Sensitivity of Acute Angle to the Heat Transfer Process of a Circular Tube with a Hemispherical Cup at the bottom of an Evacuated Solar Collector

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***Abstract*—The evacuated solar collectors are made by attaching parallel circular tubes with a hemispherical cup at the bottom and generally solar collectors are installed with an acute –angle θ to horizontal. Thus the present study is focused on the investigation of the sensitivity of the acute angle on heat transfer process in a circular tube in evacuated-solar collector. The heat and fluid flow is assumed to be unsteady, two-dimensional, laminar and incompressible. By giving uniform heat flux 950Wm^{-2}at the upper lateral surface of the tube for a period of 15minutes, the velocity and temperature profiles of the water particles within the tube are studied for several acute angles π/8, π/6, π/4, π/3 and 3π/8. For discretization of the governing equations, the finite volume method is used and as a numerical tool, the OpenFoam software, and the merged PISO - SIMPLE (PIMPLE) algorithm is used. The results show that, for small acute angles, although the maximum temperature gain is high, the majority of water particles are at low temperature level as well as the velocity profile is at a low level. For large acute angles, the velocity profile is high but maximum temperature gain is low. For moderate level acute angles, the maximum temperature gain is in somewhat high level and a lot of water particles are in high temperature level. Moreover, the velocity profile is in high level. Thus with a moderate level acute angle, the heat transfer process of water through a circular tube with a hemispherical cup at the bottom of the tube improves the performance.**

Keywords; Heat Transfer; Evacuated tube; Buoyancy Driven Flow; Numerical Study

I. INTRODUCTION

The modern human civilization in Sri Lanka, highly depends on fossil fuels, even though the indigenous traditional sources such as Biomass, hydropower, solar power and wind power are frequently available [1]. The shortages of non-renewable fuels result in a rapid increase in the global prices of fossil fuels. The emissions from burning fossil fuels increase the carbon dioxide concentration in the Earth's atmosphere which leads to the global warming. In long term consequences, this can lead to raising the sea levels and can contribute to instabilities in global climate. Also due to the combustion byproducts when burning fuels, the ozone layer is damaged badly. The massive increase in fossil fuel prices and their negative impact on the environment has demanded a growing interest in solar energy and other renewable energy matrices.

Since solar energy is a sustainable and environmentally friendly source of energy, many researchers have promoted the use of solar energy as a viable source of energy. Water heating accounts for approximately 20% of the total energy used in a typical single-family home. In Sri Lanka, liquefied petroleum gas and electric water heater are the most popular energy sources of all appliances in the home. Since Sri Lanka is an island located in the equatorial belt, it receives solar radiation throughout the year. According to the department of meteorology - Sri Lanka in the lowlands, up to an altitude of 100 m to 150 m, the mean annual temperature various between 26.5 °C to 28.5 °C, with an annual temperature of 27.5 °C [2]. Thus as a tropical country, solar energy can be used to produce domestic hot water.

Solar water heaters mainly consist of two main parts, storage tank, and the solar collector. The solar thermal energy is collected in the solar collector and when it is exposed to the Sun, solar radiations is absorbed and a part of it is transferred to the fluid flowing over the collector. There are two types of solar collectors available in Sri Lanka, flat-plate collector, and evacuated-tube solar collector. The evacuated tube solar collectors are more costly than the flat- plate collectors; however, their temperature gained is higher than the flat- plate collectors. Evacuated-tube collectors are made up of rows of parallel, transparent glass tubes which having a hemispherical cup at the bottom of the tube.

Each tube consists of a glass outer tube and an inner tube, or absorber, covered with a selective coating that absorbs solar energy well but inhibits radiative heat losses. The air is withdrawn ("evacuate") from the space between the tubes to form a vacuum, which eliminates conductive and convective heat losses [3].

This study is specially focused on the passive direct solar water heater. The thermosiphon effect is used in this type of solar water heaters for heat transfer process. A thermosiphon effect relies on warm water rising, a phenomenon known as natural convection, to circulate water through the collector and the storage tank. As water in the collector heats up, it becomes lighter and rises naturally and meanwhile, cool water in the tank flows down wards through the tubes to the bottom of the collector, causing circulation throughout the system [4]. This process continues steadily for a number of hours till system reach an equilibrium state.

As explain above in solar water heaters, the circular tube is a device that plays a major role in heat absorption at transportation. Thus the present study is focused on investigating numerically the unsteady performance of solar energy gain, in a circular tube which having a hemispherical cup at the bottom of the tube. Since the solar collectors are located with angle θ to horizontal, the study focused on the numerical simulation of heat transfer process through a circular tube which is placed with an angle θ to horizontal. As the main objective of this study, by changing acute angle θ, sensitivity to the heat transfer process has been studied.

II. Mathematical Model

We consider a circular tube having a length L=1m and also inside diameter (D) equal to ~0. 05m (Figure 1). Since solar collectors are generally set with some acute angle θ to horizontal, the tube is placed with angle θ to the horizontal. The heat transfer by radiation is modeled by applying a constant heat flux (950Wm^{-2}) incident on the lateral surface (L1) of the tube f~~ 15 minutes of the heating period.

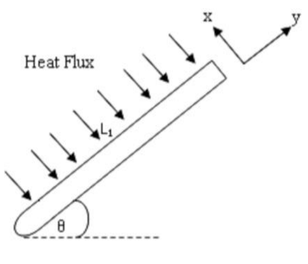

Figure 1. The physical model

The mathematical formulation of the present problem is based on the following assumptions,

- The flow is unsteady, two- dimensional, laminar and incompressible.
- The properties of water such as viscosity, thermal conductivity, thermal diffusivity and etc. are constant except for the density changes with temperature, which courses to buoyancy forces.

Based on the above assumptions, the governing equations for the unsteady heat and fluid flow are as follows:

Mass conservation equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

Momentum conservation equations:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - g\beta(T - T_0)sin\theta \qquad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - g\beta(T - T_0)cos\theta \qquad (3)$$

Energy conservation equation:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (4)$$

where u and v are velocity components in x and y directions respectively, T is temperature, p is pressure, t is time, g is the acceleration due to gravity, ρ , ν, and α are density, kinematic viscosity and thermal diffusivity of the water respectively.

Although, water has an incompressible fluid flow, due to the temperature variations density of water have been varied. Thus, the Boussinesq approximation is used for computation where the density- temperature relationship is defined as:

$$\rho \cong \rho_0[1 - \beta(T - T_0)] \qquad (5)$$

where β is the volumetric expansion coefficient, which appears in the body force term in Equations (2) and (3).

Initial and Boundary Conditions

The initial and boundary conditions for circular tube are:

At time t= 0, the temperature of the stagnant water is 300 K everywhere and no velocity. For time t > 0,

- x=0 : No slip boundary condition for velocity and Adiabatic boundary condition for temperature

  $v = u = 0,$

  $$\frac{\partial T}{\partial x} = 0$$

- x=1 : No slip boundary condition for velocity and Adiabatic boundary condition for temperature

$$v = u = 0,$$

$$\frac{\partial T}{\partial x} = 0$$

- y=0 : No slip boundary condition for velocity and Adiabatic boundary condition for temperature

$$v = u = 0,$$

$$\frac{\partial T}{\partial x} = 0$$

- y=0.05 : No slip boundary condition for velocity and adiabatic boundary condition for temperature

$$v = 0, \; u = 0$$

$$\kappa \frac{\partial T}{\partial y} = 950 Wm^{-2} \; constant\, heat \; flux$$

III. NUMERICAL SOLUTION PROCEDURE

The discretization of the governing equations described above is done with the finite volume method (FVM) , since it offers high flexibility as a discretization method and due to the fact that the discretization is carried out directly in the physical domain without the use of any transformation physical and computational domain [5].

Here we use the OpenFOAM, computational fluid dynamic software which was created by Henry Weller [6]. Two main advantages of this software make it preferable to use for present study. The first advantage is, it is free software, where it is allowed to access the source files, in order to directly modify if required. The second advantage is, it is an optimal linkage between theoretical study and numerical implementation of fluid dynamic concepts. The equation writing in software is similar to the mathematical language.

As the numerical tool, the merged PISO-SIMPLE (PIMPLE) algorithm is used that can handle the pressure velocity coupling. For heat transfer problem in turbulence, a transient state which uses Boussinesq approximation, in OpenFOAM inbuilt toolbox: BuoyantBoussinesqPimpleFoam is available. Although, the present problem has a laminar flow. Thus the parameters of this toolbox are modified for the laminar flow.

Since our main task is to evaluate the effect of variation of an acute angle in heat transfer process, the governing equation has been solved with OpenFOAM software for various angle θ.

IV. RESULTS AND DISCUSSION

The governing equations are solved under the given initial and boundary conditions for the system shown in Figure 1. The sensitivity of the acute angle in heat transfer process is examined by varying the acute angle θ. The results are presented and discussed as follows.

The maximum temperature profile within 15 minutes of the heating period, of a circular tube with a hemispherical cup at the bottom for various acute angles, is given by Figure 2.

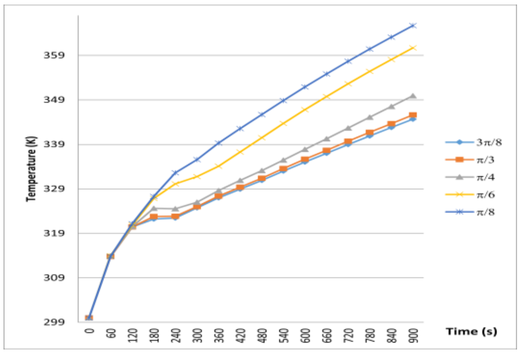

Figure 2. Maximum Temperature

According to the Figure 2, when acute angle is π/8 have the highest temperature profile compare to the other angles that we have considered. With this Figure, we can see when the acute angle of the tube is lower; we can obtain a high, maximum temperature. Although, it can't be concluded that, when the acute angle is low, the processes of heat transfer is efficient without considering the other parameters.

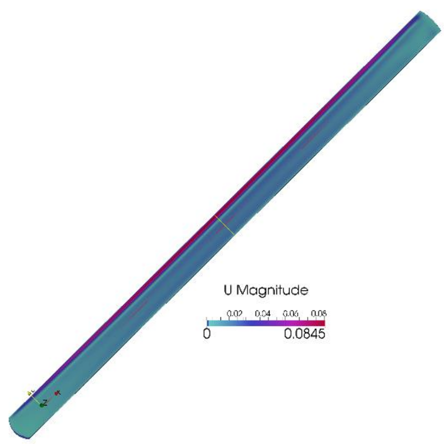

Figure 3. Velosity profile when acute angl is 3π/8

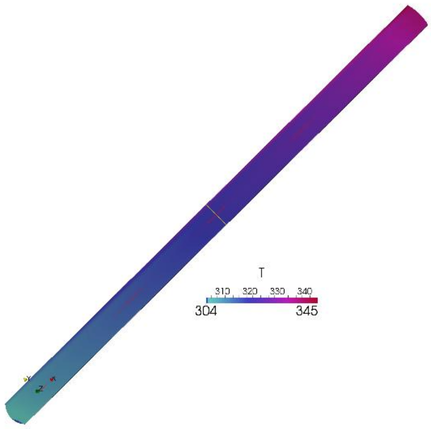

Figure 4. Temperature profile when acute angle is 3π/8

Figure 3, Figure 4 are described the velocity profile and temperature profile of water flow trough a circular tube with a hemispherical cup at the bottom for acute angle 3π/8. Figure 5, Figure 6 are described the velocity profile and temperature profile of water flow trough a circular tube with a hemispherical cup at the bottom for acute angle π/8.

Here 3π/8 is the largest and π/8 is the smallest acute angles that we have considered. As discussed with Figure 2, when we have a smallest acute angle, the maximum temperature is high. Although, considering the Figure 6, when we have a smallest acute angle, few portion of fluid particles have the highest temperature. Further, when considering the velocity profile (Figure 5), the range of velocity is between 0 and 0.058 and it is low compare to the velocity profile of water flow through a circular tube with a hemispherical cup at the bottom for acute angle 3π/8.

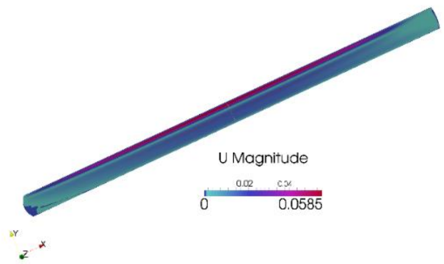

Figure 5. Velocity profile when acute angle is π/8

Figure 7 and Figure 8 represents the velocity profile and temperature profile of water flow through a circular tube with a hemispherical cup at the bottom for acute angle π/4. Here π/4 is the middle point of acute angles that we have considered. As discussed with Figures 2, 3, 4, 5, and 6, when the acute angle is small the maximum

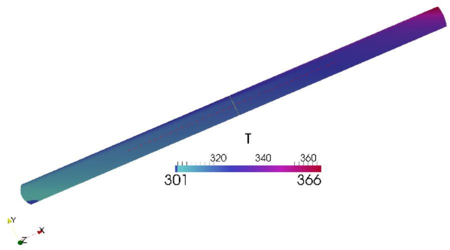

Figure 6. Temperature profile when acute angle is π/8

temperature is high but the majority of fluid particles are at low temperature.

On the other hand, when the acute angle is large the maximum temperature is low, but the majority of fluid particles are in high temperature. Thus when we have middle point of the acute angle, the temperature profile (Figure 8) is in moderate level and the maximum temperature is also in somewhat high level. The velocity profile is also in somewhat high level.

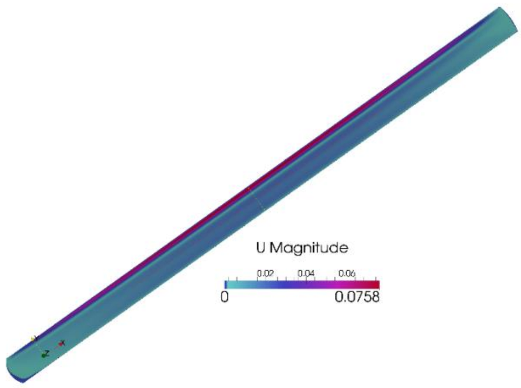

Figure 7. Velocity profile when acute angle is π/4

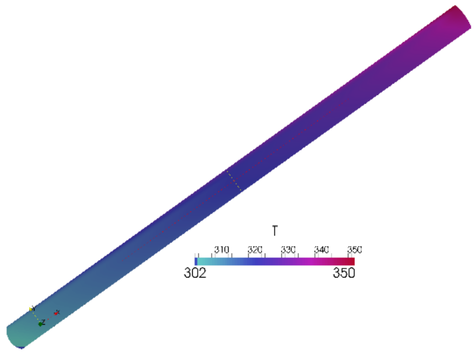

Figure 8. Tempearture profile when acute angle is π/4

V. CONCLUSION

Due to the facts, evacuated solar collectors are made up of rows of parallel circular tubes with hemispherical cup at the bottom of the tubes and solar collectors are placed with acute angle θ to horizontal, this study is focused to numerically evaluate the sensitivity of acute angle θ on heat transfer processes of water through a circular tube with hemispherical cup at the bottom of the tube.

According to the findings, when the acute angle is small, maximum temperature gain is high, but the majority of water particles are in low temperature level. Moreover, the velocity profile is low when the acute angle is small. On the other hand, when the acute angle is large, the maximum temperature is low and the majority of water particles are in high temperature level. The velocity profile is high when the acute angle is large. Thus no one can be concluded that the heat transfer process is efficient when the acute angle of the tube is small or large.

Although, results shows that, when the acute angle is in moderate level the maximum temperature gain is in somewhat high level and a lot of fluid particles are in high temperature level. The velocity profile is also in high level. Thus, it can be concluded, when the acute angle of the tube to horizontal is in the moderate level, heat transfer process of water through a circular tube with a hemispherical cup at the bottom of the tube is efficient.

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