A Spatio-Temporal Measurement of Convective Heat Transfer Around a Body by Phase-shifting Interferometry

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論文内容要約

Chapter 1: General introduction and background

In this chapter, general introduction and background are presented. Convective heat transfer is ubiquitous and transp energy by fluid flow. This energy transport form carries large amounts of heat due to the heat capacity of the fluid. Thus, t energy transport plays a crucial role in engineering, industries and then oceanography, meteorology, astronomy, geology a other areas. There are two mechanisms according to the nature of flow; natural and forced convection. Natural convection one of the forms of convective heat transfer. It occurs in any place where a density difference including temperature a concentration differences and gravitational force exists. In contrast, convective heat transfer is called as forced convection wh external forces induce the flow. These transport phenomena can be observed in the nature and contributes advancements human life e.g. a typical application of both convection modes are utilization to cooling system for central processing unit (CPU). Numerous studies on convective heat transfer have been conducted to promote the heat exchange efficiency.

Fundamental questions on convective heat transfer still remain due to the lack of measurement techniques. An important thing in convective heat transfer is a mechanism of heat transfer between fluid flow and a surface. Previous studies produced a relation between the heat exchange rate and the convective flow structure by important dimensionless numbers. A number of theoretical and numerical studies dealt with the heat exchange mechanism and presented the temperature fields in detail. Experimental studies also treated the heat transfer, however, they offered only total heat exchange rate without showing the temperature structures. As a consequence, there is a need to develop new measurement techniques that yields reliable experimental data to gain a deeper understanding of convective heat transfer. A new measurement technique for convective heat transfer ought to enable to offer further information for the perspective, the detailed temperature structures and the temporal changes.

Optical flow visualization technique is focused to elucidate diverse convective heat transfer phenomena. Optical flow visualization technique has significant advantages compared with other measurement techniques i.e. the optical techniques has no effect on fluid flow and produces visual information. Various optical techniques have been proposed for those advantages;

however, each technique has not only advantages but disadvantages. A number of techniques are reviewed in this chapter. This study focuses on Mach-Zehnder interferometer and phase-shifting technique and defines the problems for further insight into convective heat transfer. Finally, this chapter presented the objectives and contents of this study.

Chapter 2: Measurement of natural convection by large aperture interferometry with mirror system

This chapter presents an establishment of large aperture phase-shifting interferometer with mirror system to visualize and measure natural convection. The developed interferometer consists of an original optical configuration with two concave mirrors, a rotating polarizer and an image processing unit for phase-shifting technique. This proposed optical system has features; large visualization area and high phase and spatial resolutions. The optical configuration with two concave mirrors was proposed to make large visualization area. The phase-shifting technique produces phase-shifted data with higher spatial and phase resolution than that of conventional interferometry. The rotating polarizer is utilized to implement the phase-shifting technique.

The optical flow visualization technique is applied to steady state natural convection from a vertical flat plate. The temperature structures are visualized with large visualization area. The visualization area is restricted in a diameter of approximate 100 mm due to aberration although the two mirrors have effective diameter of 280 mm. The thermal boundary layers are measured with high spatial resolution of 0.18 mm. The measured temperature profiles were used to validate the developed interferometer. First, the measure data were compared with analytical data and large differences were seen due to the three dimensional structure of thermal boundary layer. Second, comparison between the measured and numerical calculation data with regard to optical path length difference was conducted. The comparison results showed good agreements were obtained. Thus, the developed interferometer was validated. Finally, discussions on the effects of the three dimensional structure in interferometric measurement were given.

Chapter 3: Development of arbaa prism and its application

This chapter presented a proposal of a spatial phase-shifting technique with an original optical prism for transient measurement of convective heat transfer. The original optical prism is termed arbaa prism. The arbaa prism has a feature; the prism split an incident beam into four output beams at the same direction. Thus, the output beam can be acquired with one detector. This feature enables us to have more choices of detectors than previous techniques i.e. high-speed camera can be adopted. In addition, optical information is added to the output beams by attaching filters to the prism. This study attached three polarizers and a quarter wave plate to the prism to implement three step phase-shifting technique. Thus, this original prism is a key element to realize high-speed phase-shifting technique and high-speed heat transfer phenomena can be visualized and measured with high resolutions using the phase-shifting technique with the araba prism. This study developed three models of the araba prism. Each prism has characteristics by differences in the size, the aspect ratio of the output beams and the position of filters. An image processing program is also specially developed to implement the proposed phase-shifting technique. This processing program has a function that the arbitrary processing region can be defined because the output beams from the arbaa prism deform and geometric differences exist between the beams. The function can reduce processing errors due to the deformation. Additionally, this program offers both real-time processing and post processing. Thus, the combination of the araba prism and the processing program offers wide range of temporal resolution.

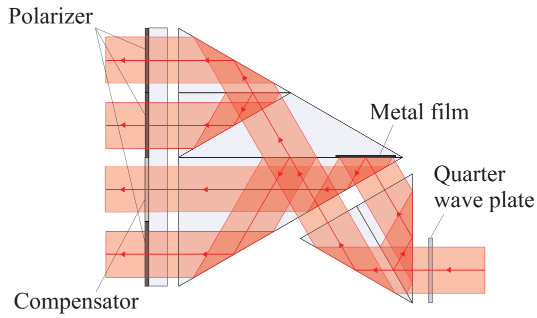

Fig. 1 Schematic of arbaa prism.

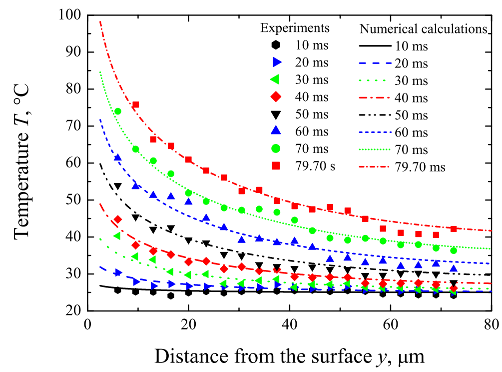

Fig. 2 Measured temperature profiles and numerical calculation results.

The arbaa prism and the image processing program are incorporated with a polarizing Mach-Zehnder interferometer to establish a high-speed phase-shifting interferometer. The high-speed phase-shifting interferometer was applied to high-speed heat transfer phenomenon: heat transfer around a heated thin wire. The characteristics of the heat transfer phenomenon are high-speed and micro scale phenomenon. Hence, the frame rate is increased to 300,000 fps and the visualization area size was 90 μm×210 μm. Accordingly, the spatial resolution was 3.5 μm. Temperature profiles around the thin wire were measured from the obtained phase-shifted data. Besides, numerical calculation on the heat conduction was conducted. The proposed phase-shifting method and the developed interferometer are validated by comparison between measured and numerical calculation data and good agreements were presented. A significant progress by the high-speed phase-shifting interferometer is a performance advance in the temporal resolution.

Chapter 4: Measurement of forced convection by large aperture interferometry with mirror system and wind tunnel

In this chapter, a large aperture phase-shifting interferometer is developed for visualization and measurement of forced convection. Based on the developed interferometer in chapter 2, a three dimensional optical path is proposed and introduced to integrate with a wind tunnel. The arbaa prism that has tolerance to various experimental conditions was adopted to implement the phase-shifting technique under an environment with vibration due to a wind tunnel. Two concave mirrors also introduced to make large visualization area and an aberration collection lens was made to reduce aberration effects observed in the chapter 2. The aberration collection lens was specially designed by measuring the distorted wavefront of the test beam with high resolution using phase-shifting technique. As a consequence, the visualization area was scaled up to approximate 200 mm in diameter.

Forced convection around a circular cylinder and a flat plate are visualized quantitatively using the developed interferometer. Visualization results on forced convection around a cylinder show a change of temperature structure induced by a change of separation point due to a tripping wire. The Reynolds number ranged from 9.5×10^{3} to 3.2×10^{4} and the change occurs at 3.0×10^{4}. These visualization results indicate that the interferometer enable to clarify transient temperature fields of forced convection with large visualization area.

Thermal boundary layers are measured using phase-shifting technique for forced convection over a flat plate with the local Reynolds number range from 0 to 9.5×10^{4}. The temperature measurement results show temperature and spatial resolution of 2.6×10^{-2} and 0.11 mm, respectively. The resultant data are compared with analytical data to validate the developed optical system. The maximum relative error with the analytical data and standard deviation in temperature measurement were evaluated and shows 4.9% and 0.39 K, respectively. The comparison results show a difference in the vicinity of the surface while almost good agreements were obtained. The cause of the difference is considered to be deflection effect due to the steep temperature gradient in the thermal boundary layer. The beam deflection and the deflection angle were calculated by ray tracing numerically to evaluate the effects. The calculation results indicated that the steep gradient affects the measurement result in interferometric experiments.

Chapter 5: Measurement of natural convection by large aperture interferometry with arbaa prism and lens system

A large aperture phase-shifting interferometer is developed by lens system to enlarge the visualization area size for both natural and forced convection in this chapter. The concepts of this interferometer are reduction of aberration, provision of a versatile optical system because the previous interferometers encountered aberration problem and can be applied to a specific wind tunnel. Thus, the interferometer developed in this chapter adopted lens system. Reduction of aberrations was conducted using a number of lenses. In addition, this lens system enables to make simple optical configuration that expands the versatility of the developed optical system. Consequently, the aberration observed in the chapter 4 was improved and the visualization area becomes more than 250 mm. Besides, both of the large and small apertures by combinations of the optical configurations with the lens system and with conventional Mach-Zehnder interferometry are realized. The large and small apertures are utilized for visualization of an entire and detailed temperature structures, respectively. This interferometer also increases its temporal resolution and has tolerance to various experimental conditions, such as vibration due to wind tunnel, by installing the arbaa prism i.e. this interferometer concentrates the developed optical elements and experienced knowledge of this thesis.

Natural convection around a sphere is investigated by the developed interferometric system. The diameter of the sphere is 50 mm and the Rayleigh number ranged from 2.0×10^{5} to 5.0×10^{5} by changing the surface temperature. The natural convection

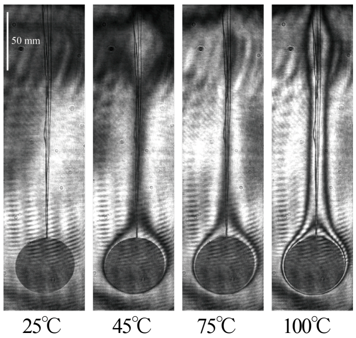

Fig. 3 Interferograms of natural convection around a sphere

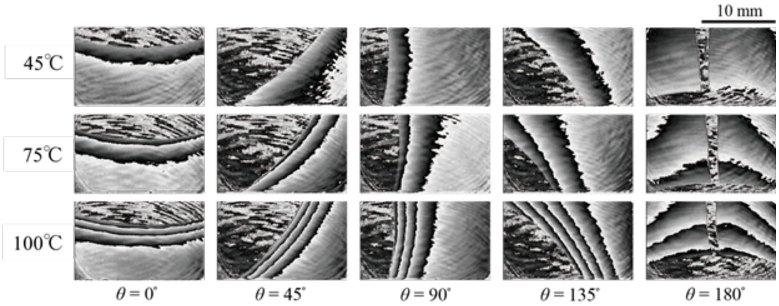

Fig. 4 Phase-shifted data of thermal boundary layers of natural convection around a sphere.

is visualized with 71 mm×266 mm of the visualization area. The plume induced by the heated sphere is visualized due to the large visualization area. The visualization results indicate the natural convective flow remain in laminar flow within 200 mm distance above the sphere. The boundary layer is also visualized with the small visualization area (15.4 mm×9.3 mm) using the optical configuration of conventional Mach-Zehnder interferometry. Therefore, this proposed interferometer realized both visualization with large aperture and detailed measurement.

Chapter 6: General conclusions

This thesis is concluded in this chapter. In this study, following result and knowledge were obtained.

1. A large aperture interferometer with mirror system is developed for quantitative visualization of natural convection. Natural convection from a vertical heated plate was visualized and the thermal boundary layers were measured with high resolution.
2. The arbaa prism was designed and developed. A spatial phase-shifting technique with the arbaa prism was also proposed to realize high-speed phase-shifting interferometry.
3. High-speed phase-shifting interferometer was developed by combining a polarizing Mach-Zehnder interferometer, the arbaa prism and a high-speed camera. This developed interferometer was applied to heat conduction around a thin wire and realized high temporal resolution measurement.
4. A large aperture interferometer with mirror system is developed for quantitative visualization of forced convection by enabling to integrate with wind tunnel. The interferometer was validated by conducting experiments for forced convection around a cylinder and a flat plate.
5. A large aperture interferometer with lens system is developed for quantitative visualization of both natural and forced convection. This interferometer offered visualization results of the whole temperature fields and the thermal boundary layers of natural convection around a sphere.