A Study for Entropy Generation of a Heat Transfer Fluid containing Multiwalled Carbon Nanotubes and Microencapsulated Phase Change Materials

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ABSTRACT

Present research work provides an entropy generation analysis due to flow and heat transfer in a slurry containing Microencapsulated Phase Change Material (MPCM) and multiwalled carbon nanotube based nanofluid. The arrengement consider for the study was slurry flowing through a channel under laminar and turbulent regime with constant heat flux conditions. The effects of specific heat, thermal conductivity and viscosity were considered using proposed theoretical and experimental models. Results comparing entropy generation of the slurry compared with the base fluid are presented. The effects of microencapsulated phase change material and multiwalled carbon nanotubes mass fractions are studied and an optimal proportion with minimal entropy generation is presented.

Keywords: Entropy generation, Microencapsulated Phase Change Materials (MPCM), nanofluids, turbulent flow

RESUMEN

El presente trabajo de investigacion presentas un analisis de generacion de entropia causado por flujo y transferencia de calor de una lechada conteniendo material de cambio de fase microencapsulado (MPCM) y nanofluidos de nanotubos de carbono multipared. El sistema considerado para el estudio es la lechada fluyendo a través de un canal bajo flujo laminar y turbulento bajo condiciones flujo de calor constante. Los efectos de calor especifico, conductividad térmica y viscosidad fueron consideradas usando modelos experimentales y teoricos. Resultados comparando la generación de entropía de la lechada con el fluido base son presentados. Los efectos de la fracción de masa del material de cambio de fase microencapsulado (MPCM) y de los nanotubos de carbono multipared son estudiados, y una proporción optima con generación mínima de entropía es presentada.

Palabras claves: Generación de entropía, Material de cambio de fase microencapsulado (MPCM), nanofluidos, flujo turbulento.

1. INTRODUCTION

In the last decade, several research efforts have been conducted in order to develop novel heat transfer fluids with improved thermophysical properties. Potential applications of these fluids are found on processing and power industries, district cooling, HVAC, refrigeration and microelectronics cooling.

The desirable engineered heat transfer fluid should have the following features: high thermal conductivity, high heat capacity, low viscosity, stability, durability, non-toxic and chemically inert. Of the two options explored by researchers, nanofluids exhibit a trade-of between thermal conductivity and viscosity (Das et al. 2008), and slurries of microencapsulated phase change material a trade of between heat capacity and viscosity (Zhao andZhang 2011)

Recent efforts to combine the advantages of nanofluids and MPCMs slurries have been done by Alvarado et al. (Alvarado et al. 2007a) and Tumuluri (Tumuluri et al. 2011) where trade offs between properties have been found, and no methodology on selecting optimal concentrations of each component of the mixed fluid have been presented.

The present research intends to present an entropy generation analysis of a simple heat transfer problem for comparison of mixtures containing Microencapsulated Phase Change Material (MPCM) and multiwalled carbon nanotube based nanofluid with a base fluid with the objective of developing a design tool for engineering applications.

2. BACKGROUND

In order to improve and engineer thermophysical properties of heat transfer fluids for single phase convection, two main options have been explored by researchers: nanofluids and microencapsulated phase change material slurries.

Nanofluids defined by Das(Das et al. 2008) as engineered dilute colloidal dispersions of nano-sized (less than 100 nm) particles in a base-fluid have been widely reported to increase thermal conductivity when compared with the base fluid. Choi (Choi andEastman 1995) was the first to report an increase in thermal conductivity of a mixture of base fluid with Cu and γ-Al_2O_3 nanoparticles beyond the basic model of thermal conductivity by Maxwell. The greatest increase in thermal conductivity have been with the use of single wall and multiwall carbon nanotubes(Xie et al. 2003). Results of thermal conductivity of different nanofluids can be found at Buongiorno (Buongiorno et al. 2009)

The physical mechanisms of increase of thermal conductivity have not been yet elucidated by the scientific community. The effects of shape, particle interaction and particle size have been taken in to account on the Maxwell model to model nanofluids thermal conductivity of fluids with particles on the milimetrical scales(Bonnecaze et al. 1991). However, these models fail to explain the increase on thermal conductivity when dealing with particles on the nanoscale. Several mechanisms have been proposed to explain the increase of thermal conductivity including brownian motion (Jang andChoi 2004), liquid layering (Xue et al. 2004), percolation(Prasher et al. 2006). Nevertheless, the phenomena is not entirely understood.

Several researchers have studied viscosity in nanofluids, most of the studies (Choi et al. 2004)agree that at low volume fraction of nanoparticles, nanofluids behave as newtonian fluid. In alumina based nanofluids, increases equal or greater than 30% of the base fluid at volume fraction of 3% of alumina have been reported(Choi et al. 2004). The use of single wall and multiwall carbon nanotubes contributes to a steeper increase of viscosity due to the entanglement that ocurred with nanotubes (Lin-Gibson et al. 2004).The issues with viscosity as well as stabilitiy problems which have hindered its application in practical systems(Keblinski et al. 2005).

With the objective of increasing heat capacity, mixtures of base fluids with phase change materials have been studied for some time presenting problems such as clogging of pipes, supercooling and durability issues(Yamagishi et al. 1999) , with recent developments of microencapsulation techniques this problems have been overcomed to a certain degree (Alvarado et al. 2007b). Heat capacities improvement ratios of up to 70% have been reported at mass fractions 16.5% of MPCMs(Alvarado et al. 2007b). However, the use of alkanes causes the mixture to decrease its thermal conductivity affecting heat transfer process(Zhao andZhang 2011). MPCMs slurries behave as newtonian fluids even at high mass fraction with a three fold increment in viscosity at mass fractions about 17%(Alvarado et al. 2007b)

Recent efforts to combine the advantages of nanofluids and MPCMs slurries have been carried out (Alvarado et al. 2007a), (Tumuluri et al. 2011) where trade offs between properties have been found. Similar behavior as MPCMs slurries were reported. It is important to point out, that the transition from laminar to turbulent was not observed in Tumuluri study (Tumuluri et al. 2011)

A tool to compare the behavior of different combination to obtain engineered heat transfer fluids is entropy generation minimization methodology. Bejan (Bejan 1995)have developed the methodology to analyse entropy generation in forced convective heat transfer for various geometries. The generation of entropy in a internal forced convective system is caused by two sources: thermal irreversibilities and flow frictional losses. Recently, Singh (Singh et al. 2010) have used entropy generation minimization methodology to study alumina based nanofluids.

3. MODEL

Any analysis of a thermodynamical system requires that properties are well defined. Density (ρ), specific heat (C_p), termal conductivity (K), and dynamic viscosity (μ) are the main thermophysical properties for a thermal analysis.

In this study a mixture of water, ocatdecane based MPCMs and multiwalled carbon nanotubes NP is used. Two models to obtain the final properties of the blend as a function of the volume fraction of MPCM (φ_{MPCM}) and NP (φ_{np}) are presented. The volume fractions of the components of the blend are limited between 0-12% for the MPCM and 0-2% for the NP.

First Blend´s Property Model

This model assumes that the volume fractions of MPCM and NP are incorporated directly into the base fluid and thereafter obtain the properties of the blend. For density, the simple mixing theory is applied for three components (water, MPCM, CNT) and Equation 1 is obtained.

$$\rho_{eff} = \rho_{np}\varphi_{np} + \rho_{MPCM}\varphi_{MPCM} + \rho_{bf}\left(1 - \varphi_{np} - \varphi_{MPCM}\right) \tag{1}$$

In the case of specific heat, the model –Equation 2- proposed by Mulligan(Mulligan et al. 1996) derived from an energy balance is used . More complicated models could be used, however Alisetti et al.(Alisetti andRoy 2000) found that the form of specific heat function was not crucial in the analysis of internal laminar convective heat transfer.

$$c_{p,eff} = \frac{1}{\rho_{eff}}\left(\rho_{np}\varphi_{np}c_{p,np} + \rho_{MPCM}\varphi_{MPCM}c_{p,MPCM} + \rho_{bf}\left(1 - \varphi_{np} - \varphi_{MPCM}\right)c_{p,bf} + \varepsilon\rho_{MPCM}\varphi_{MPCM}\frac{\lambda}{\Delta T}\right) \tag{2}$$

In the case of the blend´s thermal conductivity, Equation (3) a simple linear model (Singh et al. 2010) in which both the MPCM and NP contribute to the mixture´s conductivity according to their volume fraction is proposed

$$K_{eff} = \left(1 - \varphi_{mpcm} - \varphi_{np}\right)K_{bf} + \varphi_{mpcm}CK_{mpcm} + \varphi_{np}CK_{np} \tag{3}$$

The value of the MPCM and NP conductivity coeficients (CK_{mpcm}, CK_{np} respectively) are chosen such that at certain concentrations of (φ_{mpcm}) or (φ_{np}) matches the effective conductivity with ones presented in literature.

In the case of viscosity, Drew (Drew andPassman 1999)proposed equation for Newtonian suspensions.

$$\mu_{eff} = \mu_{bf}(1 + 2.5\varphi) \tag{4}$$

However, due to the large deviation with the experimental values of viscosity, many researchers have proposed replacing the 2.5 factor for a viscosity coefficient (Cμ) depending on the type of nanoparticle used. In this work in the case of a mixture of NP and MPCM we propose to expand the above equation to obtain the linear Equation (5).

$$\mu_{eff} = \mu_{bf}\left(1 + C\mu_{mpcm}\varphi_{mpcm} + C\mu_{np}\varphi_{np}\right) \tag{5}$$

The MPCM and NP viscosity coefficient ($C\mu_{mpcm}\varphi_{mpcm}, C\mu_{np}\varphi_{np}$ respectively) are chosen such that at certain concentrations of MPCM and nanoparticles match the effective experimental viscosity presented in literature(Tumuluri et al. 2011).

Second Blend´s Property Model

This model assumes the mixing of a base fluid, MPCM slurry and multiwalled carbon nanotube based nanofluid. The MPCM slurry and nanofluid contain fix volume fractions of MPCM and multiwalled carbon nanotube. Equations (6,7,8) use simple mixing theory to express density.

$$\rho_{eff} = \rho_{nf}\varphi_{nf} + \rho_{Slurry}\left(1 - \varphi_{nf}\right) \tag{6}$$

$$\rho_{nf} = \rho_{np}\varphi_{np} + \rho_{bf}\left(1 - \varphi_{np}\right) \tag{7}$$

$$\rho_{Slurry} = \rho_{MPCM}\varphi_{MPCM} + \rho_{bf}\left(1 - \varphi_{MPCM}\right) \tag{8}$$

The specific heat for this model can be computed with equation (9).

$$C_{p,eff} = \frac{1}{\rho_{eff}}\Big(\rho_{np}\varphi_{nf}\varphi_{np}C_{p,np} + \rho_{MPCM}\varphi_{Slurry}\varphi_{MPCM}C_{p,MPCM} + \rho_{bf}\left(1 - \varphi_{nf}\varphi_{np} - \varphi_{Slurry}\varphi_{MPCM}\right)C_{p,bf} + \varepsilon\rho_{MPCM}\varphi_{Slurry}\varphi_{MPCM}\frac{\lambda}{\Delta T}\Big) \tag{9}$$

The thermal conductivity for the blend can be model using a "linear blending rule" for two components equation (10). Other models have a deviation of less than 10% respect to this "linear blending rule"(Assael et al. 1992).

$$K_{eff} \cong X_{nf}K_{nf} + \left(1 - X_{nf}\right)K_{Slurry} \tag{10}$$

Where $X_{nf} = \dfrac{\rho_{nf}}{\rho_{nf} + \left(\frac{1 + \varphi_{nf}}{\varphi_{nf}}\right)\rho_{Slurry}}$.

For MPCM slurry, we use Maxwell's relation equation 11.

$$K_{Slurry} = K_{bf}\left[\frac{2K_{bf} + K_{MPCM} - 2\varphi_{MPCM}\left(K_{MPCM} - K_{bf}\right)}{2K_{bf} + K_{MPCM} - \varphi_{MPCM}\left(K_{MPCM} - K_{bf}\right)}\right] \tag{11}$$

In the case of nanofluid, we use equation (12,13) proposed by Hamilton and Crosser (Hamilton andCrosser 1962).

$$K_{nf} = K_{bf}\left[\frac{K_{np} + (n-1)K_{bf} - (n-1)\varphi_{np}\left(K_{bf} - K_{np}\right)}{K_{np} + (n-1)K_{bf} + \varphi_{np}\left(K_{bf} - K_{np}\right)}\right] \tag{12}$$

Where $n = 3/\xi$ and ξ is called the sphericity and is defined as the ratio of the surface areas of a sphere with the volume equal to that of the MWCNT.

For MWCNT, equation (13) is used for compute the sphericity.

$$\xi = \frac{\left(1.8*\left(D^2\right)*L\right)^{\frac{2}{3}}}{D*L + 0.5*D^2} \tag{13}$$

Where D is diameter and L is length of nanoparticle

The approach to model viscosity is the same used in the first blend's property model, equation 5.

Table 1 provides the input parameter used in this analysis which consist of the thermal physical properties of the components of the blend..

Table 1

Thermophysical properties of slurry components at 25C

Parameter	Symbol	Value
Base Fluid Density	ρ_{bf}	1000 Kg/m^3
NP Density	ρ_{np}	2100 Kg/m^3
MPCM Density	ρ_{MPCM}	0856 Kg/m^3
Base Fluid Especific Heat	$C_{p,bf}$	4.179 $KJ/(Kg\ K)$
NP Especific Heat	$C_{p,np}$	0.485 $KJ/(Kg\ K)$
MPCM Especific Heat	$C_{p,MPCM}$	2.180 $KJ/(Kg\ K)$
MPCM Latent Heat	λ	244.0 $KJ/(Kg\ K)$
Base Fluid Conductivity	K_{bf}	0.616 $W/(m\ K)$

Parameter	Symbol	Value
NP Conductivity	K_{np}	80 $W/(m\ K)$
MPCM Conductivity	K_{MPCM}	0.152 $W/(m\ K)$
NP Conductivity Coef.	CK_{np}	11
MPCM Conductivity Coef.	CK_{mpcm}	0.152
Base Fluid Viscosity (25°C)	μ_{bf}	0.89E-3 Pa/s
NP Viscosity Coeficient	$C\mu_{np}$	120
MPCM Viscosity Coeficient	$C\mu_{mpcm}$	15

Entropy Model

The problem consists of a blending flowing through a channel under laminar and turbulent regime with constant heat flux conditions. Three different diameters (1,5, 10 mm) and two different heat fluxes (1000, 10000 W/m^2) have been used, it is also assumed the the totality of MPCM goes through the phase change process.

In the case of laminar regime, the following correlations{{917 Incropera, Frank P 1985}} are used to model heat transfer process:

$$Nu = \frac{h*D}{K_{eff}} = 4.36 \quad (14) \quad \text{where} \quad f = 64/Re_D \quad (15)$$

In the case of the turbulent regime, the Dittus-Boelter for the Nusselt number and Blasius correlation for the friction factor are used {{917 Incropera, Frank P 1985}}.

(Incropera andDe Witt 1985)

$$Nu = \frac{h*D}{K_{eff}} = 0.023 Re_D^{0.8} Pr^{0.4} \quad (16)$$

$$f = 0.316 Re_D^{-1/4} \quad ; 4000 < Re_D < 10^{\wedge}5 \quad (17)$$

The rate of entropy generation per unit length can be compute with Bejan's equation (18) for an internal flow

$$S'_{gen} = \frac{q''^2 \pi D^2}{kT^2 Nu(Re_D, Pr)} + \frac{8\dot{m}^3}{\pi \rho^2 T D^5} f(Re_D) \quad (18)$$

Where is necessary assume homogeneous mixture (simple system), incompressible flow (since ΔT is small and percentage of water in the blend is greater), entropy per unit area, velocity, and heat flux are one-dimensional, no changes in chemical composition and Newtonian behavior. T is surface average temperature.

For each fluid at an initial flowrate of the base fluid, equivalent flowrates of the blended fluid are computed by equating heat capacity rates of working fluid and base fluids (equation 19).

$$C_{p,eff}\dot{m}_{eff} = C_{p,bf}\dot{m}_{bf} \quad (19)$$

This implies that for MPCM slurry with 100% phase change $\dot{m}_{eff} < \dot{m}_{bf}$

For laminar flow equation, equation 20 is used to calculate entropy generated.

$$\dot{m}_{eff} = \frac{c_{p,bf}}{c_{p,eff}}\left(\frac{1000\pi D\mu_{bf}}{4}\right)$$

$$\dot{S}'_{gen} = \frac{q''^2\pi D^2}{4.36kT^2} + \frac{(8\times10^6)\pi}{T}\left(\frac{c_{p,bf}}{c_{p,eff}}\frac{\mu_{bf}}{\rho D}\right)^2\mu_{eff} \qquad (20)$$

For turbulent flow, equation 21 is used to calculate entropy generated

$$\dot{m}_{eff} = \frac{c_{p,bf}}{c_{p,eff}}\left(\frac{10000\pi D\mu_{bf}}{4}\right)$$

$$\dot{S}'_{gen} = \frac{q''^2\pi D^2(C_{p,eff}\mu_{eff})^{0.4}}{36.45k^{0.6}T^2(C_{p,bf}\mu_{bf})^{0.2}} + \frac{(28.097\times10^3)}{\rho^2D^2T}\left(\frac{C_{p,bf}}{C_{p,eff}}\right)^{2.75}\mu_{bf}^{2.75}\mu_{eff}^{0.25} \qquad (21)$$

4. RESULTS AND DISCUSSION

Figure 1a shows results of entropy generation rate ratio for laminar flow regime with $1000W/m^2$ heat flux and 1mm diameter. Results show that a maximum concentration of MPCMs is desired due to the decreasing mass flow rate needed to transport the same amount of heat which reduces entropy generated by viscosity. Figure 1b presents results for turbulent flow, where the impact of a decreased mass flowrate is more pronounced, exhibits a reduction of the entropy generation rate ratio greater than laminar regime because the exponential decrease of entropy as a result of a larger effective specific heat is greater in the case of turbulent flow.

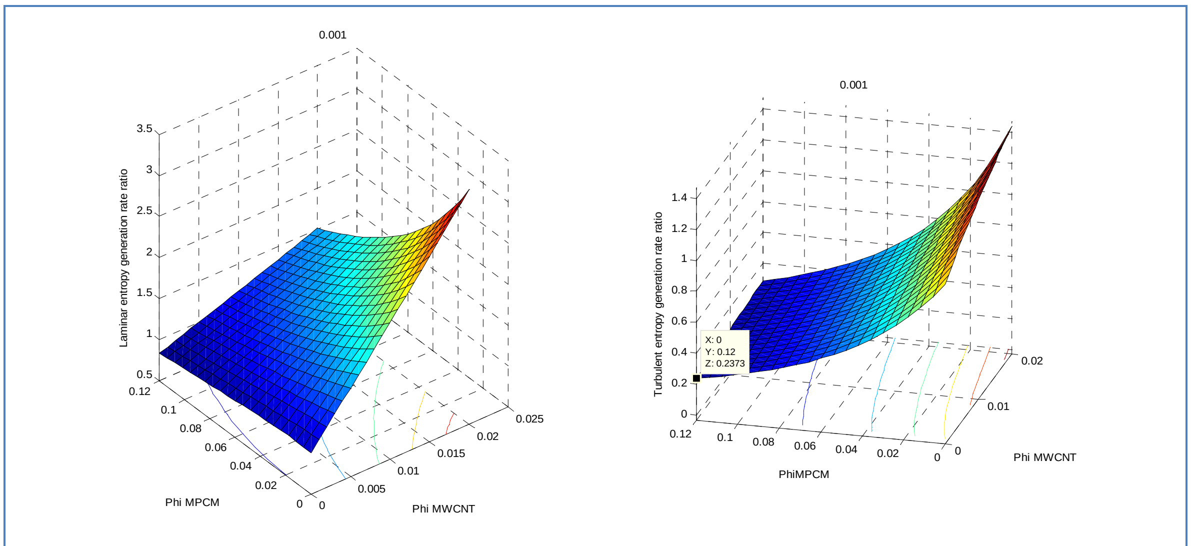

Figure 1: Entropy Generation Rate Ratio, $1000W/m^2$ Heat Flux, 1mm Diameter

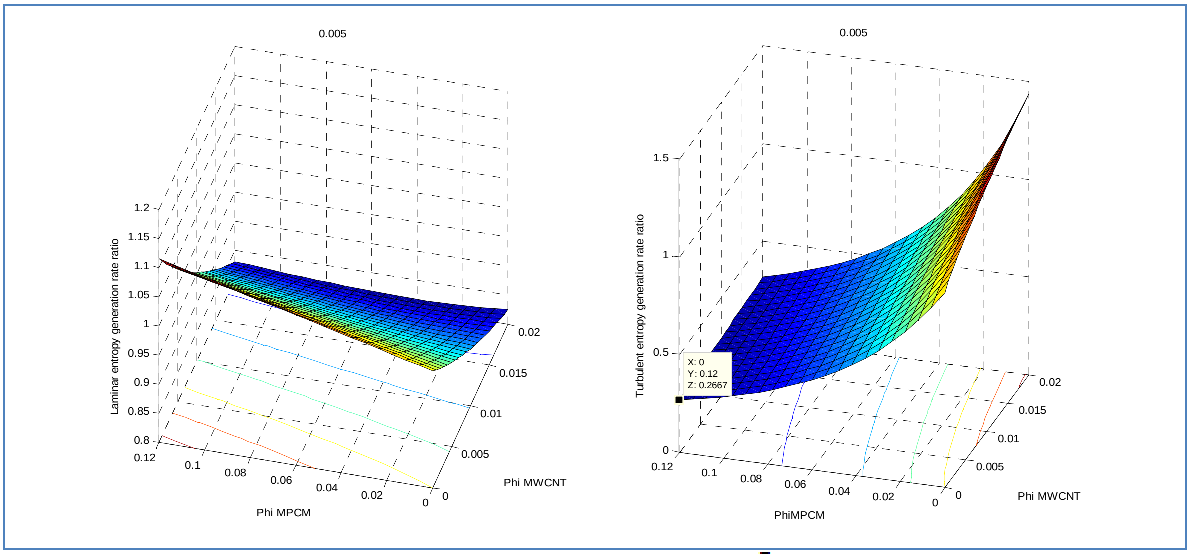

Figure 2: Entropy Generation Rate Ratio, $1000W/m^2$ Heat Flux, 5mm Diameter

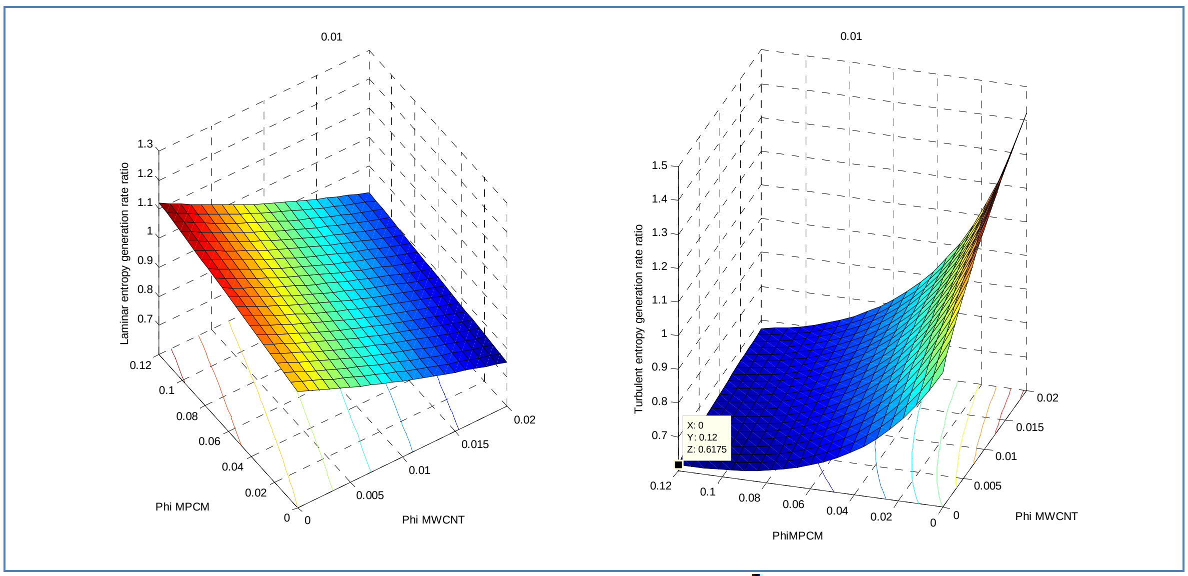

Figure 3: Entropy Generation Rate Ratio, $1000W/m^2$ Heat Flux, 10mm Diameter

For larger diameters (Figure 2 and Figure 3) the tendencies in the laminar regime change, the heat transfer entropy generation term becomes more significant than the friction entropy generation term, increasing NP concentration increases effective thermal conductivity decreasing the entropy generation rate ratio. This implies that for larger diameters using nanoparticles is better. However, certain concentrations of CNT nanoparticles using certain amounts of MPCM reduce entropy generation rate ratio a little more in Figure 2, this behavior is seen when the diameter allows both terms to be comparable in magnitude. For turbulent flow the tendencies continue invariable, however, for larger diameters the MPCM´s effect on entropy generation rate ratio is less significant.

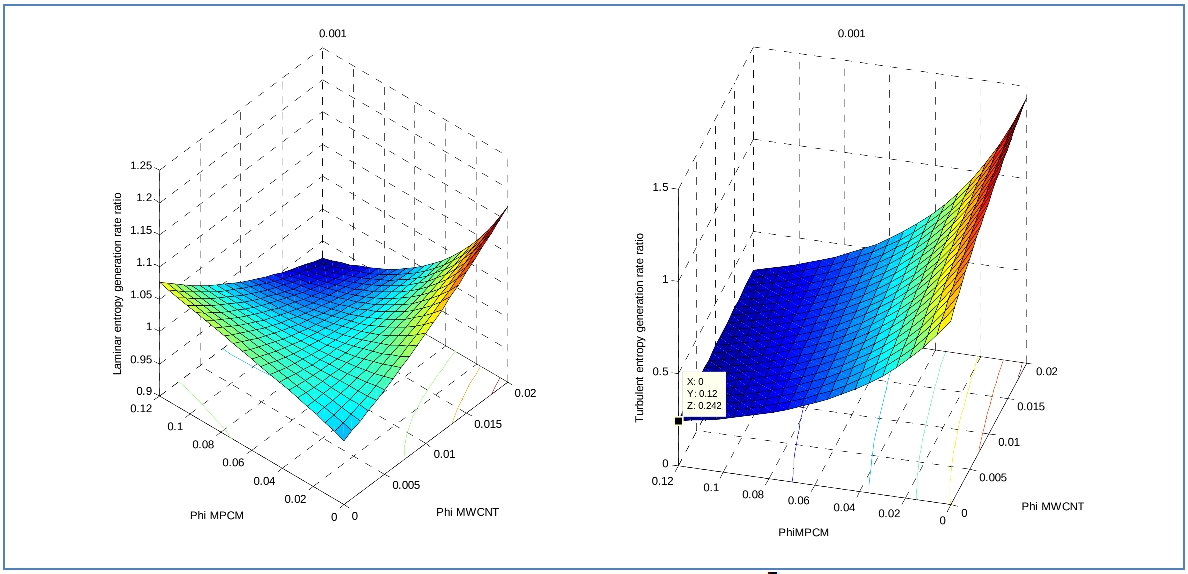

Figure 4: Entropy Generation Rate Ratio, $10000 W/m^2$ Heat Flux, 1mm Diameter

In the case of heat fluxes of with $10000\ W/m^2$ and diameters of 1 mm, figure 4 indicates the heat transfer entropy generation term becomes comparable with the other term, and in this model the combined action of MPCM and CNT fractions near 12% and 2% respectively reduce the entropy generation rate ratio (although small) but increases it when individual concentrations increase. For the turbulent flow case there is no change in the trends presented for heat fluxes of 1000 W/m^2.

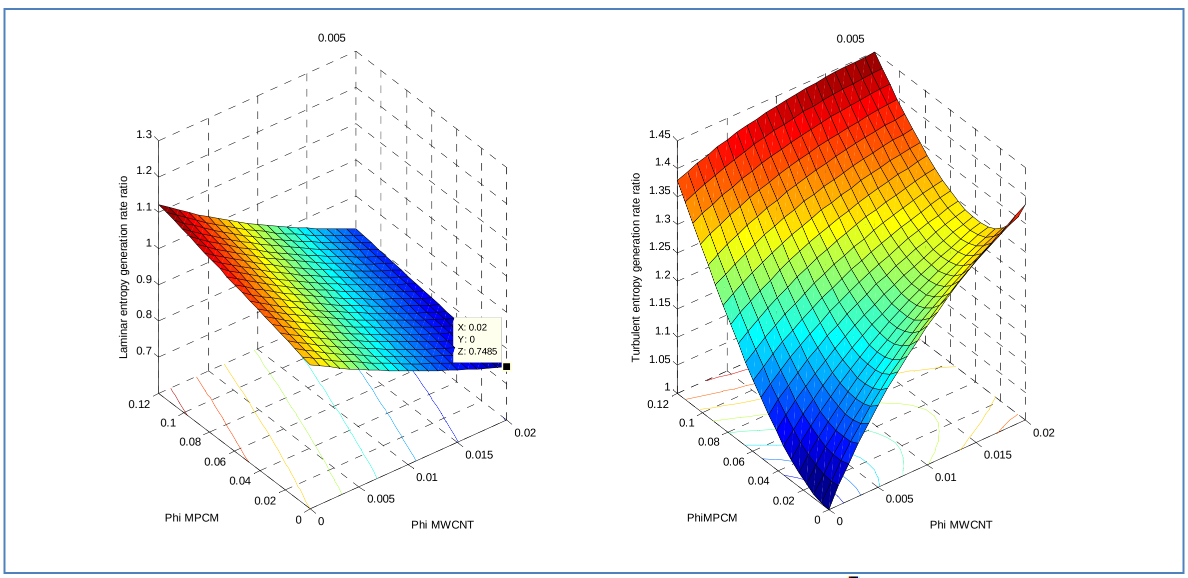

Figure 5: Entropy Generation Rate Ratio, $10000 W/m^2$ Heat Flux, 5mm Diameter

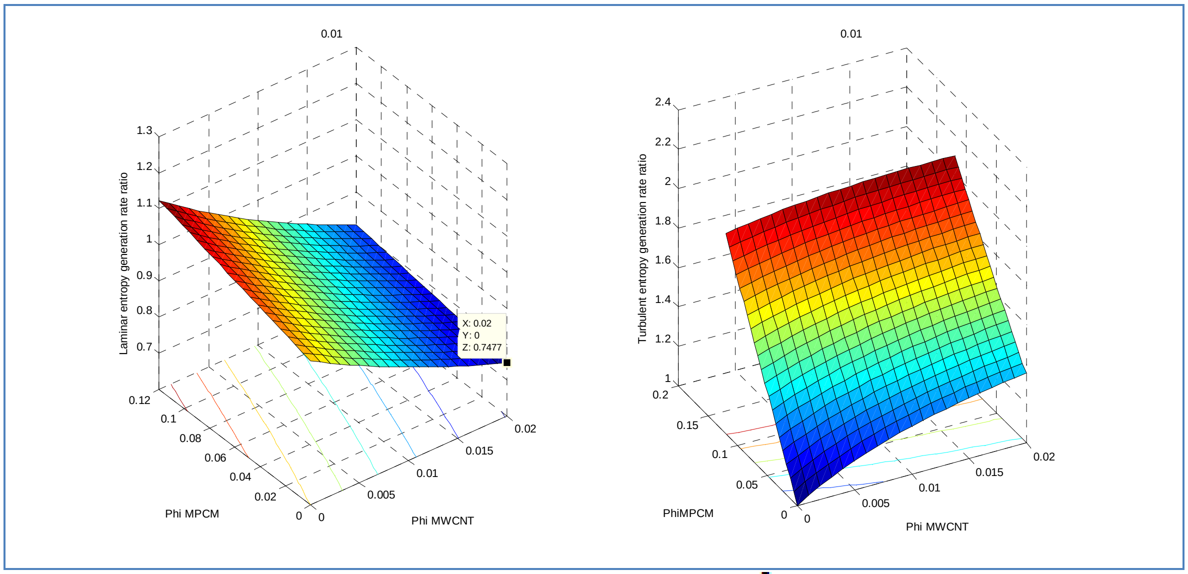

Figure 6: Entropy Generation Rate Ratio, $10000W/m^2$ Heat Flux, 10mm Diameter

Increasingly diameters and higher heat fluxes (Figure 5 and Figure 6) shows that regardless of blend´s composition the entropy generation rate ratio is always greater than 1 in turbulent regime. For laminar regime the heat transfer entropy generation term is always higher than the friction entropy generation term, and results are similar as $1000W/m^2$ heat flux 5mm and 10mm diameters cases.

5. CONCLUSIONS

The present paper shows two models to predict the final properties of a blend of MPCM, NP and water. Howeverm further experimental research for themophysical properties is needed to better understand the behavior of this type of fluids and verify the mathematical models this implies an increased accuracy in heat transfer models, pressure drop models and entropy generation models.

This Study for Entropy Generation of a Heat Transfer Fluid containing MWCNT and MPCM highlight the importance of diameter pipe, heat flux and flow regime in irreversibility's of the process. The results shows that for reduced diameters and low heat fluxes (for both laminar an turbulent regimes) it is not recommended the use of nanoparticles instead it is recommended the usage of MPCM as long as there is an increase in effective specific heat, which means working near MPCM´s phase change temperature range. For greater diameters and heat fluxes it is not recommended the usage of MPCM instead it is recommended the NP usage especially for laminar flow because it appears to become important the increased effective thermal conductivity, in the case of turbulent flow the irreversibility's of the blend will be higher than the associate with water.

Authorization and Disclaimer

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