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Numerical study on the temporal variations and physics of heat transfer coefficient on a flat plate with unsteady thermal boundary conditions

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ABSTRACT

Numerical simulations with unsteady RANS method have been performed to study the effect of unsteady thermal boundary conditions on the temporal behavior of heat transfer coefficient in unsteady heat transfer processes. Steady flow velocity condition of U = 21 m/s was used in the computational models, including conjugated model and unconjugated models, to focus on the effects of unsteady flow temperature and thermal boundary conditions on the wall. Especially for the unsteady heat flux boundary condition, analysis has been performed on the effects of pulsation frequency, mean value and amplitude which range from 0 to 8 Hz, 1000–4000W/m^2 and 500–1000W/m^2 respectively. Temporal behavior of two kinds of heat transfer coefficient with different reference temperature has been analyzed. The results show that the conventionally defined heat transfer coefficient $h_{Tg}(\tau)$ with the mainstream temperature pulsates intensely for the conditions with unsteady flow temperature. When the local adiabatic wall temperature $T_{aw}(\tau)$, which has phase shift from local mainstream temperature $T_g(\tau)$, is used to define the heat transfer coefficient $h_{Taw}(\tau)$, it can exclude the influence of unsteady flow temperature and make the $h_{Taw}(\tau)$ be a good invariant descriptor in heat transfer under unsteady flow temperatures. Unsteady heat flux boundary condition, which can cause unsteady $h_{Taw}(\tau)$ under flow conditions with steady velocity and temperature, is an important reason for the temporal variations of heat transfer coefficient in unsteady heat transfer processes. However, the temporal behavior of heat transfer coefficient keeps the same under different unsteady heat flux boundary conditions which are temporally similar. The reason for the effects of adiabatic wall temperature and heat flux boundary condition on the temporal behavior of heat transfer coefficient has been revealed with an analysis method on the spatial distribution of the "Unsteady Term" $\partial T(y)/\partial\tau$.

1. Introduction

Unsteady convective heat transfer is a topic of much interest in the field of heat transfer research due to the fact that many thermal systems, such as regenerative heat exchangers, nuclear reactor fuel rods and turbo-machines, are often subjected to time varying thermal boundary conditions, for instance, time-varying flow temperature and heat flux.

A commonly accepted hypothesis in unsteady convective heat transfer analysis is that the heat transfer coefficient is basically determined by the flow conditions and less influenced by the unsteadiness in flow temperature. This quasi-steady hypothesis prevails in analyzing turbulent convective heat transfer with unsteady flow temperatures, while it has been questioned and checked by many researchers for laminar flow conditions. Sparrow and De Farias [1] performed numerical computations on the effect of unsteady flow temperature on the conjugated laminar convection for a steady channel flow. Numerical results of time-resolved Nusselt number were obtained and compared to the results from quasi-steady approach. The range of operating conditions under which the quasi-steady hypothesis can be applied was analyzed. In Sucec [2,3], an improved quasi-steady approach for conjugated laminar convection of steady flows with unsteady temperature was

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Nomenclature

c	specific heat capacity, [J/(kgK)]
h	heat transfer coefficient, [W/(m^{2}K)]
k	conductivity, [W/(mK)]
q	specific heat flux [W/m^2]
T	temperature, [K]
U	velocity, [m/s]
UT	Unsteady term $\partial T(y)/\partial\tau$, [K/s]
x	streamwise coordinate, [m]
y	coordinate normal to plate surface, [m]
ρ	density, [kg/m^3]
τ	time, [s]

Subscripts

QS	transient measurement method with assumption of quasi -steady constant heat transfer coefficient
C − F	Cook-Felderman method
g	mainstream
aw	adiabatic wall condition
w	wall
T_{aw}	defined with adiabatic wall temperature
T_g	defined with mainstream temperature

proposed based on an analytical solution for the problem consisting of a plate interacting with a steady laminar flow with sinusoidally pulsating temperature. A recent analytical study of Hadiouche and Mansouri [4] showed that the Nusselt number for a fully developed laminar steady flow with periodically varying inlet temperature became highly time-dependent under higher flow temperature frequency and the quasi-steady approach was inadequate. Studies on the behavior of periodic responses of convections for laminar steady flow with time varying temperatures, including amplitudes and phase lags of oscillations in the wall temperature, flow bulk temperature and heat flux, can be found in Refs. [5–9] which addressed the problems with analytical and numerical methods. Investigations on the temporal heat transfer behavior of laminar convection with unsteady wall thermal conditions can be found in Refs. [10–12]. In these studies, the flow velocity and temperature were kept steady. The transient measurement results by Butler and Baughn [10] showed that the upstream surface temperature conditions could significantly influence the laminar heat transfer coefficient on a flat plate. Lachi et al. [11] showed the unsteady behavior of convective heat transfer coefficient after a change of heat flux boundary condition over a flat plate based on an analytical/numerical approximate solution. Cossali [12] reported an analytical/numerical study of convection in a steady laminar flow with periodically varying wall heat flux density. The instantaneous heat transfer coefficient was shown to be unsteady due to the unsteady heat flux, especially at higher frequencies.

The quasi-steady hypothesis is commonly accepted for turbulent convective heat transfer and has many applications. For instance, the transient heat transfer measurement method commonly used nowadays [13], which bases on the theory of unsteady 1D heat conduction in a semi-infinite plate with a convective boundary condition, is based on the quasi-steady hypothesis that the time varying thermal boundary conditions have no influence on the heat transfer coefficient for a steady turbulent flow. Furthermore, periodically varying flow temperatures or surface heating power were used to develop new transient heat transfer measurement methods [14–16]. Baughn et al. [14] presented a method to calculate the local heat transfer coefficient which was assumed time-wise constant from the frequency of the periodic change in the flow temperature. Turnbull and Oosthuizen [15] introduced a periodic technique based on the measurement of the phase lag between model surface temperature and surface heating power. All these methods assume in the data analysis for the heat transfer coefficient a time-invariant behavior. Cossali [16] reported a data reduction method for calculating heat transfer coefficients by periodically varying either the flow temperature or the surface heating power. Although the time dependence of the heat transfer coefficient on the unsteady flow temperature was tried to be considered in the method of Cossali [16], quasi-steady hypothesis on the turbulent convective heat transfer coefficient was imposed due to the lack of experimental or physical information on the heat transfer coefficients under unsteady flow temperature and thermal boundary condition. Most of the performed investigations on the unsteady turbulent convection problems [17–20] mainly paid attention on the behavior of periodic responses, including amplitudes and phase lags of oscillations in the wall temperature, flow bulk temperature and wall heat flux. For instance, Kakac and Li [19] investigated the turbulent forced convection subjected to a sinusoidally varying flow temperature. Analytical solutions were obtained and compared with the experimental findings. The effects of the modified Biot number, fluid-to-wall thermal capacitance ratio and Reynolds number on the temperature amplitude along the channel were discussed.

To extend the still limited experimental knowledge on the temporal behavior of unsteady heat transfer, the authors of the present paper systematically performed experimental investigations on the time-resolved characteristics of heat transfer under periodically unsteady aero-thermal conditions. A simple rectangular channel model was used to exclude the influence of other complications. Detailed instantaneous behavior of the conventionally defined heat transfer coefficient was calculated for conditions of steady flow with periodically pulsating flow temperatures [21,22] and periodically pulsating flows with time varying flow temperatures [23]. The measurement method was based on transient conjugated heat transfer theory. Some typical experimental results for each unsteady aero-thermal condition are shown in Fig. 1, in which h_{C-F} is the heat transfer coefficient measured with the so-called Cook-Felderman method without quasi-steady restriction for the heat transfer coefficient determination. The parameter h_{QS} is the heat transfer coefficient measured with the method based on quasi-steady hypothesis and h_{QS-COR} is the heat transfer coefficient calculated with quasi-steady empirical correlation for the case with a time varying flow velocity. T_g and U_g are the flow temperature and velocity respectively. The measured results in Liu et al. [21–23] show that whether the flow velocity is steady or not, the heat transfer coefficients defined with T_g as fluid reference flow temperature can be dramatically influenced by the unsteady flow temperatures, especially when the boundary layer is turbulent. The temporal behavior of those measured heat transfer coefficients is contrary to the quasi-steady hypothesis that they are only determined by the instantaneous flow velocity and should not be influenced by the flow temperature unsteadiness. However, the reason for the temporal variations of heat transfer coefficient was not revealed in Liu et al. [21–23].

Numerical simulation has become a powerful method for heat transfer research with the development of numerical methods. Researchers can choose the most appropriate method for their problems. For instance, Sheikholeslami et al. [24,25] applied CVFEM (Control Volume based Finite Element Method) to solve the natural convection problems for ferrofluid and nanofluid. Rahman et al.