

# CFD BASED INVESTIGATION OF THERMAL PERFORMANCE OF SHELL AND TUBE HEAT EXCHANGER WITH CHARGING PCM

<sup>1</sup>Pintu, <sup>2</sup>Harimohan Sharma,

<sup>1</sup>M. Tech. Student, <sup>2</sup>Assistant Professor,

<sup>1,2</sup>Mechanical Engineering Department,

<sup>1</sup>Apex Institute of Engineering and Technology, Jaipur, Rajasthan, India

<sup>2</sup>Apex Institute of Engineering and Technology, Jaipur, Rajasthan, India

**Abstract:** Heat transfer from one fluid to another is important application in engineering science, various type of heat exchanger devices were developed by engineers from previous decades. Research on these devices continues in present era to improve thermal performance. Various shapes are used by engineers to improve thermal performance. Main common shapes are like simple straight heat exchanger, curved shape shell heat exchanger, twisted shape shell exchanger, custom shape heat exchanger. Simple shell and tube heat exchanger was used to validate the experimental results with CFD results. Experimental validation proves that CFD is effective tool for thermal performance investigation. After experimental validation, main research work was focused on effect of latent heat on thermal performance improvement of simple shell and tube heat exchanger using PCM materials in it. Co-relation equations are developed for both shapes of response conditions with linear fitting tool available in MINITAB coding software. Proper instrumentation and calibration was taken care in this study. CFD simulation was carried out on ANSYS FLUENT software

**Keywords:** Thermal performance, CFD and Phase change Material (PCM)

## I INTRODUCTION

In present era heat, storage from thermal devices is main research focus for engineers, designers, and researchers worldwide. Various new techniques were developed like extended surfaces, phase change material, latent heat storage devices, thermo electric devices and many more. Present research work will focus PCM application in shell and tube heat exchanger for charging boundary conditions. Various experimental and CFD based research work was summarized for this research work. Heat exchangers have various applications in power plants, refrigeration and air conditioning systems, nuclear reactors, automotive industries, chemical processing, heat recovery systems, and food industries.

Thermal energy includes storage of heat in one of three forms;

- Sensible Heat storage.
- Latent heat storage.
- Thermo-chemical heat storage.

### Sensible heat energy storage

It is very common method and used from hundreds of years as hot water tank as water consumes large without changing its phase. Sensible heat storage simply means changing the temperature of storage medium. Most commonly storage medium is water but rock, sand, clay and earth can also be used.

### Latent heat energy storage

It includes the storage of energy in Phase-change materials (PCM's). Phase change material are those material which changes their phases by consuming heat energy into them. Thermal energy is stored and released with change in the materials phase. Most common phase change to exploit is solid-liquid transition, as the liquid-gas transition is impractical and solid-solid (crystalline structure) transition usually have too low an energy density to be useful. When a PCM is heated initially it behaves like sensible heat energy storage and the material temperature is increased. However, once their transition temperature is reached the material will continue to absorb heat at a constant temperature while it changes state or phase. This heat absorbed at constant temperature is known as the latent heat of the transition. To retrieve the energy the PCM can be changed back from the liquid to the solid phase and the energy stored as latent heat is released.

### Thermo chemical heat energy storage

It includes storing heat energy in the form of chemical bonds. A reversible chemical reaction which absorbs heat is used to absorb the heat energy that is to be stored. This reaction can be reversed to release the stored heat. The most common reaction used for this process is the hydration of salts.

## II LITERATURE REVIEW ON PHASE CHANGE MATERIAL AND ITS APPLICATIONS

An Experimental and numerical study has been done by (Agarwal & Sarviya, 2016) to develop the latent heat storage for solar dryer and calculate its performance during charging and discharging. Stored energy in the latent heat storage is utilized during non-sunshine hours to heat ambient air by forcing the ambient air through the latent heat storage system study also indicate that heat transfer during charging is largely influenced by natural convection process. Melting of PCM first occurred at the uppermost section of the system, and then it moves downward and results show that melting rate is faster at the uppermost section due to buoyant effect, further studies show that by decreasing the temperature of HTF from 90 °C to 80 °C, the charging time is increased by 20%. Heat transfer during discharging is mainly governed by conduction and due to low thermal conductivity of PCM, the rate of heat transfer during discharging is comparatively low. Time required for discharging of LHS is longer compared to time required for charging of LHS due to low heat transfer rate between PCM and HTF during discharging. The discharging time increased by 23% by decreasing the HTF flow rate from 0.003 kg/sec to 0.0015 kg/sec

(Wang, Lin, Li, & Zheng, 2016) experimentally investigation have made to study the effects of temperature change on thermal storage performance of the phase change material paraffin with and without copper foam as a filler material. Study analyzes the relationship between the complete phase transition time and heat source temperature of paraffin and of composite PCM. It simulates the phase change process of paraffin and composite phase change material using CFD software Fluent. Results show that Copper foam can effectively improve the uniformity of paraffin's internal heat transfer while reducing the heat storage time by more than 40%, also increasing temperature can improve thermal storage efficiency. Comparison of experimental and simulation results show that: the phase transformation process of metal foam and paraffin can be effectively simulated by software melting/solidification and porous media model under a certain condition.

(Englmair et al., 2016) have experimentally investigated on data from initial testing of heat storage modules, containing different mixtures of the PCM sodium acetate trihydrate, are presented. Modules in different material configurations have previously been tested under laboratory conditions to prove the concept. The modules form a long-term heat storage as a part of a solar combi system including additionally a solar collector field and a water buffer storage. The solar combi-system was connected to an automated tapping system simulating domestic hot water tapping and space heating demands. In results Stable supercooling was achieved in three out of four modules after they were charged with solar collectors as a fluctuating heat source.

(Eslamnezhad & Rahimi, 2017) experimentally studies have done on enhancement on heat transfer method using rectangular fin to melt the PCM in a triplex tube heat exchanger has been investigated numerically to increase the efficiency of the heat exchanger and to reduce the time of PCM melting by changes done in the structure of the fins inside of the triplex tubes when the fin contacting surface with the PCM has kept constant. According to obtained results the impact of fin location on melting of the PCM is very important in triplex type heat exchangers in which the gravity and natural convection play important role in PCM melting.

(Pointner, Steinmann, & Eck, 2014) introduces the PCM Flux approach (PCM Flux consists of macro encapsulated Phase change material blocks that are arranged as parallel layers) as a new alternative for latent heat energy storage. The storage material is separated mechanically by an intermediate fluid layer from the heat transfer surfaces. This concept avoids the formation of a growing layer of solidified PCM material covering the heat transfer structure, which limits the heat flux. PCM storage systems mainly have a disadvantage while it gets discharging. The heating power decreases over time due to a growing and isolating layer of solidified PCM on the heat exchanger. Systems with locally fixed storage material, all of which show this behavior, are stationary PCM. Moving PCM by contrast, make use of locally unfixed PCM offering the possibility to remove the isolating layer of solidified PCM. Thus, a constant thermal power over a span of time is possible. PCM Flux is considered to be a very promising concept, eliminating the problem of decreasing heating power with time.

(Johansen et al., 2016) experimentally studies have done on a solar combi system with a heat of fusion storage based on the phase change material (PCM) sodium acetate trihydrate (SAT). SAT is a salt hydrate with several qualities which make it suitable for heat storage in one family houses. When SAT has been heated to a certain high temperature, above 80 °C, it is possible for the SAT to supercool below its melting point of 58 °C to ambient temperature. In this phase it still contains latent heat and can stay in this state for many months. When there is a heat required a seed, crystal is introduced to the supercooled SAT and in a matter of minutes the whole volume get solidifies releasing its latent heat. To only release an amount of heat suitable to the requirement it is necessary to divide the SAT volume into separate volumes.

(Dermardiros, Chen, & Athienitis, 2015) presents results of an experimental and numerical study focusing on the control based modelling of an actively charged/discharged phase-change material (PCM) thermal energy storage (TES) system. The PCM-TES system consists of five layers of commercial macro-encapsulated PCM panels with an air hole in its center. Air can flow through this cavity to charge/discharge the PCM panels. A detailed fifth order thermal network finite difference model for the system is developed and verified against experimental results. The detailed model is then simplified to a 2nd order model for control purposes. A five-parameter equation is developed to model the storage of heat in the PCM. An average and maximum temperature difference of 0.8°C and 2.0°C, respectively, is achieved between the experiment data and that simulated by the detailed model. The second order model has an average and maximum temperature difference of 0.2°C and 0.9°C, respectively, compared to the detailed model. After literature review, it was concluded that in most of the research, papers limited CFD simulation work was performed and detailed research work was not available for CFD based simulation work.

The conservation of energy equation for the surface heat convection

$$Q_{\text{convection}} = hA\Delta T$$

$$Q_{\text{convection}} = hA(T_{\text{wall}} - T_{\text{inside}})$$

Here,  $h$  is convection heat transfer coefficient,  $A$  is perimeter of inner surface ( $A = \pi DL$ ),  $T_{\text{wall}}$  is wall temperature of tube

Here, we consider that the inner surface temperature of a tube is constant. From energy balance equation

$$Q_{\text{flow}} = Q_{\text{convection}}$$

$$\dot{m}c_p\Delta T = hA\Delta T$$

$$h = \dot{m}c_p\Delta T / A\Delta T$$

Equation used for Reynolds number

$$Re = \frac{4\dot{m}}{\pi D\mu}$$

Equation used for Nusselt number

$$Nu = \frac{hD}{K}$$

Here,  $D$  is hydraulic diameter or inner diameter

Correlation equation for  $Nu$  number given by Dittus-Boelter

$$Nu = 0.02Re^{0.8}Pr^{0.3}$$

Correlation equation for  $Nu$  number given by Gnielinski

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{0.5}(Pr^{0.67} - 1)}$$

Where  $f$  is friction factor and formula for  $f$  is given by Petukhov

$$f = (0.79 \ln(Re) - 1.64)^{-2}$$

### III CFD MODELLING

Computational fluid dynamics (CFD) is the branch of fluid dynamics. It is a research tool which provides cost effective means, simulate real flows by use of the numerical solution of governing equation. Main governing equation is Navier-storke equation for Newtonian fluid. Computational technique used algebraic equation in the place of governing partial differential equation and solve by digital computer. It also provides testing condition which are not possible to measure experimentally and cannot solve by analytics solutions. Steps of CFD process:

- Mathematical modeling (partial differential technique)
- Numerical method (Discretization and solution technique)
- Software tool (solver, pre-andpost processing)

### CFD STEPS

Here we are used Ansys 14.5 version. In Ansys, fluent software is used as solver for analysis of fluid flow and geometries are seen in fig. 1 to fig. 4. We are used CFD steps for solving problem. These steps are:

Step1: - CAD-file making (geometry): -In this step we are creating design of given problem by used of Ansys design modular and another designing tool like catia, inventor, AutoCAD, Pro-e etc.

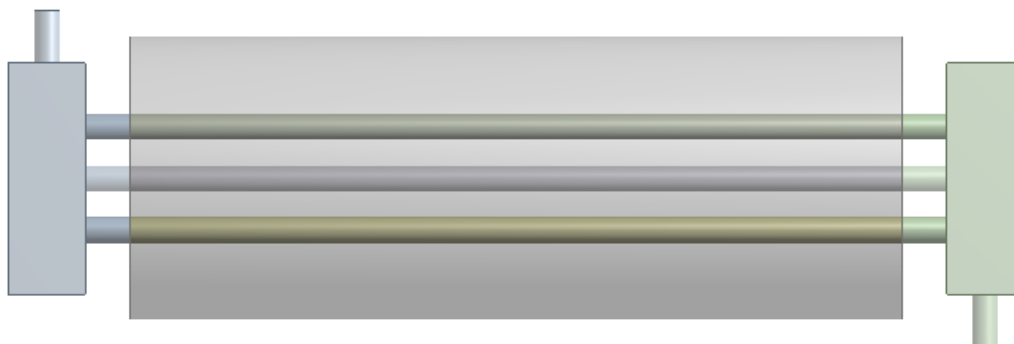


Fig. 1:Design Shell and Tube Heat Exchanger (CFD)

Step 2: -Discretization (meshing): -After designing of geometry off given fluid or component it is braked in to very small or discrete cell (Mesh Generation) by ICEM CFD. Here tube is uniform or block is non-uniform structure.

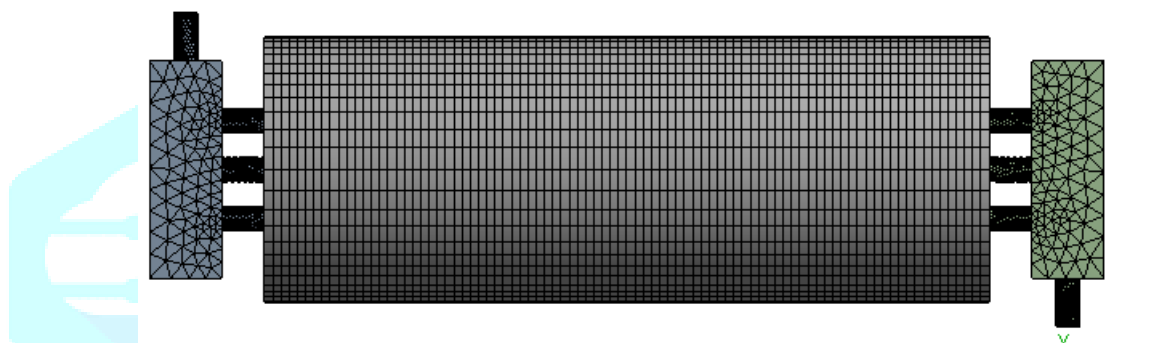


Fig. 2:Discretization of Heat ExchangerDesign 1

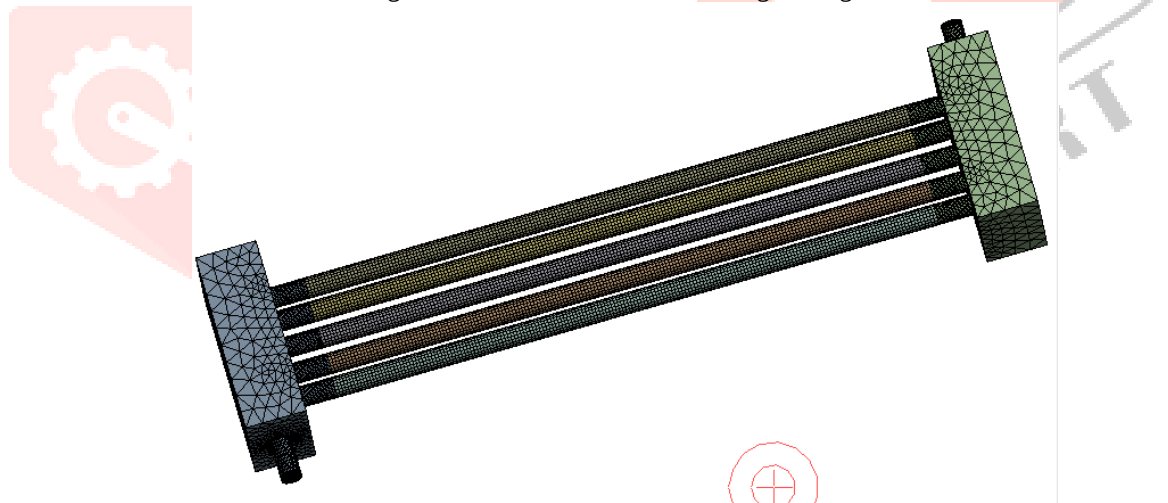


Fig. 3:Meshing of domain

Step 3: - Boundary name: -After meshing we give name of boundary.

A inlet  
B outlet

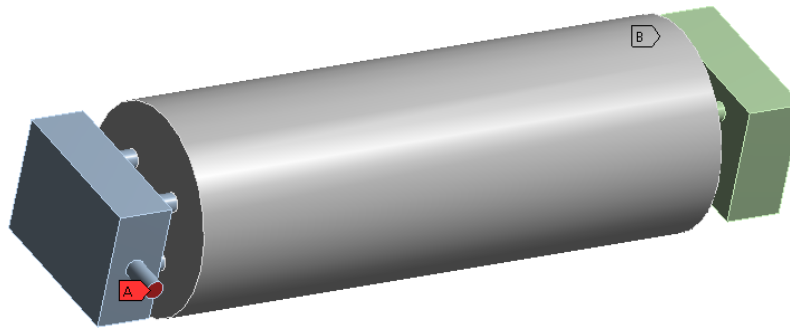


Fig. 4:CFD Boundary conditions for Heat Exchanger

Step 4:- Solver setting (setup): - After giving name of boundary, fluent software is used as solver. It is used default under relaxation factors to start a calculation. Under relaxation is includes to stabilize the iterative process for the pressure based solver.

Discretization Scheme

| Variable                   | Scheme              |
|----------------------------|---------------------|
| Pressure                   | Standard            |
| Momentum                   | Second Order Upwind |
| Turbulent Kinetic Energy   | First Order Upwind  |
| Turbulent Dissipation Rate | First Order Upwind  |
| Energy                     | Second Order Upwind |

Step 5: - Run solution (solution):-Fluent reports value of residuals, which are indications of the error in the current solution. These should decrease during the calculation. There is guideline on the reductions that indicated a solution is “converged”.

#### IV RESULTS AND DISCUSSIONS

The present chapter gives the application of the Taguchi experimental design method. The scheme of carrying out experiments (Simulation work) was selected and results are presented in fig. 5 to fig. 7 and Table 3 and Table 4.

Table 1 Factor and Level for PCM-HE

| No | Factor           | Level I | Level II | Level III | Level IV |
|----|------------------|---------|----------|-----------|----------|
| 1  | Mass flow rate   | 0.1     | 0.2      | 0.3       | 0.4      |
| 2  | Temperature (In) | 320     | 330      | 340       | 350      |
| 3  | PCM-Type         | 1       | 2        | 3         | 4        |
| 4  | HE-Design        | 1       | 2        | 3         | 4        |

PCM type represent different type of PCM material available in local market. HE-Design represent internal design of shell of heat exchanger, which should effect on efficiency of heat exchanger.

Table .2 L16 Orthogonal Array for Present research work for charging of PCM

| No. | MFR | In_Temp | PCM | Design | Charging % |
|-----|-----|---------|-----|--------|------------|
| 1   | 0.1 | 320     | 1   | 1      | 39.38      |
| 2   | 0.1 | 330     | 2   | 2      | 23.96      |
| 3   | 0.1 | 340     | 3   | 3      | 23.04      |
| 4   | 0.1 | 350     | 4   | 4      | 36.62      |
| 5   | 0.2 | 320     | 2   | 3      | 34.63      |
| 6   | 0.2 | 330     | 1   | 4      | 39.52      |
| 7   | 0.2 | 340     | 4   | 1      | 35.48      |
| 8   | 0.2 | 350     | 3   | 2      | 26.37      |
| 9   | 0.3 | 320     | 3   | 4      | 23.37      |
| 10  | 0.3 | 330     | 4   | 3      | 37.57      |
| 11  | 0.3 | 340     | 1   | 2      | 35.43      |
| 12  | 0.3 | 350     | 2   | 1      | 30.63      |
| 13  | 0.4 | 320     | 4   | 2      | 21.04      |
| 14  | 0.4 | 330     | 3   | 1      | 29.23      |
| 15  | 0.4 | 340     | 2   | 4      | 26.77      |
| 16  | 0.4 | 350     | 1   | 3      | 37.96      |

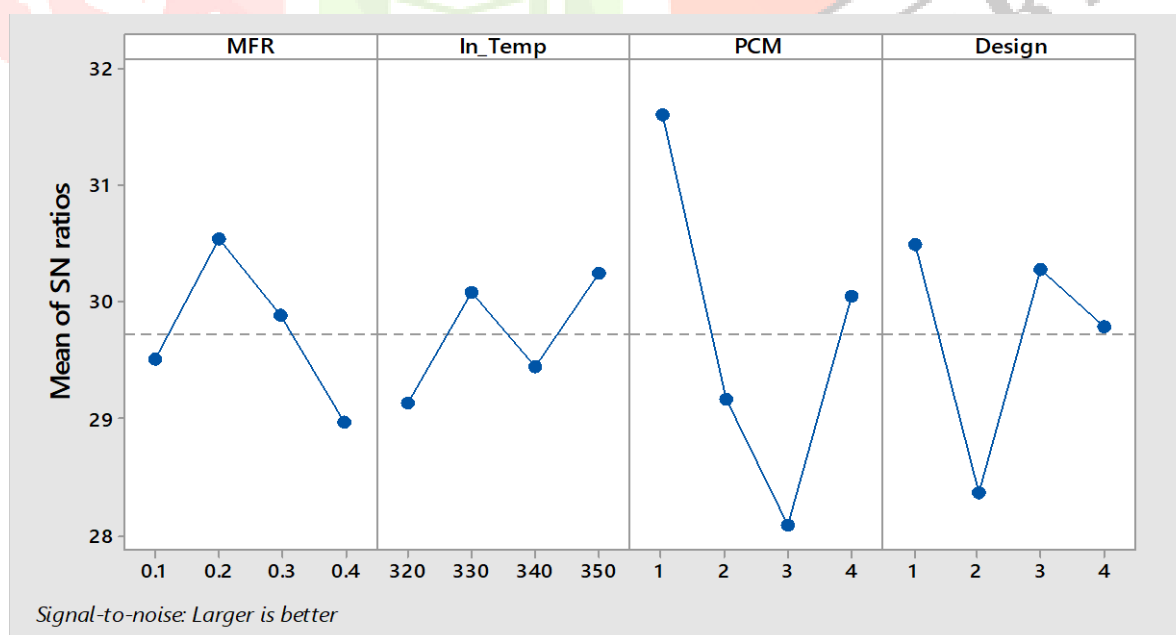


Fig. 5:S/N ratio analysis for charging of PCM

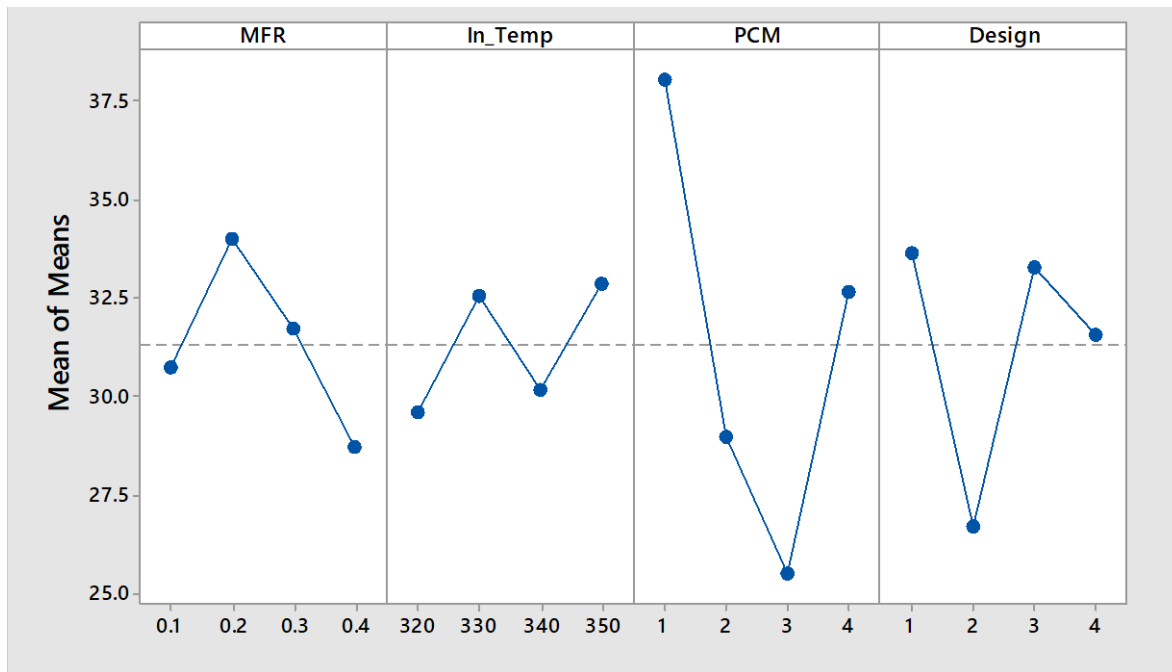


Fig. 6:Mean analysis for charging of PCM

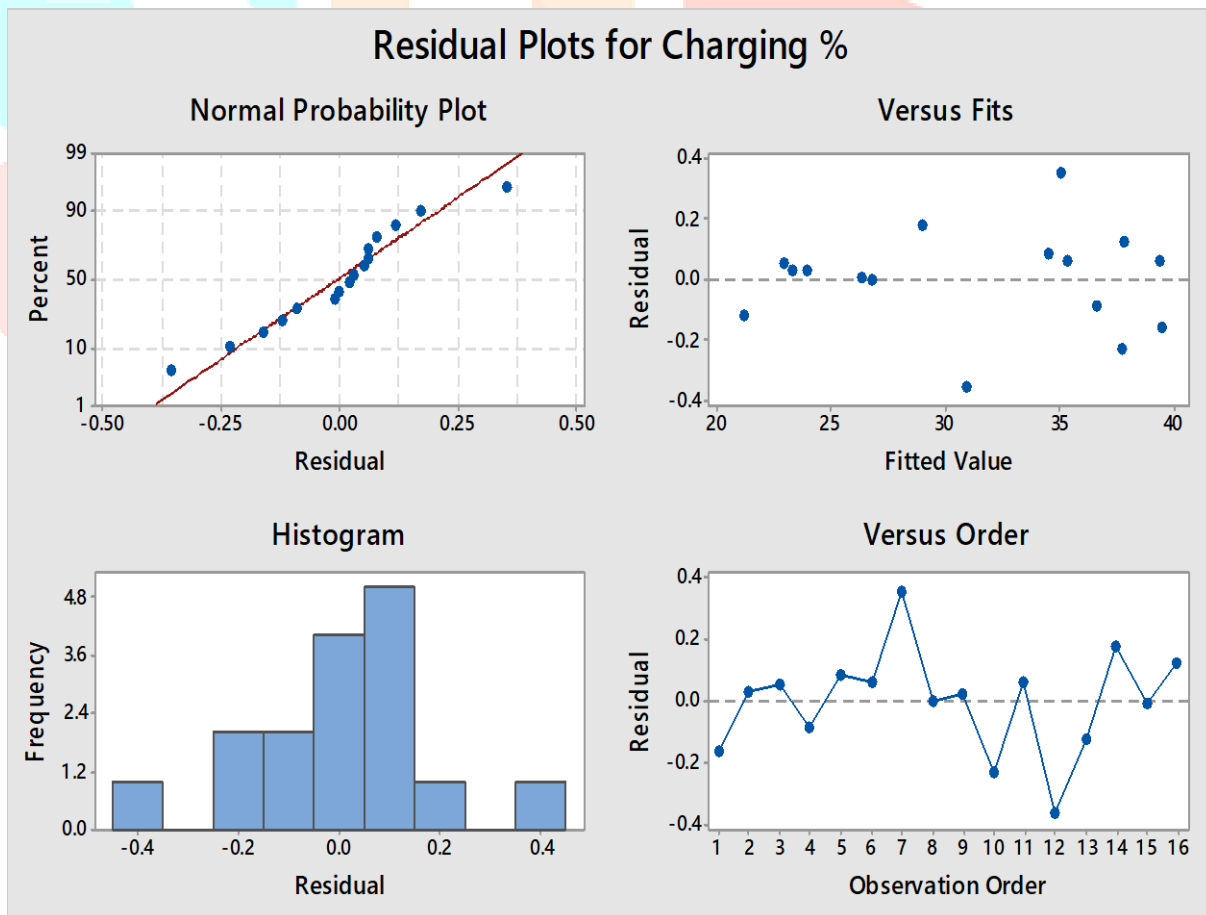


Fig. 7:Residual plots for charging ANOVA analysis

**Model Summary**

| S        | R-sq   | R-sq(adj) | PRESS   | R-sq(pred) |
|----------|--------|-----------|---------|------------|
| 0.289323 | 99.93% | 99.80%    | 5.41375 | 99.14%     |

**Regression Equation**

$$\begin{aligned} \text{Charging \%} = & 775.7 - 1490.3 \text{ MFR} - 2.3253 \text{ In\_Temp} - 8.651 \text{ PCM} - 129.88 \text{ Design} - 547.9 \text{ MFR} * \text{MFR} \\ & + 2.104 \text{ PCM} * \text{PCM} + 1.3125 \text{ Design} * \text{Design} + 5.467 \text{ MFR} * \text{In\_Temp} - 27.064 \text{ MFR} * \text{Design} \\ & + 0.3917 \text{ In\_Temp} * \text{Design} \end{aligned}$$

Present research work is complete for PCM role in heat transfer analysis used in shell and tube heat exchanger. Design of experiment technique Taguchi is used for present research work and analysis of variance is also performed for model equation generation. Table 3 represent the best case for parameter which affect the thermal performance mostly.

Table 3 Rank of factors using S/N ratio analysis for charging

| Level | MFR   | In_Temp | PCM   | Design |
|-------|-------|---------|-------|--------|
| 1     | 29.50 | 29.13   | 31.60 | 30.49  |
| 2     | 30.54 | 30.09   | 29.16 | 28.36  |
| 3     | 29.90 | 29.45   | 28.09 | 30.28  |
| 4     | 28.98 | 30.25   | 30.06 | 29.78  |
| Delta | 1.56  | 1.12    | 3.51  | 2.12   |
| Rank  | 3     | 4       | 1     | 2      |

Table 4 Best cases for case study for charging of PCM

|       | MFR | In_Temp | PCM | Design |
|-------|-----|---------|-----|--------|
| Value | 0.2 | 350     | 1   | 1      |
|       | MFR | In_Temp | PCM | Design |
| Value | 0.2 | 330     | 1   | 1      |

**REFERENCES**

Agarwal, A., & Sarviya, R. M. (2016). An experimental investigation of shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material. *Engineering Science and Technology, an International Journal*, 19(1), 619-631.

Wang, C., Lin, T., Li, N., & Zheng, H. (2016). Heat transfer enhancement of phase change composite material: Copper foam/paraffin. *Renewable Energy*, 96, 960-965.

Englmair, G., Dannemand, M., Johansen, J. B., Kong, W., Dragsted, J., Furbo, S., & Fan, J. (2016). Testing of PCM heat storage modules with solar collectors as heat source. *Energy Procedia*, 91, 138-144.

- Eslamnezhad, H., & Rahimi, A. B. (2017). Enhance heat transfer for phase-change materials in triplex tube heat exchanger with selected arrangements of fins. *Applied Thermal Engineering*, 113, 813-821.
- Pointner, H., Steinmann, W. D., & Eck, M. (2014). Introduction of the PCM flux concept for latent heat storage. *Energy Procedia*, 57, 643-652.
- Johansen, J. B., Englmair, G., Dannemand, M., Kong, W., Fan, J., Dragsted, J., ... & Furbo, S. (2016). Laboratory testing of solar combi system with compact long term PCM heat storage. *Energy Procedia*, 91, 330-337.
- Gasia, J., Diriken, J., Bourke, M., Van Bael, J., & Cabeza, L. F. (2017). Comparative study of the thermal performance of four different shell-and-tube heat exchangers used as latent heat thermal energy storage systems. *Renewable Energy*, 114, 934-944.
- Fan, J., Furbo, S., Andersen, E., Chen, Z., Perers, B., & Dannemand, M. (2012). Thermal behavior of a heat exchanger module for seasonal heat storage. *Energy Procedia*, 30, 244-254.
- Esapour, M., Hosseini, M. J., Ranjbar, A. A., Pahamli, Y., & Bahrampoury, R. (2016). Phase change in multi-tube heat exchangers. *Renewable Energy*, 85, 1017-1025.
- Faghani, M., Hosseini, M. J., & Bahrampoury, R. (2017). Numerical simulation of melting between two elliptical cylinders. *Alexandria Engineering Journal*.
- Saeedinia, M., Akhavan-Behabadi, M. A., & Nasr, M. (2012). Experimental study on heat transfer and pressure drop of nanofluid flow in a horizontal coiled wire inserted tube under constant heat flux. *Experimental Thermal and Fluid Science*, 36, 158-168.
- Joybari, M. M., Haghighat, F., & Seddegh, S. (2017). Numerical investigation of a triplex tube heat exchanger with phase change material: Simultaneous charging and discharging. *Energy and Buildings*, 139, 426-438.
- Ibrahim, N. I., Al-Sulaiman, F. A., Rahman, S., Yilbas, B. S., & Sahin, A. Z. (2017). Heat transfer enhancement of phase change materials for thermal energy storage applications: A critical review. *Renewable and Sustainable Energy Reviews*, 74, 26-50.
- Pop, O., Tutunaru, L. F., & Balan, M. (2017). Numerical model for solidification and melting of PCM encapsulated in spherical shells. *Energy Procedia*, 112, 336-343.
- Doladoa, P., Lazaro, A., Delgado, M., Peñalosa, C., Mazo, J., Marin, J. M., & Zalba, B. (2012). Thermal energy storage by PCM-air heat exchangers: temperature maintenance in a room. *Energy Procedia*, 30, 225-234.
- Omojaro, P., & Breitskopf, C. (2014). Investigating and modeling of simultaneous charging and discharging of a PCM heat exchanger. *Energy Procedia*, 48, 413-422.
- Kasibhatla, R. R., König-Haagen, A., & Brüggemann, D. (2016). Numerical modelling of wetting phenomena during melting of PCM. *Procedia Engineering*, 157, 139-147.
- Narayanan, S. S., Kardam, A., Kumar, V., Bhardwaj, N., Madhwal, D., Shukla, P., ... & Jain, V. K. (2017). Development of sunlight-driven eutectic phase change material nanocomposite for applications in solar water heating. *Resource-Efficient Technologies*.
- Oni, T. O., & Paul, M. C. (2016). Numerical investigation of heat transfer and fluid flow of water through a circular tube induced with divers' tape inserts. *Applied Thermal Engineering*, 98, 157-168.
- Dermardiros, V., Chen, Y., & Athienitis, A. K. (2015). Modelling of an active PCM thermal energy storage for control applications. *Energy Procedia*, 78, 1690-1695.