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Optimisation of Counterflow Heat Exchanger Using Box Behnken Design

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Abstract- This study focuses on the optimization of counter flow heat exchangers using the Box-Behnken design (BBD), a response surface methodology (RSM) approach for experimental design. Counter flow heat exchangers are widely utilized in various industrial processes due to their high efficiency in thermal energy transfer. However, optimizing their performance involves multiple parameters, including fluid flow rates, temperature differences, and heat transfer coefficients. The Box-Behnken design offers a systematic and efficient way to explore the effects of these variables and their interactions on the performance of heat exchangers. Our study shows higher value of effectiveness of counter flow heat exchanger as compared to the study of Sridharan (2021) and Patel and Singh, (2023). The application of RSM based BBD method improves the effectiveness of counter flow heat exchanger.

Keywords- Optimisation, counterflow heat exchanger, box Behnken design

I. INTRODUCTION

Thermal power stations, chemical processing plants, air conditioning equipment, freezers, petrochemical, biomedical, and food processing facilities are only some of the many current uses for heat exchangers with twisted-tape inserts, which promote convective heat transmission.

As the twisted tape insert adds swirl to the bulk flow, it causes the thermal boundary layer on the tube's surface to separate.

The thermal performance of heat exchangers can be enhanced by the application of heat transfer improvement methods.

Tape inserts are a common passive heat transfer augmentation method used in many settings. These include air conditioning and refrigeration systems as well as the food processing sector.

Improving the thermal performance of a heat exchange might lead to immediate savings in energy, materials, and finances.

Therefore, improving heat exchange efficiency can have a significant influence on thermal efficiency and cost-effectiveness in systems that use heat transfer processes in their design and operation [1].
The most common applications for DPHEs are in high-temperature and high-pressure environments because of their small size. They're cheap, but compared to the alternatives, they take up a lot of room.

It is possible to achieve the desired heat transfer rate within the limits of the heat exchanger's design and length with a minimum amount of pumping power by employing one of many strategies. Active and passive augmentation techniques were distinguished [2, 3].

Because of their effectiveness, low cost, and ease of installation, twisted-tape inserts have been increasingly popular in recent years to promote convective heat transmission. Because it creates a whirling motion that improves fluid mixing and guarantees a steady, uniform bulk flow. The pressure drop is negligible, the cost is low, and there are hardly any fouling difficulties.

The thermal performance of heat exchangers has been greatly improved by optimizing heat transfer surfaces in a variety of ways, but this improvement has come at a cost: higher pressure drops associated with these optimizations necessitate more powerful recycling fluid pumps to maintain flow.

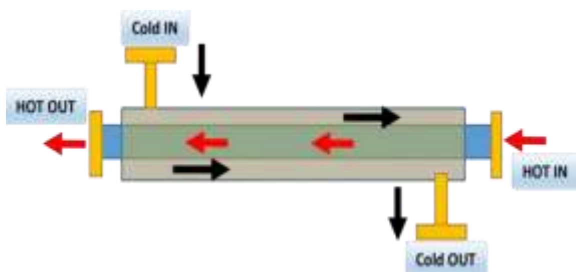


Fig. 1: Double pipe heat exchanger

II. RESEARCH METHODOLOGY

1. Model

The schematic drawing of the present study is shown in Fig. 2. Hot water enters at 65oC and cold water enters at 32oC in counter flow heat exchanger. The material of core tube is copper of length 0.89 m. The diameter in inner pipe is 0.0127 m and diameter of outer pipe is 0.0254 m. The mass flow rate of hot and cold fluid was varied from 1 to 4 kg/min (Sridharan, 2021). Further, mass flow rate of hot and cold fluid was optimised. The output parameter was measured in terms of outlet temperature for hot and cold fluid and effectiveness of counter flow heat exchanger by Response surface methodology (RSM).

Fig. 2: Schematic model

2. Governing Equation

The steady-state fluid flow characteristic in the three-dimensional computational domain can be described using the following governing incompressible fluid flow equations.

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0$$

Momentum balance without gravity force:

$$\rho_{u_i} \frac{\partial u_i}{\partial x_i} = - \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

Energy equation:

$$\rho C_p \frac{\partial (u_i T)}{\partial x_i} = \frac{\partial}{\partial x}\left(\lambda_{eff} \frac{\partial T}{\partial x_i}\right)$$

In conservative form, the partial differential equations for the RNG $k-\varepsilon$ model are Turbulent kinetic equation:

$$\rho u_j \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\mu_{eff} \alpha_k \frac{\partial k}{\partial x_j}\right] + \tau_{ij} \frac{\partial u_i}{\partial x_j} - \rho\varepsilon + G_K + \mathrm{G_b}$$

Turbulent kinetic dissipation equation

$$\rho u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\mu_{eff} \alpha_\varepsilon \frac{\partial \epsilon}{\partial x_j}\right] + C_{1\varepsilon} \frac{\partial \varepsilon}{\partial x_j} + C_{1\varepsilon} \frac{\varepsilon}{K}(G_K + C_{3\varepsilon}\mathrm{G_b}) - C_{2\varepsilon}\rho \frac{\varepsilon^2}{K}$$

The above Reynolds Averaged Navier-Stokes (RANS) turbulence models offer the most economic approach for computing complex turbulent industrial flows.

Generally, the Navier-Stokes equations describe the motion of the turbulent flow. However, it is too costly and time-consuming to solve these equations for complex flow problems [26]. Alternatively, two methods have been suggested in the past: (i) Large Eddy Simulation (LES) where the large energy containing eddies are simulated directly while the small eddies are accounted for by averaging. The separation of large and small eddies requires following, (ii) Reynolds averaging (RANS) where all eddies are accounted for by Reynolds stresses obtained by averaging the Navier-Stokes equations (time averaging for statistically steady flows, ensemble averaging for unsteady flows).

3. Boundary Conditions

In the present investigation, the commercial CFD software FLUENT 6.3, which is based on the finite volume method, is used for the numerical computation, and the SIMPLE algorithm is used for finding a solution for the coupling between the pressure and velocity. The finite-element model is built and meshed using the software Gambit, and unstructured grids are used. The tetrahedral grid is used for meshing the models, and the grid in the region near the tube wall, which is highly refined, is considered as the boundary layer. Hot water enters at 65oC and cold water enters at 32oC in counter flow heat exchanger. The material of core tube is copper of length 0.89 m. The diameter in inner pipe is 0.0127 m and diameter of outer pipe is 0.0254 m. The mass flow rate of hot and cold fluid was varied from 1 to 4 kg/min (Sridharan, 2021). No slip conditions are imposed on the tube wall and the surfaces of the twisted tape. The convergence criterion is that all the norms of the residuals for the continuity, momentum, and energy equations should be less than 10-6.

4. Meshing Of Domain

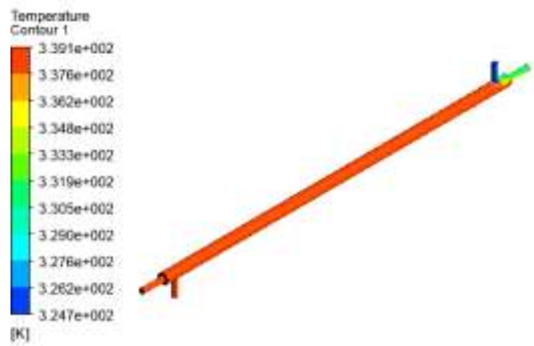
In this study, a general curve linear coordinate grid generation system based on body–fitted coordinates was used to discrete the computational domain into a finite number of control volumes. The geometries of the problems are carefully constructed. All cases were modelled and meshed with the ANSYS 16. FLUENT also comes with the CFD program that allows the user to exercise the complete flexibility to accommodate the compatible complex geometries. The refinement and generation of the grid system is important to predict the heat transfer in complex geometries. In other words, density and distribution of the grid lines play a pivotal role to generate accuracy. Due to the strong interaction of mean flow and turbulence, the numerical results for turbulent flows tend to be more dependent on grid optimisation than those for laminar flows [11].

Fig. 3: Mesh model

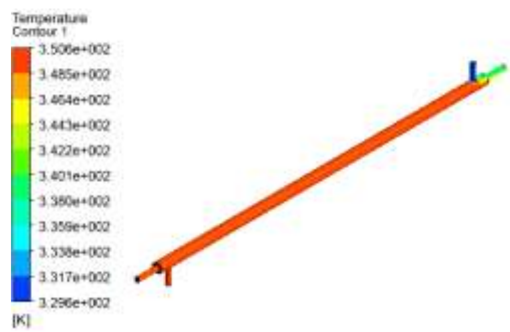
III. RESULTS AND DISCUSSION

1. Contour Plots

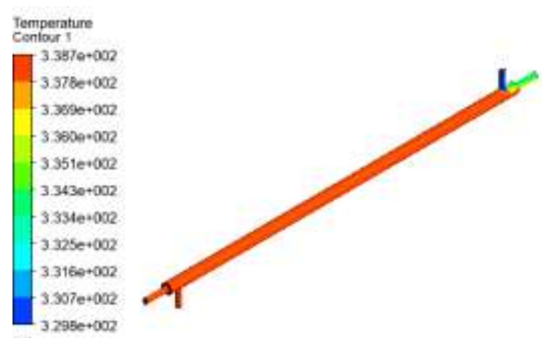
CFD simulation has been done based on the range of flow rate of hot and cold fluid. Some of the contour plot of temperature is shown below.



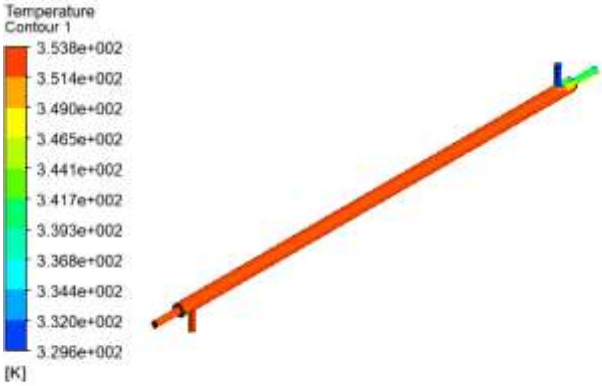
Simulation 1



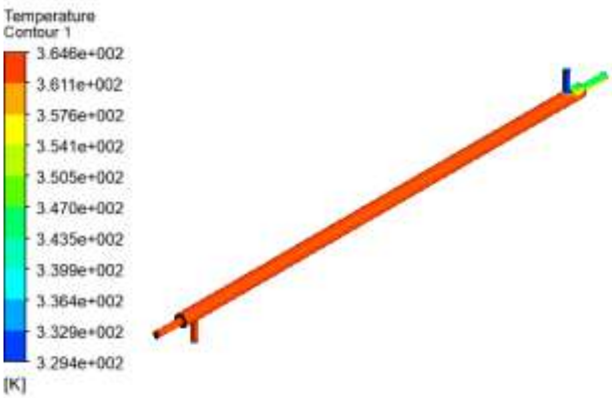
Simulation 3



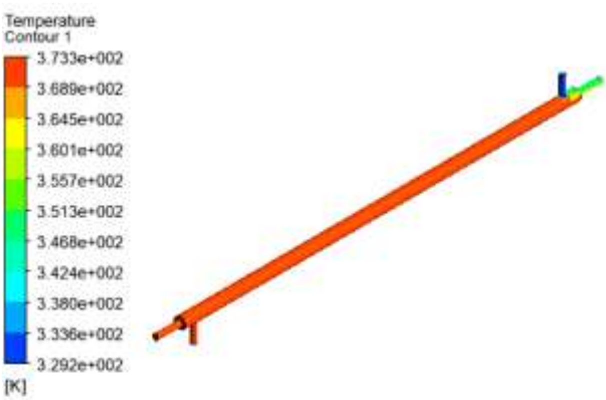
Simulation 6



Simulation 8



Simulation 10



Simulation 12

Fig. 4: Contour plot of temperature

Optimization by RSM Method

Following the mathematical modeling and statistical analysis of the performance indices, a multi-objective optimization has been performed. The quality characteristics, used for the optimization modeling is the transmission losses and this work has been performed by the desirability approach.

Desirability is as an objective function, D, introduced by Myers and Montgomery and its desirable value (di) ranges from 0 to 1, least to most desirable, respectively.

The function searches a point in the specified design space within the constrained levels of factor settings and according to weights and importance (ri) that exaggerates the function value, where di = 1 is the target value, by sufficing all the goals those are addressed. During the optimization process, the aim was to achieve the optimum levels of factor settings which yield the maximum transmission loses. Combination of one or more goals which may apply to either factors or responses is optimized by numerical optimization. The possible goals are: maximize, minimize, target, within range, none (for responses only) and set to an exact value (for factors only).

$$D = (d_1 \times d_2 \times \cdots \times d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}}$$

$$D = (d_1^{r_1} \times d_2^{r_2} \times \cdots \times d_n^{r_n})^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i^{r_i}\right)^{\frac{1}{\sum r_i}}$$

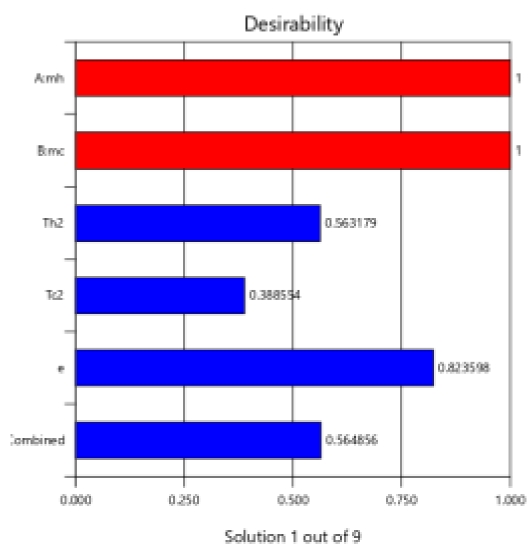


Fig. 5: Desirability plot

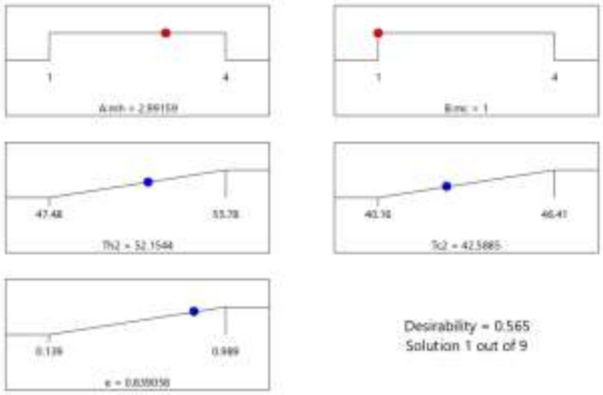


Fig. 6: Optimum parameter plot

Table 1: Results validation

Parameter	Present study	Sridharan, 2021	Patel and Singh, 2023
Th2	52.15	40	50.27
Tc2	42.58	45	40.65
ε	0.839	0.58	0.753

Our study shows higher value of effectiveness of counterflow heat exchanger as compared to the study of Sridharan (2021) and Patel and Singh, (2023).

IV. CONCLUSION

Our study shows higher value of effectiveness of counterflow heat exchanger as compared to the study of Sridharan (2021) and Patel and Singh, (2023). The application of RSM based BBD method improves the effectiveness of counterflow heat exchanger. Best result is achieved from applying of RSM based BBD method. The Box-Behnken design stands out as a powerful tool for optimizing counterflow heat exchangers, contributing to advancements in thermal management and energy efficiency in industrial applications. Future research should continue to refine this approach, addressing its limitations and expanding its applicability to a wider range of heat exchanger configurations and operating conditions.

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