CHAPTER 11

VALIDATION OF EXPERIMENTAL RESULTS USING COMPUTATIONAL FLUID DYNAMICS

Simulation of a solar water heater system using computational fluid dynamics; geometry creation, mesh building and boundary conditions are discussed. The results obtained from the simulation are compared with the experimental values and presented.

11.1 INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involves fluid flow. Numerical methods play a vital role in obtaining the solutions of partial differential equations used in CFD analysis.

The following are the steps involved in CFD analysis.

a) Defining the geometry of the problem
b) Splitting the fluid volume into small discrete cells (mesh)
c) Defining the physical model
d) Defining the boundary conditions
e) Simulation by solving the equation
f) Analysis and visualization of results by using a post processor.

The following governing equations for viscous incompressible flows are used to find the solutions of the problem.
(i) Continuity equation
\[
\frac{\partial}{\partial t} (\rho m_k) + \nabla (\rho Um_k) = -\nabla . (j_k) + S_k
\] (11.1)

(ii) Momentum equation
\[
\frac{\partial}{\partial t} (\rho U) + \nabla . (\rho U U) = -\nabla . \pi + \rho g + F
\] (11.2)

(iii) Energy equation
\[
\frac{\partial}{\partial t} (\rho h) + \Delta (\rho U h) = -\nabla . (q) + \frac{Dp}{Dt} - (\tau : \nabla U) - \nabla \left( \sum_k h_k j_k \right) + S_h
\] (11.3)

11.2 SIMULATION SOFTWARE

Simulation is performed in fluent commercial CFD software that uses GAMBIT as the pre-processor and Fluent as the post processor. The data from the experimental studies are used as the basic data for simulation. Geometry of the riser tube with absorber plate and twist of various ratios are created and meshed by Gambit 2.3.16 and simulation is performed in Fluent 13.0.

11.2.1 Geometry Creation

The geometry is created with the following data

- Riser tube diameter (ID 11 mm and OD 12.5 mm), Length 1000 mm
- Helical, Left-Right, Kenics and customized twist and its modified forms with rod and spacer. (Regularly spaced with rod and spacer of 125mm, 250mm and 500 mm)
- Absorber plate of 122 mm width, thickness 0.5 mm and Length 1000 mm
These are created by using the method of volume splitting with face. This splitting of volume is necessary in order to create meshes with less number of elemental volumes to enable the defined problem to be solved in FLUENT 13.0 solver. After creating the geometry, boundary layer is created in the entrance and the exit faces of the riser tube. This is necessary in order to incorporate the wall effect on the flowing fluid. The absorber plate has been meshed using hex elements of ‘map’ type. The total number of nodes created is 612168 with a grid spacing of 0.5. For plain cylindrical tube hex with cooper scheme is used. The total number of nodes is 170434 with a grid spacing of 1. For tubes with twist, tetrahedron with T-grid is used. The total number of nodes including the tube with twist is 200314 with a grid spacing of 1. Fig 11.1 represent the meshed plain tube Fig.11.2 represent the tube with helical twist, Fig.11.3 represent the tube with Left-right twist, Fig.11.4 represent the tube with kenics twist, Fig.11.5 represent the structure of the tube with customized twist with rod 250 (3D meshing).

Fig.11.1 Structure of plain tube with absorber plate (3D meshing)
Fig. 11.2 Structure of tube with helical twist (3D meshing)

Fig. 11.3 Structure of tube with Left-Right twist (3D meshing)
Fig. 11.4 Structure of tube with Kenics twist (3D meshing)

Fig. 11.5 Structure of tube with modified customized twist with 250 mm rod (3D meshing)
11.2.2 Post processor

The CFD software first reads the case file and then the model has to be defined by specifying the solver, energy equation (if it has temperature), and the type of flow either turbulent or laminar. Then data regarding the materials are specified i.e. material name, material type, its chemical formula, its properties etc, by selecting from the FLUENT database. Following are the assumptions made in the analysis. (i) The walls are assumed to be completely adiabatic, for simplification of the boundary condition. (ii) The operating pressure is assumed as $1 \times 10^5$ N/m$^2$ for the entire tube with twist. (iii) For ease of generation of grid, the area of the tube models are assumed to have same dimensions. The specified boundary conditions are as detailed here.

1. Inlet: The inlet of the domain allows fluid at a velocity in a direction along the axis of the tube and the density and temperature are mentioned and zero relative static pressure is applied to the exit plane. The constant heat flux is applied on the surface of the absorber plate.

2. Wall: The wall surfaces are described with no-slip conditions and an adiabatic boundary condition is applied to the outer surface of the riser tube. An unstructured mesh is applied to the computational domain with a refined mesh density near the wall boundaries.

3. The computational domain has been solved as a steady state conjugate heat transfer problem and the solution process is performed until convergence and an accurate balance of mass and energy are achieved. The solution process is iterative with each iteration in the steady state problem treated as a pseudo-time step. In the iterative scheme, all the equations are solved iteratively, for a given time-step, until the convergence criteria are met. The simulations are carried out for the following cases.
Plain tube with absorber plate.

Tube fitted with full length helical, Left-Right, Kenics and Customized twist inserts.

Tube fitted with modified forms of helical, Left-Right, Kenics and Customized twist inserts equally spaced with rod and spacer.

Constant heat flux is applied on the absorber plate as shown in Fig.11.6. The simulated Nusselt number and pressure drop for plain tube collector is represented in Fig.11.7 and Fig.11.8 respectively. Similarly Fig.11.9 – 11.10 represent the same for collector with full length Kenics twist.

Fig.11.6 Constant heat flux applied on the absorber plate
Fig.11.7 Nusselt Number for Plain tube collector (Run 15 in A4.3)

Fig.11.8 Pressure drop for Plain tube collector (Run 15 in A4.3)
Fig. 11.9 Nusselt Number for Kenics twist (Run 15 in A4.3)

Fig. 11.10 Pressure drop for Kenics twist (Run 15 in A4.3)
The flow pattern of fluid for full length Left-Right twist is shown in Fig. 11.11. and Fig. 11.12 represents the flow pattern in helical twist with rod.

Fig. 11.11 Flow pattern of fluid in full length Left-Right twisted tape

Fig. 11.12 Flow pattern of fluid in helical twisted tape with rod
11.3 SIMULATION RESULTS AND VALIDATION

Simulation is performed for plain tube and twisted tape (helical, Left-Right, Kenics and customized) collectors are discussed in detail below.

11.3.1 Plain tube collector

The physical dimensions and various experimental parameters for plain tube collector are considered as input for simulation and simulated results are compared with the results obtained by using the fundamental equations.

The variation of Nusselt number with Reynolds number for plain tube collector for Phase 1 and Phase 2 are depicted in Fig.11.13. Similarly the variation of friction factor with Reynolds number is described in Fig.11.14. By referring Figs.11.13.a and 11.13.b one can observe that with the increase in Reynolds number increases Nusselt number whereas friction factor decreases. From Figs.11.14.a and 11.14.b it can be inferred that as the Reynolds number decreases, the Nusselt number decreases with increase in friction factor. The range of Reynolds number varies from 150 to 600. The trends obtained for Nusselt number and friction factor with Reynolds number in simulation study is similar to experimental study. The data obtained by simulation are compared with the theoretical value for plain tube collector for heat enhancement and friction factor, which shows an average deviation of less than $\pm 9.61\%$ for Nusselt number and $\pm 14.21\%$ for friction factor. The simulated and theoretical Nusselt number and friction factor are shown in Tables A4.1 and A4.2 in Appendix 4.
Fig. 11.13 Validation of simulated Nusselt number with theoretical value for plain tube collector
Fig. 11.14 Validation of simulated friction factor with theoretical value for plain tube collector
11.3.2 Twisted tape collector

The effect of full length twist and its modified forms with rod and spacer inside the riser tube of the plain tube collector is as described below.

11.3.2.a Helical twisted tape collector

The experimental Nusselt number is compared with simulated Nusselt number for Phase 1 and Phase 2 for the tube fitted with full length helical twist and its modified forms with rod and spacer is shown in Fig.11.15. Higher Nusselt number is obtained in collector with full length helical twist, which has superior heat transfer compared to others. Inclusion of rod and spacer in the twist reduces the swirl effect and this resulted in decrease in the Nusselt number. The decrease in Nusselt number for twist with rod is comparatively lower than for twist with spacer. In Phase 2 the decrease in Reynolds number minimizes the Nusselt number. The range of Nusselt number is lower in plain tube collector compared to twisted tape collector due to the absence of swirl effect.

Similarly the experimental friction factor is compared with simulated value for Phase 1 and Phase 2 as described in Fig.11.16. The simulated results for friction factor for the full length helical and its modified forms are similar to the experimental trend. The range of friction factor is higher in full length twisted tape collector and its modified forms compared to plain tube collector due to the increase in the wetted surface area. The simulated results are validated with the experimental values and the average deviation is found to be within ±12.5% for Nusselt number and ±14.8% for friction factor. The simulated and experimental Nusselt number and friction factor for full length helical twist are shown in Tables A4.1 and A4.2 and for the modified forms of helical twists is given in Tables 4.3, 4.7 and 4.11, 4.15 in Appendix 4.
Fig. 11.15 Comparison of simulated Nusselt number with experimental value for various helical twisted tape collectors
Fig. 11.16 Comparison of simulated friction factor with experimental value for various helical twisted tape collectors
11.3.2.b Left-Right twisted tape collector

The effect of full length Left-Right insert and its modified forms with rod and spacer are as described below.

The experimental Nusselt number is compared with simulated Nusselt number for Phase 1 and Phase 2 for tube fitted with full length Left-Right twist Left-Right inserts and its modified form with rod and spacer and is depicted in Fig.11.17. The overall heat transfer rate is higher in full length Left-Right twisted tape collector compared to the modified forms of Left-Right twist with rod and spacer, due to higher intensity in the change in direction of fluid in both clockwise and counter clockwise direction. Similarly the experimental friction factor is fitted with simulated value for Left-Right twist with its modified forms as shown in Fig.11.18. Higher friction factor is obtained in full length Left-Right twist compared to its modified forms due to the maximum wetted surface area. The simulated results agree with the experimental values within ±9.18% for Nusselt number and ±11.8% for friction factor.

The simulated and experimental Nusselt number and friction factor for the modified forms of Left-Right twist with rod and spacer are shown in Tables A4.4, A4.8 and A4.12, A4.16 in Appendix 4.
Fig. 11.17 Comparison of simulated Nusselt number with experimental value for various Left-Right twisted tape collectors
Fig. 11.18 Comparison of simulated friction factor with experimental value for various Left-Right twisted tape collectors
11.3.2.c Kenics twisted tape collector

The effect of full length Kenics insert and its modified forms with rod and spacer are as elaborated below.

The experimental Nusselt number is compared with simulated Nusselt number for Phase 1 and Phase 2 for tube fitted with full length Kenics twist and its modified form with rod and spacer and is depicted in Fig.11.19.

In the same way, the experimental friction factor is fitted with simulated value for full length Kenics twist with its modified forms as shown in Fig.11.20. The friction factor for full length twist is higher than its modified forms. The simulated results agree with the experimental values within ±11.23% for Nusselt number and ±12.6% for friction factor.

The simulated and experimental Nusselt number and friction factor for the modified forms of Kenics twist with rod and spacer are shown in Tables A4.5, A4.9 and A4.13, A4.17 in Appendix 4.
Fig. 11.19 Comparison of simulated Nusselt number with experimental value for various Kenics twisted tape collectors
Fig. 11.20 Comparison of simulated friction factor with experimental value for various Kenics twisted tape collectors.
11.3.2.d Customized twisted tape collector

The outcome of full length customized insert and its modified forms with rod and spacer on Nusselt number and friction factor and the comparison with simulated values are as detailed below.

The experimental Nusselt number is compared with simulated Nusselt number for Phase 1 and Phase 2 for tube fitted with full length customized twist and its modified form with rod and spacer and is portrayed in Fig.11.21.

Similarly, the experimental friction factor is fitted with simulated value for full length customized twist with its modified forms as shown in Fig.11.22. The simulated results agree with the experimental values within ±10.4% for Nusselt number and ±9.2% for friction factor.

The simulated and experimental Nusselt number and friction factor for the modified forms of customized twist with rod and spacer are shown in Tables A4.6, A4.10 and A4.14, A4.18 in Appendix 4.
Fig. 11.21 Comparison of simulated Nusselt number with experimental value for various Customized twisted tape collectors
Fig. 11.22 Comparison of simulated friction factor with experimental value for various Customized twisted tape collectors
11.4 REMARKS

The simulation trend for heat enhancement and friction factor for plain tube, helical, Left-Right, Kenics and customized twist collectors are alike the trend perceived in the experimental trials.

The CFD simulation is performed for the heat transfer augmentation in plain tube; tube fitted with helical and Left-Right twist, Kenics and customized twist using Fluent 6.13. The data obtained by simulation are matching with the theoretical value for plain tube with an average deviation within $\pm 14.61\%$ for Nusselt number and $\pm 9.21\%$ for friction factor. The simulated results for the tube fitted with full length helical, Left-Right, Kenics, customized and their respective modified forms of twists agree reasonably well with the experimental values.