Volume 5, Special Issue, June 2018 ISSN: 2348-8565 (Online)

International Journal of Modern Engineering and Research Technology

Website: http://www.ijmert.org Email: editor.ijmert@gmail.com

National Conference on
Advances in Mechanical Engineering and Nanotechnology (AMENT2018)
29-30 June, 2018
Organized by
Department of Mechanical Engineering, University College of Engineering (A),
Osmania University, Hyderabad, TS, India

Entropy Generation Due to Change in Thermophysical Properties of Nanofluids

Ravi Prattipati
Department of Mechanical Engineering
School of Technology, GITAM,
Hyderabad (T.S.) [INDIA]
Email: 1pendyala76@yahoo.com

Srinivas Pendyala
Department of Mechanical Engineering
School of Technology, GITAM,
Hyderabad (T.S.) [INDIA]
Email : rprattipati@gmail.com

Vipul Jain
Department of Mechanical Engineering
School of Technology, GITAM,
Hyderabad (T.S.) [INDIA]

Abstract

Nanofluids have been and are being investigated rigorously for the past two decades for their enhance heat transfer properties. Different base fluids are being combined with various nanoparticles of different sizes, shapes and volume concentrations. The changes influence the thermophysical properties of the operating fluid in the system. A comparison of different fluids for operating conditions becomes difficult with changing flow and heat parameters. Entropy generation rate gives an insight into the optimal operating conditions. The objective of the paper is to find the optimum thermophysical properties for a given Reynolds number and Prandtl number. It is found that for the selected values of 1500 and 10000 of Reynolds number, the representative optimal values of Pr and density are found to be around 2-5 and 2000 kg/m3 - 2500kg/m3 respectively.

Keywords:—*nanofluids, entropy, thermophysical properties, forced convection*

I. Introduction

Nanofluids, defined as suspended nanoparticles with the size of 1 to 100 nm inside fluids, have drawn vast attention due to recently claimed high performance in heat transfer. Nanofluid improves the efficiency of heat exchanging, reducing size of the system and providing much greater safety margins with reducing costs. Heat transfer plays most important role in day to day applications such as, air conditioning, power generation, transportation, electronic, etc. However, the rapid growth of these technologies and their devices during miniaturization and an improved rate of operation have brought about serious problems in the thermal management of these devices. In recent years the second law of thermodynamics has been applied for the minimization of entropy generation to find optimal engineering system designs [1]. Thermodynamic optimization involves minimizing entropy generation is the method of optimization of real pieces of equipments that are indebted their thermodynamic imperfection to mass transfer, fluid flow, and heat transfer irreversibilities. Entropy generation determines the level of irreversibilities accumulating during a process. Consequently, entropy production can be employed as a criterio n to assess the performance of engineering devices [2]. Generally, in a system entropy is generated due to thermal conductivity and viscous effects. In thermal systems where a working fluid is used both of the two effects are considered to calculate the entropy generation. The generation of entropy is due to many sources, mainly external irreversibility due to heat transfer with finite temperature difference and internal irreversibility due to fluid friction.

II. Literature Review

Nanofluids are suspensions of nanoparticles in fluids that show significant enhancement of their properties at modest nanoparticles concentrations. Engineered nonmaterials possess a unique combination of chemical, physical, mechanical, and thermal properties. This makes them promising candidates for a variety of heat transfer applications. Daungthongsuk and Wongwises [3] reviewed both experimental and numerical studies on forced convection heat transfer in nanofluid flow. Haddad et al. [4] considered both numerical and experimental studies on natural convection of nanofluids in different types of cavities. Mahbubul et al. [5] compared different models presented for the viscosity of nanofluids in the literature. A review on heat conduction in nanofluids was performed by Fan and Wang [6] where the authors focused on thermal conductivity of nanofluids. Oztop and Al-Salem [7] conducted a review of entropy generation in natural and mixed convection heat transfer for energy systems. Generally, in a system entropy is generated due to thermal conductivity and viscous effects. Therefore high performance cooling is widely needed in industrial technologies. Due to this fact, various studies and researches are aimed to increase cooling performance of working fluids [8-11].

The conventional method for increasing heat dissipation is to increase the area available for exchanging heat to use a better heat conductive fluid [12]. This approach involves an undesirable increase in the size of a thermal management system. Addition of nanoparticles, due to their tremendously small dimensions, leads to increase in surface area [13, 14] and thereby enhancements in heat transfer characteristics. Many researchers have measured the thermophysical properties of nanofluids while many others used well-known predictive correlations. The irreversibilities have been calculated for different nanofluids by varying the flow and heat transfer parameters. However, the entropy generation rate due to the fluid properties change alone has not been reported in open literature.

III. Research Methodology

3.1. Entropy Generation

For an infinitesimally small volume, incompressible fluid without heat generation, the volumetric rate of entropy generation is [15].

$$S''' = \frac{k}{T^2}\left[\left(\frac{\partial\theta}{\partial x}\right)^2 + \left(\frac{\partial\theta}{\partial y}\right)^2\right] + \frac{\mu}{T}\left\{2\left[\left(\frac{\partial v_x}{\partial x}\right)^2 + \left(\frac{\partial v_y}{\partial y}\right)^2\right] + \left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right)^2\right\} \quad (1)$$

For circular pipes subjected to uniform heat flux, the velocity and temperature profiles can be substituted and integrated for finding the entropy generation rate.

$$S' = \frac{1}{\pi Nu}\frac{q''^2}{kT^2} + \frac{32\dot{m}^3 f}{\rho^2 T d^5} \tag{2}$$

The equation can be used for finding the entropy generation rate for internal flows in circular ducts. A close observation of equation 2 shows that entropy generation rate is dependent on geometry, fluid and flow parameters.

3.2. Nanofluids

With the wide usage of nanofluids for enhancing heat transfer characteristics of devices, the parameters for calculation of irreversibilities caused by fluid flow and heat transfer have changed. The thermophysical properties play an important role due to adding particles in base fluids. The nanofluid is usually tested for uniformity and care is given that the nanofluid stability is not changed for evaluating the heat transfer and pressure drop. The thermophysical properties such as density, specific heat, viscosity and thermal conductivity can be evaluated with formulae in literature. The estimation is done for variety of base fluids and nanoparticles for this study and the range is used for calculating the entropy generation rate.

The density is calculated by

$$\rho_{nf} = \rho_f(1-\phi) + \rho_p\phi \tag{3}$$

For specific heat

$$C_{nf} = \frac{\rho_f C_f(1-\phi) + \rho_p C_p \phi}{\rho_{nf}} \tag{4}$$

Corcione [16] by regression analysis presented an empirical correlation

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{1-34.87\left(d_p/d_f\right)^{-0.3}\phi^{1.03}} \tag{5}$$

In literature, many empirical correlations have been given to determine the thermal conductivity of different nanofluids. A model presented by Patel et. al. [17] is chosen for this study.

$$\frac{k_{nf}}{k_f} = 1 + \frac{k_p A_p}{k_f A_f} + C_e k_e \frac{u_p d_p A_p}{\alpha_f k_f A_f} \tag{6}$$

C_e is constant given by experiments and the ratio

$$\frac{A_p}{A_f} = \frac{d_f}{d_p}\frac{\phi}{1-\phi}$$

The objective of the current study is not to determine the properties accurately but to get the range of the thermophysical properties for different nanofluids, which includes metallic and non-metallic nanoparticles dispersed in the coolants that are found in literature.

3.3. Forced Convection Inside Ducts

The flow and heat transfer in ducts with uniform heat flux can be divided into two regimes, laminar and turbulent. For laminar flow, the friction factor and Nusselt number are given as [2]

$$f = 64/Re \tag{7}$$

$$Nu = \frac{48}{11} \tag{8}$$

For turbulent flow, an accurate estimation of friction factor is presented by Romeo et. al. [18] for smooth and rough pipes.

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{\varepsilon/D}{3.7065} - \frac{5.0272}{Re}\log\left(\frac{\varepsilon/D}{3.827} - \frac{4.567}{Re}\log\left(\left(\frac{\varepsilon/D}{3.7065}\right)^{0.9924} + \left(\frac{5.3326}{208.815+Re}\right)^{0.9345}\right)\right)\right) \tag{9}$$

The Nusselt number is provided by Gnielinski's correlation [2] for turbulent flow in tubes which is valid for Prandtl number from 0.5 to 2000, covering most of the properties of nanofluids, and Reynolds number from 3000 to 5×10^6.

$$Nu = \frac{(f/8)(Re-1000)Pr}{1+12.7(f/8)^{1/2}(Pr^{2/3}-1)} \quad (10)$$

The equations are used to calculate the entropy generation rate by varying the thermophysical properties and making sure the properties are not effecting the flow parameters.

IV. Results and Discussion

Entropy generation rate is dependent on friction factor and heat transfer rate other than fluid properties and geometry. In literature, the entropy generation rate has been calculated for varying geometries, flow parameters and viscosity. The variation of viscosity, from the definition of Reynolds (*Re*) and Prandtl (*Pr*) numbers, varies these dimensionless parameters and hence the entropy generation rate is varied due to this change. The Reynolds number and Prandtl number are fixed for analysis and the variation of one parameter only effects other fluid properties and not the flow parameter.

The entropy generation rate given in equation (2) is devoid of specific heat and viscosity terms. The specific heat does not influence the flow either and for a given *Pr*, the entropy generation rate wouldn't change. Viscosity influences the flow and heat transfer rate, however for a constant *Re* and *Pr*, the viscosity change can be reflected in the change of density and thermal conductivity respectively. For these reasons, specific heat and viscosity results have not been presented.

4.1. Laminar Flow

The laminar flow equations are given in section 4.3. A value of 1500 is chosen to be constant *Re* to represent laminar flow. The variation of any property on entropy generation rate is dependent on not only the property itself, but also the flow parameter it is associated with. For example, the change in density changes the *Re* but for comparison purposes, the *Re* needs to be constant. This change can be reflected in the thermal conductivity or viscosity while maintaining *Pr* also constant. This allows for the comparison for constant flow and change in only the thermophysical properties of the fluid. Hence, for a different nanofluid operating at the same *Re*, comparison is facilitated.

It is observed in figure 1, that with the increase in density of the fluid, the entropy generation rate is reduced. The particle density is usually higher than the density of the base fluid of the nanofluid system. The increase in density of the nanofluid can be achieved by dispersing higher density nanoparticles or increasing the volume concentration.

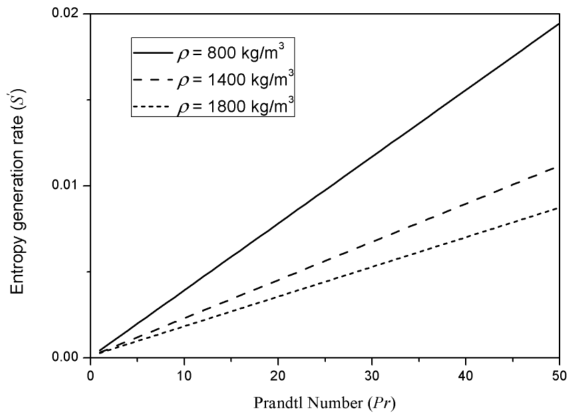

Figure 1: Variation of entropy generation with change in density for laminar flow

The thermal conductivity change for laminar flow is presented in figure 2. The increase in thermal conductivity leads to decrease in the entropy generation rate. This is a favorable outcome as the purpose of using nanofluids for heat exchange is served where addition of nanoparticles not only increase the thermal conductivity but also reduce the irreversibilities. For laminar flow conditions, the addition of nanoparticles increasing the density and thermal conductivity results in the reduced values of entropy generation rate.

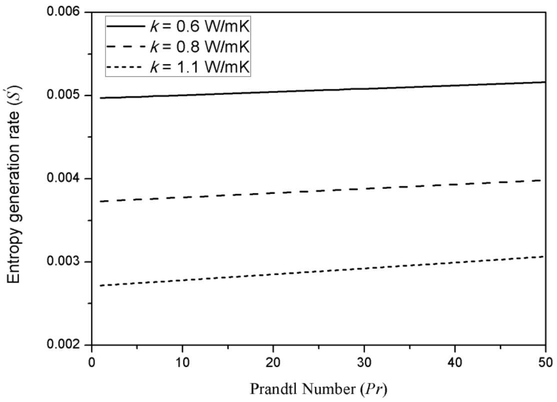

Figure 2: Variation of entropy generation with change in thermal conductivity for laminar flow

4.2. Turbulent Flow

The equations used for turbulent flow are given in section 3.3. The *Re* is maintained constant at a value of 10000. The density change is analogous to the result obtained for laminar flow but is not linear. However, the density change causing the entropy generation rate deviates to large extent for higher *Pr*.

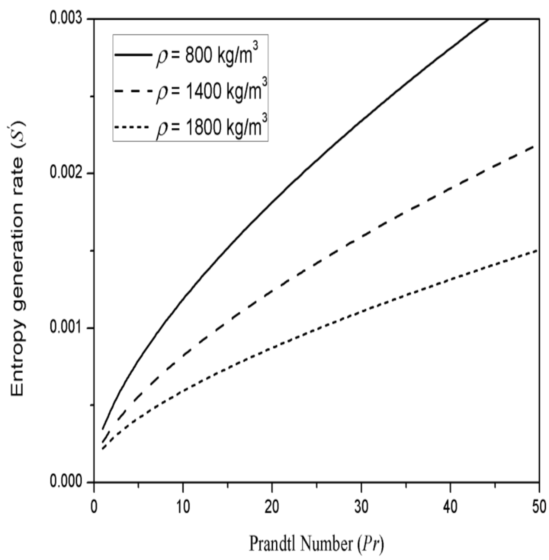

Figure 3: Variation of entropy generation with change in density for turbulent flow

The thermal conductivity change for turbulent flow can be observed in figure 4. With the increase in *Pr*, the entropy generation reduces initially and then increases.

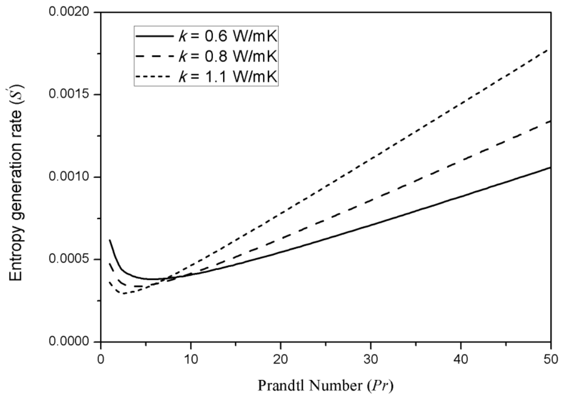

Figure 4: Variation of entropy generation with change in thermal conductivity for turbulent flow

For varying values of thermal conductivity, the trend does not change. As the thermal conductivity increases, there is a shift of minimum entropy generation rate towards the lower values of *Pr*. This is particularly interesting as it provides the optimized values for a given *Re* and *Pr*. For *Pr* beyond the optimized values, lower thermal conductivity is beneficial and vice-versa. For value of *k=1.1 W/mK,* the optimum conditions were found to be *Pr =3* and $\rho = 2291\ kg/m^3$.

V. CONCLUSIONS

For a given *Re* and *Pr*, entropy generation rate is calculated for change in thermophysical properties of the nanofluid. It is found that while higher density and thermal conductivity is preferred for laminar flow, the same cannot be extended to turbulent flow. The optimal conditions for turbulent flow changes with thermal conductivity.

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