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Assessment of a lubricant based nanofluid application in a rotary system

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ABSTRACT

Rotary systems and nanofluids are frequently used in energy conversion and management systems. In this paper, a numerical study is performed to evaluate the application of metallic nano-particles in a rotary system filled with a lubricant from first and second laws of thermodynamics points of view. The nano-lubricant (lubricant based nanofluid) is considered inhomogeneous with dependent transport properties on nano-particles volume fraction, nano-particles size and the temperature. A two-phase model is undertaken to account for the Brownian motion and thermophoresis diffusion. The principal objective centers in the advantages and penalties of using nano-lubricant over the pure lubricant on the basis of first and second law (of thermodynamics). The numerical results demonstrate that the nano-particles enhance the thermal performance of the rotary system. However, undesirable aspect from hydro-dynamical and second law (of thermodynamic) perspectives are reported. While a nano-lubricant with limited volume fraction in low speed rotary system is recommended, the disadvantages of nano-lubricants with high volume fractions and/or used in a high-speed rotary system are dominant to nano-lubricants advantages and must be avoided.

1. Introduction

In the recent century, nanofluids has played a significant role in saving energy for heat transfer and cooling. Solar cells [1,2], PV cells [3], Heat exchangers [4], electronic cooling packages [5–7], and lubricating systems [8] benefit from nanofluids. Nano-particles are suspended in the liquid fluids such as water, oils, ethylene and enhance the convective heat transfer of the base fluid, increase friction and change the entropy generation within the system [9–12].

Thermal conductivity and viscosity of nanofluids are among the most significant transport properties of nanofluids that must be determined preceding any evaluation of applying such fluids from first and second law of thermodynamics. Therefore, there are many publications in literature that deal with the determination of nanofluids properties. For example, Colangelo et al. [8] in their experimental work studied viscosity, and thermal conductivity of Al_2O_3 - diathermic oil nanofluids with and without surfactants as heat transfer fluid in high temperature solar energy systems. They indicated that the presence of surfactants in the nanofluids fails to change their thermal conductivity. They also reported that the viscosity and conductivity of the nanofluid is enhanced by increasing the nano-particles volume fraction. A comprehensive experimental work by Patel et al. [13] has been carried out to give a general correlation for determination of thermal conductivity variation of nanofluids with respect to volume fraction, nano-particles size and the fluid temperature. More interested readers in experimental and theoretical -based studies of nanofluids thermal conductivity/viscosity are invited to study the review papers by Corcione [14], Chandrasekar et al. [15] and Paul et al. [16].

From first law view point, effects of nano-particles on heat transfer and mechanical lost should be investigated after their transport properties are appropriately determine. For example, numerical study of applying Ag-water nanofluids in a water-cooled photovoltaic thermal system is performed by Khanjari et al. [17]. They indicated that the efficiencies from first and second laws of thermodynamics are increased by increasing the nano-particle volume fraction. Azaditalab et al. [18] numerically examined the skin friction factor of a nanofluid in a cylindrical Couette flow using a single-phase flow assumption. Analytical and numerical investigation of a nanofluid-cooled microchannel heat sink using fin and porous media approaches are carried out by Ghazvini and Shokouhmand [20] to show that the thermal efficiency and frictions are increased by using CuO-water nanofluid compared with pure water.

Applying lubricant-based nanofluids are also considered in literature. For example, Akhavan-Behabadi et al. [21] experimentally investigated convective heat transfer rate of the heat transfer oil-copper oxide nanofluid flow in horizontal smooth tubes and observed 32% enhancement in Nusselt number by using a 1.5%

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Nomenclature

Br	Brinkman number
D_B	Brownian diffusion coefficient
D_T	thermal diffusion coefficient
d_p	particle diameter [nm]
Jp	diffusions by Brownian and thermophoretic
k	thermal conductivity (dimensionless)
N_{BT}	the ratio of Brownian to thermophoretic diffusivities
N_F	number of entropy generation due to friction
N_H	number of entropy generation due to heat tr4ansfer
N_S	number of entropy generation due to summation of friction and heat transfer
r	radial coordinate, (dimensionless)
r_i	radius ratio of the cylindrical domain
R	radius of the cylindrical domain
T	temperature, (dimensionless), Eq. (1)
u	velocity, (dimensionless), Eq. (1)
Ω	angular velocity
μ	viscosity (dimensionless), Eq. (1)

Greek symbols

ϕ	Volume fraction
τ	Shear stress

Subscripts/superscripts

b	bulk quantities
f	base fluid
n	nano-particle
n_f	nanofluid
$*$	dimensional variables, Eq. (1)

CuO nano-particles compared to the pure oil. Sokhansefat et al. [22] numerically studied mixed convection heat transfer of Al_2O_3/synthetic oil nanofluid in a trough collector tube with a non-uniform heat flux and assuming three-dimensional fully developed turbulent flow to show that the volumetric concentration of nano-particles has a direct effect on convection heat transfer coefficient and the heat transfer enhancement reduces when the absorber operational temperature is augmented. Heat transfer and pressure drop characteristics of nanofluid flow inside horizontal helical tube under constant heat flux are experimental investigated by Hashemi et al. [23]. The effect of Reynolds number, fluid temperature and nanofluid particle volume fraction on heat transfer coefficient and pressure drop of the flow were studied. They observed increments in heat transfer coefficient as well as pressure by applying CuO nano-particles suspended in the pure oil.

In addition to investigating the effects of nano-particles from first law perspective, the second law of thermodynamics must be applied in conjunction with first law to monitor the quality of the transport process and to ensure that less entropy within the system is generated. Therefore, many research studied are devoted to evaluate nanofluid from second law. For instance, effects of Al_2O_3 nano-particles on the entropy generation of water based and ethylene glycol-based nanofluids through a circular pipe are analytically studied by Moghaddami et al. [24] in laminar and turbulent regimes. It is indicated that nano-particles increase entropy generation in the cases that irreversibility due to hydro-dynamical lost is dominant. Under exponentially decaying wall heat flux with constant pumping power condition in a low-Peclet-number nanofluid flow in circular microchannel heat sinks, Ting et al. [25] analytically studied entropy generation within a nanofluid. Entropy generation minimization method for a synthetic oil–Al_2O_3 nanofluid as a heat transfer fluid in a parabolic trough receiver tube is used by Mwesigye et al. [26]. Their numerical results revealed that there exists a critical Reynolds number and critical volume fraction beyond which the use of nanofluids undesirable from second law perspective. Same conclusions were made in Ref. [27] for a high concentration ratio parabolic trough solar collector by applying Cu-based nano-particles. Mahian et al. [28] analytical investigated fluid flow, heat transfer and entropy generation of Al_2O_3-EG nanofluid and TiO_2-Water nanofluid between co-rotating cylinders with constant heat flux boundary condition to show that TiO_2-Water nanofluid is more suitable than Al_2O_3-EG nanofluid to use as the working fluid at low Brinkman numbers. Their research was based on the single-phase assumption model. In single phase assumption, the same governing equations of pure fluid flow are solved and only the pure fluid properties are replaced by effective transport properties of the nanofluid. This approach is highly simplified and is very sensitive to selecting the appropriate correlation for predicting transport properties of the nanofluid to reach and acceptable agreement with experimental results. Therefore, two-phase models are found closer to reality and more suitable for analyzing nanofluids. For example, Siavashi et al. [29] flow characteristics, heat transfer and entropy generation of nanofluid flow inside an annular pipe partially or completely filled with porous media using two-phase mixture model. The study of the second law also reveals that an optimum porous media thickness exists for each nanofluid flowing in a porous medium at a specific Reynolds.

Two-phase models including; mixture model [30], VOF (volume of fluid) [31], Eulerian models [32], and Buongiorno [33,34] and [35] are introduced and are applied in the recent years for analyzing nanofluids flow and heat transfer. The model applies four equations including two conservation of mass, a single conservation of momentum and a single conservation of energy by considering the effects of Brownian diffusion and thermophoresis.

In this article, the principal objective is to evaluate the application of nano-particles suspended in a lubricant in a rotary system described by a stationary housing and a rotating cylinder (shaft), from first and second laws of thermodynamics perspectives. The originality and novelty of the present paper is that; in a rotary system, for the first time, a non-homogenous two-phase model suggested by Buongiorno [33] is used instead of the classical and simplified model of single-phase flow or the models that simplify the fluid as a homogenous medium. Further, evaluating metallic nano-particles in the rotary system under study is undertaken from several perspectives: thermal aspects, hydrodynamic effects and the entropy generation (second law analysis) perspective.

2. Physical system

Consider a nanofluid that fills the gap between an inner cylinder (shaft) of radius R_i^* and a concentric cylindrical housing of radius R_o^* as sketched in Fig. 1. Copper/PAO is considered as the lubricant-based nanofluid. The effective viscosity of nanofluid is μ_{nf}^* and its effective thermal conductivity of k_{nf}^*. Fluid flow and heat transfer occurs in an incompressible laminar flow. The subscripts 'n' and 'f' represent the *nano-particles* and the base *fluid*, respectively, while 'nf' denotes the *nanofluid*. ϕ is the nano-particle volumetric fraction and Ω is the angular velocity of the inner ring. The inner ring (shaft) is rotary and is assumed perfectly insulated while the outer ring (housing) is stationary and its temperature is