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Quantitative evaluation of spatio-temporal heat transfer to a turbulent air flow using a heated thin-foil

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ABSTRACT

Spatial and temporal variation of heat transfer to a turbulent air flow was evaluated experimentally, employing a technique from high-speed infrared thermography that records temperature fluctuation on a heated thin-foil. Although the temperature variation on the foil attenuated in time and space due to the thermal inertia and lateral conduction, it was possible to restore the quantitative heat transfer by solving the inverse heat conduction equation. In this paper, the experimental technique and the procedure to evaluate the heat transfer coefficient are described which includes low-pass filtering to reduce measurement noise and inverse heat conduction analysis inside the test surface. The time-spatial variation of the heat transfer evaluated here was confirmed to be reliable by comparing the statistics with the existing experimental and numerical results. In addition, a unique feature of the spatio-temporal heat transfer for the turbulent boundary layer is observed that correlates with flow features in the near-wall region such as the streak structure.

1. Introduction

Convective heat transfer is, by nature, generally nonuniform and unsteady, a fact reflected by flow turbulence. However, because of difficulties in obtaining spatio-temporal measurements, most experimental analyses concerning heat transfer between a solid wall and a fluid have used time-averaging or one-point measurements. Therefore, little is known experimentally so far about the spatio-temporal characteristics of heat transfer caused by flow turbulence.

Measurement techniques to obtain heat transfer characteristics have been developed using liquid crystals (Iritani et al. [1]) or using infrared thermography (Hetsroni and Rozenblit [2], Oyakawa et al. [3], Nakamura and Igarashi [4]), employing a thin test surface having low heat capacity. However, the major problem with these measurements is the attenuation of temperature fluctuation due to thermal inertia of the test surface. Also, lateral conduction through the test surface attenuates the amplitude of the spatial temperature distribution. These attenuations are large, especially for heat transfer to air for which the heat transfer coefficient is low (Nakamura [5]).

The recent improvement in infrared thermography with respect to temporal, spatial, and temperature resolutions enable instantaneous temperature distributions and fluctuating patterns on solid surfaces caused by flow turbulence to be investigated (Hetsroni et al. [6], Golobic et al. [7], Stafford et al. [8]). Although the temperature variation in the thermo-images is attenuated in time and space because of thermal inertia and lateral conduction of the solid wall, it is possible to restore the quantitative heat transfer by solving the inverse heat conduction equation.

This paper describes an experimental technique to measure the spatio-temporal temperature on a heated thin-foil and a procedure to evaluate quantitative heat transfer, including a low-pass filter to reduce measurement noise and an inverse heat conduction analysis inside the test surface. Also, a unique feature of the spatio-temporal heat transfer on the wall of a turbulent boundary layer is described; its statistics such as the mean spanwise wavelength of thermal streaks and characteristic fluctuating frequency are examined.

2. Experimental

2.1. Experimental setup

The measurements were performed using a wind tunnel, 400 mm high × 150 mm wide (W) × 1070 mm long (Fig. 1a). The freestream velocity ranged between $u_0 = 1–6$ m/s; the turbulent intensity in this range was about 0.5%. A turbulent boundary layer was formed on both faces of an 840-mm-long flat plate (aluminum plate) set horizontally mid-height in the wind tunnel. A test plate (Fig. 1b and c) for heat transfer measurements was positioned behind the aluminum plate across a thermal insulator (balsa prism of 10 mm streamwise length) without vertical steps.

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Nomenclature

c	specific heat
f, f_{cut}	fluctuating frequency (s^{-1}), cutoff frequency of low-pass filter
h	heat transfer coefficient
k, k_{cut}	spatial wavenumber = $1/l$ (m^{-1}), spatial cutoff wavenumber of low-pass filter
l, l_{cut}	spatial wavelength (m), spatial cutoff wavelength of low-pass filter
$P(f)$	power spectrum
$\dot{q}$	heat flux
$R(t)$	autocorrelation function
Re_{99}	Reynolds number based on boundary layer thickness = $u_0\delta_{99}/\nu$
Re_{θ}	Reynolds number based on momentum thickness = $u_0\delta_{\theta}/\nu$
T	temperature
T_0, T_w	freestream and wall temperatures
$(T_{IR})_{rms}$	noise equivalent temperature difference of infrared thermograph = $(T_{IR0})_{rms}/\varepsilon_{IR}$
$(T_{IR0})_{rms}$	noise equivalent temperature difference of infrared thermograph for a blackbody
t	time
t_p	fluctuating period = $1/f$ (s)
u	velocity
u_0, u_{τ}	freestream velocity, wall-friction velocity
x, y, z	streamwise, vertical, and spanwise coordinates
α	thermal diffusivity = $\lambda/(c\rho)$
δ	thickness
δ_{99}, δ_{θ}	boundary layer thickness, momentum thickness
ε_{IR}	spectral emissivity for infrared thermograph
λ	thermal conductivity
ν	kinematic viscosity of fluid
ρ	density

Subscripts

a	air
cd, cv	conduction, convection
rd, rdi	radiation to outside, radiation to inside

Other symbols

$(\bar{\ })$	mean value
$\Delta()$, $()_{rms}$	spatial or temporal amplitude, root-mean-square value

The test plate fabricated from acrylic resin (6 mm thick) had two sections removed, which were covered with two sheets of 2-μm-thick titanium foils arranged in parallel on both the lower and upper faces (see Fig. 1c). Both ends of the foil were tightly adhered to electrodes with high-conductivity bond to suppress contact resistance. The foil was not coated with high-emissivity paint to keep the heat capacity to a minimum value. A 4-mm-thick copper plate was inserted mid-height in the removed section (see Fig. 1b). This plate was necessary to impose boundary condition of Eq. (6) at $y = -\delta_a$ for steady uniform temperature, as described later in Section 4.1. On the surface of the copper plate, gold leaf (0.1 μm thick) was glued to suppress thermal radiation. The titanium foil was heated by applying a direct current so that the temperature difference between the foil and the freestream was about 30 °C. Because both faces of the test plate were simultaneously heated, heat conduction losses into the plate were suppressed. Under these conditions, air-layer (1 mm thick) enclosed by both the titanium foil and the copper plate did not convect because the Rayleigh number was lower than 10, well below the critical value $Ra_{cr} = 1708$ (Pellow and Southwell [9]).

To suppress deformation to the heated thin-foil from thermal expansion of air inside the plate, thin relief holes were connected from the air-layer to the atmosphere. Also, the titanium foil was stretched from heating as the thermal expansion coefficient of the titanium is smaller than that of the acrylic resin. This suppresses the mechanical vibrations of the foil against flow fluctuations. The rms value of the vertical displacement due to the vibration, measured using a laser displacement meter, was less than 1 μm (Nakamura et al. [10]), which was one or two orders smaller than the wall-friction length of the turbulent boundary layer.

The infrared thermograph (IRT), positioned below the plate, measured the fluctuation of the temperature distribution on the underside of the titanium foil through a hole on the lower wall of the wind tunnel. In this study, a high-speed infrared thermograph of SC4000, FLIR was used (420 frames per second with a resolution of 320 × 256 pixels, integration time 0.961 ms; the frame rate increased up to 1000 Hz with a reduction of pixels to 160 × 168). The thermal images were acquired up to 4096 frames in each run. The catalog value of the noise-equivalent temperature difference (NETD) was $(T_{IR0})_{rms} = 0.018$ °C at the room temperature.

2.2. Wall temperature evaluation

The temperature on the titanium foil, T_w, was determined using

$$E_{IR} = \varepsilon_{IR} f(T_w) + (1 - \varepsilon_{IR}) f(T_a), \tag{1}$$

where E_{IR} is the spectral emissive power detected by the infrared thermograph, $f(T)$ is the calibration function of the infrared thermograph for a blackbody, ε_{IR} is the spectral emissivity of the foil for the infrared thermograph, and T_a is the ambient wall temperature. The right-hand-side terms of Eq. (1) represent the emissive power from the test surface and surroundings, respectively. To suppress the diffuse reflection, the inner surface of the wind tunnel (the surrounding surface of the test surface) was coated with black paint. Also, to keep the second term constant, the surrounding wall temperature was kept strictly uniform. The thermograph was set at an inclination angle of 20° against the test surface to avoid reflections from infrared radiation emitted from the thermograph itself.

The spectral emissivity of the foil, ε_{IR}, was estimated using the titanium foil fastened tightly to the heated copper plate. The value of ε_{IR} can be calculated from Eq. (1) by substituting E_{IR} detected by the infrared thermograph, the copper plate temperature ($\approx T_w$) measured using calibrated thermocouples, and the ambient wall temperature T_a. The estimated emissivity of the titanium foil used here was $\varepsilon_{IR} = 0.197$.

2.3. Accuracy verification

The accuracy of this measurement was verified by comparing the heat transfer coefficient of a laminar boundary layer with a 2D heat conduction analysis, which was performed using an actual structure of the test model. The velocity distribution was assumed to be a theoretical value. Fig. 2 shows the result, which agrees very well with the present experiment (within 3%), indicating that at