Entropy Generation Analysis of EG – Al_2O_3 Nanofluid Flows through a Helical Pipe

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Abstract:
Nanofluids, i.e. fluid suspensions of nanometer-sized solid particles are the new generation of heat transfer fluids for various industrial applications because of their excellent thermal performance. This study analytically and experimentally examines the effects of nanoparticle dispersion on the entropy generation of EG–Al_2O_3 nanofluid flows through a helical pipe as a heat exchanger under constant wall heat flux thermal boundary condition in laminar regime. It is found that adding nanoparticles improves the thermal performance of EG–Al_2O_3 flow with Re numbers less than 3700. On the other hand the results shows that adding the 5% by volume Al_2O_3 nanoparticles in the EG in Dean numbers less than 100 can decrease the entropy generation by 4.511%. Also it is shown that adding nanoparticles leads to increase entropy generation in the cases that fluid flow (pressure drop) irreversibility is dominant. Moreover, optimum conditions of radius ratio and Dean Number for laminar nanofluid flow are obtained.
Keywords: *Thermodynamic optimization, Nanofluid, Helical coil, Entropy generation, Laminar flow.*

1. INTRODUCTION

Nanofluid is envisioned to describe a fluid in which nanometre sized particles are suspended in conventional heat transfer basic fluids. Conventional heat transfer fluids, including oil, water and ethylene glycol mixture are poor heat transfer fluids since the thermal conductivity of these fluids play an important role on the heat transfer coefficient between the heat transfer medium and the heat transfer surface.

Since the solid nanoparticles with typical length scales of 1–100 nm with high thermal conductivity suspended in the base fluid (low thermal conductivity) have been shown to enhance effective thermal conductivity and the convective heat transfer coefficient of the base fluid.

Nanofluid convective heat transfer and viscosity measurements, and evaluates how they perform heating buildings in cold regions have been investigated. Use of nanofluids to heat applications can reduce the size of the heat transfer system and reduce the accompanying pressure loss and the subsequent pumping power. This will reduce energy consumption that comes from power plants and will thus indirectly reduce environmental pollution [1].

Choi [2] is the first who used the term nanofluids to refer to the fluid with suspended nanoparticles. Choi et al. [3] showed that the addition of a small amount (less than 1% by volume) of nanoparticles to the conventional heat transfer liquids increased the thermal conductivity of the fluid up to approximately two times. The performance of any thermodynamic system can be truly judged by thermodynamic performance only.

Entropy generation in a system is the measure of entropy created by the irreversibility such as fluid friction and heat transfer through a finite temperature difference, etc. [4]. The above two interrelated phenomena which are manifestations of thermodynamic irreversibility and investigation of a process from this standpoint are known as second law analysis.

EGM (Entropy Generation Minimization) is the method of modelling and optimization of the devices accounting for both heat transfer and fluid flow irreversibilities. The second law analysis of thermodynamic irreversibilities in a coiled tube heat exchanger has been carried out for both laminar and turbulent flow conditions.

The expression for the scaled non dimensional entropy generation rate for such a system is derived in terms of four dimensionless parameters: Prandtl number, heat exchanger duty parameter, Dean number and coil to tube diameter ratio. It has been observed that for a particular value of Prandtl number, Dean number and duty parameter, there exists an optimum diameter ratio where the entropy generation rate is minimum. Coiled tube heat exchanger was optimized thermodynamically under the constant heat flux condition by Ashok [5].

With increase in Dean or Reynolds number, the optimum value of diameter ratio decreases for a particular value of Prandtl number and duty parameter. Pawan et al. [6] have discussed the entropy generation of the nanofluids through three channels with different diameters: conventional tubes, micro and mini channels.

For both the types of flow, laminar and turbulent, there is an optimum diameter at which the entropy generation rate is the minimum. In case of turbulent flow the optimum diameter is higher than that of laminar flow. For microchannel and NFs with laminar flow, the entropy generation is rate ratio is always above unity and increases with volume fraction. Moghaddami et al. [7] investigated the flow of Alumina- water nanofluids considering analysis of the second law of thermodynamic. The results showed that significant irreversibility caused by pressure drop led to the entropy generation improvement. The optimized conditions according to the entropy generation rate for the laminar and turbulent flow have been obtained. In addition, a few works have studied friction factor characteristics of nanofluids flow besides the convective heat transfer. Experimental investigation of forced convective heat transfer coefficient in nanofluids of Al_2O_3/EG and CuO/EG in a double pipe and plate heat exchangers under turbulent flow have been investigated [8]. Also the effects of nanoparticles on flat-plate collector efficiency by using nanofluids have been studied [9].The heat transfer characteristics in spirally coiled heat exchangers have been rarely investigated. Experimental studies on the heat transfer and pressure drop characteristics of Cu–water and Al–water nanofluids in a spiral coil have been done [10].

In this study, the entropy generation of the γ-Alumina (gamma type) - EG (ethylene glycol) nanofluid through the helical tube under the constant heat flux and laminar flow will be investigated analytically and experimentally. Furthermore, by applying the EGM optimization method, optimized values of the nanoparticles volume fraction, Dean Number and radius ratio will be calculated.

2. THERMOPHYSICAL PROPERTIES OF NANOFLUIDS

By considering a little change in the temperature of the fluid, all of Thermophysical properties such as density, specific heat, viscosity and thermal conductivity can be calculated by the functions of volume fraction. The density of nanofluids can be calculated by utilizing of general equation for mixtures. This equation is being mentioned as below:

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

Refer to [11], if the nanoparticles and base fluid are in thermal equilibrium, the thermal capacity of nanofluid obtains by equation 20.

$$C_{p,nf} = \frac{(1-\varphi)\rho_{bf}C_{p,bf}+\varphi\rho_p C_{p,p}}{\rho_{nf}} \quad (2)$$

Viscosity and thermal conductivity of EG–Al_2O_3 nanofluids are evaluated by the model developed by Maiga et al. [12] based on experimental works of previous researchers. They suggested the equation 3 and 4 respectively for viscosity and thermal conductivity.

$$\mu_{nf} = \mu_{bf}(306\varphi^2\text{-}0.19\varphi + 1) \quad (3)$$

$$k_{nf} = k_{bf}(28.905\varphi^2 + 2.8273\varphi + 1) \quad (4)$$

In that equation the changes of temperature is less than. All of the property of the nanoparticles and the EG are mentioned in the Table 1.

Table 1: *The properties of nanoparticles and EG*

Materials	Density (kg/m^3)	Viscosity ($N.s/m^2$)	Thermal conductivity (W/m.K)	Specific heat (j/kg.K)
EG	1132	0.0157	0.258	2349
Al_2O_3	3900	-	40	880

3. GOVERNING EQUATIONS

The problem investigated in this paper consists of the nanofluid flow entropy generation inside a helical pipe. The geometrical configuration under consideration is shown in Figure 1. As shown in the figure, the outer perimeter of the pipe receives a constant heat flux (q=500 watt). The pipe has an inner diameter represented by d. The coil diameter (measured between the centers of the pipes) is represented by D. The distance between two adjacent turns is called pitch, b. The ratio of pipe diameter to coil diameter (d/D) is called curvature ratio and the invert of this parameter is called radius ratio, δ.

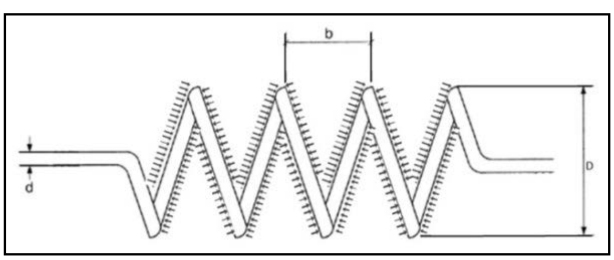

Figure 1: *Basic geometry of a helical pipe*

Nanofluid flow in laminar regime and nanoparticles volume concentration (ϕ) ranged from 1% to 5% are studied in this paper. The Reynolds number is based on the mass flow rate (m), the pipe diameter, d, and intrinsic properties of the nanofluids.The temperature rise along the coil is small (<5°C), thus the properties of the base fluids and nanoparticles are evaluated at a mean temperature (about 300 K). Since the variation of thermal conductivity and viscosity is less than 2.5% when temperature changes about 5°C [13], the temperature dependency of the nanofluid properties is neglected.

This method is one of the current procedures for analysing the behaviour of nanofluids in the both aspect, thermal and hydrodynamic. As previously mentioned in this article, entropy generation of nanofluid flow through a helical pipe is analytically investigated. So it is vital to find a relation in which entropy generation is given in terms of fluid, flow and geometry parameters. By using the first and second law in thermodynamic, heat transfer equation, fluid mechanic equation and equations which are related to thermo physical properties of nanofluid, we can obtain the objective function which is the minimum entropy generation. There are two possible irreversibility mechanisms for any fluid flow. These mechanisms are heat transfer and pressure drop through the passage. So it can be considered that:

$$\acute{S}_{gen} = \acute{S}_{gen,\Delta T} + \acute{S}_{gen,\Delta P} \quad (5)$$

Where $\acute{S}_{gen}$, $\acute{S}_{gen,\Delta T}$ and $\acute{S}_{gen,\Delta P}$ are the entropy generation rate per unit length, the entropy generation rate per unit length due to heat transfer and the entropy generation rate due to fluid friction respectively. Considering a passage of length (dx) as the thermodynamic control volume, the first and the second law state can be derived:

$$\dot{m}dh = \acute{q}dx \quad (6)$$

$$\acute{S}_{gen} = \dot{m}\frac{ds}{dx} - \frac{\acute{q}}{T+\Delta T}, \Delta T = T_w - T \quad (7)$$

Where ΔT is the temperature gap between the wall temperature (T+ΔT) and the bulk temperature of the stream (T). Using the fundamental thermodynamic relation [14] it can be concluded that:

$$dh = Tds + vdP \quad (8)$$

Combining Eqs. (6) – (8), $\acute{S}_{gen}$ becomes:

$$\acute{S}_{gen} = \frac{\acute{q}\Delta T}{T^2(1+\frac{\Delta T}{T})} + \frac{\dot{m}}{\rho T}\left(-\frac{dP}{dx}\right) \quad (9)$$

Where is the heat transfer rate per unit length. Note that is a very small term in comparison to unity. So it can be neglected and as the result, Eq. (9) becomes:

$$\acute{S}_{gen} = \frac{\acute{q}\Delta T}{T^2} + \frac{\dot{m}}{\rho T}\left(-\frac{dP}{dx}\right) \quad (10)$$

The first term on the right hand side of Eq. (10) represents the entropy generation contributed by heat transfer while the second one represents the entropy generation caused by pressure drop. In order to apply Eq. (10), we recall the definitions of friction factor (f), Stanton number (St), mass velocity (G) and hydraulic diameter (Γ):

$$f = \frac{2\rho d}{G^2}\left(\frac{dP}{dx}\right) \quad (11)$$

$$St = \frac{\left(\acute{q}/_{\Gamma\Delta T}\right)}{C_p G} \quad (12)$$

$$G = \frac{\dot{m}}{A}, \Gamma = \pi d \quad (13)$$

Where Γ is the wetted perimeter and A is the cross-sectional area. Using these definitions, entropy generation rate (Eq. (10)) becomes:

$$\acute{S}_{gen} = \frac{\acute{q}^2}{4T^2\dot{m}C_p}\frac{d}{St} + \frac{2\dot{m}^3}{\rho^2 T}\frac{f}{dA^2} \quad (14)$$

The above equation is derived for a straight tube of any arbitrary cross-section and can be safely applied to a helical coiled tube provided that is calculated on the basis of unit center-line length of the tube. The first part of the quantity on right hand side of Eq. (14) arises due to heat transfer, while the second part is due to friction. It is evident from Eq. (14) that a high Stanton number contributes to reducing the heat transfer share of S'_{gen}, while a higher friction factor has the effect of increasing the entropy generation rate due to viscous effects. In a round tube of internal diameter **d**, Eq. (14) assumes the form:

$$\acute{S}_{gen} = \frac{\acute{q}^2}{\pi k T^2 Nu} + \frac{32\dot{m}^3 f}{\pi^2\rho^2 T d^5} \quad (15)$$

The following non-dimensional quantities are then defined:

$$Re = \frac{4\dot{m}}{\pi d\mu} \quad (16)$$

$$Pr = \frac{\mu C_p}{k} \quad (17)$$

$$Q = \frac{q'}{kT} \quad (18)$$

$$B^2 = \frac{q'^2\rho^2 m^2}{kT\mu^5} \quad (19)$$

Where Q is non-dimensional heat flux, Re is Reynolds number, Pr is Prantdl number and B is the heat exchanger duty parameter that represents the heat load. Using above dimensionless quantities Eq. (14) thereby reduces to

$$S_t = \frac{1}{\pi Nu} + \frac{\pi^3}{32}\frac{fRe^5}{B^2} \quad (20)$$

Where St is scaled non-dimensional entropy generation rate (entropy generation number) given by:

$$S_t = \frac{S_{gen}}{kQ^2} \quad (21)$$

Indeed the term in Eq. (20) is our objective function, by respecting that in this study we perused the laminar flow of nanofluids in the helical coils, we substituted the thermo physical properties and the equations of Nusselt number and friction factor for laminar flow in the helical coils and after that we discussed about the optimization of this new equation.

4. RESULTS AND DISCUSSIONS

Similar to Reynolds number for flow in pipes, Dean number is used to characterize the flow in a helical pipe. The Dean number, Dn is defined as:

$$Dn = Re\sqrt{\left(\frac{d}{D}\right)} \quad (22)$$

According to the research of Srinivasan [15], the critical Re for the helical pipe flow, which determines whether the flow is laminar or turbulent, is related to the radius ratio as follows:

$$Re_{crit} = 2100\left(1 + 12\left(\frac{1}{\delta}\right)^{0.5}\right) \quad (23)$$

Therefore in this study for the radius ratio 10, the calculations for the laminar flow have been done to Reynolds number 10000 and Dean number 3184. The friction loss in flow through helical coiled tubes has been studied by Ito [16] and the following correlation has been recommended to predict the friction factor:

$$f = 0.37\left(\frac{64}{Re}\right)Dn^{0.36} \tag{24}$$

Janssen and Hoogendoorn [17] have experimentally studied the heat transfer in a single helical coiled tube subjected to a constant heat flux and presented the data as

$$Nu = 0.7Re^{0.43}Pr^{\left(\frac{1}{6}\right)}\left(\frac{d}{D}\right)^{0.07} \tag{25}$$

Substituting the values of friction factor and Nusselt number from Eqs. (24) and (25) into Eq. (20) and after recasting the constants, the non-dimensional entropy generation rate can be derived as

$$S_t = \frac{0.455}{Pr^{\left(\frac{1}{6}\right)}Dn^{0.43}\delta^{0.145}} + \frac{4.47Dn^{4.36}\delta^2}{B^2} \tag{26}$$

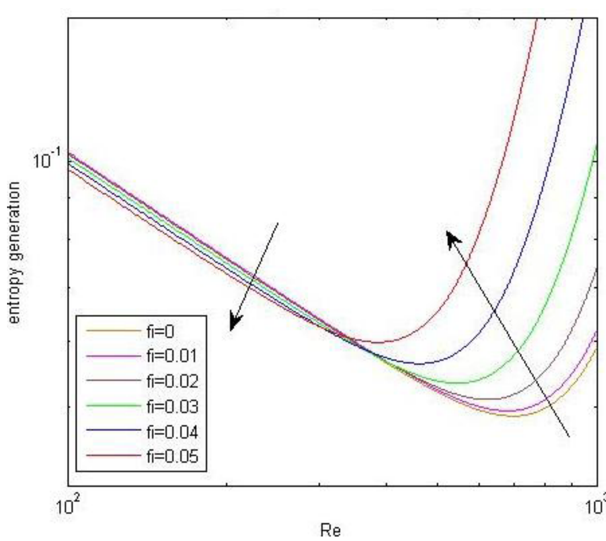

Figure 2: *Vicissitude of entropy generation by changing the Reynolds number and volume fraction*

In the Figure 2 vicissitude of entropy generation by changing the Reynolds number and volume fraction of nanoparticles in laminar flow and radius ratio 10 has been investigated. In the laminar flow at first by increasing the Reynolds number and volume fraction of nanoparticles, the generation of entropy has been decreased but gently by increasing the Reynolds number the situation has been completely inversed. In the Reynolds number 4000 and more (than 3700) by increasing the Reynolds number and volume fraction of nanoparticles, increasing in amount of entropy which is caused by fluid friction is more than decreasing in amount of the part which is caused by heat transfer and totally the generation of entropy has been increased.

This phenomenon has been shown clearly in the Figure 3. By considering this fact that the Dean number and Reynolds number has direct relationship, this figure is similar to figure number 2. For example in Dean number 100 and radius ratio 10, by increasing the volume fraction of nanoparticles, the generation of entropy has been decreased but in the Dean number 300 and volume fraction of nanoparticles more than 0.01 with enhancing the Dean number the entropy generation has been increased quickly. In the Table 2 the percentages of decreasing in the entropy generation for each volume fraction and the Dean number less than 100 have been mentioned.

Figure 4 shows the change in the entropy generation rate by changing the radius ratio and volume fraction of nanoparticles in the Dean numbers 30 and 100 for laminar flow. According to the Figure 4-a in the Dean number 30, by increasing the radius ratio and volume fraction of Table 2. It's indicating the percentages of decrease in the entropy generation for each volume fraction and the Dean number less than 100.

Table 2: *Decreasing the volume fraction of nanoparticles*

Volume fraction	0.01	0.02	0.03	0.04	0.05
Percentages of decreasing	0.0	0.376	1.128	3.008	4.511

nanoparticles, the rate of total entropy generation has been decreased; this process continues till Dean number 100 and after that it completely inverses and by increasing the radius ratio and volume fraction of nanoparticles, the rate of total entropy generation has been increased. (Figure

4-b) In low Dean numbers by considering this fact that the decreasing of entropy generation which is caused by heat transfer is more than the increasing entropy generation caused by fluid frictions, by increasing the radius ratio, the rate of total non-dimensional entropy generation decreased. But in the higher Dean number by considering that the entropy generation which is caused by pressure drops increased, by increasing the radius ratio, the rate of total non-dimensional entropy generation is enhanced.

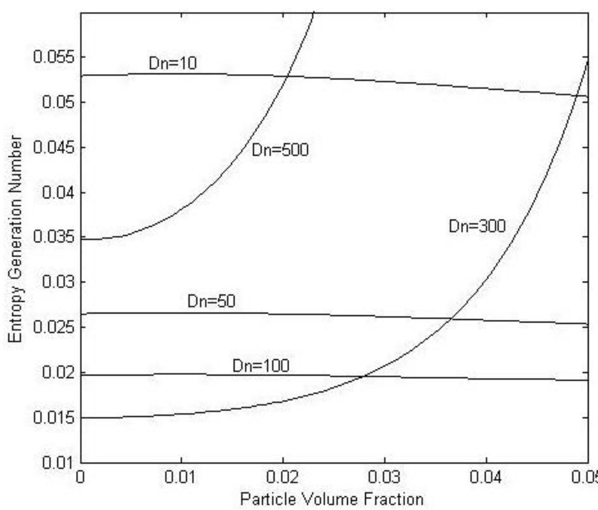

Figure 3: *The vicissitude of entropy generation by changing the volume fraction and Dean number*

For every Dean number, a thermodynamically best design can be achieved by adopting an optimal value of radius ratio, for which St would be the minimum. This minimum can be obtained by differentiating St with respect to δ and equating the derivative to zero. Under such operation, solving for δ gives:

$$\delta_{opt} = \frac{B^{0.932}}{9.86Pr^{0.078}Dn^{2233}} \qquad (27)$$

According to this Equation for each determined Dean number, by increasing the volume fraction of nanoparticles, the optimum radius ratio decreased. This attitude can be explained by this statement:" Increasing the pressure drop because of adding the nanoparticles has been compensated by decreasing of radius ratio".

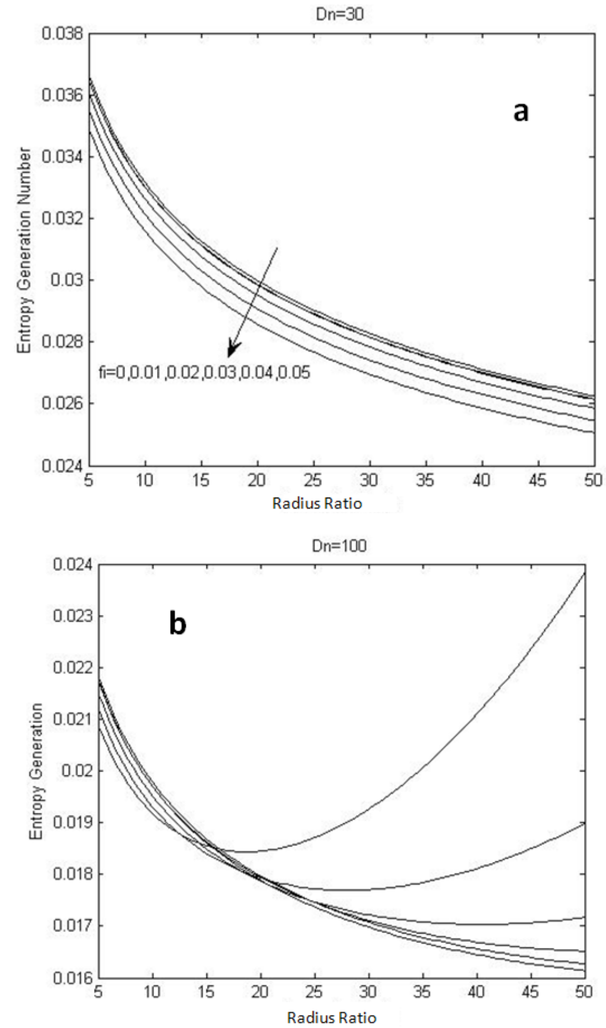

Figure 4. *The change in the entropy generation rate by changing the radius ratio and volume fraction of nanoparticles in the Dean numbers 30 and 100.*

5. CONCLUSION

In this study entropy generation for laminar flow in the Al_2O_3 - EG nanofluid in the helical coil for constant heat flux has been investigated and by the EGM method we found the optimum amount for volume fraction of nanoparticles, Reynolds number, Dean number and radius ratio.

Results of this study showed that adding the nanoparticles for improving the output of coil is effective till the amount of irreversibility due to fluid friction is lower than the amount of irreversibility due to heat transfer. In the laminar flow for each especial amount of radius ratio at the beginning by increasing the Dean number and volume fraction of nanoparticles we can see the entropy generation in the helical coil decreased but when the Dean number is more than 1200, by increasing the Dean number and volume fraction of nanoparticles, the entropy generation was enhanced. On the other hand the results showed that adding the 5% by Volume of Al_2O_3 nanoparticles in the EG in Dean numbers less than 100 can decrease the 4.511% entropy generation.

The investigation of the effect of coils geometry on the entropy generation in laminar flow showed that in the beginning, by increasing the ratio of coil diameter to pipe diameter and volume fraction of nanoparticles, the entropy generation decreased but when the Dean number is more than 100, by increasing the radius ratio and volume fraction of nanoparticles, the entropy generation was enhanced.

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