CFD Analysis of Solar Hot Water Heater with Integrated Storage System

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Abstract:-This paper outlines a research project about fluid flow and computational investigations of flow patterns in a solar water store. Investigations have shown the flow patterns in solar water stores strongly influences the hot spot position of solar heating system. Mixing caused by water entering the solar water store will destroy stratification. For increasing the system tilted at 10^o from the horizontal plane the thermal performance increasing. In order to describe the fluid flow behaviour of the water inside the solar water store, a finite element based on model was generated for the system and was simulated using the FEMLAB programmed. The goal of the project is to gather knowledge about flow phenomena occurring in solar hot water stores with different tilted and time. The result of the simulation could be used as guidance to locate the suitable position of appropriate components such as helical coils as well as the size of the solar hot water heater system to be built.

Key-Words: CFD Analysis, FEMLAB programmed, solar hot water heater, thermal performance.

1 Introduction

The use of the renewable especially the solar energy is continuously increasing and gaining popularity because of the price of traditional energy resources and serious environmental pollution problem. One of classical way of using solar energy is to make hot water. Usually, the system should consist of two main elements, i.e., a solar collector and a storage tank.

Studies of thermosyphonic solar hot water systems with integrated storage tank have been conducted by [1-3]. Although many types of conventional collectors have been commercialized, their investment costs are still relatively high. To overcome this problem, we have developed a low cost solar collector system using blackened glass fiber reinforced polyester (GFRP) as main materials to collect solar energy. And another attractive way to reduce the cost of the solar heater is to remove the collector cover [4]. A flat plate solar collector does not need collector cover for water temperature around 70^oC. Unglazed, transpired solar collectors [5-6] have been the subject of a number of recent investigations.

A knowledge of the fluid flow pattern in the storage tank system is necessary to understand the performance of a solar hot water system (SHWS). The generation of water flow in the storage tank is due to the change in density, followed by the heat gained from the solar radiation. Many details of the flow cannot be captured by experimental analysis; therefore, computational fluid dynamic procedures are needed to have deeper understanding of these processes. In [7] have developed a model to solve the energy equation in tube under laminar flow regime. The fluid is incompressible and its axial velocity component is assumed to have a parabolic profile. The fluid properties are constant and their study was primarily concerned to analyze axial conduction at the tube walls. The studied on the similar laminar flow, which focused their attention in determining axial conduction at the wall of the tubes [8]. They assumed a parabolic profile for axial velocity and the properties are considered to be independent on temperature. The developed a method combining the finite element method with the superposition principle to solve simultaneously the momentum and energy equations in order to analyses axial conduction at the walls was conducted by [9]. The properties are also assumed to be constant in this case. A numerical model of the inclined open thermosyphon has been developed using a finite difference algorithm to solve the vorticity vector potential form of the Navier-Stokes equations [10]. Fluid flow and heat transfer inside channels with simple geometry at different boundary conditions is one of the fundamental researches in engineering [11]. Analyses of simpler systems are often useful to understand some important features of complex pattern forming processes in various fields of science and technology. These types of geometry appear in many engineering applications as single unit or as a combination. Theoretical and numerical analysis of second law for flow and heat transfer inside rectangular duct was developed by [12]

In the present paper we give the results of a new design of solar hot water system (SHWS) with integrated storage system, which the fluid flow behaviour of the water inside the system was simulated by the FEMLAB programmed [13]. This system operates without a pump, which makes the system work free from electrical power source. The compact system can reduce the cost of SHWS and will remove aesthetic objections to roof top installation.

2 Component of a Solar Hot Water with Integrated Storage System

Schematics of non-metallic an unglazed integrated collector-storage type of solar hot water system is shown in figure 1. The solar hot water system consists of the following main components:

- The *solar collector* has half elliptical shape geometry (absorber plate), which is made of glass fiber reinforced polyester (GFRP) using special resin composition. The collector has consisted of 19 tubes with of 0.12 m^2 surface area each and has thickness of 3 mm. The absorptivity of the collector tubes is about 0.95. The absorber plate can be inserted into the body without any additional fixing or sealing. The absorber is connected to the storage tank through two inlet tubes in the lower header and two outlet tubes in the upper header.
- The *storage tank* is the bottom part of the system. Heat is transferred into the store from the collector loop. The storage tank has a capacity of 329 liters and with 50 mm thickness of polyurethane foam as insulation a round the casing to prevent heat loss. Back up water can be also introduced in the tank at the upper section of the tank. A small outlet at the bottom section of the tank can be used for drainage purposes.

The rise of the water temperature inside the absorber due to the absorption of incident solar radiation gives rise to water uprising motion into the storage tank and generates a circulation loop through the whole collector.

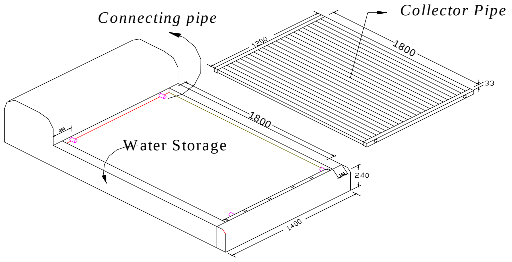


Figure: 1 Schematics of non-metallic unglazed collector solar hot water with integrated storage system

3 Computational Fluid Dynamic Model

Defining the domain:

The sketch of the inlet pipe on a square box arrangement, like the shown in Fig.2. The inlet pipe length of 5 cm (*l*). The computational domain is also bounded by the planes $x = 0$ and $x = l$. In the drawing, *V* represents the suction velocity or the volumetric rate at which water is flow through pipe per unit area. At distance *l* from the square box this water stream is assumed to be in uniform motion.

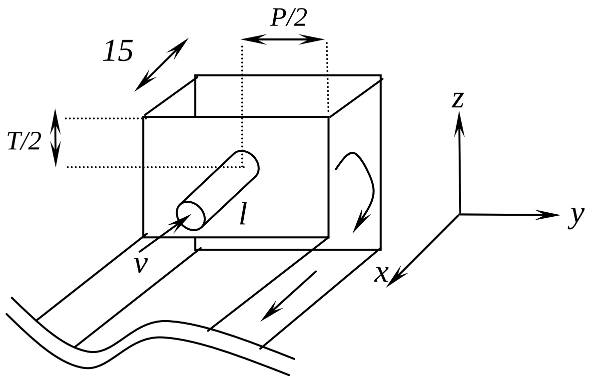


Figure 2: Sketch of the inlet water pipe bounded on a square box arrangement

Governing Equations and Boundary Conditions

To study fluid motion a fluid can be regarded as a continuum in most case of interest. The relevant governing equations for the water velocity (u, v) is the equations for the conservation of mass, momentum, and energy, assuming laminar flow, steady conditions, constant properties, no external forces and no viscous heat dissipation. These are given in textbooks [14] and will not be repeated here. However, The partial differential or integral-differential equations are non-linier, couple and difficult to solve. Usually simplifications are necessary to reduce the computation time. The simplified equations are approximated by system of the algebraic equations by the use of a discretization method and the Boussinesq approximation is assumed.

Boundary conditions as well as discretization method (finite difference, finite volume, finite element, spectral schemes, boundary element, etc) and coordinate and basis vector system need to be specified [15].

The inlet boundary condition is the plane $x = l$, Ideally, this plane would be located an infinite distance from the plate, but any CFD representation has to place it at a finite distance of magnitude sufficiently large to realistically represent the infinite distance. The following boundary conditions were assumed to apply there:

$$\text{at } x=0, \text{ and } x = l;\ u = u_\infty,\ v = 0$$

$$\text{at } y = 0 \text{ and } y = P/2;\ \frac{\partial u}{\partial y} = 0,\ v = 0$$

The governing equations were solved with the appropriate boundary conditions using FEMLAB programmable, which a finite volume-based CFD code.

Grid design

The domain was broken down into a set of control volumes, with a node at the center of each volume. The total number of nodes *N* in the resulting grid is limited by constraints on the computer memory and also by CPU time. The approximations introduced in the discretization process become more precise as the gird is refined, i.e. as the number of nodal points *N* is increased. Grid refinement studies are used to study the sensitivity of the numerical solution to the size of the grid and then decide what value of *N* will be used for the bulk of the simulations. A grid refinement study is usually carried out by systematically increasing the number of nodes. The two dimensional grid of a inlet water into solar water store with a smaller pipe connection to it is shown in Fig.3 as follow:

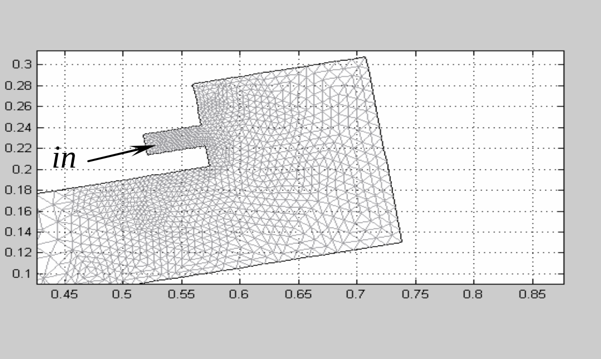
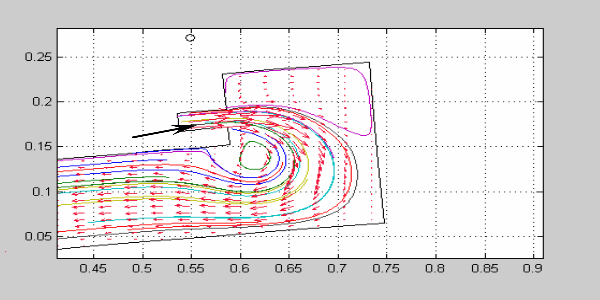


Figure 3: The number of nodes of an inlet water into solar water store

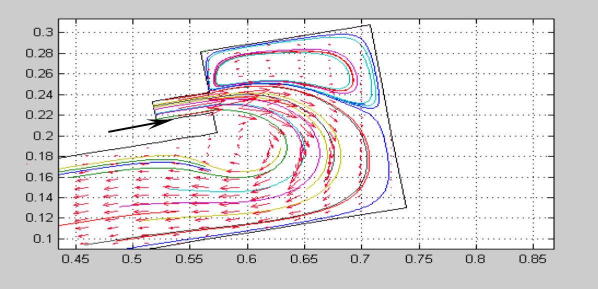
4 Result and Discussion

Tilted dependence

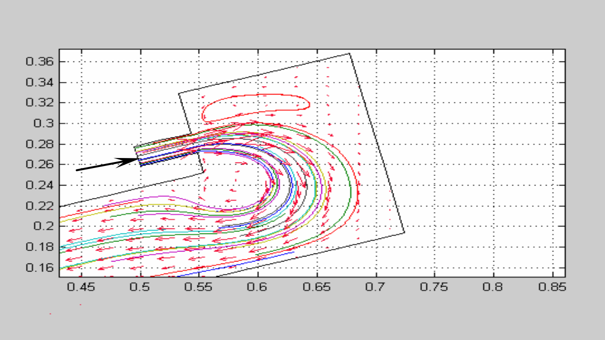
The typical water flow pattern in solar water store obtained previously from simulation with certain data, which is given as function of the time for a difference tilted is shown in Fig. 4. It was clear that at difference tilted were performed which showed qualitatively the same behaviour of the fluid flow during the heating up process at one hour operation. The hot spot position at tilted of 10^{o} was slightly better than other one.



(a)



(b)

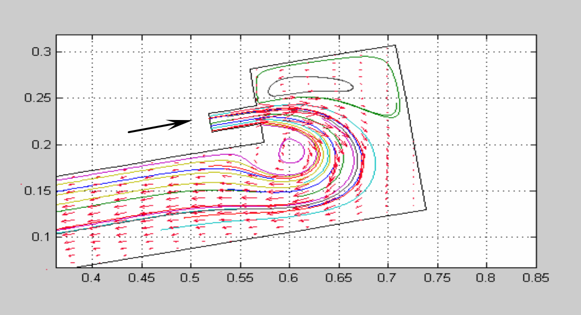


(c)

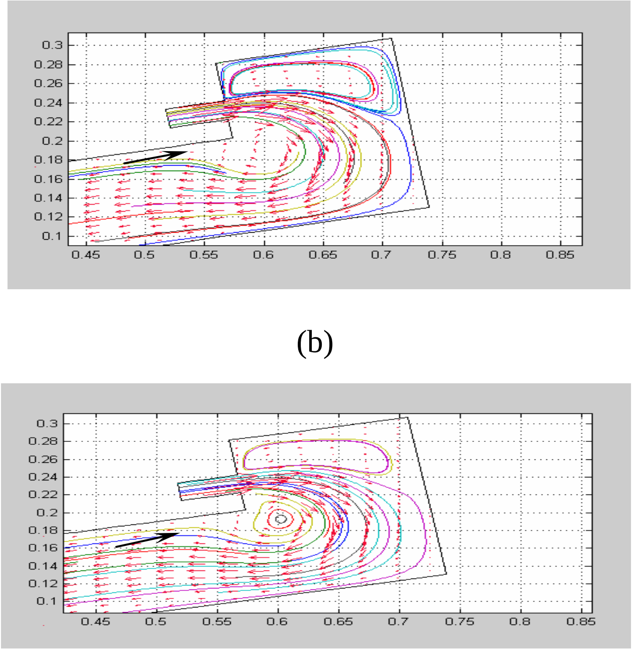
Figure 4: Flow profile of water in solar water store for 1 hr operations (a) $\theta = 5^{o}$; (b) $\theta = 10^{o}$; (c) $\theta = 15^{o}$

Time dependence

The flow profile in solar water store for 10^{o} titled at difference time is shown in Fig. 5. At certain times with sufficient solar radiation absorbed on collectors, the water temperature out of the collector more high than before. During the first hour (see fig.5a) only in a thin layer near the wall a remarkable upward movement of the fluid is observed. In contrast in the water bulk of the storage tank only a respective slow downward movement is found. Heated fluid is transported to the upper surface and a quite stable flow stratification is established, continuing the heating up, this gives buoyancy driven flow along the walls in the inner store, mainly space above the store.



(a)



(b)

(c)

Figure 5: Flow profile of water in solar water store for 10^o titled (a) t = 1 hr; (b) t = 2 hrs; (c) t = 3 hrs

At the second hours the flow fluid at the upper part of solar water store the hot spot build more stabiles than the first hour one, it can be seen in fig. 5b. The buoyancy driven flows in the tank have increased and the thermal stratification is building up further.

Due to the higher temperature in the top of the mantle the incoming fluid is driven downwards by negative buoyancy forces. This means that the thermal stratification in the inner tank is not disturbed by low temperature flow into the mantle.

The temperature rises until it reaches a plateau where the maximum water temperature of 65^oC at time 16:00 can be achieved. At the other positions, the profile of the water temperatures is nearly flatter in general, which is due to the large volume of the storage tank.

To understand well the behaviour of the distribution water temperature in storage tank can be shown in fig. 5. The flow will enter at the middle of storage header with a uniform velocity profile, and fluid layer will start to develop as the fluid moves along the horizontal geometry. The velocity in the x-direction is set to a constant value. We assume slip conditions at the wall boundaries. Except for the coil wall is no slip boundary at all. The outlet is represented by the vertical boundary at the bottom of the system. Here, we assume straight-out boundary conditions.

5 Conclusion

The CFD-results illustrate, how the fluid motion, by buoyancy convection in the inner tank, builds up thermal stratification. Further, the results show how the heat flux from the solar collector fluid in channel to the inner tank is dependent on the buoyancy driven flow.

From the above discussion about the fluid flow and the resulting heat transfer in the storage tank of the solar hot water system, it is understood that there should be a strong relation between the two phenomena in controlling themosyphonic action in the collector. From the knowledge of heat transfer, it is known that, in natural circulation loops, which may be employed in a number of similar applications.

For the simulation of the hot water making system a block-oriented approach was used, modeled and simulated using FEMLAB. The simulated results achieved so far shows a good agreement with the measurements.

Nomenclature

A_c	Effective collection area, m^2
b	Distance between absorber plate and horizontal plate (baffle) = 5 mm
$c_{p,w}$	Specific heat of water, J/kg·K
$c_{p,a}$	Specific heat of air, J/kg·K
F_R	Efficiency factor
F'	Collector efficiency factor
g	Gravitational acceleration, m/s^2
I	Solar radiation, W/m^2
L	Length of the absorber channel, m
m	Mass, kg

$\dot{m}$	Mass flow rate of water in absorber channel, kg/s
$\dot{m}_a$	Mass flow rate of air in coil, kg/s
Q	Useful heat gain of absorber channel, W
r	Radius of riser, m
T_a	Ambient temperature, K
T_i	Water temperature in the absorber channel, K
T_o	Water temperature in the tank, K
$T_{a,i}$	Inlet air temperature into the coil, K
$T_{a,o}$	Outlet air temperature from the coil, K
V_E	Expansion volume, m^3
V_C	Compression volume, m^3
U_c	Overall heat transfer coefficient for collector, W/m^{-2}·K
U_{cl}	Overall heat transfer coefficient for coil, W m^{-2}·K

Greek letters

α	Radiation sbsorbtion factor
ρ	Density, kg/m^3
μ	Dynamic viscosity, Pa·s

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