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A novel technique for heat transfer enhancement from a horizontal heated pipe by using nanofluid restrained flow

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ABSTRACT

In this paper, a numerical investigation using an in-house CFD code written in FORTRAN is carried out for an effective cooling of a horizontal heated pipe. The study focuses on the heat transfer enhancement by using nanofluid as a cooling medium comprising CuO nanoparticles and water as a base fluid. Moreover, a confined circular jacket surrounds the heated pipe with axial slot inlet and outlet ports. Via the circular jacket, the eccentricity between the heated pipe and the circular jacket centers is implemented as a control key for the heat transfer rate. Also, the circular jacket enables the nanofluid to be in direct contact with the hot pipe. Cold nanofluid exchange heat by both forced and natural convection (mixed convection). The presented study is performed for two mixed convection cases, assisting and opposing. The Grashof number is fixed at 10^4 while the Richardson number is varied in the range of 0.01–100 via the Reynolds number of the nanofluid. The CuO solid volume fraction has been varied from 0 to 0.05 while the eccentricity ratio has been changed from −0.5 (downward direction) to 0.5 (upward direction). Through the study, the radius ratio is kept constant at 2. The numerical solution was compared with previous work, and good agreement was found. It was also found that the assisting flow enhanced the rate of heat transfer when compared to the opposing flow. Moreover, the nanoparticles have a positive effect on the rate of heat transfer over the entire range of Richardson number; however, for natural convection domain ($Ri > 10$), the nanoparticles concentration should be extensively increased in order to enhance the heat transfer rate.

1. Introduction

Mixed convection heat transfer in confined annulus between two concentric cylinders continues to be one of the most important problems which have been a subject of intense research for several decades due to its wide and numerous engineering applications. These applications such as cooling towers, nuclear reactor design, tubular and compact heat exchangers, aircraft cabin insulation, and cooling of electronic components [1–4]. The analysis of mixed convection for these types of problems is more complicated than that of the pure forced or free natural convection [5,6]. Different studies have been performed to study the fluid flow and heat transfer over different cross-sections as circular cylinder, triangular, trapezoidal and so forth [7–11]. The fluid flow and thermal patterns across bodies are significantly influenced by the buoyancy effects [12–17] particularly at low Reynolds numbers with weak effect of forced convection. Bhattacharyya and Mahapatra [18] studied the effect of buoyancy effect on vortex shedding and heat transfer from a square cylinder for a wide range of Reynolds and Richardson numbers. The results showed an increase in the rate of heat transfer due to the increase in both Reynolds and Grashof numbers. One of the early studies of the mixed convection heat transfer around circular cylinder has been performed by Badr [19]. He investigated theoretically the problem of cross buoyancy from an isothermally heated circular cylinder to air in the steady flow regime. Also, Badr [20] extended the study for the aiding and opposing flow regimes. Several studies on mixed convection are concerned with the unconfined flow past circular cylinders [21]. Dhiman et al. [22] studied the effects of Reynolds and Prandtl numbers on heat transfer across a square cylinder. Anjaiah et al. [23] analyzed numerically laminar mixed convection heat transfer from a square cylinder. The variation of Nusselt number has been calculated for different values of Reynolds, Prandtl, and Richardson numbers. Dhiman et al. [24,25] extended their previous study to analyze the mixed convection flow and heat transfer to Newtonian fluids from a heated square cylinder. It was found that the drag coefficient was to be less sensitive to the Richardson

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Nomenclature

b	annulus gab width, $(r_o–r_i)$, m
C_P	specific heat at constant pressure, J/kg K
e	eccentricity, m
g	acceleration of gravity, m/s^2
Gr	thermal Grashof number
k	thermal conductivity, W/m K
L	inlet and exit ports width, m
Nu	average Nusselt number
Nu_ϕ	local Nusselt number
p	pressure, N/m^2
P	dimensionless pressure
Pe	Péclet number
Pr	Prandtl number
r	radial coordinate
r_i, r_o	inner and outer radii respectively, m
R	dimensionless radial coordinates
Ra	thermal Rayleigh number
Ri	Richardson number
Re	Reynolds number
Rr	radius ratio
T	local temperature, K
T_c, T_h	temperatures at outer and inner radii respectively, K
ΔT	temperature difference, $(T_h–T_c)$, K
u	the nanofluid inlet velocity, m/s
v_r	velocity in r-direction, m/s
v_ϕ	velocity in ϕ-direction, m/s
Greek symbols	
α	thermal diffusivity, m^2/s
β	coefficient of thermal expansion, K^{-1}
ε	eccentricity ratio
ϕ	angular coordinate
ζ	solid volume fraction
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
θ	dimensionless temperature
Subscript	
f	fluid
nf	nanofluid
s	solid

number than the lift coefficient. The effect of channel-confinement with various degrees on flow and heat transfer characteristics around a heated/cooled square cylinder was studied by Sharma and Eswaran [26,27]. It was found that by increasing blockage ratio, both the width of the wake and entrainment of the fluid into the wake cavity decreases for the opposing buoyancy case. An additional investigation to the effect of Peclet number and blockage ratio on the flow and heat transfer characteristics in a square cylinder confined in a planar channel has been studied numerically by Dhiman et al. [28]; this study included the effect of Reynolds and Prandtl numbers as singular number that is represented by Peclet number. Sharma et al. [29] studied numerically the mixed convection flow and heat transfer around a long cylinder under the effect of aiding buoyancy. The results showed that heat transfer increases with increase in Reynolds number and/or Richardson numbers. Mixed convection in the open-ended enclosures has been studied experimentally for natural and forced convection inside open-ended cavities [30]. Chan and Tien [31] performed sequential studies on an open square cavity considering the effect of the cavity inclination and Grashof number in natural convection heat transfer. Decent investigation for the mixed convection in the open-ended enclosure has been investigated by Stiriba et al. [32]. They investigated numerically the effects of mixed convective flow over a three-dimensional open cavity on the flow structure and the heat transfer characteristics over a wide range of the Grashof number and two Reynolds numbers. In recent years, nanofluids have often been used as an alternative heat transfer medium due to its superior thermal properties, improved uniformity, and stability. Extraordinary considerable efforts to augment the rate of heat transfer in different ways have been executed by several investigations. As a pioneering idea, nanofluid has been announced [33–36]. Sarkar et al. [37] numerically investigated the effect of aiding and opposing buoyancy on the flow and heat transfer in unconfined vertical medium with two different types of nanoparticles. Liao and Lin [38] executed a numerical investigation for natural and mixed convection inside domains with stationary and rotating cylinder, the immersed-boundary method was the numerical methodology. Average heat transfer features were deliberate around the surfaces of both inner cylinder and outer enclosure at different Rayleigh number, Prandtl number and the aspect ratio between inner cylinder and outer enclosure.

Recently, Sarkar et al. [39] proposed a theoretical analysis to investigate buoyancy driven convection of nanofluids in an infinitely long channel under superimposed magnetic field and two distinctive wall boundary conditions. Also, the total entropy generation due to magnetohydrodynamic fluid friction and heat transfer irreversibilities has been obtained. Sarkar et al. [40,41] investigated mixed convective flow and heat transfer of nanofluids past a stationary and rotating cylinder placed in a uniform cross stream. It was observed that for the stationary cylinder, the presence of nanoparticles communicated a counterbalancing force to that of buoyancy force. This tried to vanish the effect of buoyancy force for the flow stabilization. This behavior for the nanofluid was a new phenomenon. Also, for the rotating cylinder, all contributed parameters that affected the heat transfer and fluid flow have been introduced such as the nano-sized, the dimensionless cylinder rotation rate, and the nanoparticle volume fractions in addition to the Richardson number. The entropy generation due to mixed convective heat transfer of nanofluids past a rotating circular cylinder placed in a uniform cross stream was investigated by streamline upwind Petrov–Galerkin-based finite element method [42], the total entropy generation was found to decrease sharply with the cylinder rotation rates and nanoparticle volume fractions. Sarkar et al. [43] established entropy generation due to laminar mixed convection of water-based nanofluid past a square cylinder in vertically upward flow. It was found that for mixed convection flows past the square cylinder with nanofluids, the thermal dissipation was much higher than that of frictional dissipation. Consequently, the Bejan number decreased with increasing the nanoparticle concentration.

However, as can be seen from the above review, and up the author knowledge, this study is the first trial to utilizing a confined circular jacket to horizontal hot pipe in mixed convection heat transfer with nanofluid.

2. The novelty of the present work

The novelty of this work arises from the new proposed effective cooling method of hot pipes. The proposed method is conducted in the surrounding of a hot pipe by a restrained external circular jacket with inlet and outlet axial slot ports. Via this jacket; new various heat transfer parameters as the eccentricity ratio, nanoparticles concentration, and mixed convection heat transfer mode (assisting and opposing), as well as the flow inlet velocity (Reynolds number value), are studied. By these combined parameters effects, the heat transfer rate could be controlled according to the amount