Non-intrusive Temperature Measurement of Curved Surface Using Laser Interferometer and Computer Tomography

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Abstract In manufacturing process of polymer film, optimization of temperature control is required for improving both the productivity and the quality of the product. The accurate measurement of temperature is desired when molten polymer is going to be film. An intrusive measurement by using thermometer such as thermo couples has difficulty because the thickness of molten polymer blown out from the ring die is less than 1 mm. Also the temperature measurement with infrared camera is not appropriate because the polymer film is lightly transparent for the infrared radiation and thus the intensity of infrared radiation from the polymer film is too weak. A novel method of non-intrusive temperature measurement is therefore required. In this research, we proposed a novel method for non-intrusive temperature measurement with laser interferometer and Computer Tomography (CT), and discussed its applicability for measuring the temperature distribution on a curved surface. In the method, phase variation of fringe pattern resulted from variation of refractive index of air in the adjacent to the curved surface was converted to temperature variation. The measurements were conducted under natural and forced convective flows around the surface by using CT, reconstruction process of the fringe pattern. As a result, it was confirmed that the optical measurement of temperature distribution on a cylinder surface can be measured to an accuracy of a few degrees in natural convection flow around the measuring surface. In forced convection, however, the relative error of the temperature increases up to 30 % because of this thermal boundary layer around the curved surface.

1. Introduction

Today, polymer film becomes increasingly sophisticated and the cost of its raw material that consists of fossil fuel becomes higher[1-3]. Thus it is required to produce polymer film accurately and to improve the productivity and the quality. Figure 1a and Figure 1b show the typical shape of molten polymer in film manufacturing processes. The method shown in Figure 1a and Figure 1b are called inflation method and T-die method respectively. In the inflation method, the polymer melt blown out from a ring die is swollen by the internal air pressure blown into the tube and is cooled by the surrounding jets at the same time. In the T-die method, the polymer melt is formed in the T-die and stretched by the drawing roll.

The inflation method is more productive than the T-die method so as to do film-forming and drawing simultaneously. However control of the thickness of the product and monitoring the temperature is more difficult. Above all, temperature control of the molten polymer in cooling process is very important for the productivity and the quality of the product. Since molten polymer blown up from the ring-die is very thin and easily changes its own shape, the intrusive thermometers, such as thermocouple, could not be used. It is also difficult to use implement measuring infrared radiation such as thermo-camera because the polymer film is lightly transparent for the infrared radiation.

Therefore a novel temperature measurement method, which can be applied for polymer film manufacturing process, is required. In this research, a new method using laser interferometer and Computer Tomography (CT)[4-6] was proposed, and its applicability for measuring the temperature distribution on curved surfaces was experimentally examined.

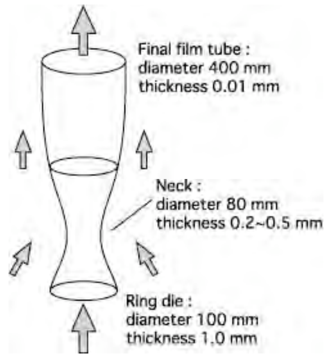

Figure 1a: Inflation method. Molten polymer blown out from ring die and is cooled by surrounding air jets simultaneously

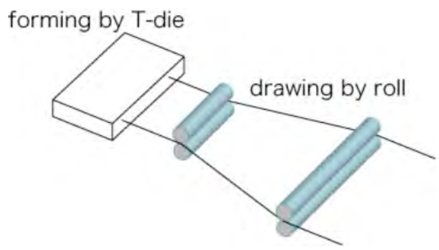

Figure 1b: T-die method. Molten polymer is formed by T-die and stretched by drawing roll.

2. Principle of the system and Experimental set up

In order to measure the temperature profile on curved surface of the polymer tube, the temperature of air surrounding the surface was measured[7][8]. The surface temperature and the air temperature in vicinity of wall surface are considered to be equal from the viewpoint of heat transfer as shown in Figure 2. Therefore the surface temperature can be determined by the refractive index distribution in the air in vicinity of the surface. To obtain the refractive index distribution, laser interferometer is used in this research. One laser beam passes through the air near the surface and the other is reference one. Both beams are merged again by the beam combiner and interfere with each other on the imaging plane. The fringe patterns which recorded in circumferential direction were reconstructed by CT. The experimental range of surface temperature was from room temperature (= 23˚C) to 250˚C approximately.

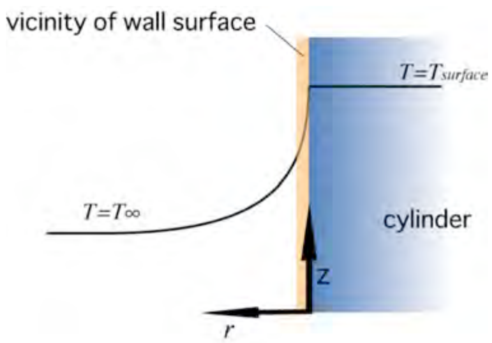

Figure 2: The temperature in the vicinity of cylinder surface.

Figure 3 shows the finite fringe patterns captured at the different surface temperature. Phase shift distribution of the fringe images were analyzed by Hilbert transform[9] by which the detailed pixel-by-pixel phase distribution could be obtained in contrast to the conventional ridgeline detection and interpolation. The phase shift quantity ϕ between fringe images arises from the integration of the refractive index difference $n - n_0$ divided by the wavelength of the light source λ. The integrating direction x is tangential direction of the surface.

$$\phi = \frac{2\pi}{\lambda} \int (n - n_0) dx \tag{1}$$

Under the assumptions that both the Gladstone-Dale relation for refractive index and ideal gas laws can be applied to the fluid:

$$n = 1 + K\rho \quad (2)$$
$$P = \rho RT \quad (3)$$

where K, n and ρ are the Gladstone-Dale constant, the refractive index and the density of gas respectively. P, R and T represent the pressure, the gas constant and the absolute temperature, respectively. Due to the equations (1), (2) and (3), the surface temperature T_s obtained from the phase shift quantity ϕ between the fringe images.

Two experiments are conducted in this research. First experiment was performed so as to confirm applicability of the CT reconstructing technique for a cylinder surface which has circumferential temperature distribution. Second experiment is conducted for confirming the feasibility of measurement of the curved surface temperature of in forced convection flow. Figure 4 shows the set up for the first experiment with Mach-Zehender interferometer. In this experiment, He-Ne laser was used for its good coherency. A circular cylinder having circumferential temperature distribution was used as the test curved surface. A portion of the cylinder was heated by an electric heater and the other portion was cooled by the water flow. Eight thermocouples fixed on a certain location of its surface simultaneously monitored the surface temperature of the cylinder. The cylinder was rotated by 360˚ to capture the interferograms from various directions around the cylinder by using the fixed optical setup. Diameter and rotation rate of the cylinder were 60 mm and 0.5 rad/s respectively. Under the experimental configuration, beam bend due to the spatial temperature gradient was negligible. The finite fringe patterns were recorded by using a CCD camera at each 1˚ of rotation of the cylinder. Spatial resolution of the temperature was 0.3 mm for radial and axial axis, 0.5 mm for angular direction. The first experiment is conducted under natural convection of the surround air. The other specifications of the optical setup are shown in Table 1.

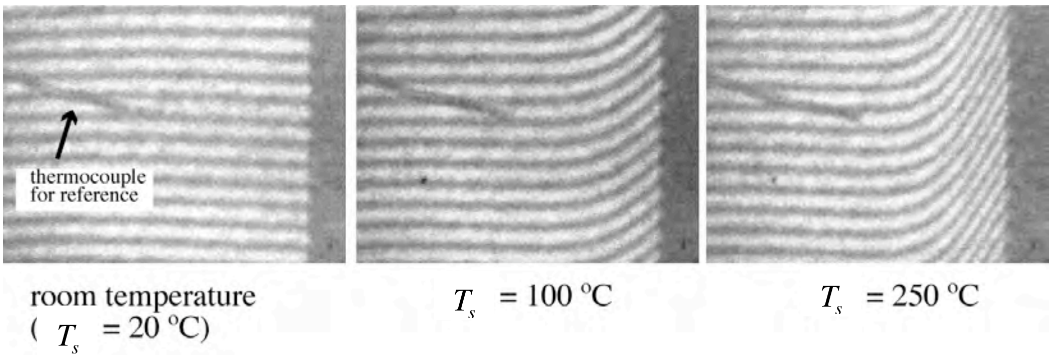

Figure 3: Captured finite fringe images at different surface temperatures. Ambient air temperature, T_∞, was equal to 20˚C. An inclined shaded line in the images is a thermocouple for the reference temperature measurement.

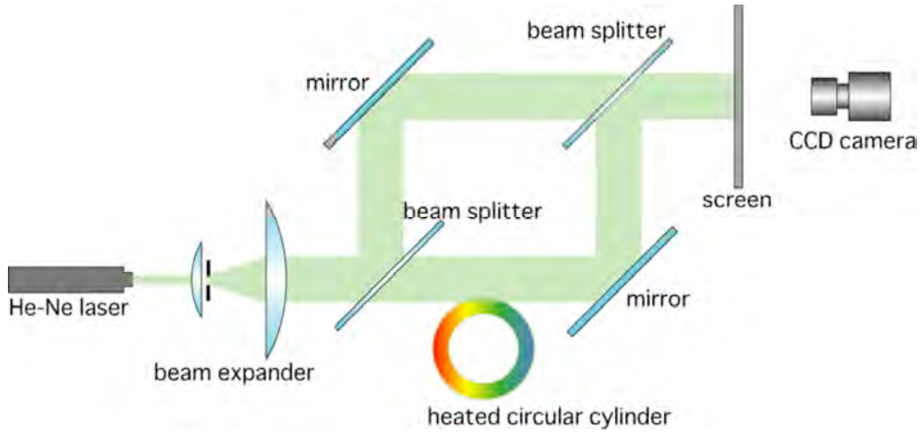

Figure 4: Mach-Zehender interferometer.
The surrounding area of the heated cylinder is in natural convection.

Table 1: Specifications of experimental setup in the first and second experiment.

Mirror		
	diameter	100 mm
	surface flatness	1/20 λ
Beam splitter		
	diameter	100 mm
Beam expander		
	magnification rate	25
He-Ne laser		
	wavelength	632.8 nm
	optical output	10 mW
Nd:YAG laser		
	wavelength	532 nm
	optical output	500 mW
Ar^+ laser for PIV		
	wavelength	514.5, 488.0 nm
	optical output	< 5 W
CCD camera		
	pixel	640×480
	frame rate	30 fps
	bit number	8
High-speed camera module		
	pixel	512×512
	frame rate	~100000 Hz
	bit number	8

Figure 5 shows the second experimental setup with Michelson interferometer using YAG laser, which has higher output power and shorter wavelength compared with He-Ne laser. The spatial resolution was 16 μm for radial and axial axis, 16 μm for angular direction. The sensitivity of Mach-Zehender interferometer is twice as high as of Michelson interferometer because the two optical passes passed near the cylinder. This experiment was conducted in forced convection of the surrounding air, which was made by the device as shown in Figure 6a. The air was blown up to the cylinder through air tubes fixed around the cylinder. The flow velocity was controlled within a range of 2 m/s. The air tubes blowing the air were set around the cylinder as shown in Figure 6b. A Particle Image Velocimetry (PIV) system with Ar^+ laser was used for measuring the air velocity distribution around the cylinder. The tracing particle, smoke of incense sticks whose diameter was less than a few micrometers, was mixed in the air box. Laser sheet was illuminated from the upper side of the cylinder in order to prevent the laser beam reflection by the surface. The effective thickness of the laser sheet was 200 μm approximately. It should be considered that the laser used in PIV system must have high power because the tracing particle is very small and the measuring region has sharp velocity gradient. The second experiment conducted under a condition that the temperature distribution around the cylinder surface is constant in order to evaluate the effect of the flow field around the cylinder.

CT with the Hilbert transform was not used for reconstructing the temperature in the second experiment. Since the air temperature distribution around the cylinder was regarded as being constant, the total phase variation of the fringe patterns was transformed to radial refractive indexes distribution by using Abel transform method.

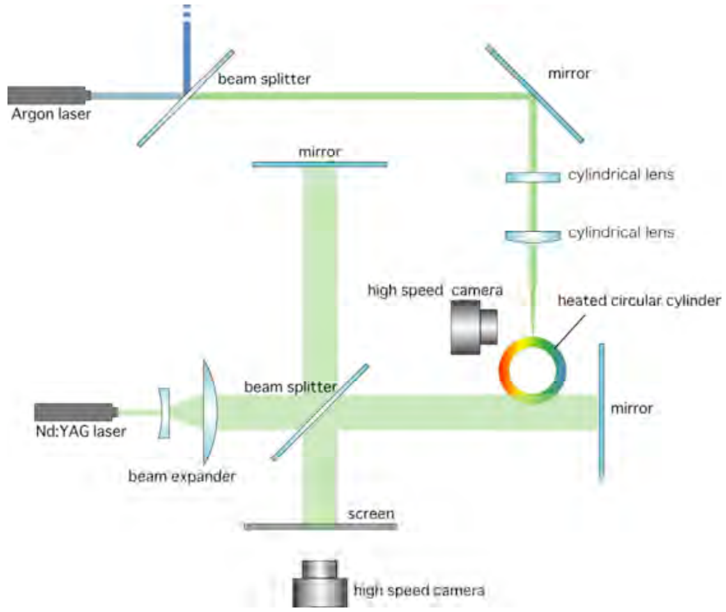

Figure 5: Second experimental setup using Michelson interferometer and PIV system. The air flow around the heated cylinder is forced convection.

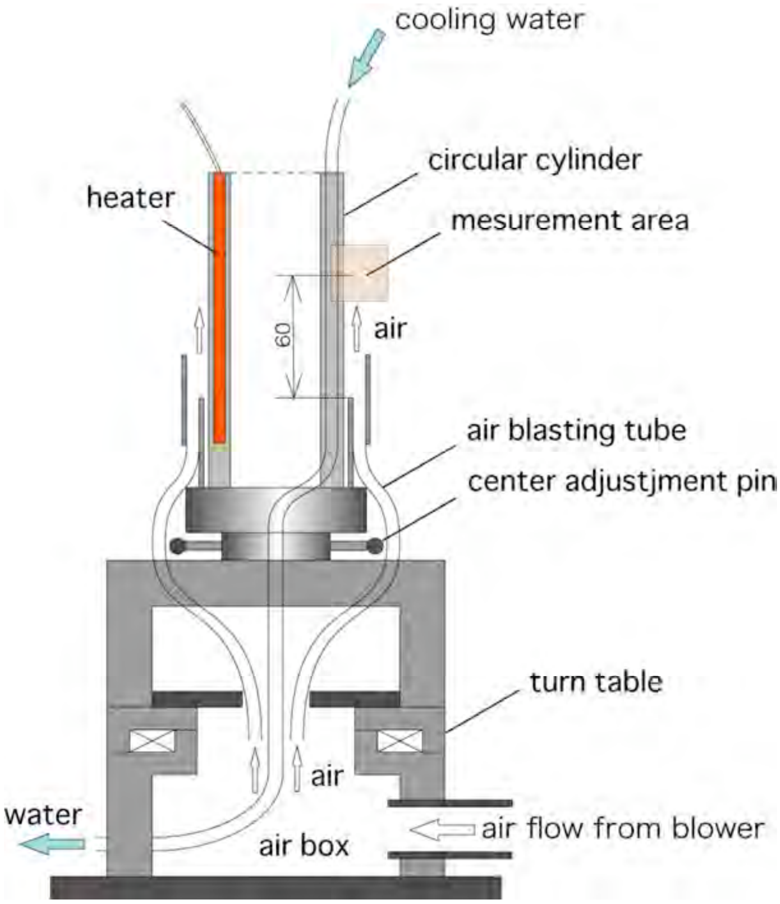

Figure 6a: An instrument makes forced convection around the cylinder.

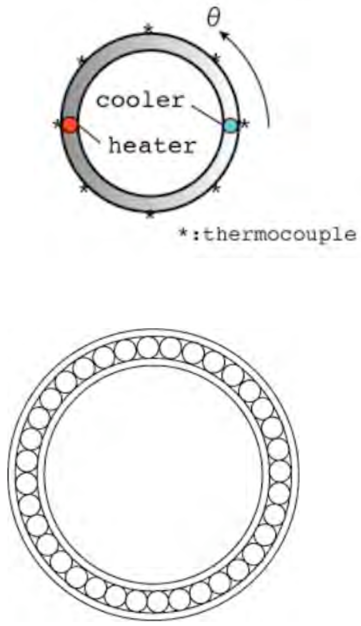

Figure 6b: Top view of the cylinder and the instrument, which makes forced convection around the cylinder used in the second experiment.

4. Results and Discussion

Figure 7 illustrates temperature distribution measured by the method in the first experiment when the highest temperature is 40 ˚C and the lowest temperature is 15.6 ˚C, which were measured by thermocouples. Figure 8 shows the result in the first experiment when the highest temperature is 90 ˚C and the lowest temperature is 40 ˚C. As shown in these figures, surface temperature T_s obtained by using the present method agrees very well with that measured by thermocouple. It is confirmed that the possibility of measuring the surface temperature distribution of the cylinder to an accuracy of a few degrees in the range from 10 ˚C to 100 ˚C. However, over 100 ˚C range, temperature discrepancy increased as the surface temperature rose.

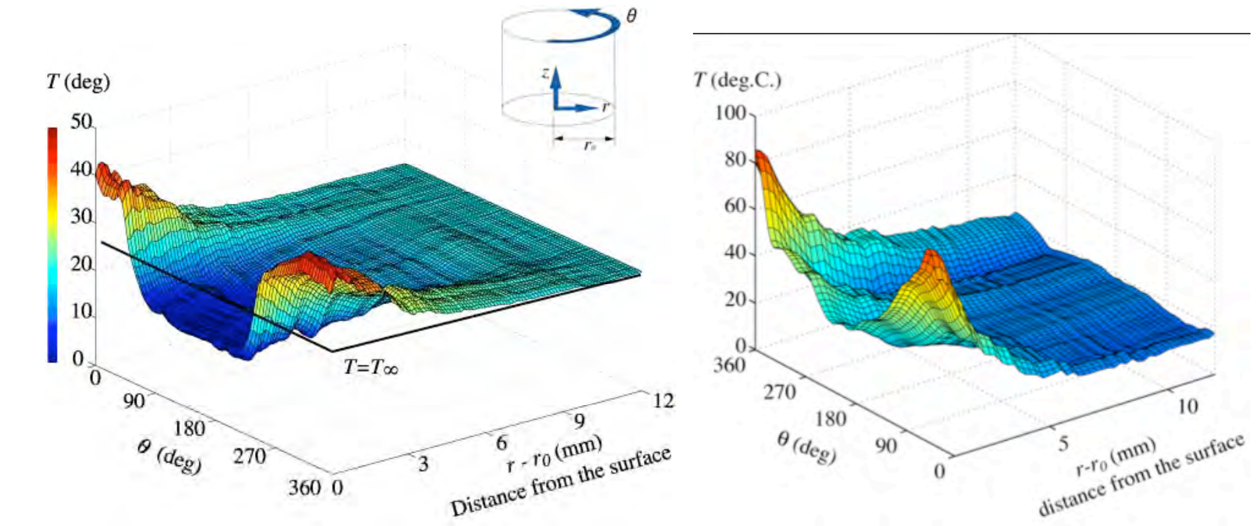

Figure 7a: The temperature distribution around the cylinder obtained by the first experiment. The highest temperature is 40 degrees and the lowest temperature is 15.6 degrees. Figure 7b: the highest temperature is 85 degrees and the lowest temperature is 20 degrees.

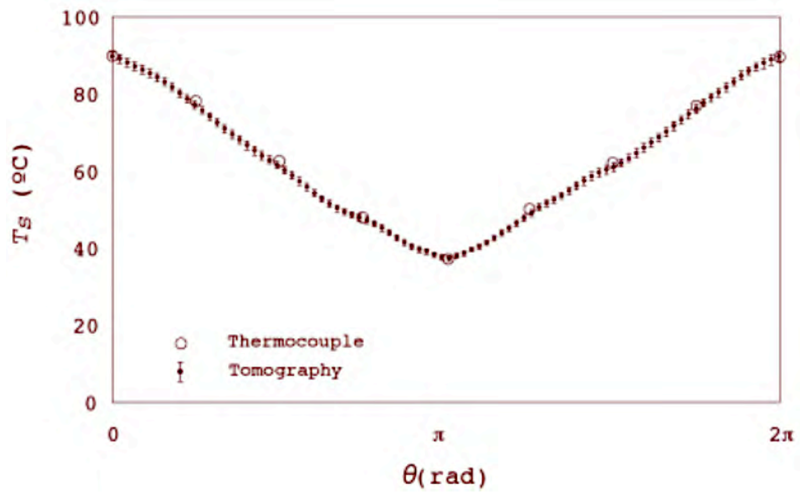

Figure 8: Comparison of measured surface temperatures by the method in first experiment and by the eight independent thermocouples fixed on the cylinder surface.

In the second experiment, 4 different flow rates were given by adjusting the electric blower. Although the flow rate was fixed during the velocity and temperature measurement, the velocity distributions shown in Figure 9 are not identical due to the properties of fluid such as kinematic viscosity due to the effect of natural convection. Flow rate A means that the velocity at the region 1.8 mm far from the surface is 0.3 m/s when the surface temperature is room temperature. B, C and D are defined 0.65 m/s, 0.85 m/s and 1.1 m/s respectively. N means the blasting velocity was 0 m/s. Figure 9 compares each air velocity distribution in the vicinity of the cylinder surface in various surface temperatures. Each different flow rates was regarded as a parameter in the discussion. Under the higher temperature or larger velocity, it becomes difficult to observe the fringe displacement in the vicinity region of the cylinder surface because of the thinner thermal boundary layer. The gradient of the fringe curve at the region of 0.48 mm from the surface was extrapolated so as to obtain the refractive index distribution in the vicinity region. Figure 10 shows the comparison of temperatures estimated by the extrapolation and those evaluated without the extrapolation. The reference temperatures captured by thermocouples were also shown in this figure. As shown Figure 10, the temperature evaluated without using the extrapolation is lower than the reference temperature as the surface temperature and the flow velocity gradient increased. After the extrapolating, the error between the obtained temperature and the reference one decrease.

Relative error of the evaluated temperature is defined as the temperature difference between the obtained temperature T_s and the reference one $T_{s,r}$ captured by the thermocouple divided by the temperature difference between the reference temperature and the room temperature T_∞.

$$relative \quad error = \frac{T_{s,r} - T_s}{T_{s,r} - T_\infty} \tag{4}$$

The relative errors correlating to the data shown in Figure 10 are shown in Figure 11. As shown in this figure, the relative error is decreased by adopting the extrapolation of figure curve in the vicinity region of the surface.

However, the relative error increases with increasing the flow velocity, and reached up to 30 %. This means that the gradient of the fringe pattern in the vicinity of the surface became higher than that extrapolated in the method as the air flow velocity increased.

It was obtained in the experiments that, the fringe image was distorted as the flow velocity increased. The amount of the distortion increased as the surface temperature became high. This is partially because the bending of laser beam due to large temperature gradient in the vicinity region of the surface. In this experiment, the temperature was reconstructed using CT by using an assumption that the laser beam could not be bent even in high temperature condition. However it is known that the laser beam is bent in the direction back away from the high temperature surface slightly. Therefore, in order to measure the surface temperature with more high accuracy, it is desirable that the extrapolation of fringe curve is achieved by using more appropriate function, and that the effect of bending of laser beam due to temperature gradient is taken into account.

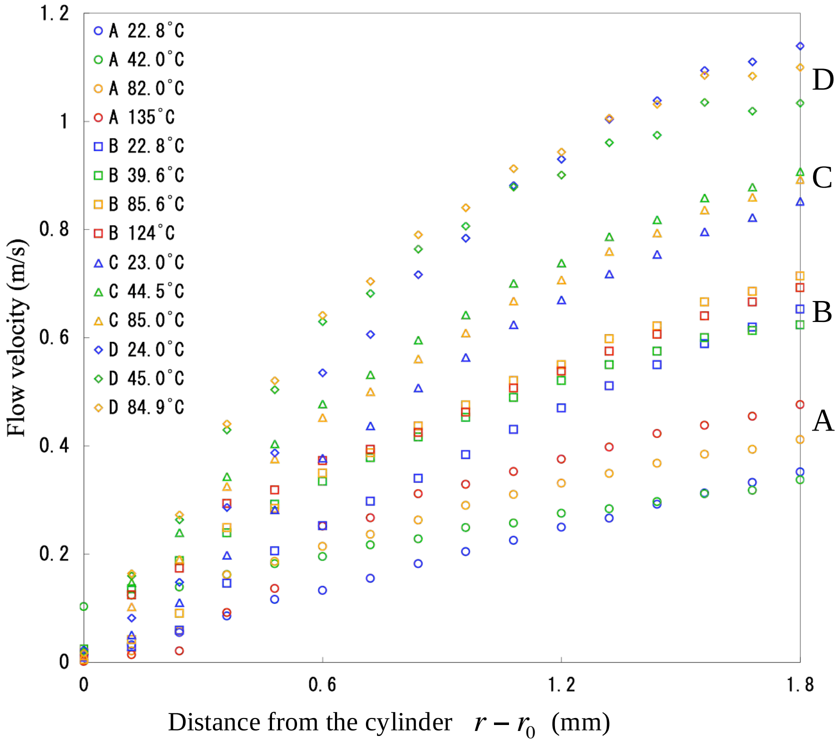

Figure 9: Velocity distribution of each condition near the cylinder surface. The horizontal axis and vertical axis are the distance from the cylinder surface and the flow velocity respectively.

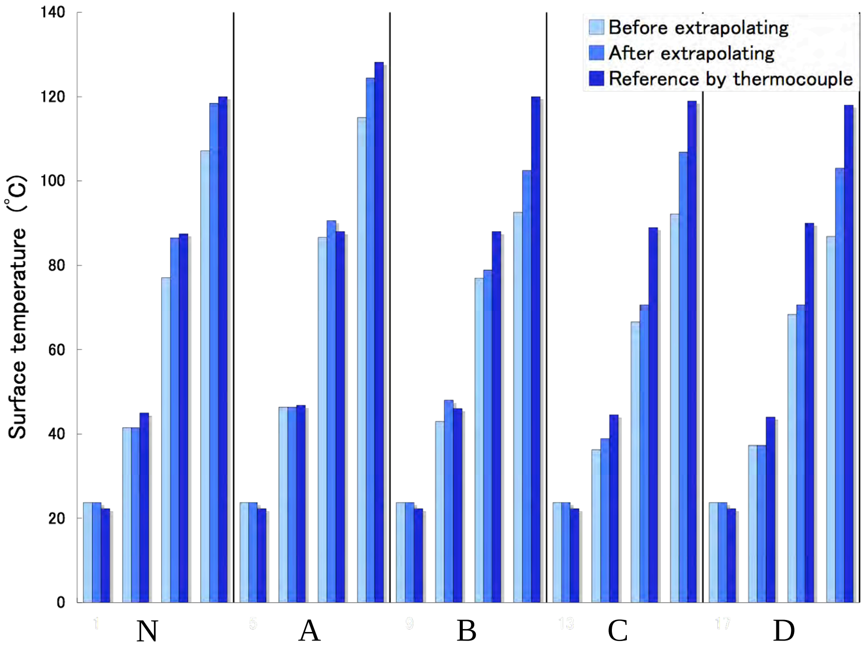

Figure 10: The temperature comparison among the temperature that was estimated by the method, the reference temperature captured by thermocouple, and the extrapolated temperature in different flow rates respectively. N means the condition that the blasting velocity is 0 m/s.

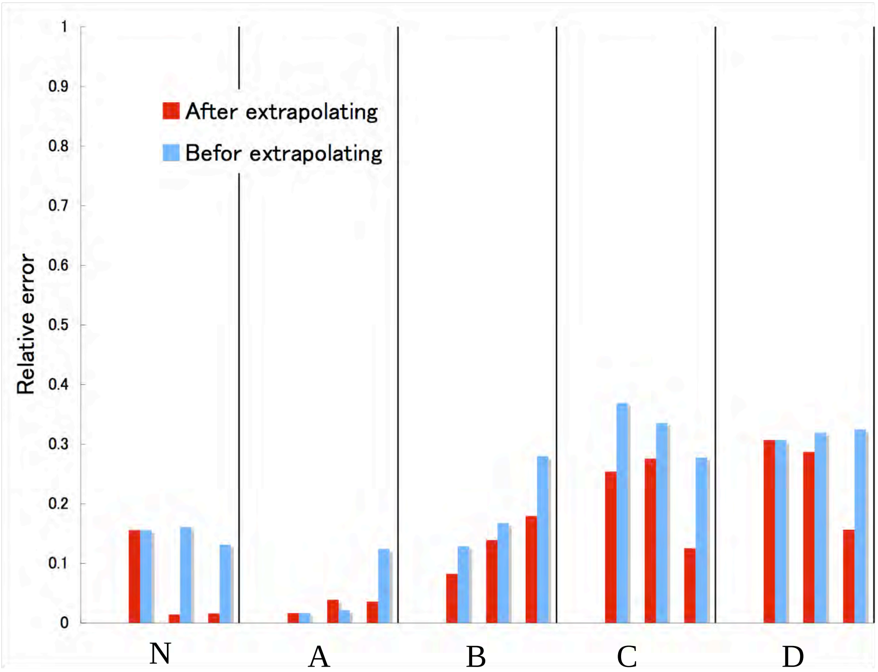

Figure 11: The relative error of the surface temperature obtained by the method. 4 flow conditions are shown in the horizontal axis correlate to Figure 9. N means natural convection.

5. Conclusion

In the research, a novel optical technique for measuring the temperature distribution on the surface of circular cylinder was developed. The feasibility of this method using laser interferometer and CT was firstly confirmed. The accuracy of the method is a few degrees within the range from the room temperature to 100 ˚C. It was also confirmed that the method could be applied to the measurement of surface temperature in forced convection flow up to 2 m/s in second experiment.

The base error between the temperature measured by the method and the temperature captured by the thermocouple still remains. And the error increased with increasing the surface temperature and the flow rate. The error is reduced by extrapolating the gradient of the fringe curve near the surface by referring to the gradient at 0.48 mm far from the surface. From the practical point of view, it is concluded that this technique could be applicable to measure the temperature distribution of the polymer tube in manufacturing process of inflation film blowing.

6. Reference

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