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Forced convection and thermal predictions of pulsating nanofluid flow over a backward facing step with a corrugated bottom wall

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ABSTRACT

In this study, laminar forced convection of pulsating nanofluid flow over a backward-facing step with a corrugated bottom wall was numerically examined by using finite volume method. Part of the bottom wall downstream of the step was corrugated and kept at constant temperature. Effects of Reynolds number, length and height of the surface corrugation wave, nanoparticle volume fraction, amplitude and frequency of flow pulsation on the fluid flow and heat transfer were numerically investigated. It was observed that average Nusselt number enhances as the Reynolds number, length and height of the corrugation wave increase. Average Nusselt number versus Strouhal number shows a resonant type behavior and flow pulsation amplitude increment results in heat transfer enhancement. Average heat transfer rate increases with the inclusion of the nanoparticles but the rate of enhancement depends on the nanoparticle solid volume fraction interval. An efficient computational strategy for the thermal performance prediction of the system was developed by using proper orthogonal decomposition and artificial neural networks.

1. Introduction

Flow separation and its subsequent reattachment occur in a wide range of engineering applications such as flow around buildings, airfoils, electronic devices, combustion chambers and many others. Flow over a backward or forward facing step is a benchmark problem where this phenomenon occurs and therefore many numerical and experimental studies for flow over a backward/forward facing step were conducted [1–10]. Surface corrugation and flow pulsation are two techniques to alter the flow and heat transfer characteristics in a variety of geometries in various thermal boundary conditions [11–20]. Hasan et al. [21] numerically examined the free convection in a differentially heated cavity with sinusoidally corrugated side walls by using finite element method. It was observed that the corrugation amplitude and frequency significantly affect the transient phenomena in the cavity. Kumar and Rosen [22] investigated the performance of solar water heater having a corrugated absorber surface and it was reported that as compared to plane surface solar water heater, the corrugated surface based solar water has a higher operating temperature for longer time. Hydro-thermal performance of a refrigerant in a horizontal smooth tube and corrugated tube are compared experimentally by [23] and it was observed that the corrugation pitches significantly affect the hydro-thermal performance of the tube. Khoshvaght-Aliabadi and Nozan [24] studied the effects of corrugation for a water cooled mini-channel heat sink. As the corrugation-length decreases and the corrugation amplitude enhances, Nusselt number and pumping power were found to increase. The influence of discrete corrugated rib roughened tube on the fluid flow and heat transfer characteristics for various fluid flow rates was experimentally examined by Kathait and Patil [25]. It was reported that higher heat transfer rates at the cost of additional pressure drop were observed with corrugated tubes.

Flow pulsations in thermal systems may result in heat transfer enhancement or deterioration depending on the geometry and flow conditions [26–28]. Cho and Hyun [29] performed a numerical study on hydro-thermal characteristics of pulsating flow in a pipe. It was observed that for higher frequencies, the effects of pulsation are significant in a tin layer near the solid wall and the Nusselt number enhances as the amplitude of pulsation increases for Prandtl number below unity. In the study by Faghri et al. [30], the interaction of the velocity and temperature oscillations was found to induce additional terms in the energy equation and thus effect the heat transfer rates for the problem of heat transfer in a cylindrical pipe. Chattopadhyay et al. [31] numerically examined the fluid flow and heat transfer in a circular tube in pulsating flow

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Nomenclature

a	length of the corrugation
a_i	modal coefficient
A	pulsation amplitude
b	height of the corrugation
D	data set
f	pulsation frequency
h	local heat transfer coefficient
H	step height
k	thermal conductivity
n	unit normal vector
Nu	local Nusselt number
p	pressure
Pr	Prandtl number
Re	Reynolds number
St	Strouhal number
T	temperature
u, v	x-y velocity components
x, y	Cartesian coordinates

Greek characters

α	thermal diffusivity
ϵ	modal contribution
θ	non-dimensional temperature
ν	kinematic viscosity
ρ	density of the fluid
σ	singular value
τ	non-dimensional time
ϕ	nanoparticle volume fraction

Subscripts

c	cold wall
h	hot wall
mean	average
nf	nanofluid
p	particle

and observed no effect of the pulsation on the time-averaged heat transfer by analyzing the data from the simulation in the studied range of configuration. Nield and Kuznetso [32] analytically studied the forced convection in a channel with fluctuating pressure gradient (small amplitude) by using perturbation technique. They noted that the fluctuating part of the Nusselt number changes in magnitude and phase when the dimensionless frequency enhances. An experimental study of heat transfer in pulsating flow in a grooved channel was conducted by Jin et al. [33]. They showed that due to the mixing caused by the repeating sequence of vortex generation, growth and expansion from the groove to the main stream by the pulsating flow results in heat transfer enhancement.

Recently, thermal applications that use nanofluids as heat transfer fluids capture great attention. Nano-sized metallic or non-metallic particles whose average particle size less than 100 nm are added to heat transfer fluids such as water or ethylene glycol to achieve favorable thermal properties. Nanofluids were shown to improve heat transfer characteristics with little pressure drop as compared to base fluids [34–36]. Different nanoparticle types and various nanoparticle shapes other than spherical ones can be used in heat transfer applications. A numerical study of forced convection of nanofluids over a backward facing step with different nanoparticle types was performed by Aswadi et al. [37]. It was shown that nanofluid with SiO_2 nanoparticles has the highest velocity and nanofluid with Au nanoparticles has the lowest velocity among other nanofluids. Abu-Nada [38] numerically studied the convection over a backwardfacing step with nanofluids. It was shown that average Nusselt number enhances with nanoparticle voulme fraction and nanoparticles with low thermal conductivity performed better heat transfer characteristics in the recirculation zone. Togun et al. [39] numerically studied turbulent flow of nanofluids over a double forward-facing step with finite volume method by using two different nanoparticle types. The highest heat transfer enhancement was observed for Al_2O_3 nanoparticle at the highest volume concentration. In the study by Selimefendigil and Oztop [40], the combined effect of flow pulsation and nanoparticle on the heat transfer was examined for backward facing step with finite element method. Average heat transfer was an increasing function of frequency of the oscillation, nanoparticle volume fraction and Reynolds number.

Based on the above mentioned literature survey and to the best of authors' knowledge, laminar forced convection of nanofluid flow over a backward facing step with a corrugated bottom wall in pulsating flow conditions has never been studied in the literature. The combined effect of surface corrugation, flow pulsation and change of thermo physical properties with the addition of the nanoparticles can be encountered in variety of configurations or such a thermal system may be specially designed for an energy efficient solution. The preset numerical study aims at investigating the effects of Reynolds number, solid volume fraction of the nanofluid, flow pulsation parameters and surface corrugation parameters on the fluid flow and heat transfer characteristics. A reduced order model of the system based on proper orthogonal decomposition was further derived which is helpful in optimization study of the thermal system.

2. Mathematical formulation

Fig. 1 represents a schematic description of the backward-facing step geometry with a corrugated surface. Expansion ratio is two

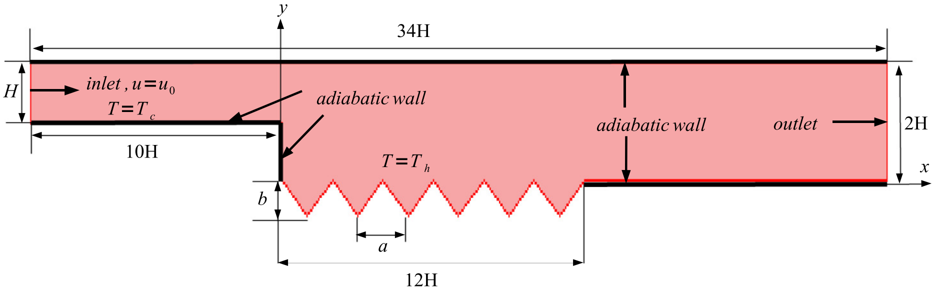

Fig. 1. Schematic diagram of the physical model with boundary conditions.