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Effect of water-based AL_2O_3 nanofluids on Exergy destruction of fully developed laminar flow regime in duct under constant wall heat flux

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ABSTRACT

This paper analytically examines the effects of adding nanoparticles on the exergy destruction of water– Al_2O_3 nanofluid flow through a circular duct under constant wall heat flux for thermally and hydrodynamic laminar regime. The single phase model is employed to simulate the nanofluid convection, taking into account appropriate thermophysical properties. Particles are assumed spherical with a diameter equal to 13 nm and are easily fluidized. In this approach, nanofluid can be treated as a pure fluid. Results show that with increasing the volume concentration of particles, the values of both of exergy transfer and heat transfer rate, decreases, especially for lower values of Reynolds number. These results indicate that along the duct at a fixed volume concentration, exergy destruction, decreases.

Introduction

Nanostructures materials can have a major impact on the liquids used for the transport of heat in ducts. Many researchers have investigated the effects of adding nanoparticles on the heat transfer and hydrodynamic properties of fluid flow.

Xuan and Roetzel [1] have investigated the conductivity and heat transfer enhancement of the nanofluid based on the assumption that the nanofluid behaves more like a fluid rather than a conventional nanofluid mixture.Das et al. [2] have investigated the increase of thermal conductivity with temperature for nanofluids with water- based fluid and nanoparticles of Al_2O_3 or CuO as the suspension material using the temperature oscillation technique. Rea et al. [3] have investigated Laminar convective heat transfer and viscous pressure loss for alumina–water and zirconia–water nanofluids in a flow loop with a vertical heated tube. The experimental result show that, for given velocity and channel geometry, 6 vol % alumina nanofluid heat transfer coefficient can be up to 27% higher than that of water in the entrance region, while the zirconia nanofluid heat transfer coefficient displays a much lower enhancement with respect to water.

Wang et al. [3] measured the relative viscosity of EG-Al_2O_3 nanofluid. Results showed that relative viscosity increase with increasing solid volume fraction.

The experimental studies of Eastman et al. [5], Choi et al. [6], Assael et al. [7], among others, have reported significant enhancement of nanofluid thermal conductivity, beyond the predictions of classical heterogeneous mixed media models such as Hamilton and Crosser [8]. This finding generated great interest in nanofluids and their potential for heat transfer enhancement.

The second law analysis is the gateway for optimization in thermal equipments and systems. Entropy generation or exergy destruction due to heat transfer and fluid flow through a duct has been investigated by many researchers and non-dimensional entropy generation number is always employed in the irreversibility examination of convective heat transfer. A study of entropy generation in fundamental convective heat transfer process was carried out by Bejan [9]. He demonstrated spatial distribution of irreversibility and entropy generation maps in the flow field and indicated that the flow geometric parameters could be selected in order to minimize irreversibility associated with the specific problem. Sahin [10] presented the second law analysis for different shaped duct such as triangular, sinusoidal etc, in laminar flow and constant wall temperature boundary conditions. He made a comparison between these ducts to find an optimum shape. He found that the circular duct geometry is the favorable one among them. He made another study in order to investigate the constant heat flux effects on these cross-sectional ducts without taking into account the viscosity variation in the analysis [11]. Viscosity variation was considered by Sahin [12] for turbulent flow condition for circular ducts [13]. Since Soma [14] and Dunbar et al. [15] put forward the concept of exergy transfer and its equation, the research on exergy transfer has led to some researchers' attention.

Exergy is an important parameter for increase the system efficiency. To the best of the author's knowledge the exergy destruction of nanofluid in circular duct with constant heat flux and laminar flow has not yet been investigated.

In the present study, the effect of water-Al_2O_3 nanofluid on exergy destruction and energy transfer of fully developed laminar flow regime in circular duct under constant wall heat investigated.

Exergy transfer analysis

Consider the constant cross-sectional area duct shown schematically in Fig. 1. The wall heat flux q_w keeps constant and the inner diameter of duct is d_i . An incompressible viscous fluid with mass flow rate, $\dot{m}$, and the inlet temperature, T_i , enters the duct of length L, and the exit temperature is T_e . The convective heat transfer and flow processes are in a steady state and thermally and hydrodynamic fully developed. The average convective heat transfer coefficient, h , is constant. In addition,

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the physical properties of the fluid are assumed to be constant within the range of temperature considered in this study, the axial heat conduction, viscous dissipation and heat losses of duct are neglected.

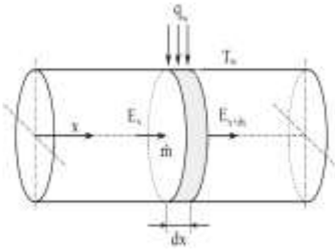

Fig. 1. control volume for exergy destruction

The exergy transfer equations of convective heat transfer may be written as follows on the basis of the linear non-equilibrium thermodynamics theory

$$E = hA\Delta T \quad (1)$$

$$e = \frac{E}{A} = h_e\,\Delta T \quad (2)$$

where

$$\Delta T = T_w - T_b = \frac{q_w}{h} \quad (3)$$

The bulk temperature variation of the fluid along the duct can be obtained as

$$T_b = T_i + \frac{4q_w}{\rho C_P\, u_m\, d_i}x = T_i + \frac{4q_w\,x}{h\,d_i}St \quad (4)$$

The expression of outlet temperature is

$$T_e = T_i + \frac{4q_w}{h}St\,\lambda \quad (5)$$

where

$$St = \frac{h}{\rho C_P} \quad (6)$$

and

$$\lambda = \frac{L}{d_i} \quad (7)$$

Using the equation (2), T_w is

$$T_w = T_b + \frac{q_w}{h} \quad (8)$$

The exergy transfer rate over a differential element of length dx is given in the following equation [16]

$$dE = h_{ex}\,dA\Delta T_x \quad (9)$$

where

$$dA = \pi\, d_i\, dx \quad (10)$$

Using specific exergy transfer rate definition

$$de' = dh - T_o\,ds \quad (11)$$

and from thermodynamic equation

$$T\,ds = dh - v\,dp \quad (12)$$

rearranging equation (11) by (13) one obtains

$$de' = C_P(1 - \frac{T_o}{T_b})dT + \frac{v}{T_b}T_o\,dp \quad (13)$$

Thus, the exergy change rate of working fluids over a differential element of length is given by

$$dE = \dot{m}\left[C_P\left(1 - \frac{T_o}{T_b}\right)dT_b + \frac{v}{T_b}T_o\,dp\right] \quad (14)$$

From equations (9) and (14)

$$h_{ex} = \frac{\rho h d_i u_m}{4q_w}\left[C_P\left(1 - \frac{T_o}{T_i + \frac{4St\,q_w\,x}{hd_i}}\right)\frac{dT_b}{dx} + \frac{vT_o}{T_i + \frac{4St\,q_w\,x}{hd_i}}\frac{dp}{dx}\right] \quad (15)$$

where

$$\frac{dp}{dx} = -\frac{f\,u_m^2}{2d_i}\rho \quad (16)$$

Putting equations (4) and (16) into equation (15) gives

$$h_{ex} = h\left[1 - \frac{T_o}{T_i + \frac{4q_w\,St\,x}{h\,d_i}}\left(1 + \frac{f\,\mathrm{Re}^3\,\mu^3}{8q_w\,d_i^3\,\rho^2}\right)\right] \quad (17)$$

Using the local exergy transfer Nusselt number definition

$$Nu_{ex} = \frac{h_{ex}\,d_i}{k} \quad (18)$$

From equations (17) and (18)

$$Nu_{ex} = Nu\left[1 - \frac{1}{\theta}\frac{1}{1 + \frac{4N_q\,X}{\mathrm{Re}\,\mathrm{Pr}}}\left(1 + \frac{f\,\mathrm{Re}^3}{8N_{qw}}\right)\right] \quad (19)$$

Combining equations (2) and (17), the local exergy flux becomes

$$e_x = h_{ex}\,\Delta T_x = q_w\left[1 - \frac{1}{\theta}\frac{1}{1 + \frac{4N_q\,X}{\mathrm{Re}\,\mathrm{Pr}}}\left(1 + \frac{f\,\mathrm{Re}^3}{8N_{qw}}\right)\right] \quad (20)$$

In these equations some parameters can be made dimensionless as follows

$$\theta = \frac{T_i}{T_o} \quad (21)$$

$$X = \frac{x}{d_i} \quad (22)$$

$$N_q = \frac{q_w\,d_i}{k\,T_i} \quad (23)$$

$$N_{qw} = \frac{q_w \rho^2 d_i^3}{\mu^3} \quad (24)$$

Heat transfer analysis

If the duct is in constant wall heat flux, the local and mean heat fluxes are

$$q_x = q = q_w \quad (25)$$

The total heat transfer rate is

$$Q = \pi d_i L q_w \quad (26)$$

The non-dimensional heat flux and heat transfer rate are defined as follows

$$q^* = \frac{q_w}{T_o k / L} = N_q \theta \lambda \quad (27)$$

$$Q^* = \frac{Q}{\dot{m} C_P T_o} = \frac{4 N_q \theta \lambda}{\mathrm{Re}\,\mathrm{Pr}} \quad (28)$$

Thermophysical properties of nanofluid

Assuming small temperature variations the thermophysical properties (density, specific heat, viscosity and thermal conductivity) of the nanofluid may be calculated as a function of nanoparticle volume concentration (ϕ), base fluid and nanoparticles properties. Using the general formula for the mixtures, the following equation can be obtained to evaluate the density of nanofluid:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi \rho_p \quad (29)$$

Where indices ‘‘p”, ‘‘bf” and ‘‘nf” refer to particle, base fluid, and nanofluid respectively. As mentioned in Buongiorno [17], assuming that the nanoparticles and the base fluid are in thermal equilibrium, the nanofluid specific heat is derived from:

$$Cp_{nf} = (1-\phi) Cp_{bf} + \phi\, Cp_p \quad (30)$$

These equations, which are based on the physical principle of the mixture rules, have been found appropriate for use with nanofluids through experimental validation by Pak and Cho [18] and Xuan and Roetzel [1].

These equations are valid for particles with these features: Spherical naoparticles with 13 nm mean diameter and for low particle volumes concentration ($\phi \langle 5\%$).

Viscosity and thermal conductivity of water-Al_2O_3 nanofluid are evaluated by the model developed by Maiga et al. [19] based on experimental works of Masuda et al. [20], Lee et al. [21] and Choi et al. [4]. For water-Al_2O_3it was proposed:

$$\mu_{nf} = (123\phi^2 + 7.3\phi + 1)\mu_{bf} \quad (31)$$

$$k_{nf} = (4.97\phi^2 + 2.72\phi + 1) k_{bf} \quad (32)$$

Although the gravity effects on distribution of the particle in case of long pipe and laminar flow, this feature is not considered in this study, equations which are used in this study are calculated due to uniform distribution of particles.

In these equations it is assumed that the temperature variation is smaller than 10^o The true effect of augmentation technique (such as adding nanoparticles) on the thermodynamic performance can be evaluated by comparing the irreversibility of the heat exchanger apparatus before and after the implementation of the augmentation technique.

Result and discussion

In this section, exergy and energy transfer characteristics of water based Al_2O_3 nanofluid laminar fluid flow through a circular duct with constant wall heat flux has been considered. The inlet temperature of fluid is $303K$ and the surrounding temperature is $298K$. The length and inner diameter of duct are 1 and $0.01mm$. Respectively, for hydrodynamically and thermally fully developed laminar flow in smooth duct [22],

$$f = \frac{64}{\mathrm{Re}} \quad (33)$$

$$Nu = 4.36 \quad (34)$$

The thermophysical properties of nanofluid are shown in Table 1.

Fig. 2 shows the local exergy transfer Nusselt number for difference X at different volume concentration. In this figure, Nu_{ex} increases considerably while the X is increased. As the value of volume concentration (ϕ) is increased Nu_{ex} decreased for fixed X . Fig. 3 shows variation of Nu_{ex} for difference X and Reynolds numbers.

As Reynolds number is increased Nu_{ex} decreases. For a fixed Reynolds number as volume concentration (ϕ) values are increased Nu_{ex} values are decreased, especially for lower values of Reynolds number.

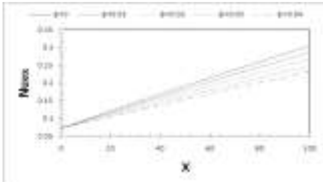

Fig. 2. Variation of Nu_{ex} with X in different volume concentration ($\mathrm{Re} = 500$)

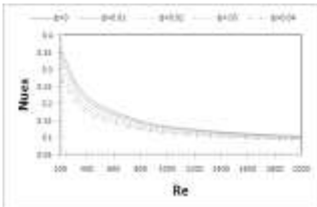

Fig. 3. Variation of Nu_{ex} with Re in different volume concentration ($X = 50$)

Fig. 4 shows the effects of N_q on Nu_{ex} at different volume concentration for a fixed Reynolds number. When N_q is increased Nu_{ex} increases. For a fixed N_q as volume concentration (ϕ) values are increased Nu_{ex} values are decreased, especially for higher values of N_q .

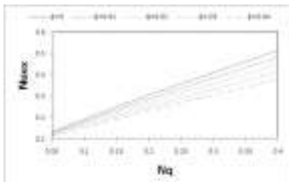

Fig. 4. Variation of Nu_{ex} with N_q in different volume concentration ($\mathrm{Re} = 500, X = 50$)

From Fig. 5, it is seen that ex increases with increases in X, For a fixed X as volume concentration (ϕ) values are increased ex values are decreased, especially for higher values of X. Fig. 6 shows variation of ex for various number of corrugation and Reynolds numbers. Increasing Reynolds number yields lower ex values for fixed volume concentration (ϕ). As the number of volume concentration is increased ex values decreases for fixed Reynolds number, especially for lower values of Reynolds number.

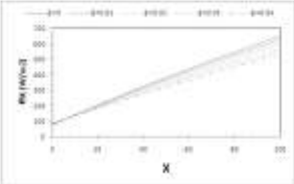

Fig. 5. Variation of ex with X in different volume concentration ($\mathrm{Re}=500$)

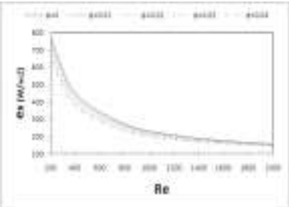

Fig.6. Variation of ex with Re in different volume concentration ($X=50$)

Fig.7 shows the effects of Reynolds number on E at different volume concentration (ϕ). As volume concentration (ϕ) is increased, E decreases. Thus, lower E is obtained for larger value of Reynolds number.

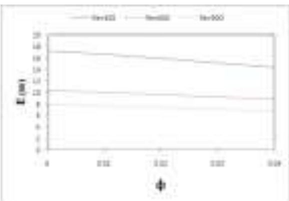

Fig.7. Variation of E with ϕ in different Reynolds number ($X=50$)

Fig. 8 shows the effects of Reynolds number on Q^* at different volume concentration (ϕ). As volume concentration (ϕ) is increased, Q^* decreases. Thus, higher Q^* is obtained for smaller value of Reynolds number.

Fig. 9 shows variation of Q^* with volume concentration (ϕ) at different N_q. As volume concentration (ϕ) is increased, Q^* decreases. Thus, higher Q^* is obtained for larger value of N_q.

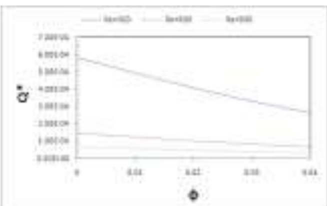

Fig.8. Variation of Q^* with ϕ in different Reynolds number ($X=50$)

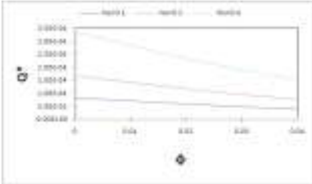

Fig.9. Variation of Q^* with ϕ in different N_q ($\mathrm{Re}=500, X=50$)

Conclusion

In this study exergy transfer characteristics of fully developed laminar water-Al_2O_3 nanofluid flow subjected to constant wall heat flux has been obtained for circular ducts. Some conclusions can be given as follows:

The exergy destruction in nanofluid is lower than base fluid. The exergy analysis depicts that exergy destruction decreases with increasing Reynolds number and volume concentration, but along the duct, at fixed volume concentration, exergy destruction increases.

References

[1]Xuan Y, Roetzel W. Conceptions for heat transfer correlation of nanofluids. International Journal of Heat and Mass Transfer 2000;43:3701–7.

[2]Das SK, Putra N, Thiesen P, Roetzel W. Temperature dependence of thermal conductivity enhancement for nanofluids. Jornal of Heat Transfer 2003;125:567–74.

[3]Rea U, McKrell T, Hu L.W, Buongiorno J. Laminar convective heat transfer and viscous pressure loss of alumina–water and zirconia–water nanofluids. International Journal of Heat and Mass Transfer 2009; 52:2042-8.

[4]Wang X, Xu X, Choi S.U.S. Thermal conductivity of nanoparticle fluid mixture. Journal of Thermophysics and Heat Transfer 1999; 13: 474-480.

[5]Eastman J, Choi S.U.S, Li S, Yu W, Thompson J. Anomalously increased effective thermal conductivities of ethylene-glycol-based nanofluids containing copper nanoparticles. Journal of Applied Physics Letters 2001; 78 : 718–720.

[6]Choi S.U.S, Zhang Z.G, Yu W, Lockwood F.E, Grulke E.A. Anomalous thermal conductivity enhancement in nanotube suspensions. Journal of Applied Physics Letters 2001; 79 : 2252–2254.

[7]Assael M.J, Chen C.F, Metaxa I, Wakeham W.A. Thermal conductivity of suspensions of carbon nanotubes in water, International Journal of Thermophysics 2004; 25 : 971–985.

[8]Hamilton R.L, Crosser O.K. Thermal conductivity of heterogeneous two component systems. Industrial Engineering Chemical Fundamental 1962; 3: 187–191.

]Bejan A. Entropy generation minimization. CRC Press 1996, Boca Raton.

[10]Sahin AZ. A second law comparison for optimum shape of subjected to constant wall temperature and laminar flow. Heat and Mass Transfer 1998;33: 425–430.

[11]Sahin AZ. Irreversibilities in various duct geometries with constant wall heat flux and laminar flow. Energy 1998;23:465–473.

[12]Sahin AZ. Second lawanalysis of laminar viscous flow through a duct subjected to constant wall temperature. Journal Heat Transfer 1998;120:76–83.

[13]Sahin AZ. Entropy generation in turbulent liquid flow through a smooth duct subjected to constant wall temperature. International Journal Heat and Mass Transfer 2000;43:1469–1478.

[14]Soma J. Exergy transfer: A new field of energy endeavor, Energy Engineering 1985; 82: 11–22 .
[15]Dunbar W.R, Lior N.R, Gaggioli A. Component equations of energy and exergy. Journal Energy Resource and Technology 1992; 114: 75–83.
[16]Wu S.Y, Chen Y, Li Y.R, Zeng D.L. Exergy transfer characteristics of forced convection heat transfer through a duct with constant wall heat flox. Journal of Energy 2007; 32: 686-696.
[17]Buongiorno. J. Convective transport in nanofluids. Journal of Heat Transfer 2006; 128: 240–50.
[18] Pak B.C, Cho Y.I, Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles. Journal of Experimental Heat Transfer 1998, 11:151–70.
[19]Maiga S.E.B, Nguyen C.T, Galanis N, Roy G, Heat transfer behaviors of nanofluids in a uniformly heated tube. Journal of Super lattices Microstructure 2004, 35: 543–57.
[20]Masuda H, Ebata A.A, Teramae K, Hishinuma N, Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles. Netsu Bussei 1993, 4:227–33.
[21]Lee S, Choi S.U.S, Li S, Eastman G, Measuring thermal conductivity of fluids containing oxide nanoparticles. Journal of Heat Transfer 1999, 121:280–9.
[22]P. Holman, Heat transfer (9th edition). McGraw-Hill, New York (2002).

Table 1. Thermophysical properties of water-Al_2O_3

	water	*Al_2O_3*
$k\ (W/m^2\ K)$	0.613	36
$C_P\ (J/kg\,K)$	4179	733
$\rho\ (kg/m^3)$	998	3880
$\mu\ (kg\,m/s)$	855×10^{-6}	———
ϕ	———	$0-4\%$