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Research Paper

Heat transfer fluctuation in a pipe caused by axially non-uniform heat distribution

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HIGHLIGHTS

- Turbulent convection under non-uniform thermal boundary conditions is studied.
- Local *Nu* fluctuation is remarkable under the heat flux with large non-uniformity.
- FSP and entropy generation analytical methods are used to interpret the problem.
- *Nu* fluctuation is related to variations of synergy angle and entropy generation rate.

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ABSTRACT

This paper numerically investigates the impact of non-uniform boundary heat fluxes on the local and global Nusselt numbers of a circular pipe in fully developed turbulent flow regime. The numerical study is carried out basing on a validated three-dimensional CFD model under a series of prescribed sinusoidal wall heat fluxes. Results show that local Nusselt number fluctuation is remarkable under the heat flux with large non-uniformity and the local fluctuation ratio relatives to the uniform boundary condition is within the range of −26% to +15%. The phase-difference between heat flux profile and Nusselt number profile is expounded via mathematical treatment. To explore the underlying mechanism of the foregoing phenomenon, the analytical tool of field synergy principle is employed and is executed in a more rigorous way. It indicates that the local heat transfer fluctuation attributes to the local synergy-angle change in the very near-wall region. Besides, the average Nusselt number is also investigated. It is shown that, for a fixed amount of total heat flux, the average Nusselt number slightly decreases when the boundary heat flux changes into non-uniform, which dues to the global enlargement of synergy angle as well as the global augmentation of entropy generation increment.

1. Introduction

The non-uniform distribution of energy is always encountered in engineering practice, especially in high-power systems or devices, which brings challenge to energy management technology. For instance, the highly non-uniform power distribution in a highly-integrated computer processor would result in large temperature gradient with localized hot spots which may have detrimental effects on the computer performance and product reliability [1]. Another example is the scramjet engine for hypersonic vehicle, the heat load on the chamber wall of a typical scramjet engine is 0.3 MW/m^2 at engine inlet, while it substantially elevates to 2.7 MW/m^2 at the exist during operation [2]. Generally, this kind of engine is convectively cooled by the coolant flow through the channels inserted in the chamber wall [3]. The convective heat transfer performance in this special situation needs reassessment on the basis of the ultra-high heat flux gradient imposed to the boundary.

Majority of the studies referred to force convection usually under the uniform thermal boundary condition while the impact of non-uniform boundary condition on convective heat transfer drawn relatively little attention. Reynolds [4] first studied the turbulent heat transfer in a tube with non-uniform circumferential heat flux distribution. The heat flux had arbitrary circumferential distributions, but was invariant along the axial direction. Basing on his numerical results, he concluded that the influence of the non-uniformly circumferential heat flux on the local heat transfer coefficient was striking. After Reynolds, there emerged serval further researches focusing on the same problem [5–9]. Black and Sparrow [5] performed experimental studies on the variations of

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Nomenclature

a, b	bounds of integration, $a = 0.2, b = 0.3$ (m)
A	heat flux fluctuation amplitude (W/m^2)
B	heat flux fluctuation period (m)
D_h	hydraulic diameter (m)
f	friction factor
k	turbulent kinetic energy (m^2/s^2)
Nu	Nusselt number
Pr	Prandtl number
q	heat flux (W/m^2)
r	radial distance from tube centerline (m)
R	radius of the tube (m)
Re	Reynolds number
s	area of the finite wall cell (m^2)
S_{gen}	entropy generation rate (W/(m^3 K))
T	temperature (K)
∇T	temperature gradient (K/m)
$\vec{U}$	velocity vector (m/s)
v	volume of the finite fluid cell (m^3)

Greek symbols

δ	distance from the wall (m)
ε	turbulent dissipation rate (m^2/s^3)
θ	synergy angle (degree)
λ	thermal conductivity (W/(m K))
ρ	density (kg/m^3)
τ	shear stress (N/m^2)

Subscripts

avg	average value
c	discretized cell
f	fluid
w	wall
x	streamwise direction
0	uniform boundary condition

local heat transfer, local temperature, as well as the thermal entrance length caused by the non-uniform circumferential thermal boundary. Schmidt and Sparrow [6] and Knowles and Sparrow [7] proceeded the experimental and numerical studies to investigate the roles that buoyancy effect, fluid properties and wall conduction played in turbulent flow and heat transfer with non-uniform circumferential heat flux. Gärtner et al. [8] and Chieng and Launder [9] made their efforts on accurately modeling the turbulent transport and heat transfer with non-uniform boundary condition.

Above literatures [5–9] mainly concentrated on the turbulent flow and heat transfer with respect to the non-uniform heat distribution in the tube circumferential direction while another branch of researches focused on the forced convection in ducts with axially varying thermal boundary conditions. Hsu [10] developed an analytical solution for the laminar heat transfer in a tube heated with a half-period sinusoidal boundary heat flux. Pearlstein and Dempsey [11] analytically investigated the two-dimensional laminar flow with non-uniform thermal boundary condition by solving the constructed energy equation. Quaresma and Cotta [12] applied the integral transform method to solve the Nusselt number of laminar tube flow under axially varying wall heat flux. Lee et al. [13] investigated the heat transfer performance of oscillating flow in a pipe under sinusoidal temperature distribution. Barletta and his co-workers [14–18] conducted a series of studies on the heat transfer of fully developed laminar flow in two-dimensional tubes or parallel-plates with sinusoidal boundary heat fluxes. The effect of viscous dissipation [15] and wall conduction [16–18] on the local Nusselt number and local wall temperature were successively investigated. Yapıcı and Albayrak [19] numerically studied the temperature field and thermal stress distribution in a two-dimensional circular pipe under non-uniform wall flux in laminar entrance region. Zniber et al. [20] presented an analytical solution to the problem of heat transfer of two-dimensional MHD flow between parallel-plates with sinusoidal wall heat flux. Zueco [21] analytically solved the transient conjugate problem of the Poiseuille flow subjected to periodic variation temperature boundary condition. Ho et al. [22] investigated the temperature distribution and the local Nusselt number of laminar flow in a double-pass countercurrent heat exchanger whose outer surface subjected to a sinusoidal heat flux. Esfahani and Shahabi [23] put their interests in the entropy generation of laminar pipe flow under various non-uniform axial heat flux profiles basing on the “Entropy generation minimization” theory of Bejan [24–26]. They found that there existed an optimum distribution of heat flux which generated the minimum entropy, thereby enhanced the heat transfer performance in thermal developing region. Astaraki et al. [27] solved the conjugate heat transfer problem of the Poiseuille flow with the boundary subjected to sinusoidal temperature distribution. They mainly elucidated the temperature variation in the fluid–solid domain due to different level of thermal conjugation. Aydin et al. [28] studied the conjugate heat transfer of the Poiseuille flow under sinusoidal heat flux boundary condition. The influences of fluid-to-solid conductivity ratio and sinusoidal heat flux amplitude on local and average Nusselt number were their main interests. Latterly, Aydin and Avci [29] also analytical investigated the laminar slip flow in a microduct with non-uniform boundary condition. The recent work of Altun [30] focused on the transient conjugate heat transfer of laminar pipe flow with time periodically varying wall temperature boundary condition. Hajmohammadi et al. [31–33] analytically investigated the developing laminar flow and convection with discrete heat sources distributed along the streamwise distraction. They sought to minimize the “hot spots” temperature by optimizing the design parameters such as adiabatic spacing, heaters size and heat generation rates basing on the constructal theory. Besides, Hajmohammadi et al. [34,35] also numerically studied the duct flow with optimized non-uniform boundary heat flux distribution. It was found that, for a fixed amount of total heat flux on a duct, the peak wall temperature can be minimized by properly redistributing the heat flux elements in axial direction.

It is worthy of note that the axially non-uniform boundary condition is usually implicit in the conjugate heat transfer process. The uniform heat flux imposed at the heated surface is redistributed by the solid conduction. As a result, heat flux is transformed into non-uniform when it reaches another side of the wall (fluid–solid interface) [36,37]. It was found that in these conjugate cases, the local heat transfer coefficient was changed compared to the non-conjugate cases due to the revolutionized boundary condition [36].

From above review, it can be noticed that most all of the previous literatures applied analytical methods to solve the heat transfer problem with respect to the axially non-uniform boundary condition. The two-dimensional developed or developing laminar flow were their most preferred fundamental models since the analytical solutions for laminar flow and heat transfer were available. However, there lacks research focused on the heat transfer of turbulent flow under non-uniform thermal boundary condition. Since it is tricky to analytically solve such problems in turbulent flow