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Conjugate heat transfer in a duct with an axially varying heat flux

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ABSTRACT

In this numerical study, steady laminar conjugate heat transfer of in a tube subjected to an axially varying heat flux at the outer wall is investigated using the finite volume method. The effects of the thermal conductivity ratio, the diameter ratio and the dimensionless amplitude of the axially varying or periodic heat flux on the local and mean Nusselt numbers as well as on the temperature and the interface heat flux distribution are determined for a range of corresponding parameters. Results obtained for some limiting cases are found to be in a good harmony with those given in the literature.

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1. Introduction

Convective heat transfer in ducts has been a classical and still popular research topic due to its wide practical applications and interesting physics. When studying forced convection in ducts, conduction in the duct walls is generally neglected assuming that the wall thickness is too small to compare with regarding hydraulic diameter. However, in practice, convective heat transfer of fluid usually interacts with conduction in the solid wall, which is referred as conjugate heat transfer.

There are many experimental and numerical studies on the conjugate heat transfer in ducts in the existing literature [1–11]. Ignoring the conjugate effect can lead to wrong results in the estimation of heat transfer coefficients, especially for high conductivity ratios and small channel lengths. Maranzana [6] investigated the effect of wall conduction in microchannel flow between two parallel plates. They disclosed that disregard of the wall conduction could result in very large bias in the experimental estimation of the heat transfer coefficients, especially for small values of the Reynolds number. Weigand and Gassner [7] investigated the wall conduction effect for the extended Graetz problem for laminar and turbulent channel flows with a thick walled model numerically. Then channel wall only had a small part located in the center being kept at high temperature while the rest at lower temperature. The heat conduction within the solid wall was shown to change the temperature distribution at the interface between the solid and the fluid. An increase in the wall thermal conductivity was found to lead to reducing the abrupt temperature change at the interface. Nonino et al. [8] numerically analyzed the conjugate heat transfer in microtubes of various lengths, wall materials under the uniform heat flux. It was concluded that the magnitude of the local Nusselt number decreased significantly with an increase in the wall thickness or the wall thermal conductivity, or a decrease in the channel length.

Arici and Aydin [9] numerically investigated thermally developing laminar forced convection in a pipe including viscous dissipation and wall conductance under the uniform heat flux. Ates et al. [10] numerically studied unsteady conjugated heat transfer in thick-walled pipes for thermally developing laminar flow under uniform heat flux. The effects of the wall thickness ratio, the wall-to-fluid thermal conductivity ratio, the wall-to-fluid thermal diffusivity ratio and the Peclet number were predicted. Avci et al. [11] numerically investigated hydrodynamically developed, thermally developing, steady, laminar conjugate heat transfer of a liquid flow in the entrance region of a microtube. The effects of thermal conductivity ratio, channel length and viscous dissipation on the Nusselt number were examined.

Many of the studies on conjugate or non-conjugate forced convection in ducts assume constant or uniform heat flux/temperature, i.e. axially non-varying thermal boundary conditions at the outer wall. However, axially varying thermal boundary conditions at wall are sometimes encountered in practice, e.g. cooling tubes of nuclear reactors and heat exchanges of Stirling-cycle machines. Compared to the studies involving the uniform thermal boundary conditions, there is a scarcity of those involving axially varying ones.

Many of the studies on forced convection in ducts with axially varying thermal boundary conditions at wall neglect the wall

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Nomenclature

A	dimensionless amplitude, Eq. (2)
d	diameter [m]
k	thermal conductivity [W/mK]
L	length [m]
Nu	Nusselt number
Pe	Peclet number (=$RePr$)
Pr	Prandtl number
$q''_{iw}(x)$	heat flux at the inner wall of the tube [W/m^2]
q''_{iw}	mean value of the heat flux at the inner wall of the tube [W/m^2]
$q^{*''}_{iw}$	nondimensional heat flux at the inner wall of the tube (=$q''_{iw}(x)/q''_{iw}$)
$q''_{ow}(x)$	heat flux at the outer wall of the tube [W/m^2]
q''_{ow}	mean value of the heat flux at the outer wall of the tube [W/m^2]
$q^{*''}_{ow}$	nondimensional heat flux at the outer wall of the tube (=$q''_{ow}(x)/q''_{ow}$)
r	radius [m], radial coordinate
R	dimensionless radial coordinate
Re	Reynolds number
T	temperature [K]
u	velocity [m/s]
x	axial direction [m]
X	dimensionless axial coordinate

Greek symbols

υ	kinematic viscosity [m^2/s]
θ	dimensionless temperature
θ^*_{fb}	dimensionless fluid bulk temperature based on q''_{iw} (=$(T_{fb}-T_e)/(q''_{iw}r_i/k_f)$)
θ^*_{iw}	dimensionless inner wall temperature based on q''_{iw} (=$(T-T_e)/(q''_{iw}r_i/k_f)$)

Subscripts

e	entrance
f	fluid
fb	fluid bulk
i	inner
o	outer
s	solid

conductance, i.e. the conjugate effect. Hsu [12] considered sinusoidal wall heat flux distribution in a tube. Quaresma and Cotta [13] analytically investigated forced convective heat transfer in a circular tube with two different axially variable wall heat flux cases, sinusoidal and exponential variations. Lee et al. [14] analytically studied oscillating flow in a circular pipe subjected to a sinusoidal wall temperature distribution. For this specific case, the occurrence of three different regimes for heat transfer was identified. Barletta and Zanchini [15] analytically considered a tube with a sinusoidal axial distribution of wall heat flux neglecting axial conduction and viscous dissipation. The fully developed Nusselt number was shown to be a periodic function of the dimensionless axial coordinate. Barletta and Rossi di Schio [16,17] extended Barletta and Zanchini's study [15] by taking the axial conduction and the viscous dissipation into account. Pearlstein and Dempsey [18] numerically investigated laminar forced convective heat transfer in a tube subjected to an axially varying wall heat flux (sinus and hyperbolic tangent) using a general iterative method. Zniber et al. [19] studied MHD flow through a 2-D channel subjected to a uniform magnetic field and heated at the walls of the conduit over the whole length with sinusoidal heat flux of vanishing mean value. The local Nusselt number was found to increase with an increase in the Hartman number.

There are a few studies on conjugate forced convection in tubes with axially varying heat flux or temperature at the tube wall. Zueco [20] investigated the effects of a time-varying pressure drop and an axially varying heat flux for a two-phase flow system in an evaporator using the network simulation. The effect of wall conduction on heat transfer was found to increase as k_{sf} decreased. Barletta et al. [21] analytically studied conjugated heat transfer in a parallel-plane channel with sinusoidally varying wall temperature. The mean Nusselt number in a longitudinal period was shown to be affected by singularities. For every longitudinal period, there existed two axial positions where the bulk temperature and the interface solid–fluid temperature assumes the same value. In a similar study, Barletta et al. [22] considered longitudinally varying wall heat flux case (with sinusoidal law) for the laminar forced convection in a parallel-plate channel. The effect of the wall conductance was studied. The averaged Nusselt number displayed an interesting feature depending upon the dimensionless pulsation. Ho et al. [23] studied laminar flow in a double-pass current heat exchanger with sinusoidal heat flux distribution. The increasing values of the Graetz number and impermeable-barrier location on heat transfer were found to increase heat transfer efficiency. Astaraki and Tabari [24] studied laminar forced convective heat transfer in a circular duct with sinusoidal wall temperature. It was shown that the mean Nusselt number increased with an increase in the dimensionless frequency of the wall periodic temperature.

The present study is aimed at numerically investigating conjugate forced convection heat transfer in a tube subjected to axially varying heat flux or periodic heating at wall. A sinusoidal heat flux is considered at the tube wall. The interactive effects of the amplitude A of the axially varying heat flux and the thermal conductivity ratio for various values of the tube diameter ratio are examined in detail.

2. Problem description and analysis

Let us consider hydrodynamically developed laminar flow in a tube with an inner diameter d_i, outer diameter d_o and axial length L (Fig. 1). The end sections of the tube are thermally insulated and the outer wall of the tube is periodically heated with sinusoidal heat flux,

$$q''_{ow}(x) = q''_{ow}(1 + A\sin(4\pi x/L)) \quad (1)$$

where q''_{ow} is the average value of $q''_{ow}(x)$ for a given length of L and A is the dimensionless amplitude of $q''_{ow}(x)$, which can be defined as:

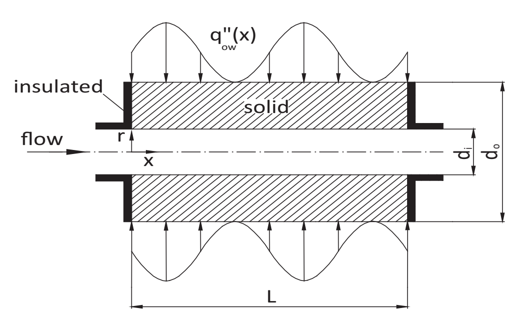

Fig. 1. Schematic of the problem.

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