Computational study of an integrated collector storage solar water heater

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Abstract

A simple low cost integrated collector storage solar water heater (ICS-SWH) which has the potential to substantially reduce domestic energy use was proposed for simulation. The system takes the form of a rectangular-shape incorporating the solar collector and storage tank into a single unit. The incorporation of extended surface fins are a good way of enhancing the construction for an inexpensive SWH and to achieve an increase in efficiency of the system. The thermal performance of the systems is critically dependant on the convective heat transfer coefficient occurring on the waterside of the inclined absorber plate and fins. A Computational Fluid Dynamic (CFD) study was undertaken to model flow and heat transfer in the three-dimensional (3D) SWH geometry. A first analysis was undertaken for a four fins collector designed at Napier University, Scotland, in order to improve its performance. The 3D CFD analysis allowed the optimisation of fin spacing to improve the ICS-SWH performance to create a new ICS-SWH design. Global water temperature in the collector was found to increase without impeding the flow between the fins. A minor decrease in temperature gradient was observed but stratification remained.

Keywords: CFD Modelling, Solar Energy

1. Introduction

Computational Fluid Dynamic (CFD) in simple terms is the use of computer and numerical methods to solve and analyse problems involving fluid flow. It is very often used in product concept, product development and also virtual prototyping as it provides complementary information about environmental performances and significantly reduces the amount of experimental work needed. CFD-Fluent software, based on the finite volume method offering a wide array of physical 2D and 3D models, was used for this study. Recent studies indicate an increase in the use of CFD tools for analysing and optimising design and performances of solar collector. A pioneering study on cavities used a finite element method to solve the flow in a square cavity [1]. In the 1980's the knowledge of flows was extended by numerical investigation of 3D aspects [2] and the influence of varied fluid properties and radiation were inspected [3]. Recent work has been done [4] on inclined cavities based on laminar natural convective flow in inclined rectangular glazing cavities. However the work on flow pattern inside the storage tank of integrated collector storage solar water heater (ICS-SWH) is still largely unexplored. To date only two studies [5-6] from the author's knowledge have been recorded. A 2D CFD analysis involving both radiation and convection in a solar collector to compare with experimental results showed that CFD model results underestimated experimental data [5]. The second phase of research involved intensive 3D CFD analysis on ICS-SWH on flow behaviour of air and water cavities for different angles and different boundary conditions in order to optimise the design of the ICS-SWH [6]. Based on published research [6-11], a 3D CFD study was undertaken to model flow and heat transfer in a simple low cost ICS-SWH geometry. This model provided useful information about collector performance and was a useful tool for design improvements providing detailed pictures of fluid movements and stratification occurring in our collector.

2. Preliminary

2.1. ICS-SWH Design

The tested aluminium ICS-SWH was designed and manufactured with 3mm thick aluminium sheets incorporating fins to improve the thermal efficiency and structural stability of the heater. The water tank was placed in a hard wooden box insulated with layer of fibre glass wool on all sides and bottom as shown in Figure 1. A gap of 35mm between the absorber plate and glazing was used to reduce heat losses by restricting air movement.

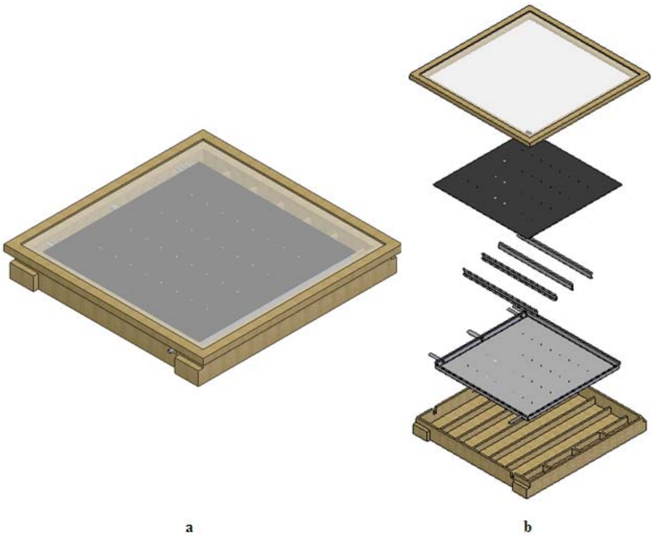

Figure 1: Solar water heater assembly, a: Plain view, b: Explode view

2.2. Purpose and fin optimisation parameters

The CFD analysis of the ICS-SWH was undertaken in order to improve the four fin ICS-SWH performance by optimising the fin spacing. Prior to simulation issues regarding the parameters influencing fin optimisation need to be determined, constrains need to be stated, heat transfer parameters need to be outlined and the type of CFD analysis need to be established.
Fin material, length and thickness and the number of fins in the ICS-SWH are the four main parameters to be outlined when analysing fin optimisation. The material thermal conductivity is an intrinsic parameter for effective ICS-SWH. The low density, high thermal conductivity and recyclable properties of aluminium highlighted this material as an effective choice. The fin length was fixed at the maximum length of 800mm. Fins are used to increase the heat transfer from the heated surface by increasing the effective surface area. The effectiveness of the fin is enhanced by increasing the ratio of the perimeter to the cross-sectional [7] therefore the use of thin, but closely spaced fins is preferred, with the provision that the fin gap is not reduced to a value where flow between the fins is severely impeded, thereby reducing the convection coefficient. The present study thus looks at the increase in performance of the ICS-SWH by increasing the number of fins.

Three main constraints affect this study; cost, volume (50litre tank size) and manufacturing ability which need to be borne in mind when choosing the new design.
Three main heat transfer parameters influence the ICS-SWH performance and can be recapitulated as: the shape of fins, the angle of inclination of the heater, and time of exposure to incident solar radiation. Due to manufacturing constraints, simple rectangular shapes of fins were considered. A 45 degree inclination angle and a 300W/m^2 heat flux were taken as the reference conditions [6]. Finally, the type of CFD analysis, 2D or 3D, is an important parameter to consider. Previous studies [9] outlined that 2D analysis was sufficient for a good analysis of the system. However, 2D analysis would only suffice for a horizontal inclination of the heater. For any angle above zero a gradient exists in the longitudinal direction making a 2D analysis insufficient. Hence, based on a 45 degree inclination of the collector, a 3D analysis was undertaken. As the Quiescent fluid is unavailable in CFD simulation, the process was assumed transient.

2.3. Model calibration and boundary conditions

The modelling process was carried out for 3D analysis using CFD-Fluent 6.2 software. Gambit 2.2 was used to mesh the model. The simple and regular geometry of the model suggested the use of a quad structured mesh of size 1mm. Two different boundary condition types were applied on the absorber plate for tests, depending on the purpose of the simulation. Optimisation simulations used constant heat flux of 300W/m^2 as the boundary condition on the absorber plate. Constant absorber plate temperature boundary condition was taken when comparing the heat absorbed by the two ICS-SWH designs. According to those conditions the program calculated the temperature field in the geometry and as a result values at the nodes were displayed.

3. Modelling results

Stratification is essential for the good performance of a solar collector and is significant when trying to optimise the collector for draw off. However better mixing in the tank results in higher rates of heat transmission when trying to get solar energy into the water. Then the addition of fins might give a differential of temperature lower from the top to the bottom of the ICS-SHW but will optimise the transfer of energy into water. A CFD stratification analysis was developed for the four fin ICS-SWH design and then undertaken for a second design using five fins to compare both water stratification and velocity magnitude for a given time and heat transfer through time.

3.1. Extended heat transfer fins

A good understanding of the influence of extended surfaces is important when seeking performance enhancement of the ICS-SWH. Figure 2 represents the temperature of the fins with height after a lapse time of 60 minutes and a simulated heat flux on the absorber plate of 300 W/m^2. Heat is transferred through the fins from the top of the collector to the bottom where the water temperature is cooler. This results from gravity and buoyancy effects. Water with different temperatures will settle at a corresponding height in the ICS-SWH according to the density of the fluid. Hot water of low density will naturally settle in upper layers while cold water of high density will fall to the bottom layers. During the first three hours of the charging process, high temperature stratification occurs in the ICS-SWH. With time, temperature in the upper layers get fully established and reach an equilibrium influencing the lower layer to increase in temperature and therefore decrease the density gradient of water inside the ICS-SWH.

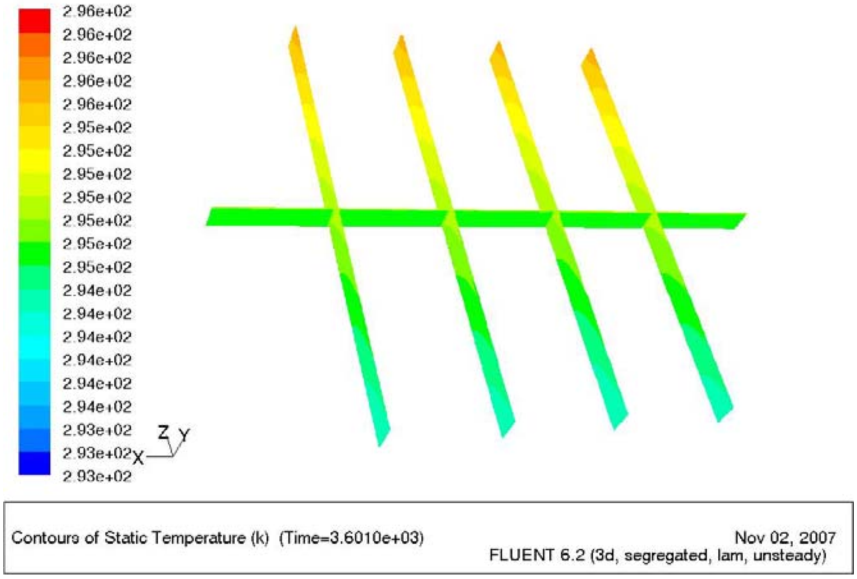

Figure 2: Temperature stratification of fins and middle line of water collector

In order to ease the comprehension of the analysis process a discussion of the original four fin collector design is discussed below.

3.2. Four fin collector design

The display of the velocity profile was completed in Figure 3. Velocity was observed to increase with the longitudinal length and then decrease as it gets closer to the top of the collector. This can be explained by the accumulation of hot water at the top of the collector reducing the velocity boundary layer and promoting diffusion of heat with time. A horizontal plane would show that high velocities occur at the absorber plate where high temperatures take place. It is observed in Figure 3 that an increase, followed by a decrease, pursued by an increase in velocity occurs between the fins. This decline in velocity in the middle of the fins suggests the addition of fins to increase the velocity magnitude. The horizontal view of velocity profile supports this observation.

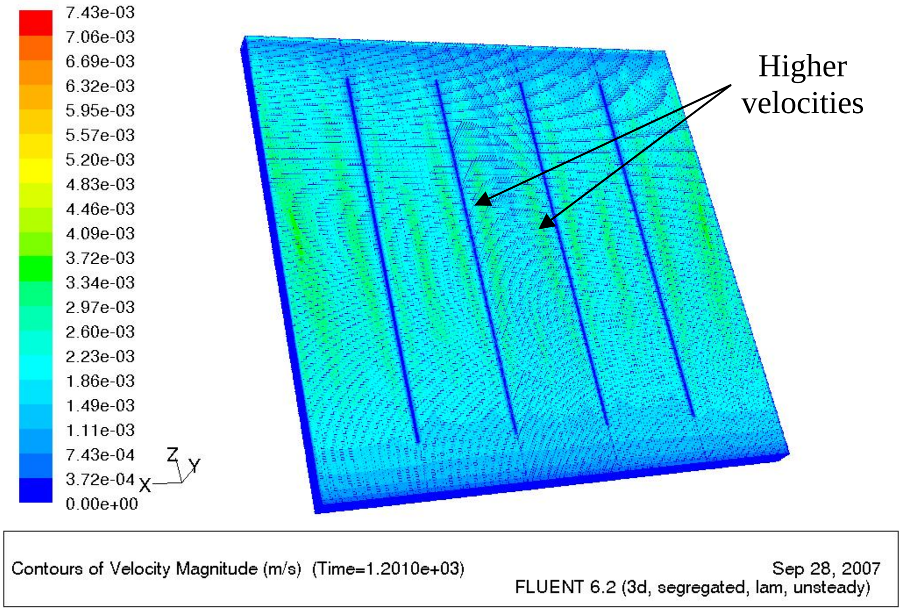

Figure 3: Velocity profile – 4 fins, top view, after 20 mn

Results showed that the overall velocity increased with time until it reached a peak value from which velocity magnitude declines with the passage of time. The increase is due to a high heat flux through the fins to the water occurring after the initial capacitance effect of the system. With time, hot water builds up at the top of the collector resulting in a decline of heat transfer and therefore heat is diffused from the system.

Figure 4 represents the longitudinal temperature stratification in the collector inclined at 45°. As predicted higher temperatures occur on the top of the collector. Stratification occurs from a maximum water temperature of 295.9°K at the top of the collector to a minimum temperature of 293.3°K at the bottom; a 2.6°K temperature gradient.

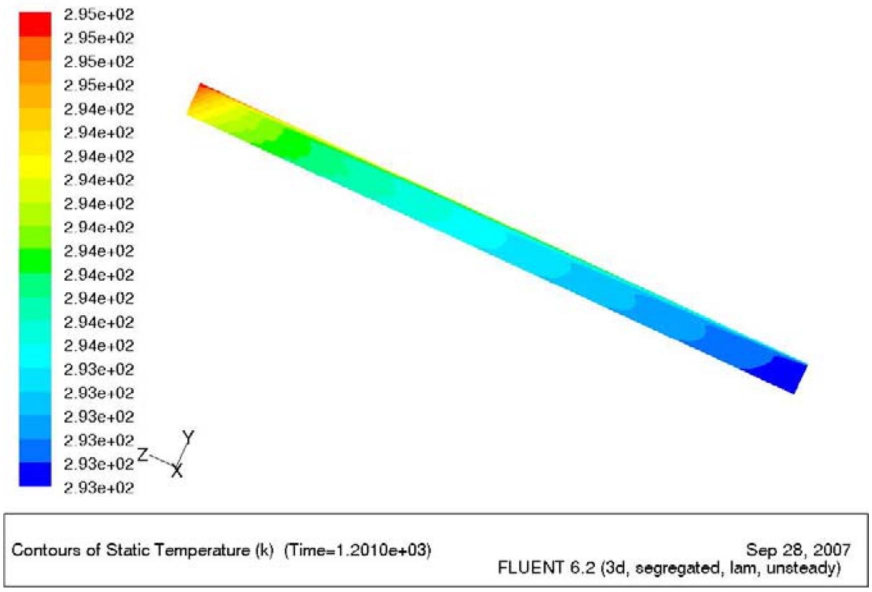

Figure 4: Longitudinal water temperature stratification – 4 fins, side view, after 20mn

In an attempt to improve the heat transfer one fin was added to the original ICS-SWH design. New 3D velocity and stratification analysis were undertaken for the five fin ICS-SWH.

3.3. Five fin collector design

Figure 5 display the velocity profile of the new ICS-SWH. An increase in velocity, compared to the four fin design, was observed resulting in an increase of the maximum velocity of 2%. The main velocity pattern occurs between 1.90mm/s to 3.8mm/s compared with a 1.86mm/s to 3.72mm/s for the five and four fins collectors respectively.

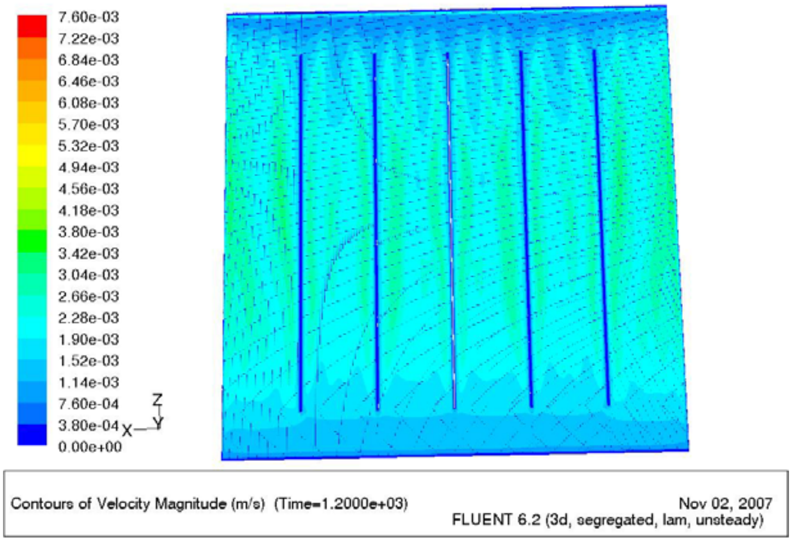

Figure 5: Velocity profile – 5 fins, top view, after 20 mn

The longitudinal temperature stratification of the five fin collector is shown in Figure 6. Stratification occurs from a maximum water temperature of 295.9°K to a minimum temperature of 293.8°K at the top and bottom of the collector respectively resulting in a 2.1°K temperature difference from top to bottom. This corresponds to a 19% decrease in stratification.

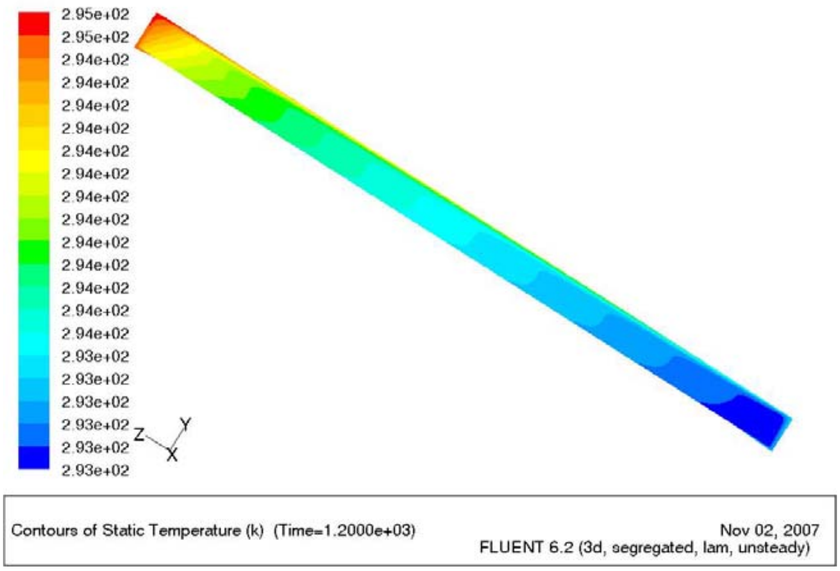

Figure 6: Longitudinal water temperature stratification - 5 fins, side view, after 20mn

3.4. Improvements: Comparing four and five fin collector designs

Previous observation showed that the five fins collector achieved an increase in velocity of 2% compared to the four fin design, while longitudinal water temperature stratification decreased by

19%. This could be explained by the addition of the fins responsible for an increased transfer of heat inside the collector, thus increasing velocity and overall temperature in the collector.
In order to demonstrate that five fins is a more suitable arrangement geometry for optimal collector design, a 3D CFD analysis was carried out assuming a constant temperature boundary condition on the absorber plate set at 313°K. The fluid departure temperature was set at 293K. Despite the fact that the system is under constant heat flux, using a constant input temperature allowed the heat absorbed by both collector to be derived as shown in Figure 7.

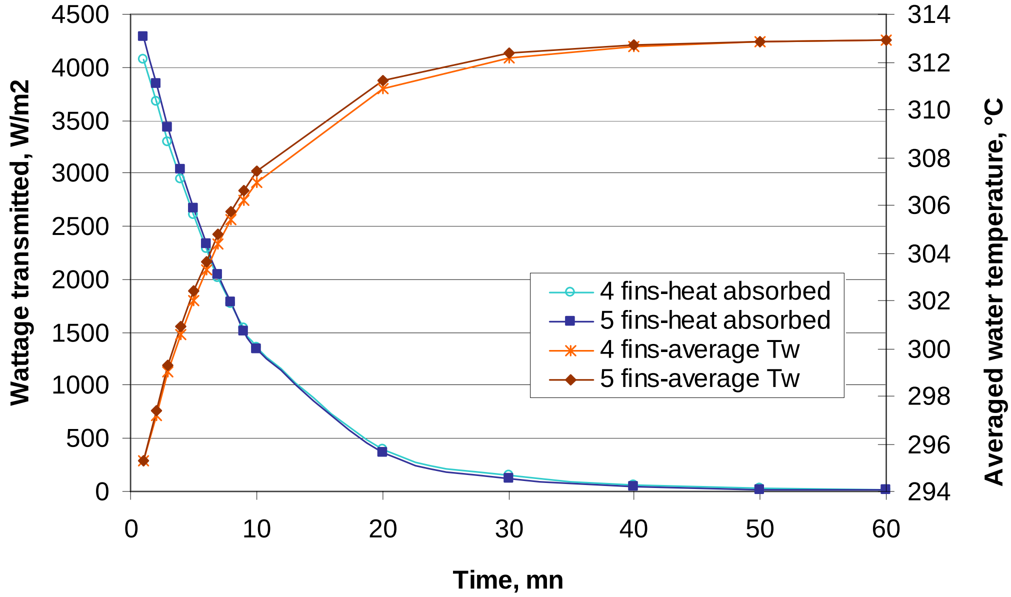

Figure 7: Heat transfer and water temperature profiles in the ICS-SWH with time

Initially, for the first 10 minutes, more heat was absorbed by the five fin collector compared to the four fin. This is linked to a frenzy of heat transfer activity; the fins are surrounded by cooler water. An increase in heat transfer activity occurs when increasing from four to five fin geometries. After 10 minutes the five fins are surrounded with hotter water than the four fins are. The difference in temperature between the four fins and the water is higher resulting in a higher heat flux. Both profiles reach a peak value at the equilibrium temperature 313°K set as the boundary condition.

4. Conclusion

This paper reported the implementation of a four fin ICS-SWH concept utilising CFD-Fluent software through Gambit in order to optimise its design performance. Initial results of the four fin ICS-SWH indicated that one fin could be added to the original design to improve the heat transfer. A 3D CFD simulation was then undertaken for a five fin ICS-SWH. Two boundary conditions were applied to the systems in order to compare the water temperature stratification achieved and the heat transferred to the water body by each collector.
The first boundary condition applied to the systems consisted in a constant heat flux on the absorber plate. This method was used to characterise the temperature stratification and the velocity magnitude within both collectors. Despite a minor decrease in temperature gradient between the top to bottom in the five fin ICS-SWH, it was clearly observed that stratification remained. It is important to state that the addition of fins should not impede the flow between the fins (as was experienced when trialling a multi-fin design in an earlier study), thereby reducing the convection coefficient. Results showed that the addition of one fin in the collector increased the velocity in the

collector which has a corresponding increase on the Nusselt number; raising the heat transfer coefficient in a predictable manner [12]. The velocity magnitude was also observed to decrease with time for both collectors with the water getting warmer.
A second boundary condition applied to the systems consisted of a constant temperature on the absorber plate which was used to characterise the heat absorbed by each collector. Results revealed that the addition of one fin accounts for the increased transfer of heat inside the collector. It was observed that the five fins supplied more energy to the collector than four at the beginning of the charging process. The intermittent availability of incident solar radiation in Scotland shows high potential for this type of improvement as it is advantageous to have rapid heating process.
In light of the results presented in this paper, the five fin collector performed generally better than the original four fins collector. Therefore this new design could be suggested as a new arrangement of the collector assuming that the cost associate to this improvement is negligible.

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