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EXPERIMENTAL AND COMPUTATIONAL ANALYSIS OF HEAT EXCHANGERS USING PCM

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Abstract:

This study presents a computational Analysis of triple-pipe heat exchangers integrated with Phase Change Materials (PCMs) to improve the thermal performance. Experimental studies are conducted on a double-pipe heat exchanger to evaluate inlet and outlet fluid temperatures, overall heat transfer rates, and thermal effectiveness under various operating conditions. For the triple-pipe heat exchanger, ANSYS fluent simulations are carried out to analyze the thermal behavior with different PCMs during melting and solidification cycles. A MATLAB-based numerical model, developed using the finite difference method and enthalpy approach, is used to validate the simulation results. The numerical and simulation results show good agreement, confirming the reliability of the computational model. The incorporation of PCMs enhances the thermal storage capacity and improves the overall effectiveness of the heat exchanger. This integrated experimental, numerical, and simulation approach provides a comprehensive basis for optimizing PCM selection and design parameters in advanced heat exchanger systems.

Key words: Phase change materials (PCMs), Heat exchangers, Effectiveness, Ansys Fluent, MATLAB.

1. Introduction

In the recent years, Heat exchangers play a important role in thermal energy management across industrial, HVAC, and renewable energy systems. Incorporating the phase change materials (PCMs) into heat exchangers enables high latent heat storage capacity and enhanced the temperature regulation, improving the energy efficiency and operational stability of the heat exchangers. Among the available designs, triple-pipe heat exchangers offer an increased heat transfer area and improved flow flexibility compared to conventional double-pipe or shell-and-tube designs, making them well-suited for the PCM integration. Ashok kumar v et al. [1] Evaluated the design and analysis of a vertical shell-and-tube thermal energy storage system (TESS) using water as the heat transfer fluid and paraffin wax RT58 as the phase change material (PCM) operating temperature between 60 °C and 80 °C. Experimental tests and ANSYS Fluent simulations during the charging and discharging performance of heat exchangers, showing the heat storage of 302.3 kJ over 100 min during charging and 295.8 kJ over 56 min during discharging with calculated heat transfer coefficients and Nusselt numbers. The results confirm the PCM-based TESS as an efficient solar energy storage method, with potential for further improvement using the composite PCMs, nanomaterial additives, finned tubes, and enhanced insulation. Badal kudachi et al. [2] Investigated, a shell-and-tube heat exchanger with thermal energy storage containing an organic PCM mixture. The phase change temperatures are 58-65 °C. The operating range is between 60–70 °C. This was tested for its heat storage capability. Experimental investigation of charging and discharging cycles, supported by the ANSYS Fluent simulations of the PCM melting characteristics, revealed that the PCM stored 458.23 kJ of heat over 100 minutes during charging and released 316.01 kJ over 50 minutes during discharging. These results demonstrate that the stored heat energy in the system can be effectively extracted and applied to processes operating at moderately high temperatures. Abdulhamit erdogan et al. [3] Measured the melting of a phase change material (PCM) in a U-tube heat exchanger using the experimental and the numerical methods. Hot water at 60 °C and 1.75 L/min was circulated, and phase change effects were modelled to track the melting percentages over the time. Complete melting occurred after the 3800 min of time, with the slowest melting in regions and farthest from the center. Experimental and numerical results were gone through closely, with an error of 4%. M. Araiz et al. [4] Analyzed the wickless thermosyphon heat exchanger with phase change for the cold side, offering a high heat-transfer rates without the moving parts or auxiliary power. A computational model was developed and validated with a prototype, predicting thermal resistance with less than 8% of error in most cases. Using thermosyphons on the cold side improved the net thermoelectric output by the 36% compared to the conventional finned dissipators under the forced convection. Ammar m et al. [5] Investigated the horizontal triplex tube heat exchanger (TTHX) with internal longitudinal fins. Incorporating a PCM melting at 78–82 °C. Complete melting was achieved faster at 90 °C with both-sides heating than with inside heating at 97 °C, and a mass flow rate of 29.4 kg/min produced quicker melting than other flow rates. Numerical analysis of the longitudinal and triangular fins showed energy storage enhancements of 11%, 12%, and 15% for internal, internal–external, and external triangular fins, respectively, with the external triangular finned tube melting PCM in 193 min of time. Simulations closely matched the experimental results. Maria K et al. [6] Investigated the operation of a Latent Heat Thermal Energy Storage (LHTES) system using a staggered heat exchanger and various organic PCMs with the melting temperatures of 40–53 °C. Experimental tests measured energy storage and release at the different heat transfer fluid (HTF) flow rates. while the CFD simulations modelled melting and solidification, showing that the buoyancy-driven convection significantly reduced the melting time compared to the pure conduction. Gabriele

Triscari [7] Analyses the Two heat exchanger designs with the radial and the longitudinal fins were evaluated in simplified FEM model validated against the laboratory tests. Results showed that the longitudinal fins provide the most efficient design, reducing steel usage by 215 kg while optimizing the thermal performance. M J Hosseini et al. [8] Investigated the experiments and numerical simulations to observe the thermal behavior and heat transfer of Paraffin RT50 PCM during melting and solidification in a shell-and-tube heat exchanger. Results show that raising the HTF temperature increases charging efficiency and discharging efficiency. M J Hosseini et al. [9] Investigated the effect of increasing heat transfer fluid inlet temperature on the melting process, while simulations used a finite-volume enthalpy-based model. Results show that the melting front progresses outward from the HTF tube at different rates, and increasing the HTF temperature to 80 °C reduces the total melting time by 37%. Nabeel S. Dhaidan et al. [10] Investigated the PCM melting in finned and unfinned horizontal concentric double-pipe heat exchangers. Results show that finned heat exchangers outperform unfinned ones, with perforated fins achieving the best performance. Annabelle joulin [11] Analyzed the numerical predictions were obtained with a custom one-dimensional Fortran code and a two-dimensional use of Fluent. Both methods showed a very good agreement with experimental observations for the melting process (65%). However, during solidification, both numerical codes failed to predict the phase change process accurately, the maximal relative error was as high as 57% (with an average of 8%).

2.Experimentation

The double pipe heat exchanger is made up of stainless steel (grade-304). The experimental was conducted on a heat exchanger with a total length of 1.2 m. The inner pipe had an inner diameter of 0.026 m and an outer diameter of 0.034 m, while the outer pipe had an inner diameter of 0.066 m and an outer diameter of 0.074 m. The hot fluid (water) flowed through the inner pipe, and the cold fluid (water) flowed through the annulus. Both fluids operated under Steady flow conditions.

Fig.2.1 Experimental Prototype

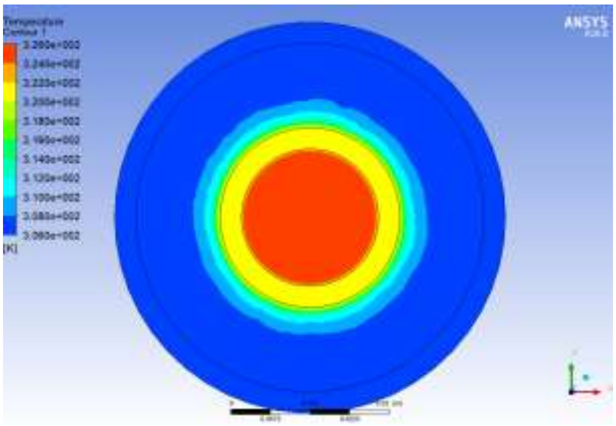

Fig 2.2 Hot inlet and Cold outlet

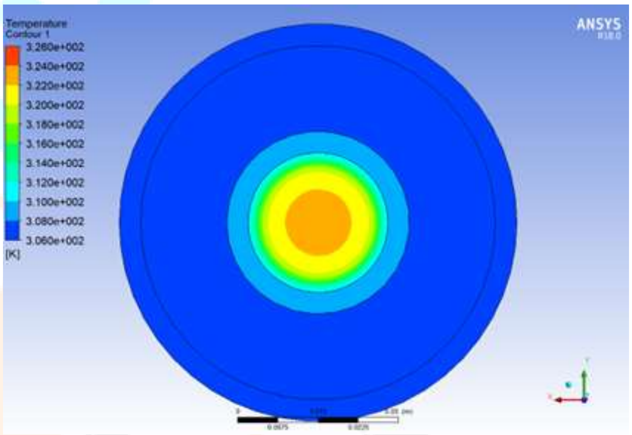

Fig.2.3 Hot outlet and Cold inlet

Formulae

$$\varepsilon = \frac{(\text{Actual heat transfer rate})}{(\text{Maximum possible heat transfer rate})}$$

$$\varepsilon = \frac{\dot{m}h \times cph \times (Th,in - Th,out)}{Cmin \times (Th,in - Tc,in)}$$

For each run, the flow rates were set and allowed to stabilize. Steady-state inlet and outlet temperatures of double pipe heat exchanger were recorded. The experimental effectiveness of the exchanger was determined using the NTU–effectiveness approach. The maximum effectiveness achieved was 30%, which was compared with the ANSYS Fluent simulation result of 31.5%, showing good agreement and validating the numerical model.

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3.Ansys Fluent Design

A triple-pipe heat exchanger was designed by modifying an existing double-pipe heat exchanger design. The geometric parameters used for the double-pipe heat exchanger configuration were retained to ensure comparability. An intermediate pipe was inserted between the inner pipe and the outer pipe, creating an additional annular region suitable for thermal energy storage. This modification enabled the integration of phase change materials (PCMs) into the heat exchangers, enhancing its heat storage and release capability. Three different PCMs with different thermo-physical properties were employed in three separate design cases to evaluate their effect on system performance.

The three simulation models were designed with different models.

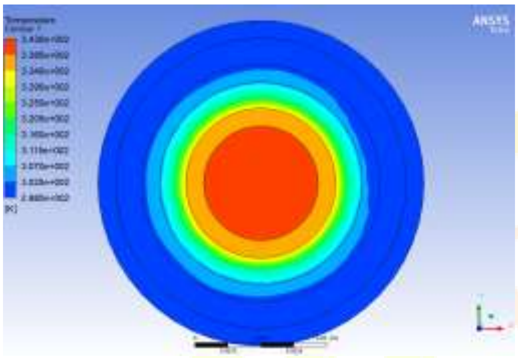

Figure 3.1 Model-1 Salt Hydrates, hot inlet and cold outlet

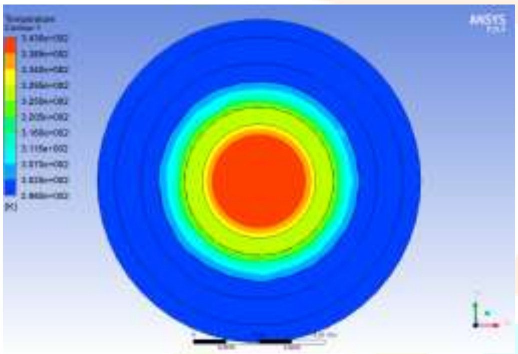

Fig.3.2 Salt Hydrates, hot outlet and cold inlet

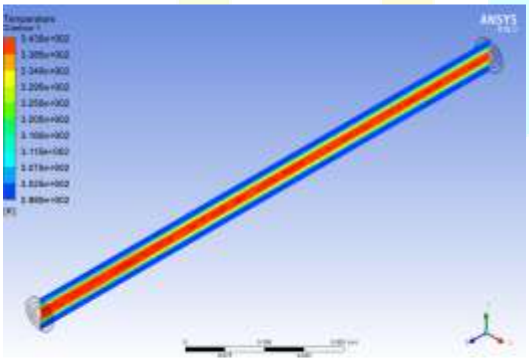

Fig. 3.3, plane along YZ axis

Model 1: A triple-pipe heat exchanger inserted with salt hydrate PCM

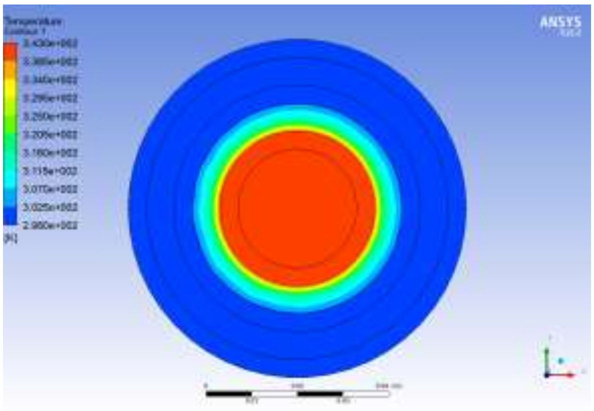

Fig.3.4, Model-2, fatty acid, hot inlet and cold outlet

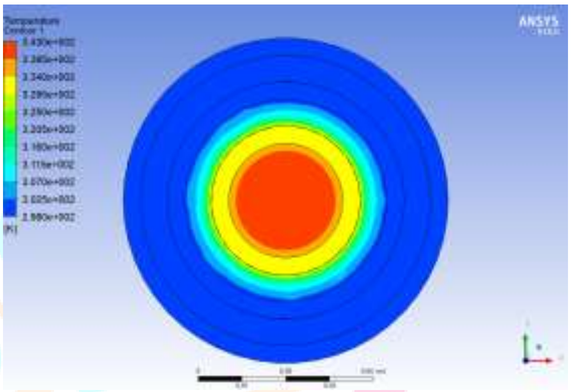

Fig.3.5 fatty acids, hot outlet and cold inlet

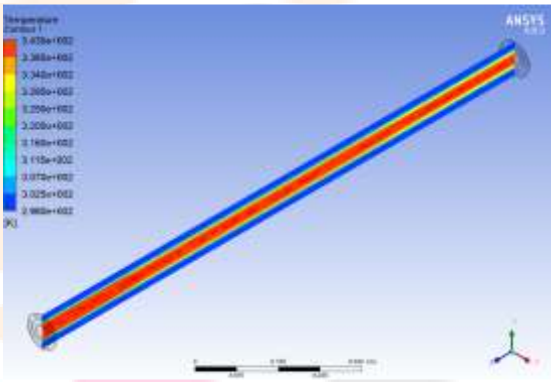

Fig.3.6, Plane along YZ Axis

Model-2: A triple-pipe heat exchanger inserted with fatty acids (lauric acid)

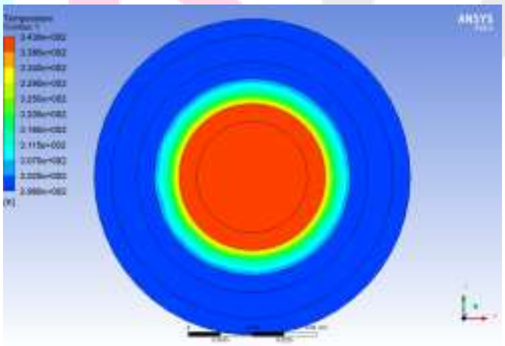

Fig.3.7, Model-3, Paraffin wax, hot inlet and cold outlet

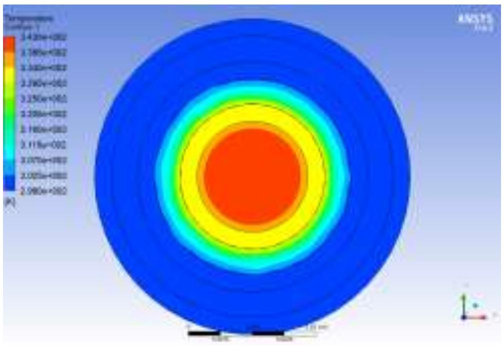

Fig3.8, Paraffin wax, hot outlet and cold inlet

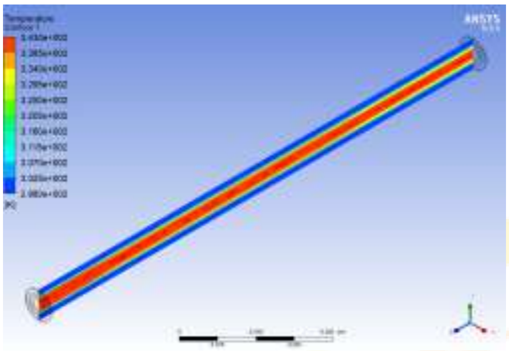

Fig.3.8, Plane along YZ axis

Model-3: A triple-pipe heat exchanger inserted with paraffin wax PCM.

The PCMs were stationary, a fixed PCM configurations commonly used in practical heat storage applications. The simulations were performed using ANSYS Fluent. The Flow Condition is transient to capture the dynamic thermal response of the system. The Flow was Laminar for the working fluids. The melting and solidification in simulation to analyze the heat storage capacity of PCMs

MATLAB-NUMERICAL MODEL

A MATLAB-based computational framework was introduced to calculate the effectiveness of a triple-pipe heat exchanger integrated with phase change materials (PCMs). In MATLAB, the PCM energy balance was computed using the heat gain from the hot fluid and the heat loss to the cold fluid. Depending on the total energy stored, the overall effectiveness was finally calculated. This MATLAB-based implementation provided a structured environment for automated effectiveness evaluation from large CFD datasets, ensuring accurate, repeatable, and time-efficient assessment of triple-pipe heat exchanger performance.

4.Results

Type of heat exchanger	Effectiveness
Triple-pipe heat exchanger with salt hydrate PCM.	0.404
Triple-pipe heat exchanger with fatty acid PCM	0.377
Triple-pipe heat exchanger with paraffin wax PCM	0.338

Table-1, Results of Effectiveness

Efficiency= Effectiveness×100.

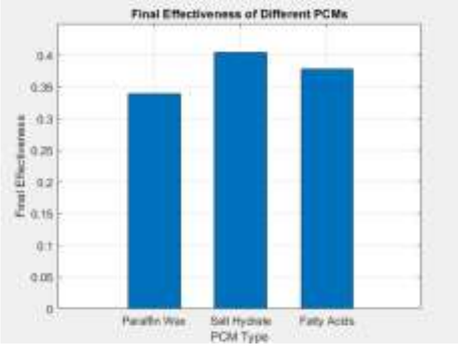

Fig.4.1, Effectiveness graph

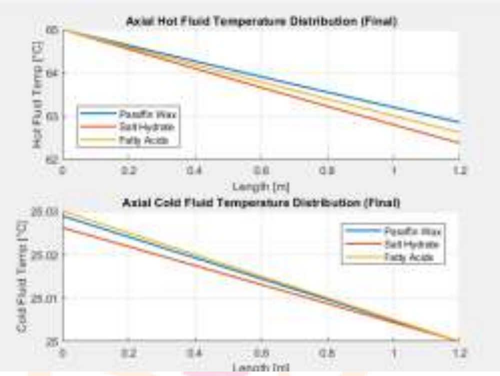

Fig 4.2, Hot vs Cold Temperature Distribution

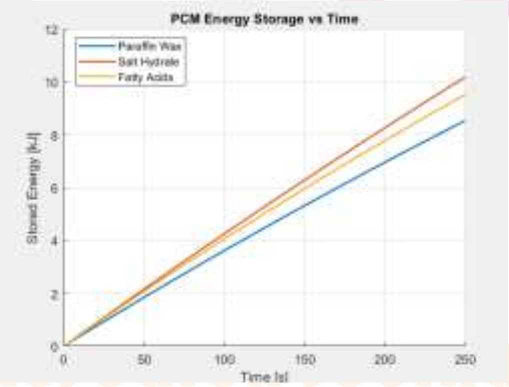

Fig 4.3, PCM Energy Storage vs Time

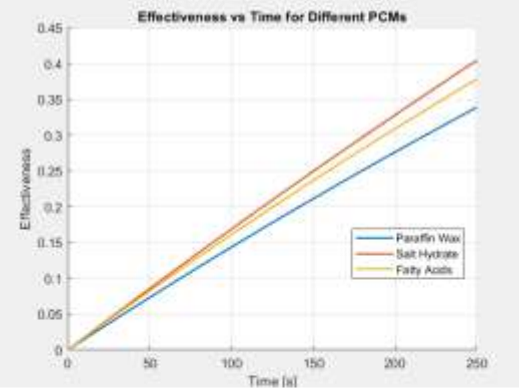

Fig 4.4, Effectiveness vs Time

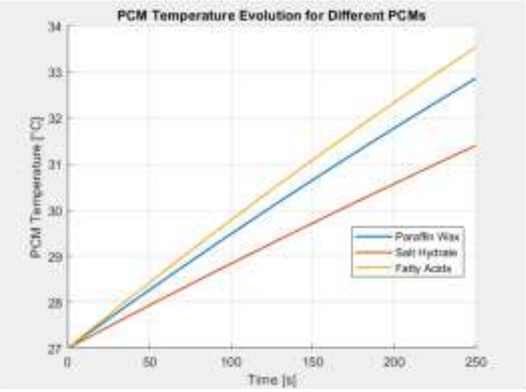

Fig 4.5, PCM Temperature Evolution for Different PCMs

The performance of the triple-pipe heat exchanger was assessed using three different phase change materials. The PCMs are salt hydrates, fatty acids, and paraffin wax. By the identical operating and boundary conditions, the calculated effectiveness values were 40.4% for salt hydrates, 37.7% for fatty acids, and 33.8% for paraffin wax. The results clearly shows that salt hydrates provide high thermal performance compared to the other PCMs due to their higher latent heat and better thermal conductivity. This determines that the selection of PCM. has a significant impact on the transient energy storage capability of triple-pipe heat exchangers.

5.Conclusion

This study presented the development and the evaluation of a triple-pipe heat exchanger integrated with different phase change materials (PCMs) under transient conditions and laminar flow. The design parameters which are used for conventional double-pipe exchanger were retained, with the addition of an intermediate pipe to incorporate with multiple PCMs. The simulations with melting and solidification enabled were performed, and the effectiveness was calculated using a MATLAB-ANN framework. Among the PCMs studied, salt hydrates achieved the highest effectiveness of (40.4%), followed by fatty acids with (37.7%) and paraffin wax with (33.8%). These results highlight the significant influence of PCM selection on the thermal performance. The integration of salt hydrates provided the higher energy storage. Demonstrated that the proper PCM selection can substantially improve the effectiveness and the thermal regulation capability of triple-pipe heat exchangers.

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