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APPLICATION OF ADVANCED THERMODYNAMIC METHODS FOR OPTIMIZING THERMAL SYSTEMS

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Abstract

This study serves as an example of an effort to raise the effectiveness of a shell-and-tube heat exchanger. A device that transfers heat from a single fluid into another is one definition of a heat exchanger. Heat exchangers come in a variety of forms, but those with shells and tubes are some of the most adaptable and widely utilised. This project optimises the structural and CFD components while also taking the entire yearly operating cost into account. As a result, research has been done to establish the ideal heat exchanger size in relation to a certain set of input characteristics and the required outputs at the outlet. Three phases of optimisation were used for the heat exchanger: (1) a mathematical model-based thermal study; (2) ANSYS nozzle optimisation with structural loads; and (3) ANSYS CFD analysis. Every technique made use of the ANSYS software. Due to the fact that each of the the necessary variables have been obtained from recognised standards and guidelines in the industry, the optimisation issue has now taken on a more realistic form.

Keywords:shell-and-tube heat exchanger,CFD elements,ANSYS nozzle optimization.

Introduction

The typical heat exchanger is an example of what is known as an indirect form of recuperative heat exchanger [4]. This type of heat exchanger involves the cold stream recovering heat from the hot stream via the use of a dividing wall. It is referred to as a direct contact type heat exchanger when heat is transferred between two fluids of different temperatures by means of the fluids' direct contact with one another. However, in storage-type or regenerator heat exchangers, the same section of the heat exchanger device comes into contact alternately with hot and cold stream of the working fluids, and the cold stream gets the heat from the heat dumped in the heat exchanger structure by the hot stream. In other words, the cold stream receives the heat from the heat dumped in the heat exchanger structure by the hot stream. Heat exchangers of the storage type find use in a variety of contexts, including the preheating of air in chemical manufacturing facilities, coal-fired steam plants, and gas turbine power plants. In heat exchangers of the direct contact kind, cold fluids and hot fluids come into direct touch with one another without a separating wall in order to facilitate the transfer of heat from one to the other. The most prominent instances of the direct contact kind of heat exchanger are found in thermal power plants, namely in the form of cooling towers and deaerators. In heat exchangers of the indirect contact type, heat is transferred from a hot fluid to a cold fluid by passing through a wall that separates the two working fluids and is shared by both. Exceptional cases of indirect contact heat are the air preheaters, super heaters, desuper heaters, evaporators, and condensers exchangers. The indirect contact heat exchangers may be further subdivided into many categories based on their structure, including the twin pipe heat exchanger, the shell and tube heat exchanger (STHE), and the spiral tube type heat exchanger.

The relative mobility of the fluids contained inside the HEs is another criterion that is used to classify the HEs. When the working fluids enter at one end, move in the same direction, and flow out together at the other end, this sort of HE is referred to as a parallel flow type HE. Fig. 1 (a) On the other hand, heat exchangers are said to be of the counter flow type when both fluids enter the device at separate ends and move in the opposite direction.

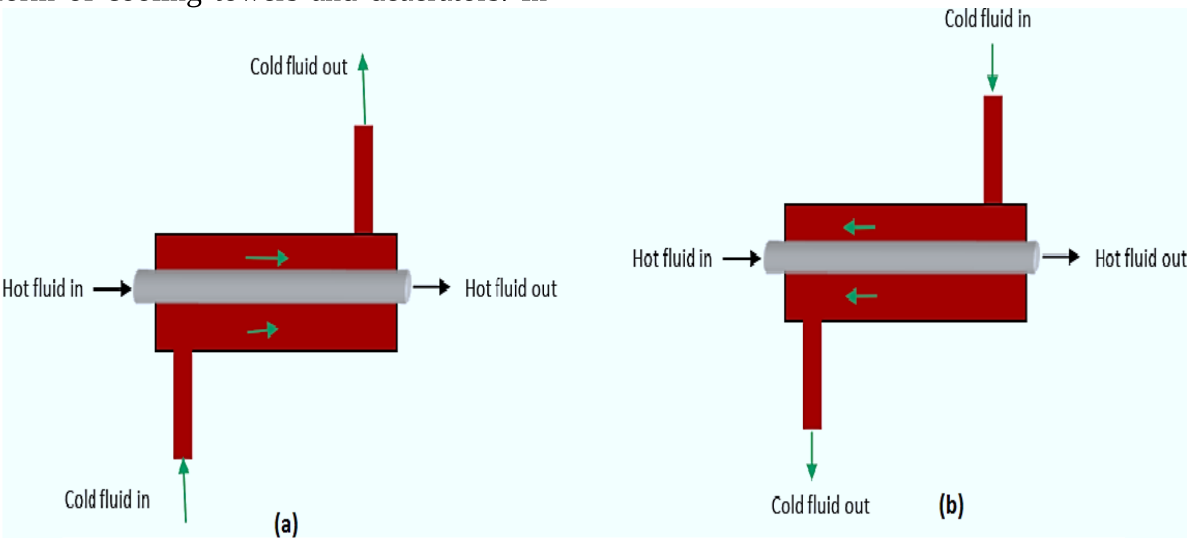


Figure 1. Concentric tube heat exchangers (*a*) Parallel flow (*b*) Counter flow

Fig. 1 The gradients for temperature values along the fluid flow in parallel-flow and counter-flow HEs are represented in Fig. 2 and Fig. 3, respectively, where T is the the temperature, Th is the temperature of hot fluid, Tc is the temperature of cold fluid, k is the thermal conductivity, and Q is the quantity of heat transfer. When one fluid flows through the surface that transfers heat at an angle equal opposite the flow vector of the other fluid, a phenomenon known as cross flow heat exchange (HE) takes place. As a result, there are a plethora of different sorts of HEs that may be used by businesses in accordance with the requirements of their processes [5].

At the beginning of this decade, the double-pipe heat exchanger (HE) may be utilized in parallel and series configurations for the purpose of achieving the pressure dip and a superior mean temperature gradient with a smaller HE surface area. These kinds of HE are utilized for the sensible heating or cooling of fluids; nonetheless, in terms of heat transfer per unit surface area, in addition to having a lesser heat transfer coefficient, they are gargantuan in size as well as expensive. The shell and tube HEs are constructed out of tubes with circular cross-sections that are placed inside of huge cylindrical shells in a manner that ensures the tube axis is aligned in a direction that is perpendicular to the shell axis (Fig. 2 and Fig. 3). The route that the hot or cold fluid takes within the shell determines whether the shell and tube heat exchanger is of the single-pass type or the multi-pass type (usually the two-pass type). This may be seen in Figure 4. Shell and tube heat exchangers have widespread use in petrochemical and thermal power plants, as well as in the refrigeration and air conditioning, and process manufacturing sectors. One kind of fluid goes through the side of the HE that contains the tubes, while the other type of fluid flows through the side that contains the shell. Shell and tube heat exchangers may be broken down into several subcategories, each of which exhibits distinct characteristics when used in a specific setting. Nevertheless, the thermal expansion, the supply of a case for cleaning, and the provision of the least costly construction with cheap cost are the primary design goals of shell and tube heat exchangers [7].

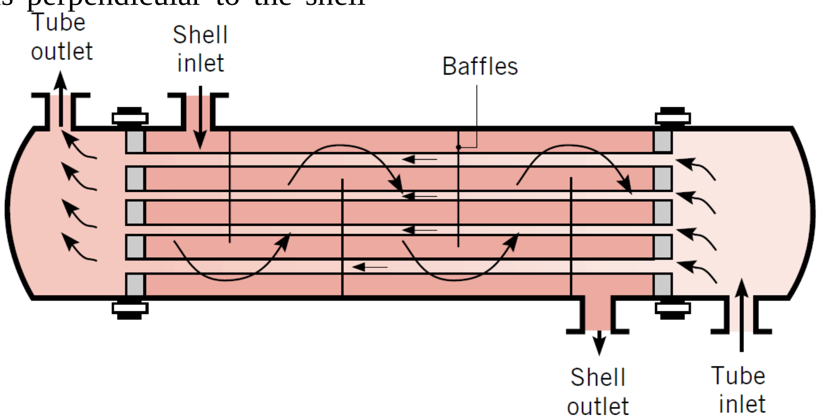


Figure.2.Schematic depictionof single-passcounter-flowshell andtubetypeHE

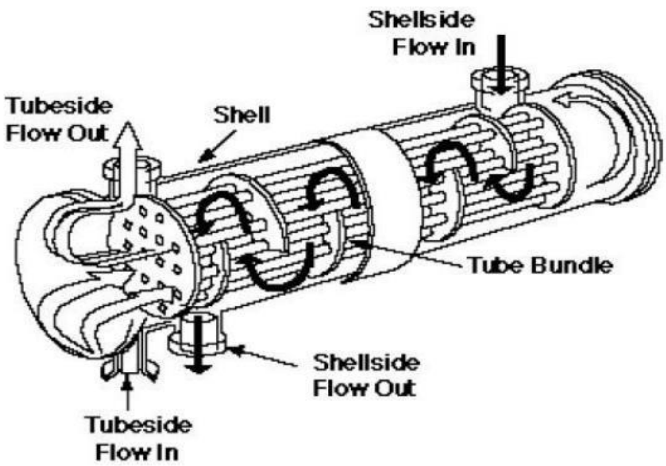


Figure 3 Schematic depictionsof two-pass counter-flowshelland tube typeHE

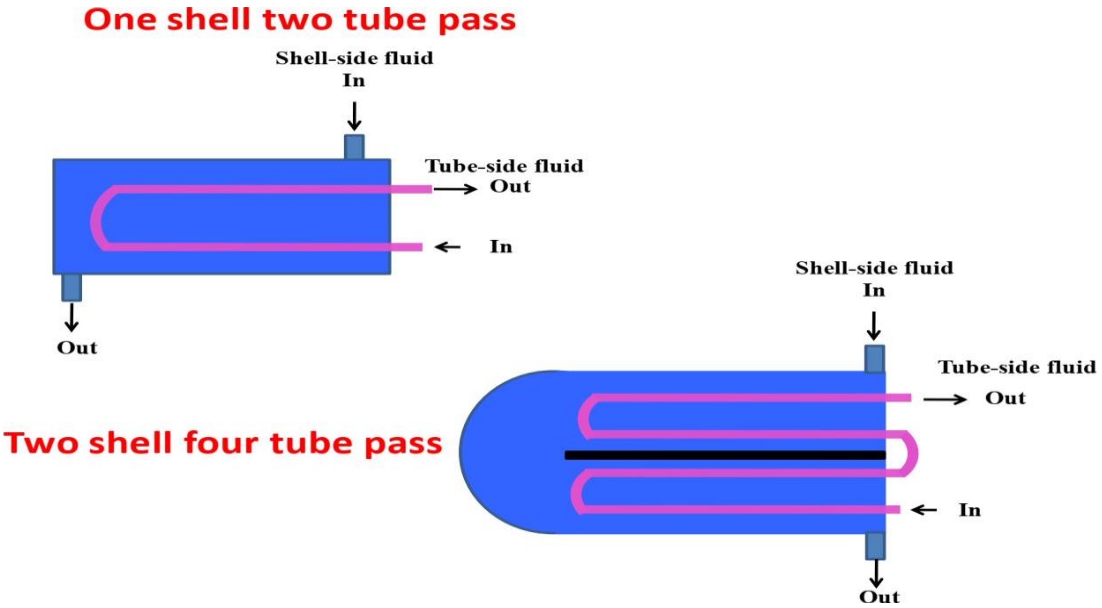


Figure 4. Shell and tube HE (a) One shell-pass and two tube-pass type (b) Two shell-pass and four tube-pass

The heat exchanger is responsible for ensuring the proper execution of the process prerequisites and design descriptions, which must contain all of the necessary detail information, including the flow rate of streams, operating pressure, stream inlet and outlet temperature, pressure drop criteria, heat exchanger area with tube length, cost, type of material, and heat exchanger type and its arrangement [9, 10]. Rating and size were identified as the most widespread issues in the thermal design of HEs, according to a research that was carried out in the early 2000s [11]. The rating problem involves calculating the heat transfer rate and fluid output temperatures for a particular mass flow rate of fluid given the intake temperature of the streams, the surface area, and the dimensions of the flow passage area [12]. However, the determination of the heat exchanger's dimensions presents its own set of challenges [11, 13, 14], as it impacts critical system parameters like the inlet and outlet fluid temperatures, the total flow rate of fluids, the thermophysical characteristics of working liquids, the substance, and the pressure drops in both fluid streams. In order to prevent difficulties and failures in the system, the HE's construction and flow configurations, the outer-inner geometry, and the materials used for the various system components need to be described [15, 16]. The operating temperature and pressure level, operation and maintenance limitations, protective measures and manufacturing feasibility of the surface, and most significantly, the costs all have a role in the decision of the HE type [17]. certain HE design may be considered realistically implementable if a certain rating scenario provides appropriate thermal operation while ensuring the requisite pressure drops remain within the allowed limitations [18].There is a possibility of numerous possible designs satisfying the requirements of the system; in these kinds of circumstances, the choices about which design to implement are ultimately determined by the cost of the HE system [19]. In addition, if the performance of the design is not satisfactory, the design should be modified such that the subsequent iteration of the same design has higher performance. This process is known as design modification. The HE are more of a state of the art than an engineering device [20], as a result of the multiple design considerations that must be made in addition to the numerous complicated and linked aspects that must be taken into consideration. As a result, the subject of higher education is one that is always evolving and calls for ongoing study with the objectives of boosting performance while simultaneously lowering costs and ensuring dependable operation. With the same goal in mind, the HEs have been chosen for the current research in order to demonstrate the many configurations of the system and to achieve optimal values for the system parameters.

Literature Review

Jiangfeng Wang*et.al.*,(2022)The transcritical CO2 (TCO2) Rankine cycle has gained popularity in recent years due to its reduced irreversible losses and enhanced thermophysical properties of CO2. However, normally this is not possible since CO2 has an extremely low critical point of roughly 31 degrees Celsius. The parametric analysis suggested that raising both the temperature and pressure at the turbine's intake and the exit of the vortex tube might improve exergy efficiency. Equipment for the TCO2 cycle may save money on initial expenditure if the pressure and heat at the turbine's intake are reduced. Furthermore, the results of the multiobjective optimisation show that the thermodynamic efficiency of the TCO2 cycle is at odds with the economic performance based on the specific investment cost of equipment.

Qingxuan Sun*et.al.,(*2021)Combining geothermal and solar power is an exciting prospect for addressing the world's pressing energy needs and environmental concerns. Some have proposed that a device termed as a solar-assisted ground supply absorption heat pumps (SGSAHP) might help alleviate the present energy crisis, especially in rural regions that do not have a reliable source of electricity. The SGSAHP setup requires little in the way of electrical power and may maximise its use of renewable sources while reducing its impact on the power grid's peak demand. The utilisation of geothermal and solar energy means that the system's COP may potentially be enhanced, allowing it to run on a much less amount of input electricity. The SGSAHP may function as a heater or a cooler, depending on the situation. In this paper, we construct a mathematical representation of SGSAHP and conduct a comprehensive simulation analysis. This research makes use of optimisation techniques, economic analysis, and parameter analysis. The results show that there is an optimal operating temperature for the generator that yields the highest COP, while increasing the temperature of the condenser or the evaporator has a negative or positive effect on the system's efficiency, respectively. Both the thermal and monetary efficiency have been maximised. Analysis of energy use found that heat was lost mostly via the solar collector and the heat exchanger.

FangyongHou*et.al.,(*2020)The Organic Rankine Cycle (ORC), which can be fueled by solar energy and employs a low-temperature heat source, might end the energy problem and cut down on pollution. This study's investigators aimed to examine a solar-powered ORC that makes use of a compound parabolic collector (CPC) and a heating storage device to collect solar energy and maintain system reliability, respectively. The performance of the system is analysed as a function of various thermodynamic factors with the help of the suggested mathematical model. To further improve the system's thermodynamic and economic efficiency, a multiobjective optimisation is carried out with the help of the nondominated sequencing genetic algorithm II (NSGA-II). The findings showed that a boost in turbine intake force and thermal oil mass circulation of the vapour generator might enhance the performance of the system. Based on the input parameters, the ideal strategy is to produce an average of 143.02

kW of net power while keeping the exergy effectiveness at 7.75%..

ModelAnalysis

Interior shell diameter (Ds), outer tube diameter (do), and baffle spacing (B) are the three design factors that make up the above mathematical model, which is rather complex.The objective cost function is a formula that depends on the heat-transmitting area and the pumping power to determine the total cost. The pump's output power is proportional to the pressure drop experienced by the fluids, which may occur on either the shell side or the tube side. A larger useful area of surface would be very desirable for maximising the exchange of heat between the two fluids; however, this would result in a larger pressure drop, necessitating a greater amount of pumping power. Therefore, it's clear that the two standards are at odds with one another. One of the design's variables is the pumping power, and another is the efficiency of the heat transfer area.

The mathematical model was solved in MATLAB by using the 'fmincon' method in conjunction with the SQP technique. The corresponding MATLAB code has been included in the report as an appendix.In order to solve the mathematical framework, a hypothetical scenario involving heat transfer between kerosene (the fluid on the shell side) and crude oil (the fluid on the tube side) has been taken into consideration. Table 1 contains an illustration of the intake and outlet conditions of the two fluids, as well as the thermophysical parameters of each of the fluids.

Table1: Processinputandphysicalparametersforsamplecasestudy

	Fluid	**MassFlow(kg/s)**	**T_i(°C)**	**T_o(°C)**	**ρ (kg/m³)**	**c_p(kJ/kg-K)**	**μ (Pa-s)**	**k (W/m-K)**
Shell Side	Kerosene	5.53	201.00	94.30	840.00	2.55	0.0007	0.16
Tube Side	CrudeOil	18.50	39.60	76.90	998.00	2.15	0.00258	0.18

The resultant function seems to be monotone with regard with the designer variable 'B' after the optimum baffle spacing value has been obtained. The best value for 'B' is 0.565, therefore increasing the baffle spacing beyond that point is not going to have the desired effect. This demonstrates that the optimisation issue has sufficient restrictions.

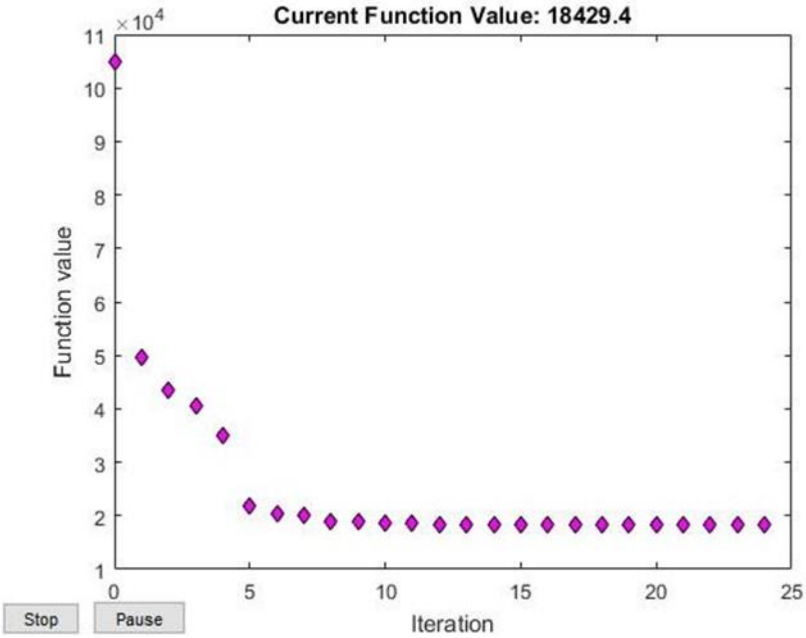


Figure5: Plotoffunctionvaluesv/snumberofiterations

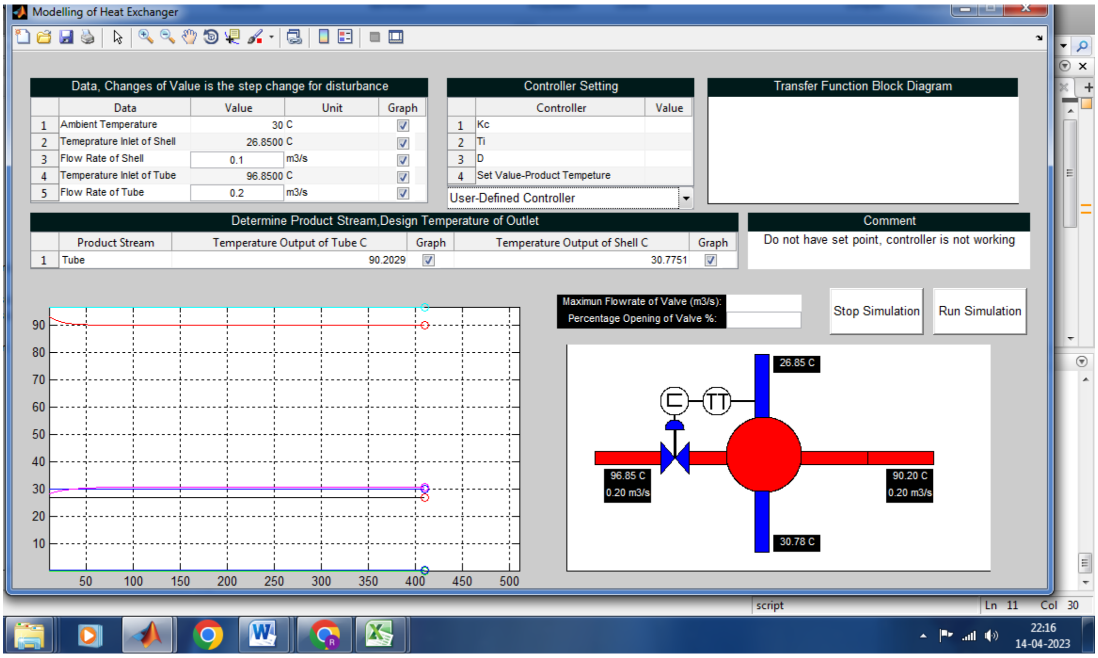


Figure 6.Simulation of the tube exchanger

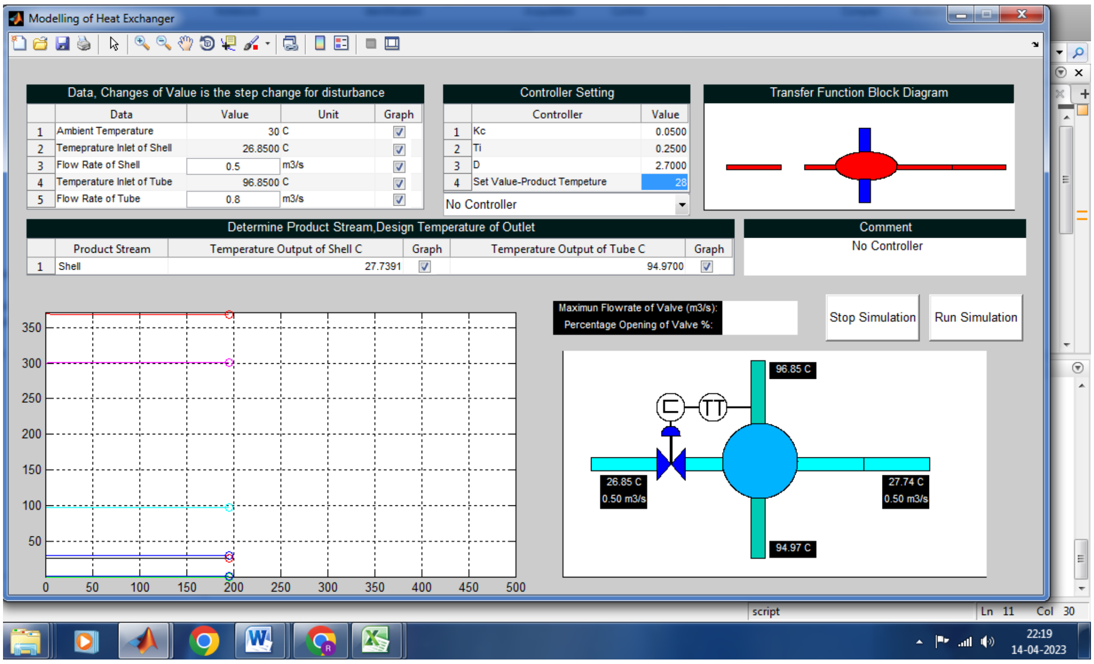


Figure 7 .Simulation of the shell exchanger

The solid works software was used to create the nozzle's 3D model. If each of the four design parameters is initially declared to be a global variable, then it may be parameterized. Design considerations include the initial span, nozzle thickness, taper angle, and inner radius. Since we are just interested in the nozzle and including the support conditions, we are only using a fraction of the shell's potential. Boundary limitations on the shell recreate the circumstances of the physical world.By maintaining a pressure of 5 MPa, the ASME pressure limits are satisfied. The heat exchanger under consideration is rated for the proposed pressure level. In order to account for expansion caused by thermal stresses and applied loads, ASME Codes permit heat exchangers to undergo deformation.

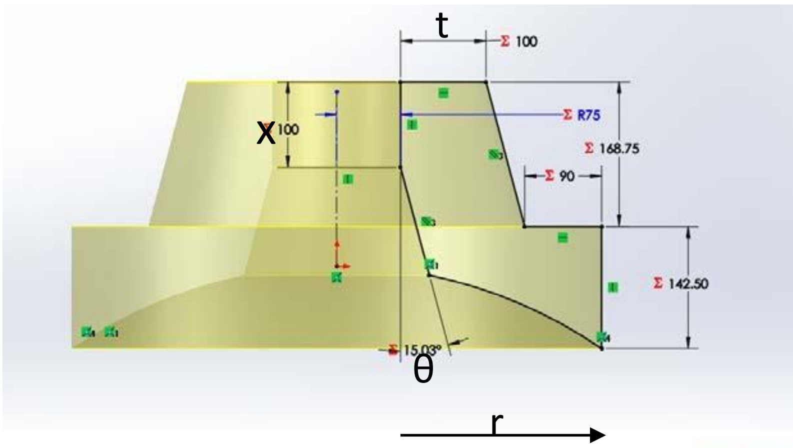
The Heat Exchanger's primary cylinder and nozzle remain in one place. This is because the Heat Exchanger has certain constraints. The key element that restricted potential layouts was a lack of available space. The minimum and maximum values for the design variables were determined by using engineering judgement. The boiler needs a deformation allowance because of the internal pressure that causes it to expand under load. Material quality is determined by reference to the ASME Boiler and Pressure Code Vessel Requirements.

MaterialpropertiesareusedofStructuralSteel(StandardMaterialforHeatExchanger).

DesignVariables	Lowerbound	Upperbound
Radiusofthenozzle(r)	68	83
Taperangle(θ)	14.2	15.89
NozzleThickness(t)	92	120
Span(x)	89	111.5
Deformation(d1)	0.158	

For modeling, meshing, and finite element analysis (FEA), ANSYS Workbench, which is software that is available for purchase, was used for the Heat Exchanger. 'Design Modeler' is a module in ANSYS Workbench that is used for CAD modeling, while 'Mechanical' is a module that is used for producing the mesh and carrying out the FEA analysis. Generally speaking, a hexahedral mesh is considered to be superior than a tetrahedral mesh in terms of its computing efficiency and overall preference. Sweep mesh is one of the approaches that can be used to create hexahedral mesh in a body. This mesh may be created in a variety of ways[20-22].

Normal operation for ANSYS Mechanical involves meshing the source face with quadrilateral elements, followed by copying that mesh onto the target face, which ultimately results in a hexahedral mesh in the body[23]. The sweep mesh approach was used in ANSYS Workbench for the purpose of developing an all- hexahedral finite element (FE) model of the heat exchanger. The heat exchanger, when considered as a single unitary structure, does not satisfy the topological criteria for sweeping and, as a result, cannot be made into a hexahedral mesh. During the process of creating the geometry for the heat exchanger, the slicing and dicing approach was applied so that the heat exchanger could be made suitable for sweep mesh. With the use of the method, the heat exchanger that could not be swept was broken up into many bodies that could be swept. After that, the individual components of the sweepable multi-body heat exchanger were bonded together to form a single component. In order to guarantee consistent nodes at the connecting faces of the sweepable bodies, the gluing is another requirement that must be met.



Maximumstressintensityontheedges

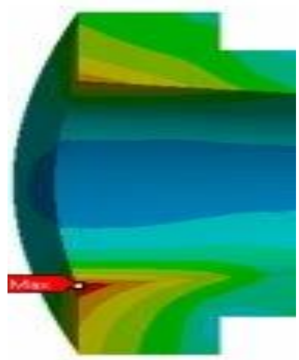
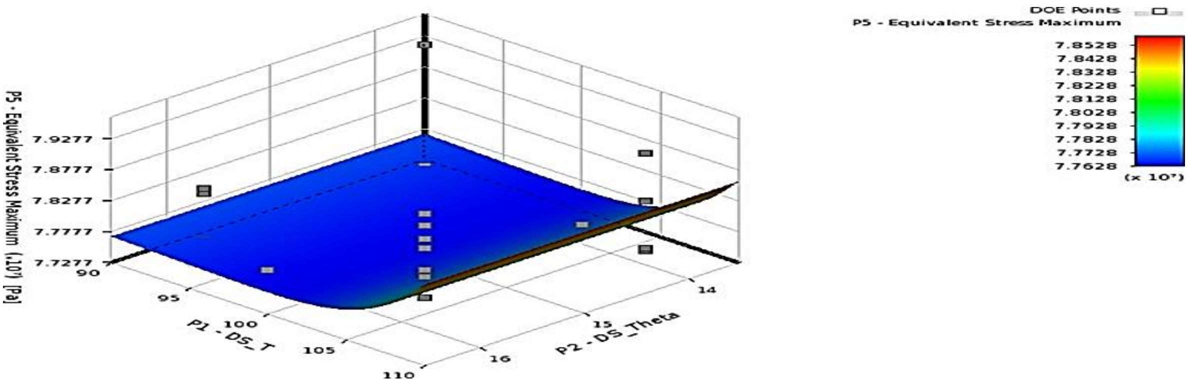
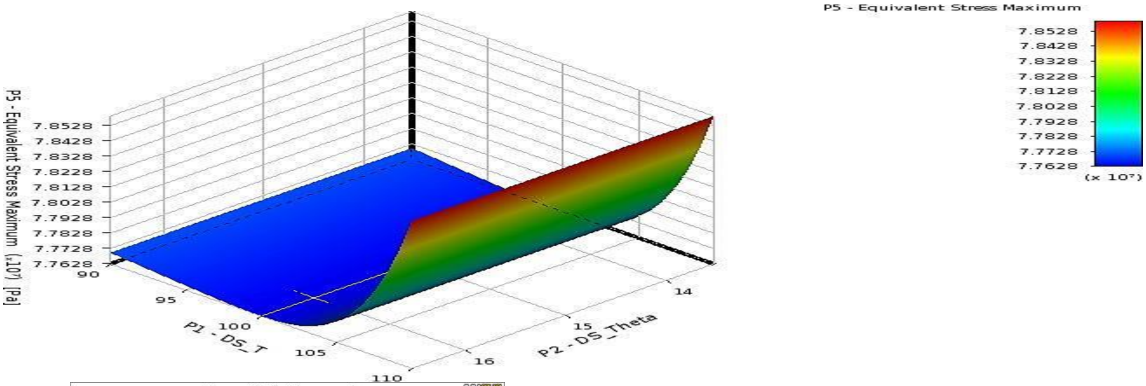
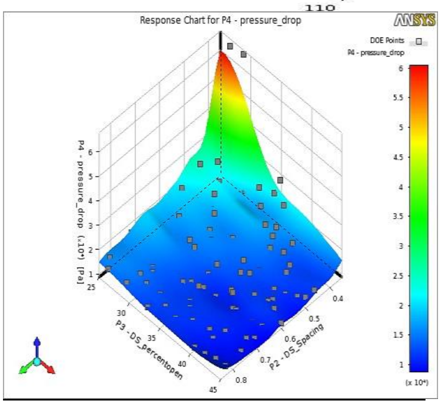


Figure 8.3D ANSYS analysis for Maximum Stress Intensity







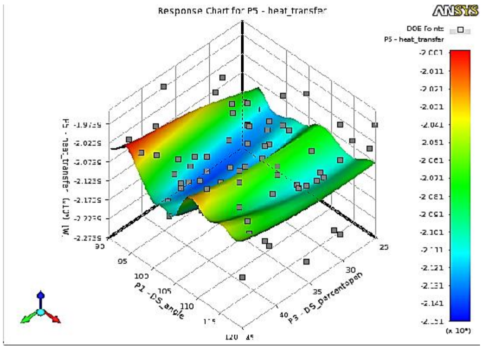


Figure 9a Figure 9b

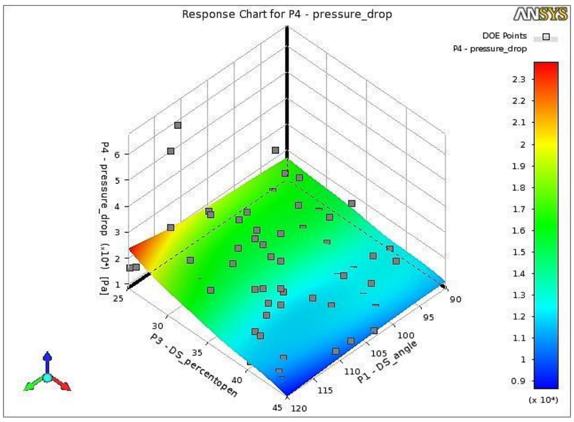


Figure9c

Figure9 (a,b,c): Responsesurfaceplots

Heat Exchanger Optimization Modeling

Heat exchanger cores with a large number of tube-rows are often used in actual manufacturing, and there are typically at least three rows of tubes present, arranged in an in-line or staggered pattern. The tubes are laid out in staggered rows that are parallel to each other. Direct modelling of the full heat exchanger using a model with three dimensions for the relevant Reynolds values remains challenging despite the availability of high-speed computers with vast quantities of memory. This is because our goal is to optimise numerous parameters simultaneously, and creating the necessary number of grids will take a considerable amount of time. An effective and fast-functioning model based on the volume averaging theory (VAT) has been created. The next step is to evaluate the complicated closure terms, which may be performed with either data from experiments or CFD simulation results. Here, the term "porous" is used in a broad sense to include both the flow of hot air and the transit of water that cools down the tube. In the VAT method, the flow parameters are averaged over a REV that is supposed to be a representation of the whole heat exchanger. This is done so that transportation-related equations may be solved. Since the averaged equations are in the form of flow equations in porous media, describing each phase and its properties throughout the whole simulation domain is a cumbersome task.

Conclusion

This paper provides an integral theory of heat transport in heat exchangers on the foundation of thermodynamic analysis and finite time optimisation. To comprehend how heat is transported better, this model was developed. The process of actual heat transfer that takes place in the heat exchanger may be faithfully simulated by the model. The model may be fully used to increase the charging capacity of the heat exchangers. The model may also show how the height on the heat exchanger and heat transfer relate to one another.

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