International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:11, No:6, 2017

Influence of Mass Flow Rate on Forced Convective Heat Transfer through a Nanofluid Filled Direct Absorption Solar Collector

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***Abstract*—The convective and radiative heat transfer performance and entropy generation on forced convection through a direct absorption solar collector (DASC) is investigated numerically. Four different fluids, including Cu-water nanofluid, Al_2O_3-waternanofluid, TiO_2-waternanofluid, and pure water are used as the working fluid. Entropy production has been taken into account in addition to the collector efficiency and heat transfer enhancement. Penalty finite element method with Galerkin's weighted residual technique is used to solve the governing non-linear partial differential equations. Numerical simulations are performed for the variation of mass flow rate. The outcomes are presented in the form of isotherms, average output temperature, the average Nusselt number, collector efficiency, average entropy generation, and Bejan number. The results present that the rate of heat transfer and collector efficiency enhance significantly for raising the values of *m* up to a certain range.

***Keywords*—**DASC, forced convection, mass flow rate, nanofluid.

I. INTRODUCTION

DUE to the rising demand of energy and lesser accessibility of fossil fuels, energy concern is shifting towards renewable energy sources. There is no doubt that from all the available sources, solar energy is the best option with its minimum environmental impact. At the present time, different types of solar collectors are commonly used to produce solar energy. The performance of the solar collector depends upon the characteristics of the working fluid which is used to collect solar energy in solar collector. DASCs have been proposed for variety of uses, for example water heating. Typical fluids commonly used in solar collectors have poor absorption properties that restrict the efficiency of the solar collectors. On the other hand, the thermophysical properties of liquid, for example thermal conductivity, have been remarkably affected by the nanofluid. The radiative properties of liquids are also prospectively improved by nanoparticles which lead to the enhancement in the efficiency of DASCs.

Efficiently collecting and converting this energy into some useful form is the problem. Solar collectors help the conversion of solar energy into heat. Flat plate type collectors are the most commonly used collectors which are simple in construction. DASCs [1] are new classes of collectors which are used to increase the efficiency of the collectors. Various studies [2], [3] have been performed to analyze the collector efficiency of DASCs utilizing nanofluids. The subject of energy saving and compact designs mainly involves with the heat transfer augmentation in solar devices. In current time, considerable concentrations of many researchers [4], [5] have been drawn with the concern of collector efficiency and heat loss in a variety of solar collectors filled with conventional fluid as well as various nanofluids.

An efficiency loss takes place in all thermofluidic processes because of involvement of irreversibilities. In actual fact, entropy generation rate measures the level of these irreversibilities. In designing practical systems, it is desirable to minimize the rate of entropy generation so as to maximize the available energy [6], [7]. Shahi et al. [8] investigated the entropy generation induced by natural convection heat transfer in a square cavity containing Cu-water nanofluid and a protruding heat source. Esmaeilpour and Abdollahzadeh [9] examined the natural convection heat transfer behavior and entropy generation rate in a Cu-water nanofluid-filled. Cho et al. [10] investigated the natural convection heat transfer performance and entropy generation rate in a water-based nanofluid-filled cavity bounded by a left wavy-wall with a constant heat flux, a right wavy wall with a constant low temperature, and flat upper and lower walls with adiabatic conditions. Very recent researches on nanofluid based DASC are found in [11]-[13]. In all these works, efficiency of the collector is analyzed, but entropy production is not introduced.

The overall goal of this study is to numerically simulate fluid flow, heat transfer, and entropy generation behaviors through a direct-absorption solar collector. The investigations are to be carried out at different as mass flow rate through the collector. Results will be presented in terms of isotherm distribution, average output temperature, mean Nusselt number, collector efficiency, rate of entropy generation, and Bejan number for different values of the mentioned parameter.

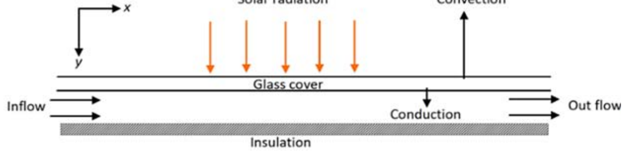

Fig. 1 Schematic diagram of the DASC

II. PROBLEM FORMULATION

Fig. 1 presents a DASC of surface area, length and height of *A*, *L*, and *H*, respectively. The enclosed space of the DASC is

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filled with nanofluid. The water-based nanofluid containing Cu nanoparticles is considered as the functioning fluid. The nanofluid enters from the left inlet with temperature T_i and exits from right opening. The solar irradiation through direct sunlight is incident on a thin flowing film of nanofluid into the DASC. The insulated bottom surface is considered so that no heat flux apart from for transmitted radiation is permitted to pass through it. The bottom wall is assumed to be very much insulated and transparent. In order to allow most of the incident solar heat flux to pass through the fluid, the DASC is covered at the top with a glass surface. Heat loss by convection takes place because the top surface is considered to be exposed to the ambient atmosphere. A two-dimensional heat transfer analysis model is developed in which the heat transfer characteristics of the top surface are assumed that it loses heat to the ambient atmosphere through convection.

TABLE I
THERMOPHYSICAL PROPERTIES [14] OF FLUID AND NANOPARTICLES AT 300 K

Physical properties	Fluid phase (Water)	Cu Copper	Al_2O_3 Alumina	TiO_2 Titanium
Cp(J/kgK)	4179	385	765	686.2
ρ (kg/m^3)	997.1	8933	3970	4250
k (W/mK)	0.613	400	40	8.9538
β (K^{-1})	21×10^{-5}	5.1×10^{-5}	2.4×10^{-5}	2.4×10^{-5}

III. MATHEMATICAL MODELING

It is assumed that the flow of nanofluid is two dimensional, incompressible, and laminar. Thermal equilibrium in water and nanoparticles is considered so that no slip can occur between them. Boussinesq approximation model is used to neglect the density variation. The steady state condition of the flow is taken account. The nanoparticles thermo-physical properties are used from Ogut [14] which is shown in Table I. The flow governs by forced convection through the DASC, and the corresponding Navier-Stokes and energy equations (dimensional form) are as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\rho_{nf}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\rho_{nf}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)-\left(\frac{1}{\rho C_p}\right)_{nf}\frac{\partial q_r}{\partial y} \tag{4}$$

The energy equation is coupled to the Radiative Transport Equation (RTE) through the divergence of the radiative flux $\frac{\partial q_r}{\partial y}=\int_\lambda K_{e\lambda}\tau I_\lambda d\lambda$, where $K_{e\lambda}$ $K_{e\lambda}$ is the spectral extinction coefficient, τ is the emissivity of glass cover, and I_λ is the incident radiation. Also, $\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s$ is the density, $(\rho C_p)_{nf}=(1-\phi)(\rho C_p)_f+\phi(\rho C_p)_s$ is the heat capacitance, $\alpha_{nf}=k_{nf}/(\rho C_p)_{nf}$ is the thermal diffusivity,

In the current study, the viscosity of the nanofluid is considered by the Pak and Cho correlation [15]. This correlation is given as $\mu_{nf}=\mu_f\left(1+39.11\phi+533.9\phi^2\right)$ and the thermal conductivity of Maxwell Garnett (MG) model [16] is

$$k_{nf}=k_f\frac{k_s+2k_f-2\phi(k_f-k_s)}{k_s+2k_f+\phi(k_f-k_s)}$$

The boundary conditions take the following forms:

- at the top and bottom surfaces: $u = v = 0$
- at the upper boundary: inward heat flux per unit area $k_{nf}\frac{\partial T}{\partial Y}=q=h_{conv}(T_{col}-T_{amb})$
- at the inlet port: $T=T_{in}$, $u = U_{in}$
- at the exit port: convective boundary condition $p = 0$
- at the bottom wall: $\frac{\partial T}{\partial y}=0$

The local and average Nusselt number (Nu) is expressed by

$$\overline{Nu}=-\frac{k_{nf}}{k_f}\frac{\partial T}{\partial y},\quad Nu=\int_0^L\overline{Nu}\,dx.$$

According to Bejan [6], the local entropy generation, s_{gen}, can be expressed by:

$$s_{gen}=\frac{k_{nf}}{T_0^2}\left[\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2\right]+\frac{\mu_{nf}}{T_0}\left[2\left(\frac{\partial u}{\partial x}\right)^2+2\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)^2\right]$$
$$=S_{gen,h}+S_{gen,v}$$

where $T_0=\frac{T_{col}+T_{in}}{2}$, $s_{gen,h}$ represents the dimensional entropy generation due to heat transfer, and $s_{gen,v}$ represents the dimensional entropy generation due to viscous dissipation.

The average entropy generation, S for the entire computational domain is as follows:

$$S=\frac{1}{\overline{V}}\int S_{gen}\,d\overline{V}=S_{gen,h,m}+S_{gen,v,m}$$

where $\overline{V}$ is the volume occupied by the nanofluid, and $S_{gen,h,m}$ and $S_{gen,v,m}$ are the average entropy generation for heat transfer and viscous effect respectively.

The Bejan number, Be, defined as the ratio between the entropy generation due to heat transfer by the total entropy generation, is expressed as

$$Be = \frac{S_{gen,h,m}}{S}$$

Collector efficiency (η) of a solar collector is a measurement of the performance which is the defined by the ratio of the useful energy gain to the available incident solar energy and the expression is as follows:

$$\eta = \frac{\text{useful gain}}{\text{available energy}} = \frac{mC_p\left(T_{out} - T_{in}\right)}{AI}$$

where *m* is the mass flow rate of the fluid flowing through the collector, C_p is the specific heat at constant pressure, and T_{in} and T_{out} are the inlet and outlet fluid temperatures, respectively.

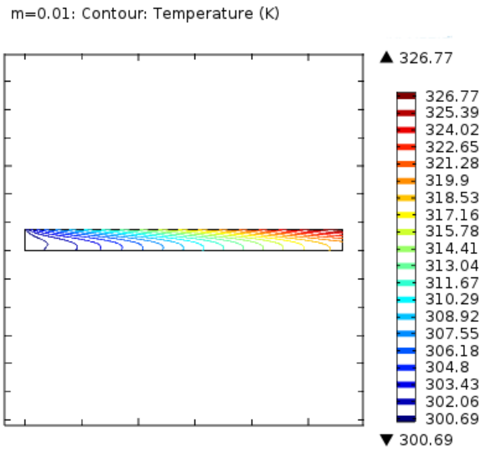
IV. Numerical Implementation

The dimensional governing equations with the appropriate boundary conditions for the considered problem are solved by the finite element method of Galerkin with weighted residual technique. Since mass conservation and this limitation may be used to find the pressure distribution, the continuity equation has been applied as a constraint. In the governing equations, the pressure *p* is eliminated by a constraint as used in the finite element method of Reddy and Gartling [17]. Large values of this constraint automatically satisfy the continuity equation. Then, using a basis set, the velocity components (*u*, *u*) and temperature (*T*) are expanded. The consequent nonlinear residual equations are given by the Galerkin finite element technique. In these equations, the integrals are evaluated by using three points Gaussian quadrature method. The coefficients of the expansions are determined by solving the non-linear residual equations where Newton–Raphson method is used. The convergence criterion is set to $\left|\psi^{n+1} - \psi^{n}\right| \le 10^{-4}$, where *n* is the number of iteration and Ψ is a function of *u*, *v* and *T*.

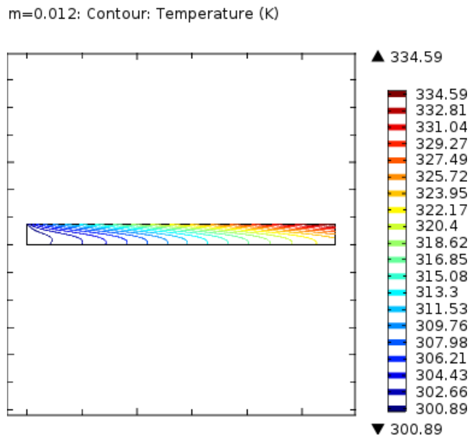
V. Results and Discussion

Numerical results are displayed in terms of isothermal lines, average output temperatures, average Nusselt number, percentage of collector efficiency, mean entropy generation and Bejan number for various values of mass flow rate(m) for a DASC filled with nanofluid. The considered values of mass flow rate m = 0.01, 0.012, 0.015, and 0.018 kg/s. Three different nanofluids: Cu-water, Al_2O_3-water and TiO_2-water are used in addition to the base fluid as water. The values of other parameters are fixed at solar irradiation I = 225 W/m^2, flow thickness D = 0.015 m and solid volume fraction of nanofluid ϕ = 2%.

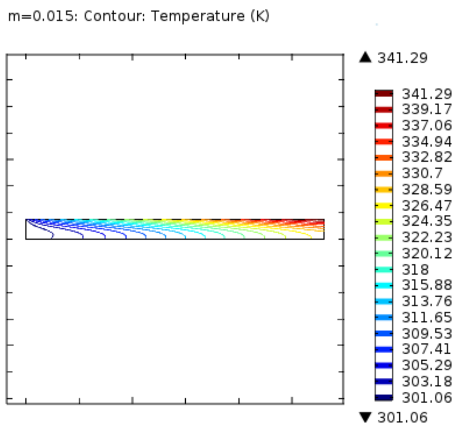
Figs. 2 (a)-(d) shows the effect of mass flow rate of Cu-water nanofluid in a DASC for four different values; m = 0.01, 0.012, 0.015, 0.018 kg/s on isothermal contours. The color legend bar is showing the various temperatures. The isothermal patterns are similar for all considered mass flow rates. The maximum temperature of the collector rises due to increasing mass flow rate. Increasing mass flow rate means increasing the velocity. The temperature rise becomes slower due to the higher mass flow rate that is high velocity.



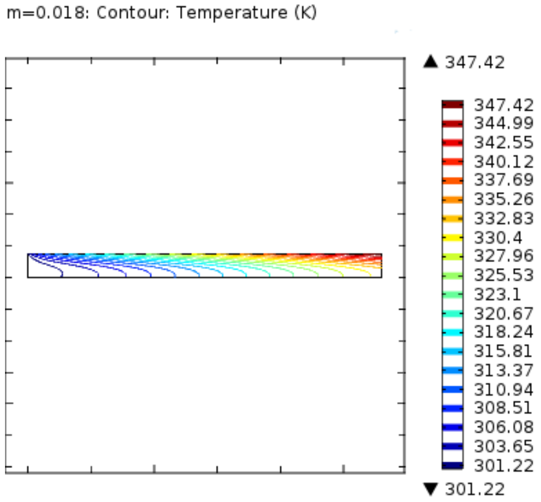
(a)



(b)



(c)

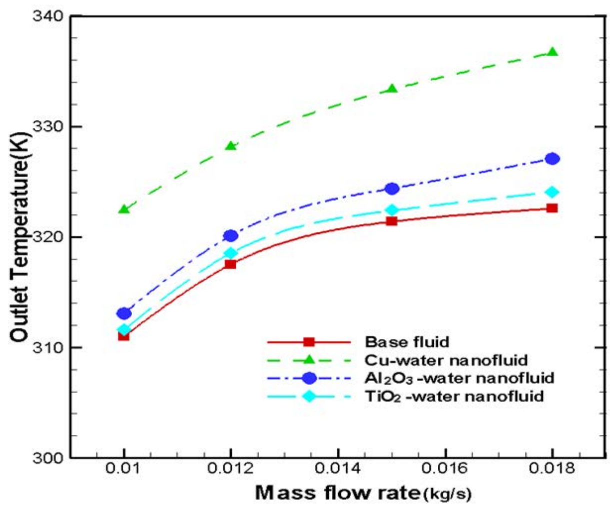


(d)

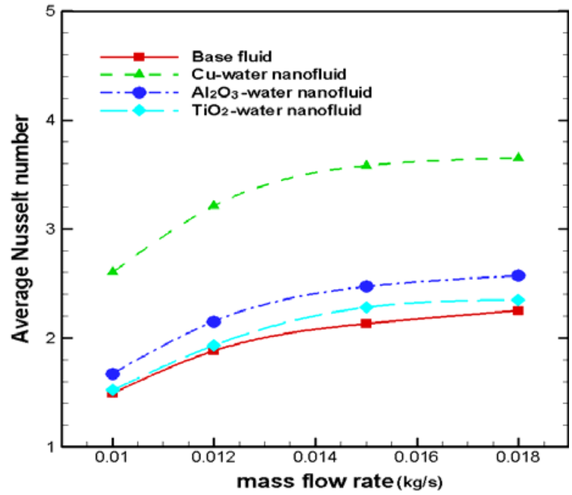
Fig. 2 Isothermal contours for different mass flow rate (a) m = 0.01 kg/s, (b) m = 0.012 kg/s, (c) m = 0.015 kg/s and (d) m = 0.018 kg/s with ϕ = 2%, I = 225 W/m^2 and D = 0.015 m for Cu-water nanofluid

The average temperature of the outlet, average Nusselt number and collector efficiency for various mass flow rate are displayed in Figs. 3 (a)-(c). The effects are presented for different nanofluid with 2% concentration and pure water also. The average outlet temperature, average heat transfer rate and collector efficiency for all nanofluid and base fluid take the parabolic shape. Similar profiles are seen for all three figures.

Rapid increment is observed due to increasing mass flow rate from 0.01 kg/s to 0.012 kg/s then the increment becomes slower and become insignificant for higher values. That is, mass flow rate higher than 0.015 kg/s cannot contribute significantly to enhancement of heat transfer or efficiency of the collector. However, the highest efficiency is observed for Cu-water nanofluid.



(a)



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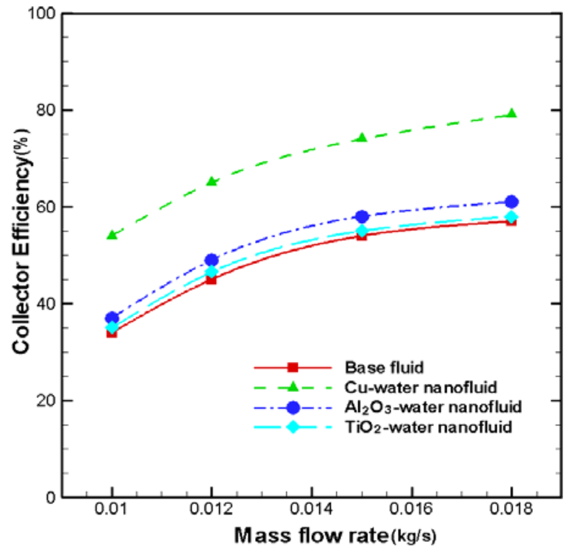
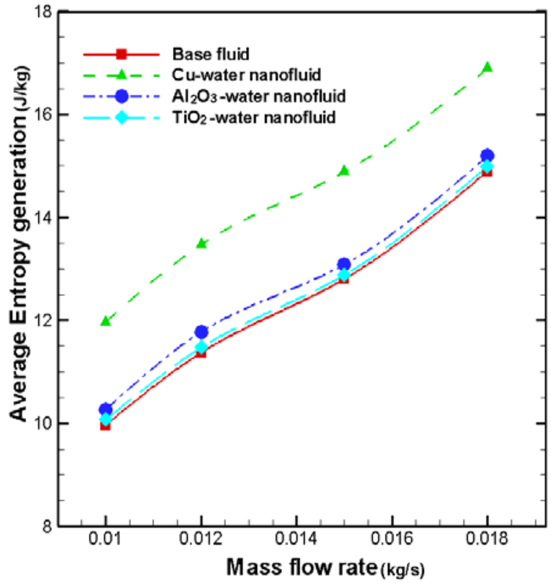


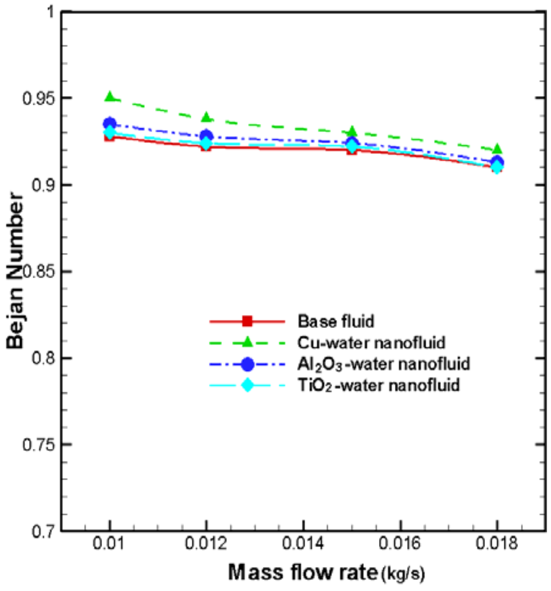
(c)

Fig. 3 Effect of mass flow rate on (a) average output temperature, (b) Average Nusselt number and (c) collector efficiency with I = 225 W/m^2, ϕ = 2% and D = 0.015 m for different nanofluids as well as base fluid

Figs. 4 (a)-(b) presents the effects of mass flow rate on entropy generation and Bejan number for various nanofluid and pure water. The entropy generation increases by mass flow rate. Though the heat transfer increment is slower for higher mass flow rate, entropy production increases sharply because viscosity plays a role here to increase the entropy which is also clear from the Bejan number picture. The Bejan number profile shows the decreasing tendency with larger mass flow rate. That is, the entropy generation due to viscous term increases, but still heat transfer entropy is dominant since the values of Bejan number is much higher than 0.5.



(a)



(b)

Fig. 4 Effect of mass flow rate on (a) average entropy generation and (b) Bejan number with I = 225 W/m^2, ϕ = 2% and D = 0.015 m for different nanofluids as well as base fluid

VI. Conclusion

The results of the numerical analysis lead to the following conclusions:

- The structure of isotherms through the solar collector is found to significantly depend upon the mass flow rate.
- The rate of heat transfer and efficiency enhances significantly for raising the values of m upto 0.015 kg/s. Further increment of the values of the parameter gives very small contribution to the heat transfer increase.
- Higher heat transport and efficiency are observed for nanofluids than the base fluid. Among the considered nanofluids, Cu-water gives much higher efficiency than Al_2O_3-water and TiO_2-water nanofluid.
- Mean entropy generation is obtained higher for rising values of the parameter *m*.
- Bejan number approaches to 1 for the variation of *m*. That is, the entropy production occurs mainly due to the heat transfer irreversibility.
- The nanofluid containing 2% Cu nanoparticles with combination of the mass flow rate 0.015 kg/s is established to be most effective in enhancing heat transfer rate and collector efficiency.

Acknowledgment

The research is conducted in the Department of Mathematics, Bangladesh University of Engineering & Technology, Dhaka and is supported by the Research Support and Publications Division, UGC, 29/1 Agargaon, Dhaka 1207, Bangladesh.

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