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OPTIMIZATION OF SHELL AND TUBE HEAT EXCHANGER USED IN A RANKINE CYCLE OF EXHAUST GAS WASTE HEAT RECOVERY SYSTEM USING CFD

T. V. S. SIVA* and P. SAI CHAITANYA

Department of Mechanical Engineering, GMR Institute of Technology, Rajam,
SRIKAKULAM – 532127 (A.P.) INDIA

ABSTRACT

The shell and tube heat exchanger model and materials used will influence the effectiveness of heat exchanger. Comparing the different models with different materials enables us to suggest a suitable model and material for heat exchanger. This suggested model and material can recover more waste heat from Rankine cycle exhaust gas waste heat recovery system. For comparing several heat exchangers under the same boundary conditions CFD is a powerful tool. So, in this context, we have to optimize the existing design of heat exchanger by varying baffles and materials. As it takes a lot of time and money to fabricate a heat exchanger with different materials and baffles, computer simulations were carried out in the present work to optimize the design of the exchanger.

Key words: CFD, Optimization, Rankine cycle, Shell and tube heat exchanger, Waste heat recovery.

INTRODUCTION

The heat exchanger is a mechanical component, which is used for the exchange of heat between two fluids at different temperatures. There are various types[2] of heat exchangers available in the industry, however the Shell and Tube Type heat exchanger[3] is probably the most used and widespread type among the heat exchanger's classification. In Shell and tube type heat exchanger, one fluid flows through tubes and other fluid flows through the shell. The transfer of heat between the two fluids takes place through the wall of the tubes. In the past, due to practical limitations a lesser attention has been given to the heat transfer capabilities of the materials as it was not possible to change the material of the tubes or shell again and again and test them under the loading conditions. But, now by the intense development of software facility, we may introduce a number of materials and their

*Author for correspondence; E-mail: tvenkatasatyasiva@gmail.com, nandu.343@gmail.com

combinations of the actual working conditions, and henceforth finds their accuracy and compatibility with the desired functions. A review was conducted on design of heat exchangers used in waste heat recovery methods[4]. In their research two cases of HEXs an optimized one and a non-optimized one, which were mounted on the exhaust of an OM314 diesel engine and from the results they concluded that a new design of optimized finned-tube HEX recovered more heat. Pandiyarajan et al.[5] designed and fabricated a finned shell and tube heat exchanger and TES tank of capacity 20 MJ and were tested by integrating them with a diesel engine of capacity 7.4 kW and 10-15% of total heat was recovered from the system. The maximum heat extracted using the heat exchanger at full load condition was around 3.6 kW. Hossain and Bari[6] in their research with 50 kW engine an extra 24% power was gained with optimized heat exchangers using water as the working fluid and the optimum pressure was found to be 30 bar and the maximum recovered additional power was 9.85 kW. Dolz et al.[7] from their work reported that when the engine dissipates more heat energy it can only recover about 8% and 9% of the total energy dissipated by the engine if internal irreversibilities were also considered. Domingues et al.[8] reported for an ideal heat exchanger that the simulations revealed increases in the thermal and vehicle mechanical efficiencies of internal combustion engine 1.4%-3.52% and 10.16%-15.95%, respectively, while for a shell and tube heat exchanger, the simulations showed an increase of 0.85%-1.2% in the thermal efficiency and an increase of 2.64%-6.96% in the mechanical efficiency for an evaporating pressure of 2MPa. The Rankine cycle system is one of the effective methods used in waste heat recovery systems, which will utilize heat exchangers to extract energy from the waste heat. The design of heat exchanger[3,9,10] used in Rankine cycle is critical as it needs to provide an adequate surface area in order to cope with the thermal duty.

Hossain and Bari[1] in their research, did experiments to measure the exhaust heat available from a diesel engine coupled to a generator to produce electricity. Two shell and tube heat exchangers, which are identical were purchased and used to produce super-heated steam. These heat exchangers were installed into the engine exhaust system. The purchased heat exchangers did not perform optimally during the experiment as they were not designed optimally for this particular application. Hence, research was conducted to design heat exchangers and to find the appropriate pressure of the working fluid for optimum working in WHR application using commercial CFD software. Two optimum heat exchangers were designed with varying different geometrical aspects of the heat exchangers such as shell diameter, length, number and diameter of the tubes. To validate their simulation model, the existing heat exchangers were modelled first and then compared with experimental results. The effectiveness of the non-optimized purchased heat exchangers was found to be 0.44, which is much lower than a well-designed heat exchanger for the effectiveness is 0.76. In this work we have taken Hossain and Bari[1] model and applied boundary conditions to it as mentioned in their journal for single shell and tube heat exchanger. Later simulations have been performed for three different models i.e. without baffle, with 50% baffle cut and with 25% baffle cut[11-13] for five different tube materials[14-17]. The properties of used tube materials were shown in Table 1. Then effectiveness for all models was calculated. Finally by considering effectiveness value and the behaviour of materials in that operating environment, we are optimizing the heat exchanger.

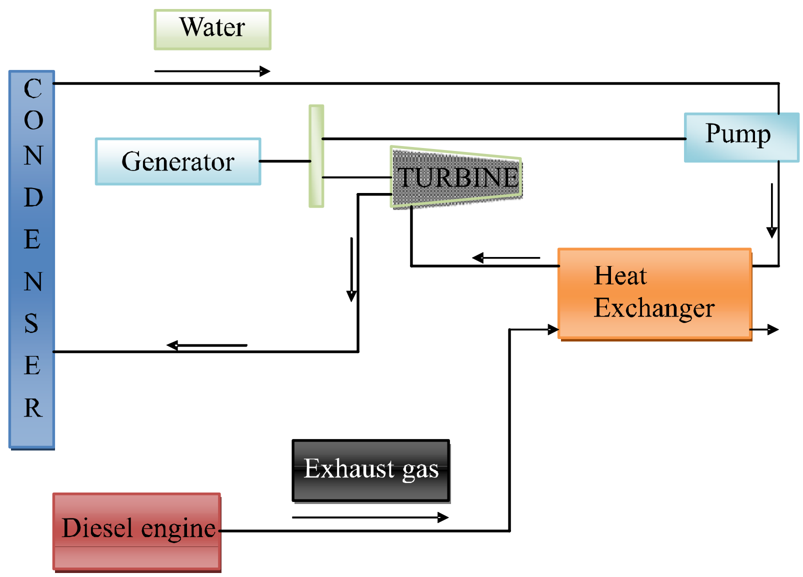

Fig. 1: Rankine cycle

From Literature review[4-8] Rankine cycle is reported as one of the best waste heat recovery technology among the conventional techniques i.e. Mechanical turbo compounding, Electrical turbo compounding, Thermo Electric Generator, Turbo Charging etc. In Rankine cycle as shown in Fig. 1 a heat exchanger is employed to generate steam using the exhaust heat, which is expanded in a turbine to produce additional power.

Heat exchanger

A heat exchanger is used to transfer thermal energy between two or more fluids, between a solid surface and a fluid, or between a fluid and solid particulate, at different temperatures and in thermal contact. There are mainly 3 types of heat exchangers among the various numbers of heat exchangers. They are the direct transfer type, storage type and direct contact type.

In many heat exchangers, the fluids are separated by a heat transfer surface and ideally they do not leak or mix and such exchangers are referred to as direct transfer type. Whereas, heat exchangers in which there is an intermittent heat exchange between the hot and cold fluids via thermal energy storage and release through the exchanger surface are referred to as indirect transfer type, or simply regenerators. Heat transfer takes place generally by the conduction phenomenon in the separating wall of a direct transfer type heat exchanger. In general, the separating wall may be eliminated, if the fluids are immiscible, and the interface between the fluids replaces a heat transfer surface, as in a direct-contact heat exchanger. Common examples of heat exchangers are shell-and tube exchangers, automobile radiators, evaporators, condensers, air preheaters and cooling towers. If no phase change takes place in any of the fluids in the exchanger, it is referred as a sensible heat exchanger. Combustion and chemical reaction may occur within the exchanger, such as in boilers, fired heaters, and fluidized-bed exchangers. Typical applications involve evaporation or condensation of single or multi component fluid streams, heating or cooling of a fluid stream of concern. In other applications, the objective may be to recover or reject heat. The shell and tube heat exchanger is generally built by bundle of round tubes mounted in a cylindrical shell with the tube axis parallel to that of the shell as shown in the Fig. 2 and its specifications were mentioned in Table 2. And the effectiveness formula was given below.

$$\varepsilon = \frac{(\dot{m}c_p)_h (T_{c,out} - T_{c,in})}{(\dot{m}c_p)_{min} (T_{h,in} - T_{c,in})}$$

Table 1: Properties of materials

Tube material	Density (Kg/m^3)	Thermal conductivity (W/m-K)	Specific heat (J/Kg-K)	α (m/m-K)
Copper	8978	387.6	381	19.3e-6
Aluminium	2719	202.4	871	31.1e-6
Brass	8600	109.0	162	21.2e-6
SS304	8030	21.4	500	18.7e-6
SS316	7990	21.4	500	18.5e-6

Table 2: Heat exchanger model specifications

Particulars	Description
Shell inside radius	46 mm
No of tubes	31
Tube arrangements	30^0 triangular staggered array
Tube pitch	15 mm
Tube inside diameter	9.44 mm
No. of Baffles	7
Length of the heat exchanger	2 m

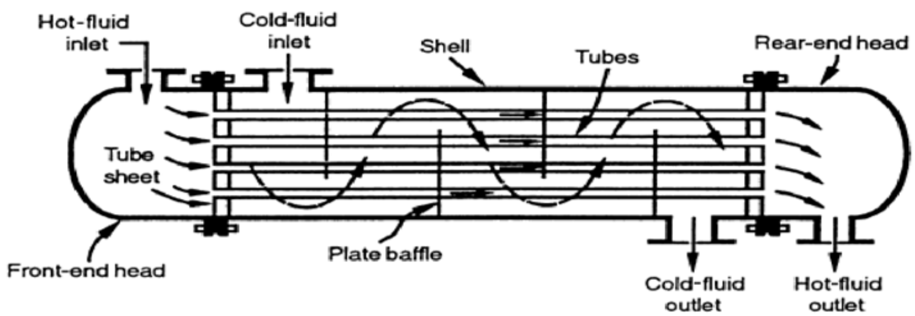

Fig. 2: Shell and tube heat exchanger

Modelling details

Computational model

The existing Heat Exchanger[1] model drawing was created in ANSYS. Fig. 3 shows the model. In the model, 30^0 triangular staggered array layout was used for the tube arrangement in the heat exchanger.

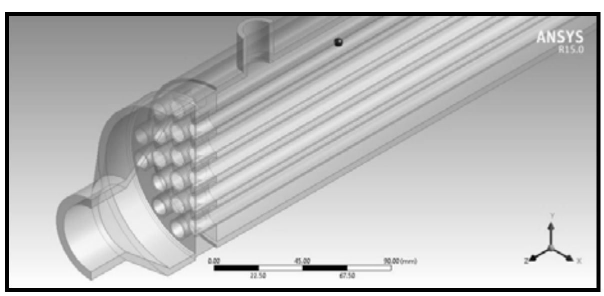

Fig. 3: Heat exchanger model

The geometrical model was then meshed using ANSYS meshing software and solved the equations for the fluid flow and heat transfer in the ANSYS FLUENT 15.0, which is based on the finite volume method. It is a high-performance, general purpose fluid dynamics program that can be applied to solve a wide-range of fluid flow and heat transfer problems.

Meshing

In order to make the simulation more effective, different meshing schemes were used. The solid tubes were meshed using sweep mesh. The final model has 28, 70, 793 nodes and 53, 76, 025 elements. Fig. 4 shows the computational domain of the heat exchangers.

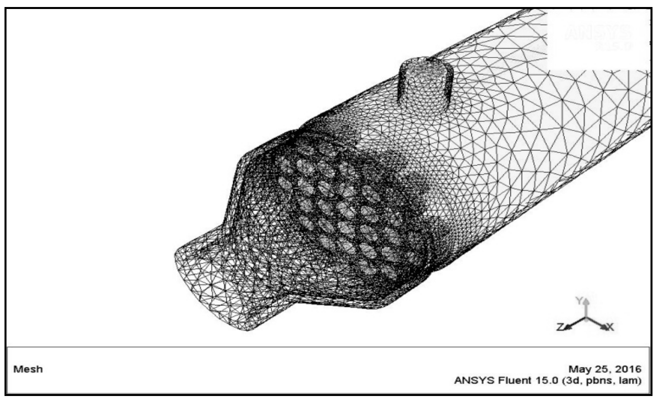

Fig. 4: Mesh computational domain

Governing equations

The numerical simulation was performed with three dimensional, steady-state, turbulent flow system and in solving the problem, k–ω based Shear–Stress–Transport turbulent model was employed and energy equation was included into the model. According to the conditions of simulation setup the governing equations for the flow and conjugate heat transfer were modified. As the problem was assumed to be steady, the time dependent parameters are neglected in the equations. The resulting equations are:

Continuity equation:

$$\nabla \cdot \left(\rho \vec{V}\right) = 0$$

Momentum equations:

$$\nabla.(\rho u\vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}$$

$$\nabla.(\rho v\vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}$$

$$\nabla.(\rho w\vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}$$

Energy equation:

$$\rho c_p \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} \right) = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

Boundary conditions

In the boundary conditions[20] of the heat exchanger model, water was taken as the cold fluid and exhaust gas from the engine was taken as the hot fluid. The cold fluid was considered in liquid phase at 27^0C at selected pressure and it came out as vapour. The hot fluid was modelled as air with mass flow rate of 0.050253 Kg/sec with temperature 479^0C. The operating pressure of hot fluid was set at 101325 Pa.

RESULTS AND DISCUSSION

In this work, five different materials, copper, aluminium, brass, SS304 and SS316 were chosen as tube material and steel as shell material, which is constant for all the tube materials. Fig. 5 shows the residual plot. Here we are taking 3 different models of heat exchanger, i.e. without baffle, with 50% baffle cut, and finally with 25% baffle cut. Among all these models, Copper with 25% baffle cut gives maximum effectiveness of 0.7. The effectiveness's of all the materials for the 3 models were calculated as per the formulae given by Hossain & Bari[1], which was the base for our work. We validated our results with Hossain and Bari work. Fig. 6 shows the process of validation. In their research for 2 heat exchangers, connected in parallel arrangement they got the effectiveness of 0.76. For their boundary conditions for a single heat exchanger we got effectiveness of 0.653.

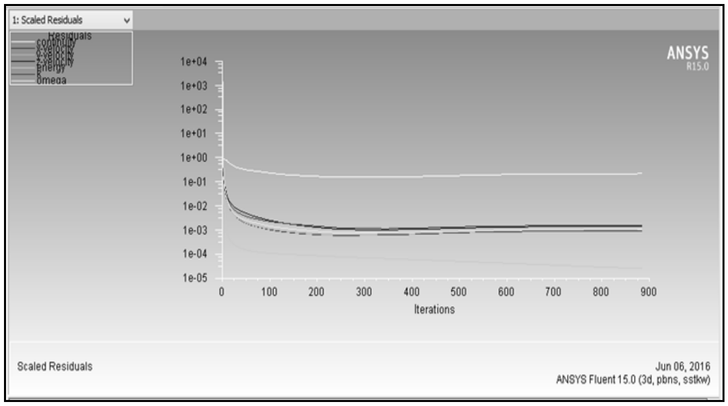

Fig. 5: Residual plot

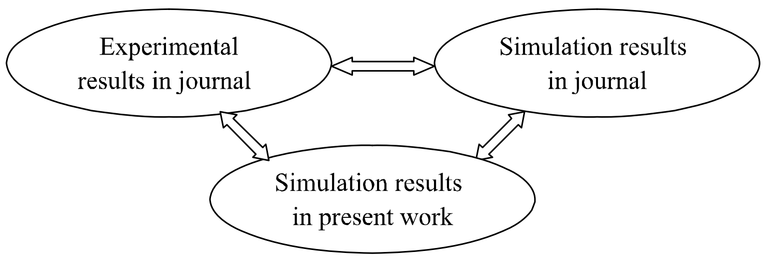

Fig. 6: Validation process

Fig. 7 (a), (b) and (c) shows the effectiveness's for 3 models with 5 different materials and comparison of effectiveness is shown in Fig. 8.

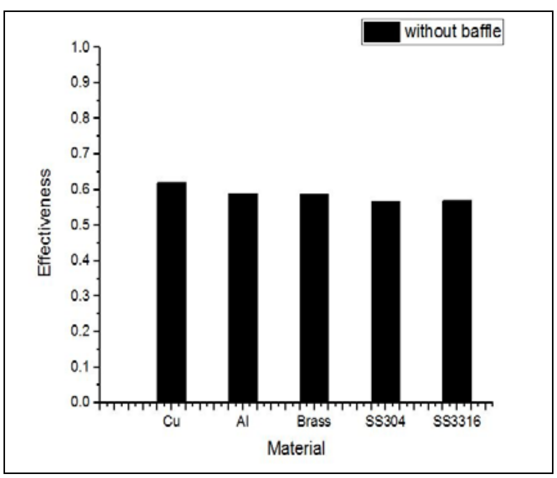

Fig. 7(a): Effectiveness's for no baffle

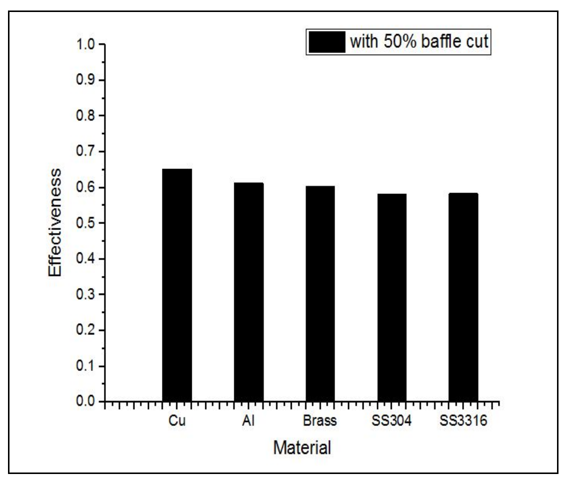

Fig. 7(b): Effectiveness's for 50% baffle cut

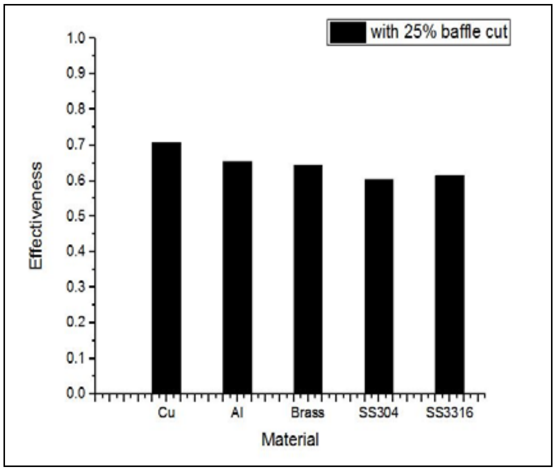

Fig. 7(c): Effectiveness's with 25% baffle cut

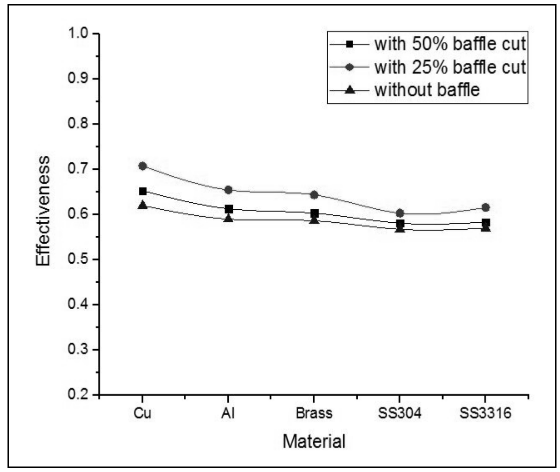

Fig. 8: Comparison of Effectiveness's

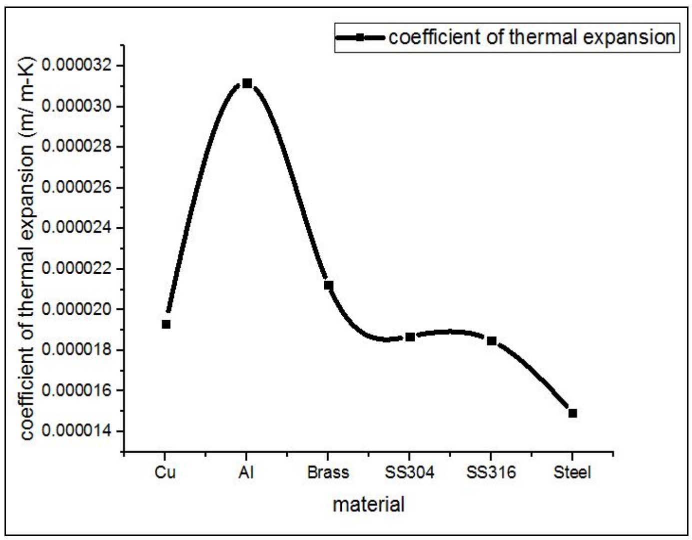

Fig. 9: Coefficient of thermal expansion of different materials

A heat exchanger model with 25% baffle cut gives maximum effectiveness values when compared to other two models. After that Heat Exchanger model with 50% baffle cut gives effectiveness values more than Heat Exchanger model without baffle. The order of materials which gives maximum effectiveness was Copper, Aluminium, Brass, SS316 and SS304. While designing heat exchanger, we were not only considering the effectiveness i.e. How much it effectively transfers heat from hot fluid to cold fluid, but also other important aspects like elongation, corrosion. For material having a high coefficient of thermal expansion, the elongation of that material will be high and then it will cause problems. Fig. 9 shows coefficient of thermal expansion of materials 5 different tube materials used in our analysis. Aluminium possesses highest value coefficient of thermal expansion, which leads to more elongation and was followed by brass and copper. SS304, SS316 is having less coefficient of thermal expansion and hence the life of heat exchanger will be more without distortion in shape. The corrosion depending on the material composition varies from one from to another. Among five different tube materials SS316 has high corrosion resistance[16] because it had molybdenum, which has high corrosion resistance property.

CONCLUSION

In this work, Shell and Tube Heat Exchangers of three different models with five tube materials were simulated. Based on simulation results, effectiveness was calculated. Shell and Tube Heat Exchanger at 25% baffle cut with copper as tube material gives the maximum effectiveness of 0.7. Among five different tube materials SS316 as tube material posses a good operating performance characteristics, and hence there is an increase in the life cycle of heat exchanger. Effectiveness of Heat Exchanger for SS316 as tube material was 0.6158, which is comparatively lesser than the effectiveness of copper as tube material.

Even though, effectiveness of Heat Exchanger decreases with SS316 as tube material but keeping other enhanced operating characteristics such as increased life cycle, corrosion resistance and lower coefficient of thermal expansion in mind, it can be concluded that replacing conventional copper as Heat Exchanger tube material with SS316 at 25% baffle cut would be advantageous for longer run of Heat Exchanger.

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