

Numerical Investigation of Nanofluid Based Thermosyphon System

Kiran Kumar K, Ramesh Babu Bejjam, Atul Najan

Abstract—A thermosyphon system is a heat transfer loop which operates on the basis of gravity and buoyancy forces. It guarantees a good reliability and low maintenance cost as it does not involve any mechanical pump. Therefore, it can be used in many industrial applications such as refrigeration and air conditioning, electronic cooling, nuclear reactors, geothermal heat extraction, etc. But flow instabilities and loop configuration are the major problems in this system. Several previous researchers studied that stabilities can be suppressed by using nanofluids as loop fluid. In the present study a rectangular thermosyphon loop with end heat exchangers are considered for the study. This configuration is more appropriate for many practical applications such as solar water heater, geothermal heat extraction, etc. In the present work, steady-state analysis is carried out on thermosyphon loop with parallel flow coaxial heat exchangers at heat source and heat sink. In this loop nanofluid is considered as the loop fluid and water is considered as the external fluid in both hot and cold heat exchangers. For this analysis one-dimensional homogeneous model is developed. In this model, conservation equations like conservation of mass, momentum, energy are discretized using finite difference method. A computer code is written in MATLAB to simulate the flow in thermosyphon loop. A comparison in terms of heat transfer is made between water and nanofluid as working fluids in the loop.

Keywords—Heat exchanger, Heat transfer, Nanofluid, Thermosyphon loop.

I. INTRODUCTION

MOST of the circulation loops are forced circulation loops (FCLs), where the movement of the fluid is caused by a prime mover like a pump or a compressor. However, second largest variation of the circulation loop is thermosyphon systems termed as natural circulation loops (NCLs). In these loops buoyancy serves the same function as is done by prime mover in FCL. Compared to FCL, NCL offers advantages such as high reliability and low cost of maintenance due to the absence of mechanical moving components [1]. High reliability makes NCL a promising option in many engineering applications such as nuclear reactors [2], solar heaters [3], electronic cooling systems [4], refrigeration systems [5], geothermal heat extraction applications [6], [7] etc.

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In most common configuration of NCLs, the loop fluid flow is driven by thermally generated density gradient so that pump is not required. The generation of density gradient is caused by variations of fluid temperature due to simultaneous heating and cooling at different locations of the loop. The loop are often heated in bottom arm and cooled in top arm of the loop, which then establishes an unstable density gradient in the fluid. Side heating and side cooling is also common configuration. Under the stable operation of the loop the lighter fluid rise and heavier fluid fall. Under the stable operation of the loop, fluid experiences a continuous unidirectional flow through the loop. Flow instabilities and loop configuration are the major problems in these NCLs. Despite above limitation it is widely used and extensive research is being done on the NCLs. Nanofluids can be proving to be more advantageous than any other conventional working fluid.

Nanofluids are a class of fluids engineered by dispersing nanometer sized materials (nanoparticles, nanofibers, nanotubes, nanowires, nanorods, and nanosheet) in base fluids. In other words, nanofluids are nanoscale colloidal suspensions containing condensed nanomaterials. They are two-phase systems with one phase (solid phase) in another (liquid phase). Nanofluids have been found to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, viscosity, and convective heat transfer coefficients compared to those of base fluids like oil or water. It has demonstrated great potential applications in many fields. Few examples of nanofluids are Al_2O_3 -water, Al_2O_3 -ethylene glycol, CuO-water, CuO-oil, Ag-water. In any heat transfer application thermal conductivity of fluid is of prime importance to be considered. Factors affecting thermal conductivity of nanofluids are Particle Volume Fraction, Particle Material, Size, Shape and temperature.

Zoubida Haddad et al. [8] presented a comprehensive review on the research progress on the natural convective heat transfer characteristics of nanofluids for both single- and two-phase models. Both experimental and theoretical studies are reviewed for natural convection of nanofluids in different types of enclosures.

J. Buongiorno [9] carried out studies on nanofluids to describe increase in properties of nanofluids to infer that the nanofluid properties may vary significantly within the boundary layer because of the effect of the temperature gradient and thermophoresis. For a heated fluid, these effects can result in a significant decrease of viscosity within the boundary layer, thus leading to heat transfer enhancement.

Khalil Khanafer et al. [10] presented a critical synthesis of the variants within the thermophysical properties of nanofluids. Correlations for effective thermal conductivity and viscosity are synthesized and developed in this study in terms of pertinent physical parameters based on the reported experimental data.

John Philip et al. [11] provide an overview of recent advances in the field of nanofluids, especially the important material properties that affect the thermal properties of nanofluids and novel approaches to achieve extremely high thermal conductivities.

It is evident from literature review that, studies on nanofluid based natural circulation loop are very scarce. Most of the available literature is based on experimental results of nanofluids based Natural circulation loop.

In the present work, steady-state analysis is carried out on thermosyphon loop with parallel flow coaxial heat exchangers at heat source and heat sink. In this loop nanofluid is considered as the loop fluid and water is considered as the external fluid in both hot and cold heat exchangers. For this analysis one-dimensional homogeneous model is developed. In this model, conservation equations like conservation of mass, momentum, energy are discretized using finite difference method. A computer code is written in MATLAB to simulate the flow in thermosyphon loop. A comparison in terms of heat transfer is made between water and nanofluid as working fluids in the loop.

II. MATHEMATICAL FORMULATION

In the present analysis, a rectangular single-phase thermosyphon loop with end heat exchangers has been considered as shown in Fig. 1. Basically the system consists of four parts namely riser, cold heat exchanger, down comer and hot heat exchanger. The loop fluid is heated at bottom with a hot stream (water) flowing through the annulus in the hot heat exchanger (HHE) and it is cooled at top with a cold stream (water) flowing through the annulus of the cold heat exchanger (CHE). As shown by arrows in Fig. 1, the internal secondary fluid flows through the loop in an anti-clockwise direction. Since the secondary fluid flow is due to buoyancy effect, the HHE should always be kept at a lower level than CHE, which may be considered as a constraint as far as these loops are concerned.

The analysis of the rectangular loop has been made based on the following assumptions:

- Total system is operating in steady-state mode.
- The flow is well mixed so that the velocity and temperature variation at any cross section of the loop is neglected.
- The external (water) and internal fluid streams are in single-phase only.
- All the minor losses due to pipe bends and fittings etc are neglected.
- Riser, downcomer, HHE and CHE are perfectly insulated.
- Coaxial parallel flow heat exchangers have been used at heat source and heat sink.

- Viscous dissipation and axial conduction effect in energy equation is neglected [12].
- Fouling effect in both HHE and CHE is neglected.

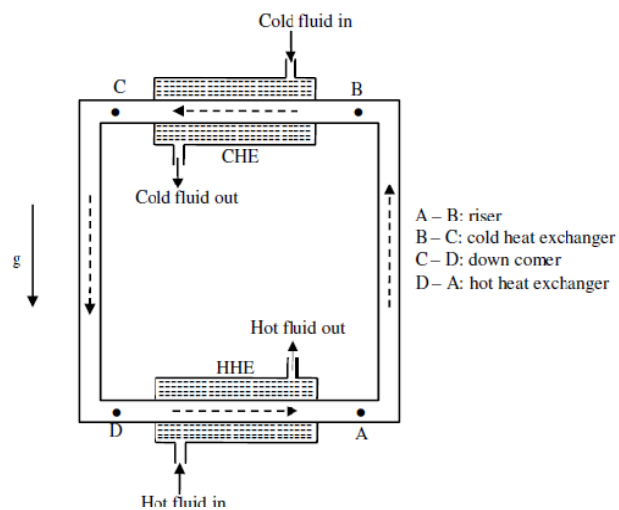


Fig. 1 Schematic diagram of the NCL

A. Steady-State Equations

For one-dimensional flow in natural circulation loop, the steady-state mass, momentum and energy conservation equations, and the equation of state can be written as follows [13]:

Continuity Equation,

$$\frac{\partial (\rho u)}{\partial s} = 0 \quad (1)$$

Momentum Equation,

$$\frac{\partial (\rho u^2)}{\partial s} + \frac{\partial p}{\partial s} + \rho g + \frac{2}{d} f_c \rho u^2 = 0 \quad (2)$$

where, f_c is the friction factor for smooth tube [13] given by,

$$\begin{aligned} \text{If } Re \leq 2300 \quad f_c &= \frac{16}{Re} \\ \text{If } Re > 2300 \quad f_c &= (1.58 \times \log(Re) - 3.28)^{-2} \end{aligned}$$

Re is the Reynolds number given by

$$Re = \frac{\rho u d_i}{\mu}$$

Energy equation for riser and downcomer section,

$$\frac{\partial h}{\partial s} + \frac{\partial}{\partial s} \left(\frac{u^2}{2} \right) + g ds = 0 \quad (3)$$

Energy for hot end heat exchanger section [14],

The expression for temperature change of loop fluid and annulus fluid (water) in hot end heat exchanger can be obtained using the following equations.

$$\dot{m} C_p \frac{\partial T}{\partial s} + \frac{(UA_{sa})_{HHE}}{L_{HHE}} (T - T_h) = 0 \quad (4)$$

$$\dot{m}_h C_{ph} \frac{\partial T_h}{\partial s} + \frac{(UA_{sa})_{HHE}}{L_{HHE}} (T_h - T) = 0 \quad (5)$$

where, T_h is the temperature of the hot fluid stream in the hot end heat exchanger. C_{ph} is the specific heat of the hot fluid stream. T is the temperature of the loop fluid stream and C_p is the specific heat of the loop fluid which has been calculated at node point. A_{sa} is the surface area and U is the overall heat transfer coefficient.

Energy equation for cold end heat exchanger section [14],

The expression for temperature change of loop fluid and annulus fluid can be obtained using the following equations.

$$\dot{m} C_p \frac{\partial T}{\partial s} + \frac{(UA_{sa})_{CHE}}{L_{CHE}} (T - T_c) = 0 \quad (6)$$

$$\dot{m}_c C_{pc} \frac{\partial T_c}{\partial s} + \frac{(UA_{sa})_{CHE}}{L_{CHE}} (T_c - T) = 0 \quad (7)$$

where, T_c and C_{pc} , are the temperature and the heat capacity of the cold stream in the cold heat exchanger.

Equations of state,

$$\rho = \text{eos}(p, h) \quad (8)$$

III. HEAT TRANSFER AND FRICTION FACTOR CORRELATIONS

A. On Loop Fluid Side

Case I: Water as Loop Fluid

Nusselt number for laminar flow condition ($Re \leq 2300$) inside the smooth circular tubes suggested by Shah [15] is valid for constant temperature boundary condition.

$$Nu = 1.61 \times \left(Re \cdot Pr \cdot \frac{d_{in}}{L} \right)^{1/3} \quad (9)$$

For turbulent flow condition ($Re > 2300$), Petukhov correlation with Gnielinski modification [16] is employed to estimate the heat transfer coefficient.

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

Case II: Nanofluid as Loop Fluid

Nusselt number for laminar flow condition ($101 < Re_{nf} \leq 2101$) inside the smooth circular tubes suggested by Y. Xuan, Q. Li [17] is valid for constant temperature condition.

$$Nu_{nf} = 0.4328 \left(1.0 + 11.285 \phi^{0.754} Pe_d^{0.218} \right) Re_{nf}^{0.333} Pr_{nf}^{0.4} \quad (11)$$

Similarly for turbulent flow condition ($Re_{nf} > 2101$), Y. Xuan, Q. Li [18] developed to estimate the heat transfer coefficient for nanofluid.

$$Nu_{nf} = 0.0059 \left(1.0 + 7.6286 \phi^{0.6886} Pe_d^{0.001} \right) Re_{nf}^{0.9238} Pr_{nf}^{0.4} \quad (12)$$

The Peclet number, Pe , describes the effect of thermal dispersion of the suspended particles. The particle Peclet number, Reynolds number and the Prandtl number for nanofluid are defined respectively as:

$$Pe_d = \frac{(\rho C_p)_{nf} u d_p}{k_{nf}} \quad (13)$$

$$Re_{nf} = \frac{\rho_{nf} u d_{in}}{\mu_{nf}} \quad (14)$$

$$Pr_{nf} = \frac{(\mu_{nf} C_{p,nf})}{k_{nf}} \quad (15)$$

B. On External Fluid Side

For laminar flow ($Re \leq 2300$) and for constant temperature boundary condition, Stephan's correlation [18] is used to estimate the heat transfer coefficient inside the annulus of both the heat exchangers. This correlation is given by:

$$Nu = Nu_{\infty} + \left[1 + 0.14 \left(\frac{d_{out}}{d_{in}} \right)^{-1/2} \right] \frac{0.19 \left(\frac{Pe d_{hy}}{L} \right)^{0.8}}{1 + 0.117 \left(\frac{Pe d_{hy}}{L} \right)^{0.467}} \quad (16)$$

where, $Nu_{\infty} = 3.66 + 1.2 \left(\frac{d_{out}}{d_{in}} \right)^{-1/2}$ is the Nusselt number

for fully developed flow. Here Pe is the Peclet number and ' d_{hy} ' is the hydraulic diameter. ' d_{out} ' is the outer diameter of the inner tube and ' d_{in} ' is the inner diameter of the tube.

IV. THERMOPHYSICAL PROPERTIES OF THE NANOFLUID

Introducing the particle volume fraction, the thermophysical properties of the nanofluid, namely the density, heat capacity, dynamic viscosity and effective thermal conductivity has been calculated from nanoparticle and base fluid properties at the ambient temperature using the following classic formulae [19]:

Density (ρ)

The density of nanofluid is based on the physical principle of the mixture rule. As such it can be represented as:

$$\rho_{nf} = (1 - \phi) \rho_f + \phi \rho_p \quad (17)$$

Heat Capacity ($C = \rho C_p$)

The specific heat of nanofluid can be determined by assuming thermal equilibrium between the nanoparticles and the base fluid phase as follows:

$$C_{nf} = \frac{(1 - \phi) \rho_f C_f + \phi \rho_p C_p}{\rho_{nf}} \quad (18)$$

Viscosity (μ)

General correlation for the effective viscosity of Al_2O_3 -water, one of the most commonly studied nanofluids, is developed using various experimental data found in the literature as a function of volume fraction, nanoparticles diameter, and temperature as follows:

$$\mu_{nf} = -0.4491 + \frac{28.837}{T} + 0.574\phi - 0.1634\phi^2 + 23.053 \frac{\phi^2}{T^2} + 0.0132\phi^3 - 2354.735 \frac{\phi}{T^3} + 23.498 \frac{\phi^2}{d_p^2} - 3.0185 \frac{\phi^3}{d_p^2} \quad (19)$$

$$0.01 \leq \phi \leq 0.09, 20 \leq T(^{\circ}\text{C}) \leq 70, 13 \text{ nm} \leq d_p \leq 131 \text{ nm}$$

Thermal Conductivity (k)

A general correlation is developed for Al_2O_3 -water nanofluid by the present authors using the available experimental data at various temperatures, nanoparticle diameter, and particle volume fraction. The developed correlation is expressed in terms of nanoparticles diameter, volume fraction, dynamic viscosity of water, effective dynamic viscosity of the nanofluid, and temperature as follows:

$$\frac{k_{nf}}{k_f} = 0.9843 + 0.398\phi^{0.7383} \left(\frac{1}{d_p(\text{nm})} \right)^{0.2246} \left(\frac{\mu_{nf}}{\mu_f} \right)^{0.0235} - 3.9517 \frac{\phi}{T} + 34.043 \frac{\phi^2}{T^3} + 32.509 \frac{\phi}{T^2} \quad (20)$$

$$11 \text{ nm} \leq d_p \leq 150 \text{ nm},$$

TABLE I
VARIOUS INPUT PARAMETERS

| Parameter | Value |
|-----------------------------------|-------------------------------------|
| Heat exchanger type | Co-axial cylindrical heat exchanger |
| Riser inlet pressure | 1.01325 bar |
| Loop height | 1 m |
| Loop inner diameter | 0.03 m |
| Loop pipe thickness | 0.003 m |
| Inner diameter of heat exchanger | 0.05 m |
| Riser & down comer inner diameter | 0.03 m |
| Length of heat exchanger | 1m |
| Hot fluid inlet temperature | 323 K |
| Cold fluid inlet temperature | 293 K |
| Hot fluid mass flow rate | 0.14 kg/s |
| Cold fluid mass flow rate | 0.14 kg/s |
| Loop wall material | Copper |
| Loop wall Thermal conductivity | 350 W/mK |

V. SOLUTION METHODOLOGY

A perfect computer code called MAT LAB developed for loop to obtain the steady-state performance of the loop. The finite difference method is used to discretize the governing equations. The results are obtained for a maximum hot fluid temperature of 323 K, and 1.01325 bar is taken as system

pressure, so that the entire loop will be in single-phase (liquid region).

VI. RESULTS AND DISCUSSIONS

The amount of nanoparticles suspended in the base fluid plays a significant role in determining heat transfer performance. For the present study, nanofluid (Al_2O_3 -water) having 0.04 particle volume fraction and 25 nanometer particle size is considered in all cases. Unless and otherwise the stated parameters listed in Table I are kept constant during the simulation. A comparison in terms of heat transfer is made between water and nanofluid as working fluids in the loop.

Temperature and pressure profiles of the both loop fluids along the loop axial length obtained by solving the all governing equations given earlier are shown in Figs. 2 and 3. It can be observed from Fig. 2, that no variation in the temperature profile at both riser downcomer sections which are assumed to be adiabatic. A steep decrease in the temperature has been observed in CHE in which heat is convected to the cold fluid and step increase is observed in the HHE. Also, it can be seen from Fig. 3, that the pressure drop in the riser section is well compensated by pressure gain in the down comer section, thus a steady state circulation of fluid is maintained.

Fig. 4 shows the effect of heat exchanger length on the performance of the NCL. Here both CHE and HHE lengths are assumed to be equal and these are varied simultaneously.

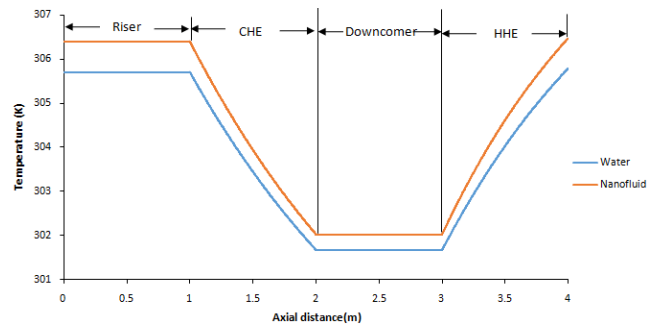


Fig. 2 Variation of temperature of loop fluids along the loop length

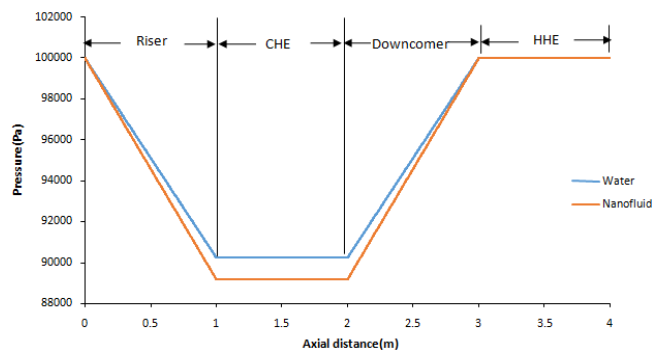


Fig. 3 Variation of pressure of loop fluids along the loop length

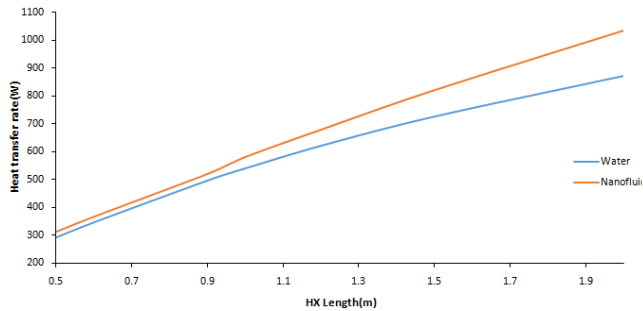


Fig. 4 Variation of heat transfer rate along the heat exchanger length

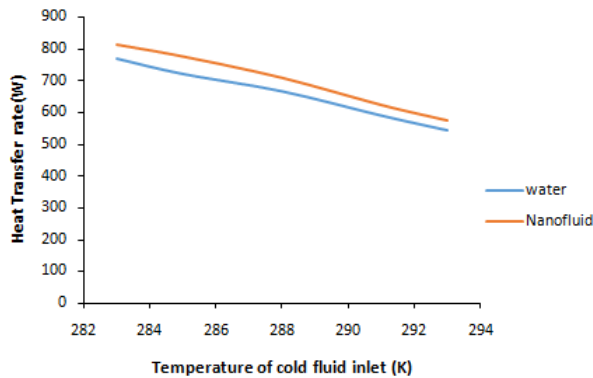


Fig. 5 Variation of heat transfer rate with cold fluid inlet temperature in CHE

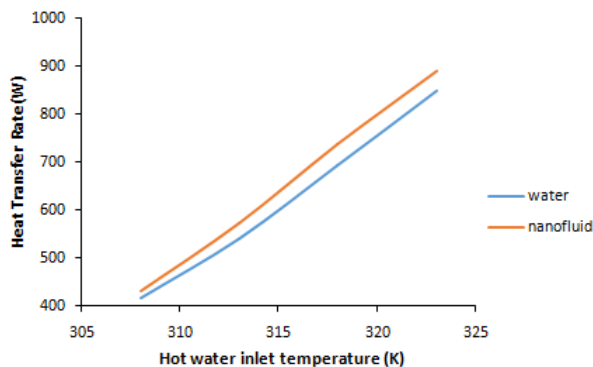


Fig. 6 Variation of heat transfer rate with hot fluid inlet temperature in HHE

Mass flow rates and inlet temperatures of the external fluid are kept constant at the values given in Table I. It can be seen from this figure, as the heat exchanger length increases the heat transfer rate increases and rate of increase of heat transfer rate with increase in heat exchanger length in case of nanofluid as loop fluid is more than the water as loop fluid.

Figs. 5 and 6 show the effect of cold and hot fluid inlet temperatures on performance of the NCL. The curves are plotted by varying the inlet temperatures of external fluids keeping other parameters constant at given values in Table I. It is observed from the figures, heat transfer rate increases with decreasing cold fluid inlet temperature in CHE and/or the temperature of the hot water at inlet to the HHE increases. The

increases in heat transfer rate with increase in hot fluid inlet temperature and/or decrease in cold fluid temperature are attributed due to increase buoyancy caused by thermally generated temperature gradients. It can also be seen from the figures, heat transfer rates with nanofluid as loop fluid are greater than water as loop fluid since nanofluid has larger values of thermal conductivity which favors heat transfer from hot fluid to cold fluid.

With increase in loop height buoyancy force also increases keeping other parameters constant at given values in Table I. Fig. 7 shows the effect of loop height on heat transfer rates. It is seen from the figure, heat transfer rate increases with increase in loop height. Since diameter of the loop is constant and loop height is increased, Reynolds number increases. As a result of which heat transfer coefficient in heat exchanger also increases. So, even though heat transfer area is constant, heat transfer rate increases with increasing loop height.

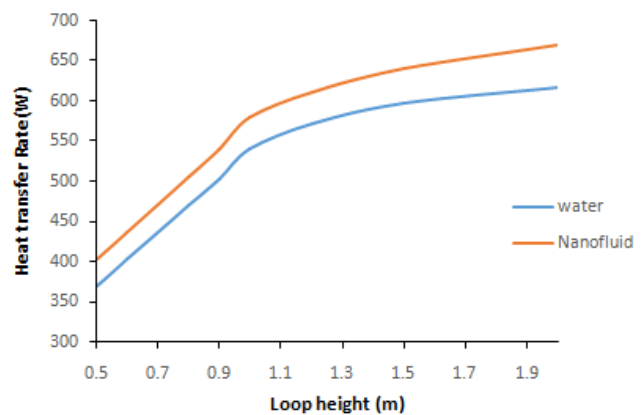


Fig. 7 Variation of heat transfer rate with loop height

VII. CONCLUSIONS

In present work, a mathematical model for steady state analysis of rectangular natural circulation loop with parallel flow double pipe heat exchangers is developed. Analysis is done for Nanofluid and water as working fluid considered as two different cases. Nanofluid is chosen as a working fluid since nanofluid possesses enhanced thermophysical properties compared to those of base fluid such as water.

Water is used as external fluid in both cold heat exchanger and hot exchanger. Homogeneous model is used for modeling of nanofluid. For the same loop configuration and other input parameters held constant it is shown from the results that heat transfer rates are larger in case of nanofluid as loop fluid than in case of water as loop fluid. It can be inferred that for the required performance, size of NCL with Nanofluid as loop fluid will be compact as compared to NCL with water as working fluid. Results show that variation in inlet temperatures of external fluids in cold heat exchanger and hot heat exchanger significantly affects the heat transfer rate in NCL. Heat exchanger length also affects the performance of the loop to great extent. It is shown from the results that

performance of NCL with Nanofluid as loop fluid improves in larger magnitudes than NCL with water.

NOMENCLATURE

| | |
|------------|---|
| L | Length (m) |
| D_h | Hydraulic diameter (m) |
| D_o | Outside diameter of inner tube (m) |
| D_i | Inside diameter of inner tube (m) |
| A | Area (m^2) |
| C_p | Specific heat capacity (J/kg K) |
| g | Acceleration due to gravity (m/s^2) |
| d | Diameter (m) |
| Nu | Nusselt number |
| T | Temperature ($^{\circ}C$) |
| Re | Reynolds number |
| f | Friction factor |
| m | Mass flow rate (kg/s) |
| k | Thermal Conductivity (W/m K) |
| h | Specific enthalpy (J/kg) |
| s | Axial distance (m) |
| Δs | Spatial grid size (m) |
| u | Velocity (m/s) |
| U | Overall heat transfer coefficient ($W/m^2 K$) |
| Pr | Prandtl number |

Greek symbols

| | |
|----------|--------------------------------|
| Φ | Nanoparticle Volume fraction |
| μ | Dynamic viscosity (Ns/m^2) |
| θ | Angle |
| ρ | Density (kg/m^3) |

Subscripts

| | |
|-----|---------------------------|
| CHE | Cold heat exchanger |
| HHE | Hot heat exchanger |
| f | Base fluid |
| Sa | Surface area |
| nf | Nanofluid |
| p | Nanoparticle |
| w | Wall material |
| i | Internal tube |
| a | Annulus of heat exchanger |
| c | Cold fluid |
| h | Hot fluid |

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