centroid estimator:

$$\theta_{\max} = \frac{\theta_1\Delta T_1 + \theta_2\Delta T_2 + \theta_3\Delta T_3}{\Delta T_1 + \Delta T_2 + \Delta T_3}, \tag{6}$$

and parabolic estimator:

$$\theta_{\max} = \theta_2 + \frac{\Delta T_1 - \Delta T_3}{2\Delta T_1 - 4\Delta T_2 + 2\Delta T_3} \tag{7}$$

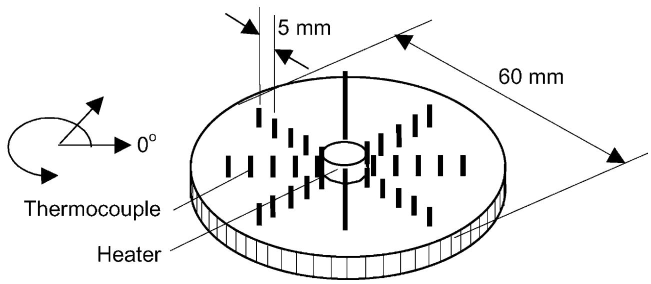

Fig. 3. Configurations of the wind sensor.

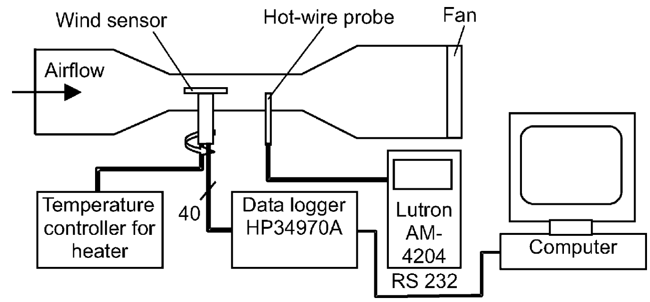

Fig. 4. Configuration of the measurement set-up.

can also be used for determining the position of the temperature peak. In PIV, all these techniques are referred to as three-point estimators.

2.2. Flow velocity measurement

The flow velocity can be evaluated with the average temperature across the sensor array:

$$\bar{T} = \frac{1}{N}\sum_{n=1}^{N} T_n \tag{8}$$

where N is the total number of temperature sensors in the array.

3. Measurement results

3.1. Sensor configuration

The sensor prototype consist of a circular heater and forty temperature sensors positioned in five concentric rings (a 5 × 8 array), Fig. 3. The radiant spacing between each ring is 5 mm. The innermost ring is 4.5 mm apart from the heater. Although only the innermost ring was used for evaluating the flow direction, other rings of the sensor array can are used for taking the thermal image and for evaluating the flow velocity.

The heater and the sensors are mounted on an aluminum disc, which is 6 cm in diameter and 1 mm in thickness. The

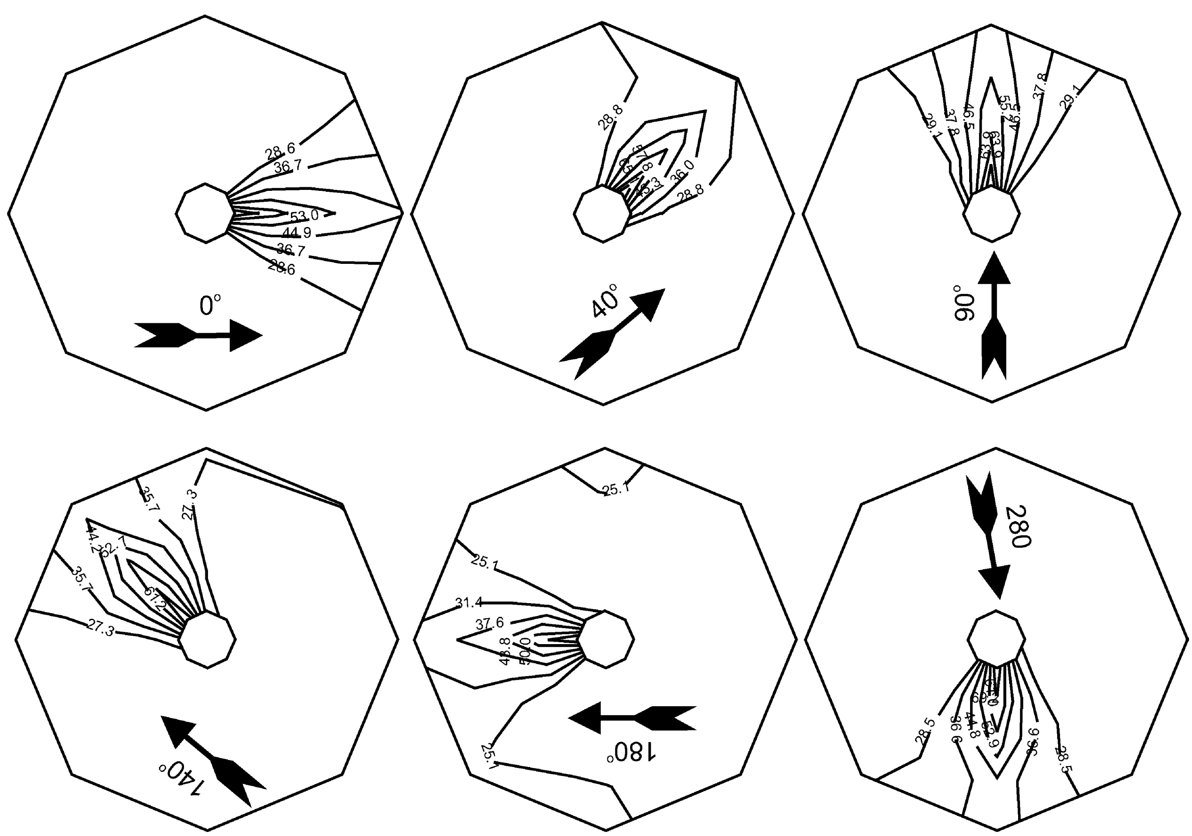

Fig. 5. Measured temperature distribution at different direction angles and a constant flow velocity of 50 mm/s (5 × 8 array, heater temperature 120 °C).

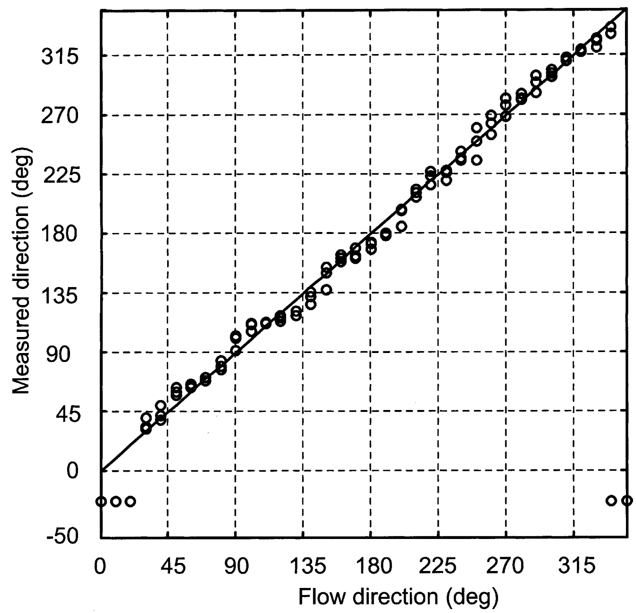

Fig. 6. Measured flow direction vs. actual values (3 data sets, Gaussian estimator, air velocity of 50 mm/s, heater temperature 120 °C, ambient temperature 25 °C).

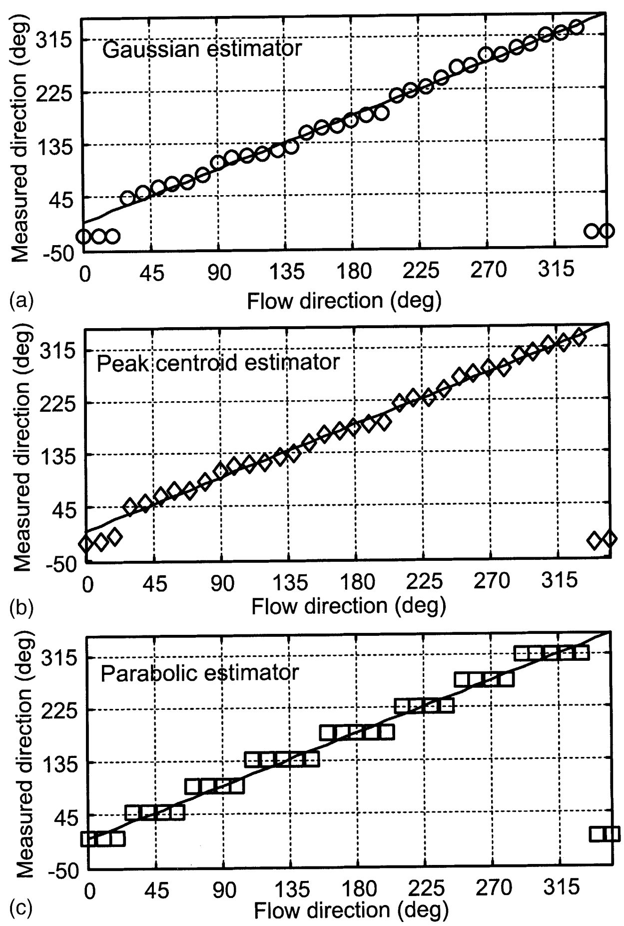

Fig. 7. Measured win direction vs. actual values, air flow velocity 50 mm/s, heater temperature 120 °C: (a) Gaussian estimator; (b) peak centroid estimator; (c) parbolic estimator.

heater is a cylindrical steel rod of 1 cm diameter containing a resistive heater and a K-type thermocouple, which allows feedback control to keep the heater temperature at a constant value. The geometric parameters of the wind sensors are depicted in Fig. 3.

The temperature sensors are K-type thermocouples, which are connected to the multiplexer board of the data acquisition unit HP 34970A. The acquisition unit in turn is linked to a personal computer by the serial interface RS-232. The temperature image on the disc is scanned and sent to the personal computer, where the data is processed by programs written in MATLAB. The pictorial schematic of the setup is shown in Fig. 4.

3.2. Characterization

The sensor was characterized in a wind tunnel, Fig. 4. The flow velocity was calibrated with the help of a hot wire anemometer (Lutron AM-4204). The flow direction was emulated by rotating the sensor relatively to the flow direction in the wind tunnel.

Fig. 5 shows the measured two-dimensional temperature distribution on the sensor disc at different direction angles and at a constant flow velocity of 50 mm/s. The measured results agree well with the simulation shown in Fig. 1. The wind direction can be clearly recognized by the measured thermal image.

The algorithms described in Section 2.1 were utilized for evaluating the direction angles. Because the innermost ring of the array always has the highest temperature, only its eight temperature sensors were evaluated. After determining the position of the temperature peak with a search algorithm, the resolution is improved by the method described in

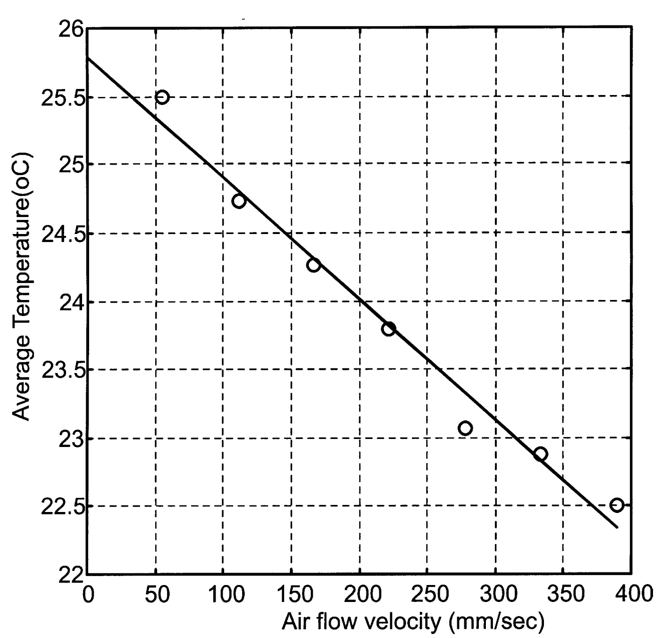

Fig. 8. Measured average temperature vs. flow velocity.

Section 2.1. Fig. 6 shows the measured direction angles versus the actual direction values. Three data sets of the same measurement conditions are presented. Results of angles at around 0° or 360° are not reliable because of the uncertainties at these two extreme values of the measurement range.

Fig. 7 compares results of the different estimators. While the Gaussian estimator (3) and the centroid estimator (6) result to almost the same, highly resolved direction values, the parabolic estimator (7) shows no improvement in resolution.

Measured temperature values were used for determining the flow velocity. While conventional hot-film sensors measure the dissipated heating power at a constant heater temperature or the heater temperature at a constant heating power, our sensor evaluates the average temperature across the entire sensor array. Despite the constant heater temperature, the average temperature above the sensor disc decreases with the increasing flow velocity. The average temperature was calculated according to (7). Fig. 8 shows the measurement results of the 5×8 sensor array.

4. Conclusion and future works

This paper presents a new concept of measuring the velocity and the direction of the wind. The concept is based on the measurement of the entire thermal image using an array of temperature sensors. This new concept allows designing wind sensors without moving parts. Gaussian estimator and centroid estimator suit best for the improvement of the resolution of the direction measurement. For determining the flow direction only a single sensor ring around the heater is needed. Future works would deal with the optimization of the number of the temperature sensors, because the concept of three-point estimators does not necessarily work well with a larger number of sensors or with a small angular spacing. A sensor, fully integrated in silicon, would offer fast response time and better accuracy for this concept. Furthermore, monolithically or hybrid integrated multiplexer and signal processor can be placed in the same sensor chip. The evaluation algorithms presented in this paper can be implemented in real-time with such a signal processor. The small size and consequently the resulting sensitivity promise applications of the sensor for very low flow velocities.

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Biography

Nam-Trung Nguyen was born in Hanoi, Vietnam, in 1970. He received his Dipl. Ing. and Dr. Ing. Degrees from Chemnitz University of Technology, Germany, in 1993 and 1997, respectively. In 1998 he worked as a postdoctoral research engineer in the Berkeley Sensor and Actuator center (UC Berkeley, USA). Currently, he is an Assistant Professor with the School of Mechanical and Production Engineering of the Nanyang Technological University in Singapore. His research is focused on microfluidics and instrumentation for flow measurement and biomedical applications. He published a number of research papers on microfluidics. His recent book “Fundamentals and Applications of Microfluidics” co-authored with S. Wereley was published by Artech House in October 2002.