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Comparison of time-resolved heat transfer characteristics between laminar and turbulent convection with unsteady flow temperatures

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ABSTRACT

Experimental investigations have been carried out to compare the time-resolved characteristics between laminar and turbulent heat transfer for steady boundary-layer-type flows with different unsteady flow temperatures. Time-resolved heat transfer coefficients at two locations were measured with two transient heat transfer measurement methods. One is the frequently used transient heat transfer measurement method with an assumption of time-wise constant heat transfer coefficient, and the other is the Cook–Felderman method without such assumption or restriction. Correction methods are applied for the direct measurements of time varying flow temperature and calculated surface heat flux to eliminate the influences of thermocouple thermal inertia effects. The results show that the temporal behavior of heat transfer coefficients is different between laminar and turbulent convection under unsteady flow temperatures. The change of flow temperature in step or multi-step form produces differences in the laminar heat transfer coefficient, while has very weak influence on the turbulent heat transfer coefficient. The heat transfer coefficient in a thermally transient process will be in steady state when the boundary layer is laminar and the flow temperature does not fluctuate with high frequencies and large amplitudes. However, the heat transfer coefficient varies intensely in the same frequency with the sinusoidally varying flow temperature when the boundary layer is turbulent.

1. Introduction

Many thermal systems, such as regenerative heat exchangers, nuclear reactor fuel rods and turbomachines, are often subjected to time varying thermal boundary conditions, for instance, periodically varying flow temperatures. Knowledge of the unsteady heat transfer in a steady flow with unsteady flow temperature is of much interest and important for many engineering applications where hot and cold fluids pass in succession.

A commonly accepted assumption in unsteady convective heat transfer is that the heat transfer coefficient is basically determined by the flow conditions and less influenced due to variations in flow temperature. This quasi-steady assumption prevails in analyzing thermal responses of solid surfaces interacting by steady flow with unsteady flow temperatures. For applied computations, the quasi-steady approach utilizes a steady-state heat transfer coefficient to the transient conjugated convection process. Researchers believe such an assumption is applicable to turbulent flows but questionable for the laminar case. Therefore many investigations were carried out to address the quasi-steady assumption under laminar flow conditions. In an early study of Sparrow and De Farias [1], the effect of unsteady inlet temperature on the conjugated, laminar convection of a steady slug flow was studied in a flat plate channel. Numerical results were obtained for the time dependence of the Nusselt number which identifies conditions under which the instantaneous Nusselt number is virtually time-independent. Comparisons between the quasi-steady approach and the numerical solution showed the validation of the quasi-steady approach for a range of operating conditions. Sucec [2] presented an analytical solution for the transient, conjugated, laminar convection problem consisting of a plate interacting with a steady flow whose temperature varied sinusoidally with time. Comparison of the analytical solution with the quasi-steady approach indicated acceptable agreement at some conditions and inadequate accuracy in predicting time varying wall temperature in general. Sucec [3] proposed an improved quasi-steady approach for transient, conjugated, laminar convection problems of steady flows with time varying temperature. Agreement of the improved quasi-steady approach with the finite difference solution, which

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Nomenclature

c	specific heat capacity [J/(kg K)]
D_h	flow channel hydraulic diameter [m]
f	flow temperature's frequency [Hz]
h	heat transfer coefficient [W/(m^2 K)]
Pr	Prandtl number
q	specific heat flux [W/m^2]
Re	Reynolds number based on the hydraulic diameter ($= \rho_g U_g D_h / \mu_g$)
Re$_x$	local Reynolds number based on the local distance to start point of boundary layer
t	time [s]
T	temperature [°C]
U	velocity [m/s]
V	volume [m^3]
x	streamwise coordinate
y	coordinate normal to the plate surface

Greek symbols

ρ	density [kg/m^3]
κ	conductivity [W/(mK)]
μ	thickness [m]
δ	time point [s]

Subscripts

QS	transient measurement method with assumption of quasi-steady constant heat transfer coefficient
C–F	Cook–Felderman method
g	gas flow
i	initial time $t = 0$
s	test plate surface $y = 0$
w	test plate
corr	corrected data
raw	directly measured raw data
real	data of real value
abs	absorbed by the thermocouple
pex	propagating into Perspex plate

were generated as benchmarks, was highly satisfactory for a reasonably wide range of conditions and much better than the standard quasi-steady approach. Sucec and Sawant [4] further applied this improved quasi-steady approach in the transient, conjugated heat transfer problem of fully developed, hydrodynamic steady flow in a parallel plate duct with a sinusoidal inlet temperature variation. Recently, Hadiouche and Mansouri [5] studied the unsteady conjugated heat transfer for a fully developed laminar steady flow with periodically varying inlet temperature. The effect of the flow temperature frequency on the Nusselt number was studied by a new analytical solution. The results showed that the instantaneous Nusselt number becomes highly time-dependent under higher flow temperature frequency and the quasi-steady approach is inadequate. Other studies on the transient conjugated convection of a laminar steady flow with time varying temperature can be found in [6–11]. Those studies solved the problem with analytical or numerical methods, and the behavior of periodic responses, including amplitudes and phase lags of oscillations in the wall temperature, flow bulk temperature and heat flux, was described.

Investigations on the temporal behavior of laminar heat transfer under unsteady thermal conditions have been carried out experimentally [12] and theoretically [13,14]. The transient measurement results by Butler and Baughn [12] showed that the laminar heat transfer coefficient on a flat plate could vary significantly for different upstream surface temperature conditions. Lachi et al. [13] presented an analytical/numerical approximate solution for the laminar forced convection problem with a time variation in the heat flux density over a flat plate. The unsteady behavior of the convective heat transfer coefficient was clearly put into evidence in a short initial period of a changed thermal boundary condition. Cossali [14] reported an analytical/numerical study of periodic convection in a steady laminar flow due to a periodic wall heat flux density. The instantaneous heat transfer coefficient was found to vary with a periodic heat flux, especially at relatively higher frequencies of the periodic heat flux. These investigations were performed under steady flow temperatures without addressing the conduction effects within the wall. Naveira et al. [15] developed a hybrid numerical–analytical solution methodology for transient laminar forced convection over flat plates of non-negligible thickness which is flexible to accommodate arbitrary time variations in wall heat flux imposed at the fluid–solid interface. An improved lumped approach for the conduction analysis was presented to account for the heat fluxes at the fluid–solid interface and the heat storage within the wall at an appropriate average wall temperature which is different from the surface temperature value.

For unsteady convection at steady turbulent flow with time varying temperatures, relatively fewer investigations have been presented. Some related investigations can be found in [16–21]. Kim and Ozisik [16] studied the turbulent forced convection inside a parallel-plate channel with a periodically varying flow temperature and an uniform constant wall temperature. They analyzed the variation in amplitudes and phase lag of both, fluid bulk temperature and the wall heat flux. Kakaç and Li [17] presented analytical solutions for turbulent flows with a sinusoidally varying flow temperature and compared their analysis with experimental results showing a satisfactory agreement. Santos et al. [18] and Arik et al. [19] studied unsteady forced convection of turbulent flows under periodically varying temperatures in a circular duct with theoretical and experimental methods. The effects of wall thermal capacitance and wall temperature boundary conditions were considered. Hybrid analytical–numerical solutions for the thermal response of the fluid were provided. The studies in Mansouri et al. [20,21] analyzed the transient conjugated heat transfer process in turbulent duct flows subjected to periodically varying temperature with both theoretical and experimental methods. They showed that the quasi-steady method is only able to predict the temperature behavior inside the channel for lower frequencies of the flow temperature.

Mathie et al. [22,23] presented a semi-analytical model to describe one-dimensional conjugate heat transfer with a time-varying heat transfer coefficient, taking into account fluctuations in the solid and fluid temperatures. The augmentation effect caused by the fluctuating temperature differences on the heat transfer coefficient was analyzed for two fundamental non-isothermal/diabatic flow problems with this model.

Although the studies introduced above, most of which were performed with analytical/numerical methods, presented some information on the temporal behavior of the laminar and turbulent convections with unsteady thermal boundary conditions, time-resolved data of heat transfer coefficient is still very scarce, especially in the experimental data. Moreover, none of the above studies compared directly the heat transfer characteristics between laminar and turbulent convections with unsteady flow temperatures. Time-resolved experimental data is important to have a deeper insight to the temporal characteristics of the