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Transient temperature field and heat transfer measurement of oblique jet impingement by thermographic phosphor

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ABSTRACT

The transient heat transfer characteristics of a hot plate cooled by an oblique jet were investigated by thermographic phosphor thermometry. The initial surface temperature was 360 °C, and 2D instantaneous temperature fields were measured with 0.1-s time intervals for a jet Reynolds number of 3500. The distance from the nozzle to the surface and the angle of impingement were varied for measurements. Manganese-activated magnesium fluorogermanate (Mg_4FGeO_6:Mn) was used as a thermographic phosphor, and a pulsed UV-LED with a 385-nm wavelength was used for the light source. A CMOS high-speed camera acquired phosphorescence images at 4000 frames per second. The decay-slope method was used for calibration, and the uncertainty in the temperature measurement was less than ±3% for the wide temperature range of 130–530 °C. A 1D semi-infinite solid model was used to obtain the local heat transfer coefficient. The transient heat transfer is almost two times greater than the steady-state value. The maximum heat transfer coefficient occurred at the stagnation point, and a secondary peak appeared at high impinging angle. When the distance from the nozzle to plate is fixed, the air jet with high impinging angle shows better cooling performance. Flow visualization and time-resolved PIV measurements reveal that the secondary heat transfer peak is associated with unsteady vortex at the beginning of the wall jet.

1. Introduction

An impinging jet has advantages for high local heat and mass transfer and is used in various industrial fields, including metal heat treatment [1], turbine blade cooling [2], local cooling and press work for electronic components [3], and drying processes in the glass industry. An impinging jet is also economical because it helps to transfer high heat locally. Studies to maximize heat and mass transfer have looked at the nozzle shape [4,5], exit conditions [6], Reynolds number, the distance between the nozzle and impinging plate [7], and curvature of the impinged surface [8]. Most of the previous research has been carried out under steady state and at room temperature. Practical applications of impinging jet cooling target high-temperature surfaces. Therefore, transient heat transfer needs to be measure to understand the initial stage of impinging jet cooling, especially in a high-temperature environment.

In research on impinging jets, thermocouples or heat flux gages have generally been used to analyze the heat transfer characteristics. Such sensors have high accuracy but have lower spatial resolution because only point measurements can be made. In addition, complicated measurement devices are needed to analyze heat transfer to cover a large area. Optical measurement techniques have higher spatial resolution compared to point measurement techniques. Moreover, they are non-invasive and do not affect flow, so analysis can be carried out more accurately [9].

Thermo-chromic liquid crystal (TLC), infrared (IR) cameras, and temperature-sensitive paint (TSP) techniques are generally used for two-dimensional optical temperature measurement. Buchlin used infrared camera to investigate the heat transfer characteristic by convection between impinging gas jets and solid surface below 100 °C [10]. Carlomagno et al. developed an experimental procedure to determine the convection heat transfer coefficients in natural and forced flows [11]. Recently, Liu et al. also used IR camera to investigate two-phase boiling flow heat transfer in a microchannel [12]. TLC is the most general method to measure the surface temperature and many researchers used it for heat transfer analysis. Yan et al. was conducted oblique impinging jet experiments to measure the local convective heat transfer coefficients by using TLC [13]. Brakmann et al. investigated heat transfer and pressure loss characteristic of an impinging cooling system for

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turbomachinery application with TLC method [14]. Baughn reviewed for studying turbulent heat transfer using liquid crystal method [15]. However, TLC and TSP techniques are limited to temperature less than 200 °C and an IR camera can be applied at high temperature, but it has limited accuracy because the emissivity depends on the surface materials and changes of its temperature.

On the other hand, Comparing to other 2D temperature measurement method, thermographic phosphor thermometry which have been used to measure the temperature since the late 1930s [16] has many advantages such as high resolution (2-dimensional), non-invasive, wide applicable measurement range and high accuracy, because they are not affected by oxygen quenching or pressure up to 10 bar [17,18]. These advantages made thermographic phosphor could be applied to harsh environment such as temperature measurement of gas turbine blade. The temperature measurement of gas turbine blade which operated over than 500 °C is a very important issue because it is directly related to the blade lifetime [19]. Thermographic phosphor technique is suitable to apply to these kinds of harsh environment with high accuracy.

To date, however, transient surface heat transfer in an oblique impinging jet flow has not been reported. Our study aims to investigate transient heat transfer characteristics on a hot plate that is cooled by an oblique impinging jet. The 2D instantaneous temperature field was obtained using thermographic phosphor with high accuracy. The effects on heat transfer of the impinging angle and distance between the nozzle and the plate were examined. Flow visualization and time-resolved particle image velocimetry (PIV) measurement were conducted to understand the flow characteristics associated with the local minimum and the secondary peak of heat transfer.

2. Theoretical background

2.1. Thermographic phosphor

A proper thermographic phosphor needs to be selected based on the range of temperature and analysis method. Manganese-activated magnesium fluorogermanate (Mg4FGeO6:Mn) was selected because it has relatively continuous decay characteristics of phosphorescence [18]. Mg_4FGeO_6:Mn can cover a wide range of temperatures from 13 K to more than 1000 K [20,21]. The manganese ion absorbs ultraviolet radiation at 385 nm and emits fluorescence at a wavelength of 650 nm. Brübach et al. [21] investigated the fluorescent characteristics of Mg4FGeO6:Mn with different dopant concentration, laser pulse energy, gas composition, pressure effects, and irreversible change by heat treatment. The decay time characteristics of Mg4FGeO6:Mn were affected by the dopant concentration, laser pulse power, and maximum temperature of heat treatment, but not the gas composition and pressure. However, the influence of dopant concentration or laser power was removed by using the same test piece and light source in both the calibration and the experiment in this study.

2.2. Decay-slope analysis method

Generally, the intensity and temporal signal are used in analysis methods to obtain the temperature field with thermographic phosphors. The absolute intensity method is based on the characteristics of changing fluorescence intensity that depend on the concentration of the quencher. However, the method needs to be controlled because the signal can differ due to other factors such as the uniformity of illumination and concentration of phosphor. In order to improve the accuracy of the absolute intensity method, an intensity ratio method was suggested [22]. This method has higher accuracy, but its measurement system is complicated.

Temporal signal methods use the emission characteristics of phosphor over time. Lifetime analysis and rise-time analysis are generally used. This method has higher accuracy than the intensity method, but data processing takes a long time [23]. To overcome the drawbacks, Yi et al. [24] suggested the decay-slope analysis method, which uses the temporal signal of phosphorescence based on Eq. (1):

$$V(t) = Ae^{\frac{t}{\tau}} + b + \varepsilon(t) \tag{1}$$

where A and b are the initial intensity and baseline offset, τ and t are the lifetime and time, respectively, and $\varepsilon(t)$ shows a noise term generated by shot noise, quantization noise, and background radiation. The noise term $\varepsilon(t)$ can be reduced by averaging repeated experiments.

Given the baseline term (b) a priori, Eq. (1) can be rewritten as:

$$I(t) = Ae^{-\frac{t}{\tau}} \tag{2}$$

where $I(t) = V(t) - b$. The normalized intensity is obtained by dividing $I(t)$ by the initial intensity (I_0) and can eliminate some of the error terms, such as those from a non-uniform light source or phosphor concentration and shot-to-shot fluctuation.

$$\frac{I(t)}{I_0} = A'e^{-\frac{t}{\tau}} \tag{3}$$

The phosphorescence lifetime can be estimated using a nonlinear least-squares approximation algorithm on Eq. (3). The trust-region algorithm was used to obtain the lifetime constant, which is related to the decay constant (λ):

$$\lambda = \frac{1}{\tau} \tag{4}$$

Eq. (3) can be rearranged using the decay slope constant λ and log-scale term:

$$\frac{I(t)}{I_0} = A'e^{\lambda t} \tag{5}$$

$$\ln\left(\frac{I_0}{I(t)}\right) = \lambda t + \ln(A') \tag{6}$$

where λ and A' can be estimated using linear least-squares curve fitting. According to Eq. (6), the intensity ratio of I_0 to $I(t)$ has a linear relationship with time t with the decay constant λ as the slope.

2.3. Transient heat transfer analysis

The transient heat transfer measurement technique is a method to obtain heat transfer coefficients assuming that the thermographic phosphor-coated test surface is a one-dimensional semi-infinite solid model. The model is subjected to a convective boundary condition. Due to the sudden changes in temperature and velocity of the flow at the wall, the temperature of the solid surface can be changed with time. The 1D conduction equation on the thermographic phosphor-coated surface is:

$$k\frac{\partial^2 T}{\partial x^2} = \rho C_p \frac{\partial T}{\partial t} \tag{7}$$

where k and T are thermal conductivity of plate and temperature, ρ and C_p are density and specific heat of the plate, and t is time. The initial and boundary conditions are:

$$\text{at} \quad t = 0, \; T = T_i$$

$$\text{at} \quad x = 0, \; -k\frac{\partial T}{\partial x} = h(T_w - T_m)$$