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Optimization of Curved Finned-Tube Heat Exchangers for Diesel Exhaust Waste Heat Recovery using CFD

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Abstract

In engines, an exhaust heat recovery system turns thermal losses in the exhaust pipe into energy. Even though the current generation engines consume less fuel than they used to, the thermal efficiency of an internal combustion engine has not much improved since its creation. The main purpose of this work is to further improve the heat recovery from exhaust of the engine. By optimizing the geometry of the HEX fins, it is required to achieve maximum heat transfer with acceptable pressure drop which makes back pressure in the exhaust. The heat exchanger used in this work is a curved finned tube heat exchanger which is supposed to deliver more heat transfer than the flat finned tube heat exchangers. Thereby, increasing the waste heat recovery. In order to achieve maximum heat recovery amount and minimum pressure drop along the heat exchanger, optimization is carried out for the geometry of the curved finned heat exchanger such as different fin curvatures, fins height, and are modelled numerically. The best combination of fin geometries for maximum desirability is to be found out. The study is conducted with the help of CFD simulation package Ansys CFX.
Keywords- CFD (Computational Fluid Dynamics), HEX (Heat Exchanger), Waste Heat Recovery, Optimization, Desirability

I. INTRODUCTION

Waste heat is by necessity produced both by machines that do work and in other processes that use energy. The need for many systems to reject heat as a by-product of their operation is fundamental to the laws of thermodynamics. Waste heat has lower utility than the original energy source. It is evident that exhaust of the engines is another main source that a large amount of energy wastes through it. Researchers confirm that more than 30–40% of fuel energy wastes from the exhaust and just 12–25% of the fuel energy convert to useful work. On the other hand, statistics show that production of a number of internal combustion engines grows very fast and concern on increasing the harmful greenhouse gases (GHG) will appear. So, researchers are motivated to recover heat from the waste sources in engines by using the applicable ways. In transportation, an exhaust heat recovery system turns thermal losses in the exhaust pipe into energy. This technology seems to be more and more of interest by car and heavy-duty vehicle manufacturers as an efficient way to save fuel and reduce vehicles' CO2 emissions. This technology can be used either on a hybrid vehicle or a conventional one: it produces either electric energy for batteries or mechanical energy reintroduced on the crankshaft. In this study we focus on improving the waste heat recovery from exhaust of the engines by keeping the pressure drop within an acceptable range.

In the study of M. Hatami & M. Jafaryar [1] response surface methodology (RSM) based on central composite design (CCD) is utilized and is applied to obtain an optimization design of finned type heat exchangers (HEX) to recover waste heat from the exhaust of a diesel engine. The design is performed for a single point operation (1600 rpm and 60 N m) of an OM314 diesel engine obtained from experimental measurements. Based on the Central Composite Design principle, fifteen HEX cases with different fins height, thickness and number are numerically modelled and the optimization is done to have the maximum heat recovery amount and minimum of pressure drop along the heat exchanger.

In the journal 'Numerical study of an exhaust heat recovery system using corrugated tube heat exchanger with twisted tape inserts', Mokkapati and Lin [3] inserted a twisted tape in the corrugated tube exhaust of a heavy duty Diesel engine to increase recovered heat and evaluated its impact on engine performance and economics. In various other researches also, the researchers are motivated to increase the effectiveness of heat transfer by various heat augmented techniques.

II. GOVERNING EQUATIONS

A three dimensional steady-state turbulent flow system is utilized for performing the numerical simulation. As an initial step, the problem was assumed to be steady. The governing equations for the flow and heat transfer were modified in order to solve the problem. The time dependent parameters were eliminated from the equations.

Continuity equation:

$$\nabla.(\rho V) = 0 \quad (1)$$

Momentum equations:

– x-momentum:

$$\nabla.(\rho u V) = -\frac{\partial p}{\partial x} + \frac{\partial \tau xx}{\partial x} + \frac{\partial \tau yx}{\partial y} + \frac{\partial \tau zx}{\partial z} \quad (2)$$

– y-momentum:

$$\nabla.(\rho v V) = -\frac{\partial p}{\partial y} + \frac{\partial \tau xy}{\partial x} + \frac{\partial \tau yy}{\partial y} + \frac{\partial \tau zy}{\partial z} + \rho g \quad (3)$$

– z-momentum:

$$\nabla.(\rho w V) = -\frac{\partial p}{\partial z} + \frac{\partial \tau xz}{\partial x} + \frac{\partial \tau yz}{\partial y} + \frac{\partial \tau zz}{\partial z} \quad (4)$$

– Energy equation:

$$\rho c_p \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) = \lambda\left(\frac{\partial^2 T}{\partial x2} + \frac{\partial^2 T}{\partial y2} + \frac{\partial^2 T}{\partial z2}\right) \quad (5)$$

In HEX analysis heat transfer amount is an important parameter. The average heat transfer amount is,

$$Qave = \frac{Qg+Qc}{2} \quad (6)$$

Q_c is the heat transferred to the coolant which is calculated as,

$$Qc = mcCpc(T\, c, out - T\, c, in) \quad (7)$$

Q_g is the heat transferred to exhaust gases which can be calculated as,

$$Qg = mgCpg(T\, g, out - T\, g, in) \quad (8)$$

Where,

m_c, m_p is the mass flow rate of coolant and gas respectively.

C_{pc}, C_{pg} is the specific heat of coolant and gas respectively.

III. GEOMETRY AND CONDITIONS

The geometry consists of a curved finned Heat exchanger. Water is used as the coolant. Both inlet and outlet of the coolant water are placed in the upper surface of the Heat exchanger. All the solid phases ie, both fins and walls are made from carbon steel.

A. Dimensions of HEX

– Length – 0.7m
– Diameter of outer tube – 0.14m
– Diameter of inner tube – 0.12m
– Diameter of gas inlet & outlet – 0.048m
– Diameter of coolant inlet & outlet – 0.02m
– Thickness of walls – 0.003m

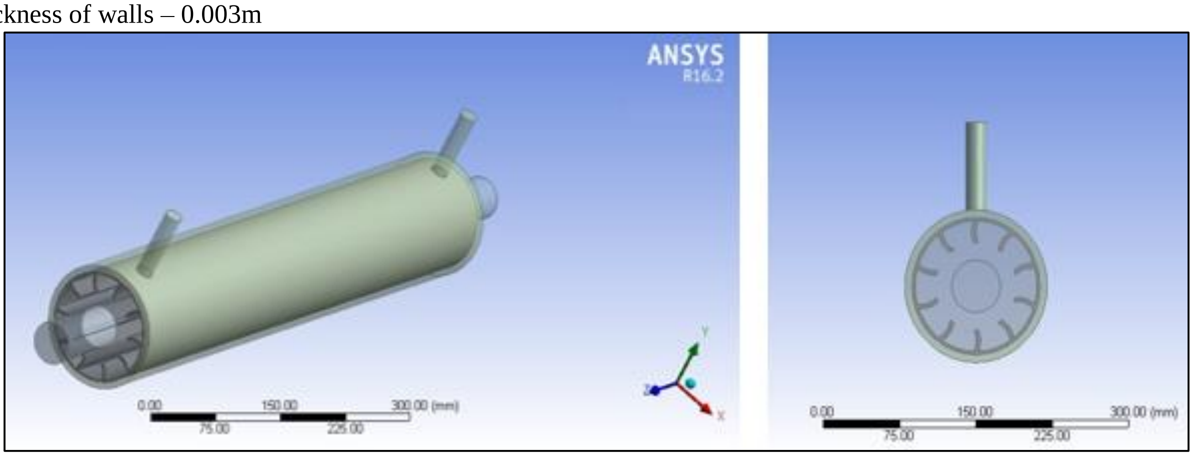

Fig. 1: Geometry

The table below shows the properties of coolant and fin material.

Table 1: Properties of coolant and fin material

Material	ρ (kg/m³)	C_p (J/kg K)	μ (kg/m s)	K (W/m K)
Water	998.2	4182	0.001003	0.6
Carbon Steel	7858	486	-	52

For this HEX analysis, 12 different cases of curved fin heat exchangers are considered. In this work, the heat transfer to the surroundings are totally neglected. ie, the heat exchangers are considered to be well insulated. Different cases are obtained by changing the geometry of fins such as fin curvature and fin height. The details of geometry and mesh statistics are given below.

Table 2: Mesh statistics of different cases

Case	Parameters				Mesh statistics			
	Fin curvature	Fin height	Fin thickness	Fin number	Domain 1 (gases)	Domain 2 (fins)	Domain 3 (water)	Total
1	25	20	4	10	715969	20020	207994	943983
2	35	20	4	10	664144	20150	207994	892288
3	45	20	4	10	686227	17160	207994	911381
4	55	20	4	10	679018	20150	207994	907162
5	25	25	4	10	654776	21140	207994	883910
6	35	25	4	10	675707	18460	207994	902161
7	45	25	4	10	679523	21560	207994	909077
8	55	25	4	10	680748	18590	207994	907332
9	25	30	4	10	668868	16640	207994	893502
10	35	30	4	10	686763	19880	207994	914637
11	45	30	4	10	686763	19880	207994	914637
12	55	30	4	10	686763	19880	207994	914637

IV. MESHING AND BOUNDARY CONDITIONS

ANSYS Workbench software is used to generate the grid system. Tetrahedral meshes are used in this HEX analysis. The detail of meshes of each cases are represented in Table 2. CFX module of ANSYS 16.2, which is having a faster convergence and user friendly UI was used for the purpose of simulation of flow. Three different domains are considered for fins (solid), exhaust gas (gas) and coolant water (water). The meshed geometry of case 1 is shown in Fig. 2. A grid independency study of each cases were conducted to ensure that the results of simulations are independent of the grid elements. For that the temperature variation along the central axis of HEX was plotted. The result of grid independency study of case 1 is shown in the Fig. 3. The last 3 results of the test were having a negligible difference. It was observed that the results obtained for grid size of 943983 and above have a negligible difference. Hence the grid size of 943983 was chosen as same limit for the model.

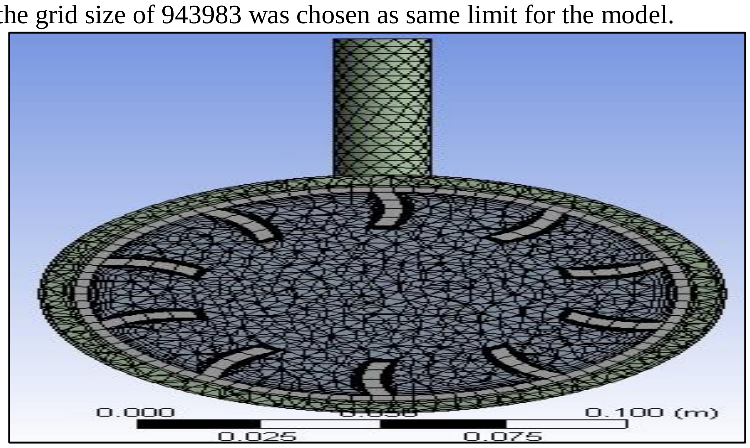

Fig. 2: Generated mesh of case 1

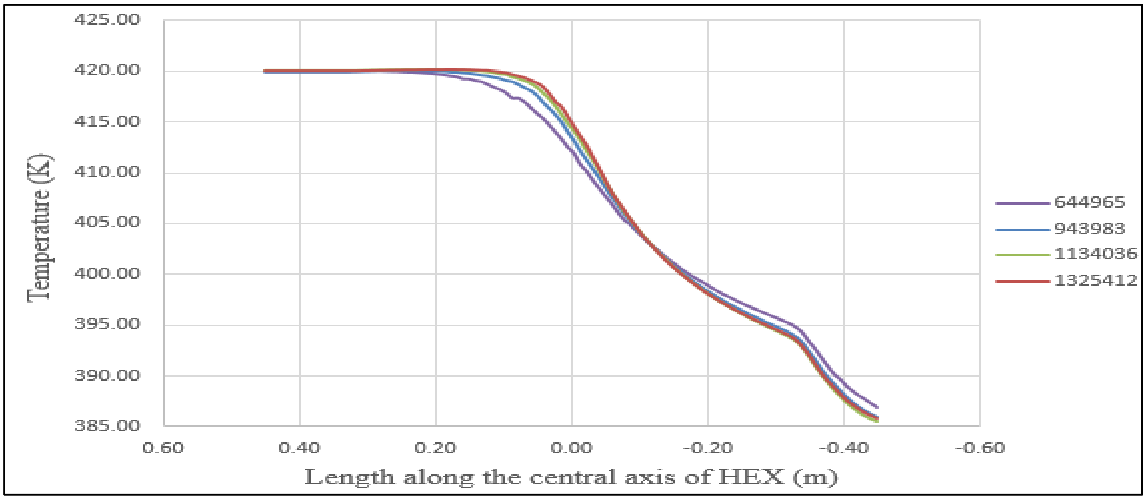

Fig. 3: Grid independency study

A. Boundary Conditions

Hot Inlet
- Gas Temperature – 420K
- Mass flow rate – 0.05838kg/s

Cold Inlet
- Water temperature – 288K
- Mass flow rate – 0.2839kg/s

Hot Outlet
- Pressure outlet, pressure – 0 bar (gauge)

Cold Outlet
- Pressure outlet, pressure – 0 bar (gauge)

MODEL - k-ε model

V. RESULTS AND DISCUSSION

In this work, initially a flat finned HEX is modelled numerically to validate the result with a case in the study of M. Hatami & M. Jafaryar [1] and it was observed that there is only 0.66% variation in exhaust outlet temperature and 0.007% variation in water outlet temperature. After validation, 12 different cases of curved finned HEX are modelled using k-ε model and they were run and results are obtained. The temperature contours of random cases are represented in Fig. 4.

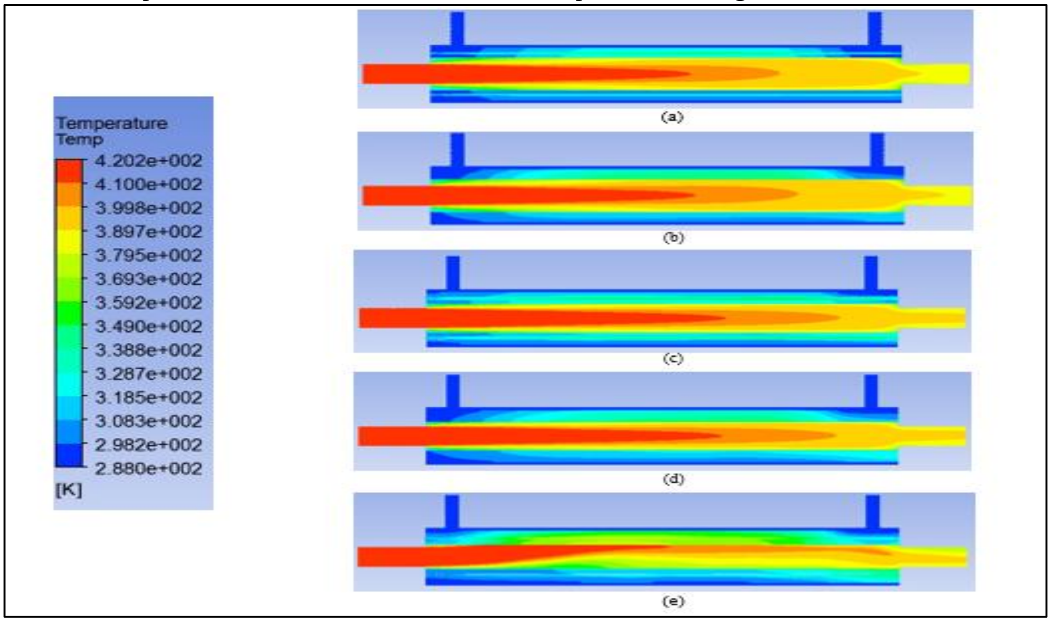

Fig. 4: Longitudinal temperature contours of (a) Case 1 (b) Case 3 (c) Case 6 (d) Case 8 (e) Case 11

The output obtained from the simulation of flow is represented on Fig. 5. Fig. 5 (a) represents the exhaust outlet temperatures. Water outlet temperature is represented by Fig. 5 (b). It was clear with increase in fin height and fin curvature (increase in term fin curvature actually means curve tending to a straight line) the exhaust outlet temperature decreases whereas the water outlet temperature increases.

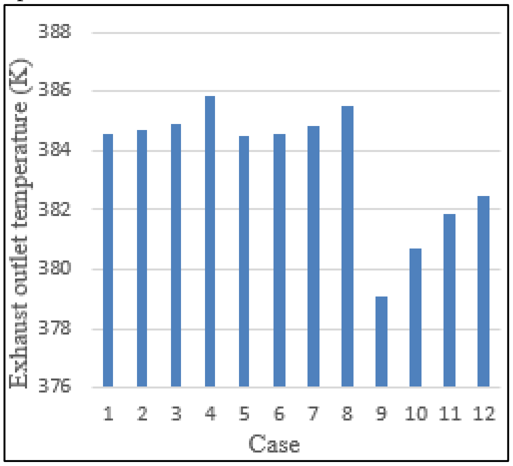

Fig. 5 (a)

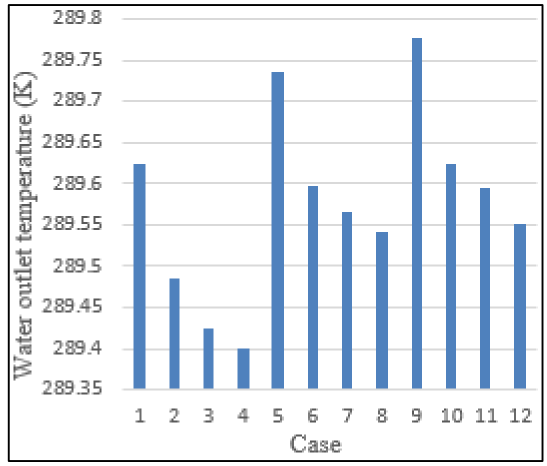

Fig. 5 (b)

Fig. 5: (a) Exhaust outlet temperatures of HEX (b) Water outlet temperatures

From the exhaust outlet temperature and water outlet temperatures, heat recovered is estimated for each cases. The Heat recovered for each fin height at different fin curvatures is shown in the Fig. 6. As the fin height increases, the heat recovered also increases. And the heat recovered decreases with increase in fin curvature (ie, when the fin is becoming less curved) for each cases of the 3 heights. The pressure drops across the HEX is also estimated for all the cases and is represented by Fig. 7. Heat recovered and pressure drops are maximum for case 9 and minimum for case 4. For all the fin heights, as the fin curvature increases the pressure drop decreases. That is, as the fins become less curved, the pressure drop decreases. The rate of increase in pressure drop is comparatively less at lesser fin heights. Also, when fins are less curved, the rate of increase in pressure drop is less compared to higher heights. Pressure drops and Heat recovered varies in the same manner. Their values are maximum when fin height is high and fin is more curved.

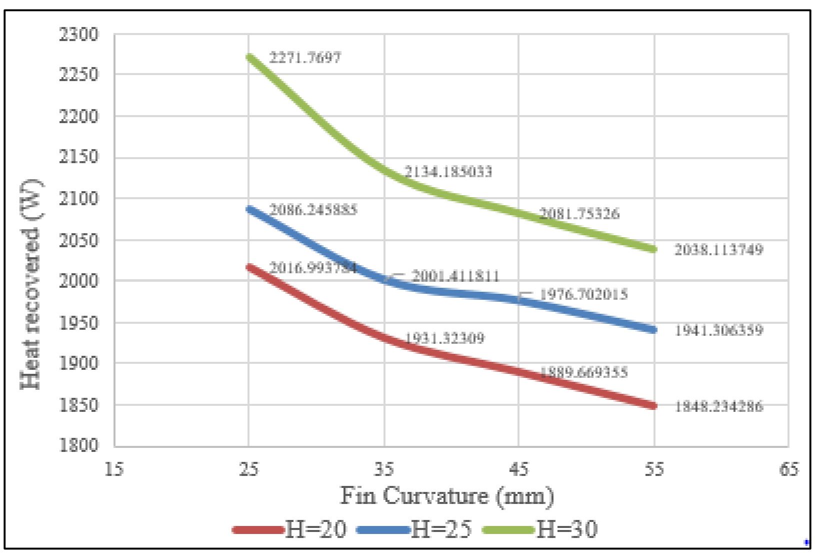

Fig. 6: Heat recovered variation with fin curvatures at H= 20, H= 25, H= 30

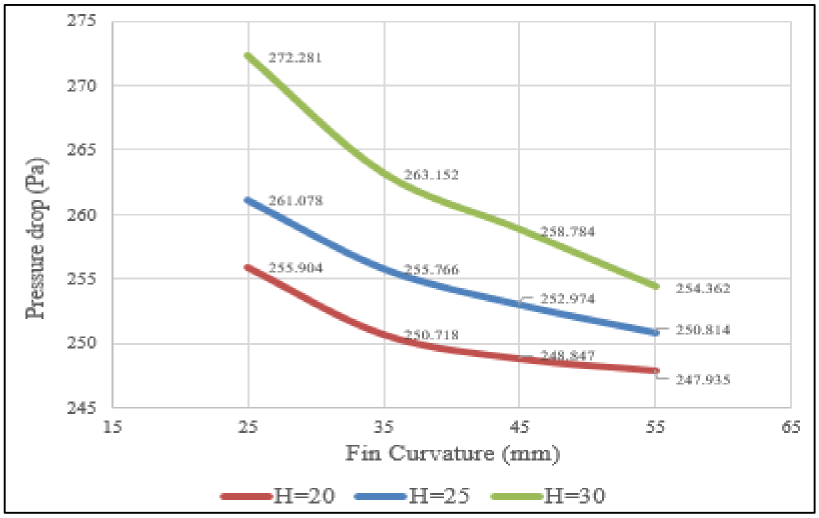

Fig. 7: Pressure drop variation with fin curvatures at H = 20, H = 25, H = 30

The effect of fin height and fin curvature on pressure drop can also be represented by a pressure contour plot as shown in Fig. 8. It can be observed that the increase in fin height and decrease in fin curvature (increase in curviness of fin), both increases the pressure drop. Increase in pressure drops is more sensible at higher fin heights and bigger curves of fin. However, fin height has a more negative effect on pressure drop than fin curvature. Fig. 9 shows a surface plot on effect of fin factors on heat recovered. Here, increase in fin height and curveness of fin increases the heat recovered. But the effect of fin height on heat recovered is slightly more sensible than that of fin curvature because of it's slightly higher slope on the surfaces. Table 3 shows the tabulated results of simulation of all cases.

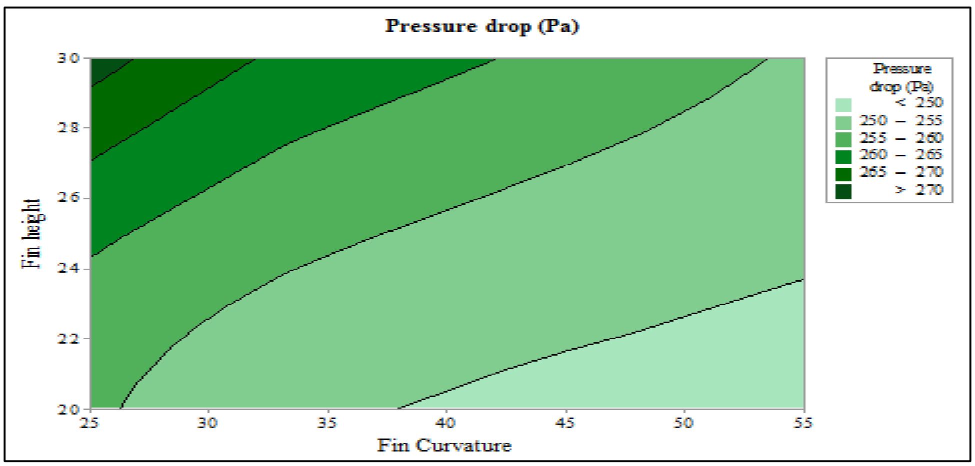

Fig. 8: Contour plot on effect of fin curvature and fin height on pressure drop

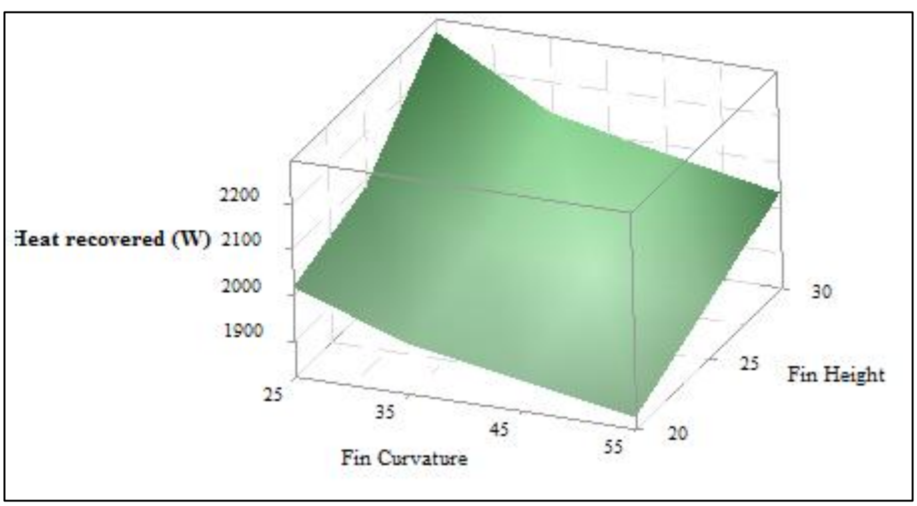

Fig. 9: Surface plot on effect of fin curvature and fin height on heat recovered

Table 3: Tabulation of results of simulation of all cases

Case	*Fin factors*				*Heat recovered (W)*	*Pressure drop (Pa)*	*Desirability*
	Fin curvature	*Fin height*	*Fin thickness*	*Fin number*			
1	*25*	*20*	*4*	*10*	*2016.993784*	*255.904*	*0.535565758*
2	*35*	*20*	*4*	*10*	*1931.32309*	*250.718*	*0.540934379*
3	*45*	*20*	*4*	*10*	*1889.669355*	*248.847*	*0.530185731*
4	*55*	*20*	*4*	*10*	*1848.234286*	*247.935*	*0.5*
5	*25*	*25*	*4*	*10*	*2086.245885*	*261.078*	*0.511060796*
6	*35*	*25*	*4*	*10*	*2001.411811*	*255.766*	*0.520004775*
7	*45*	*25*	*4*	*10*	*1976.702015*	*252.974*	*0.548173916*
8	*55*	*25*	*4*	*10*	*1941.306359*	*250.814*	*0.55074844*
9	*25*	*30*	*4*	*10*	*2271.7697*	*272.281*	*0.5*
10	*35*	*30*	*4*	*10*	*2134.185033*	*263.152*	*0.525060556*
11	*45*	*30*	*4*	*10*	*2081.75326*	*258.784*	*0.55286954*
12	*55*	*30*	*4*	*10*	*2038.113749*	*254.362*	*0.592167143*

From the results, it is clear that the heat recovered is maximum when fin height is maximum and when fin is more curved. But the pressure drops are also considerably high in such cases. The main objective of this work is to achieve maximum heat transfer within minimum pressure drop. An optimization analysis is necessary to achieve that. Maximization of heat recovered and minimization of pressure drop can be done by using the desirability approach.

– For a maximum value as the required goal, the desirability can be defined by:

$$di = \begin{cases} 0 & , \quad Yi \leq Low \\ \dfrac{Yi - Low}{High - Low} & , \quad Low < Yi < High \\ 1 & , \quad Yi \geq High \end{cases}$$

– For a minimum value as the required goal, the desirability can be defined by:

$$di = \begin{cases} 1 & , \quad Yi \leq Low \\ \dfrac{High - Yi}{High - Low} & , \quad Low < Yi < High \\ 0 & , \quad Yi \geq High \end{cases}$$

Where d_i is the desirability of i^{th} case, Y_i, High & Low are the i^{th} value, highest value and lowest value of resultant factor to be minimized or maximized respectively. Overall desirability, can be obtained by the mean of these two desirability's which is shown in Table 3. The desirability chart of 12 cases of HEX is shown by the Fig. 10. From that, it is clear than case 12 has the highest desirability. Hence, case 12 is the best design of curved finned HEX among all the 12 cases. Fig. 11 shows the contour plot on effect of fin curvature and fin height on desirability. Except for low fin heights, desirability increases with increase in fin curvature. ie, when fins become less curved.

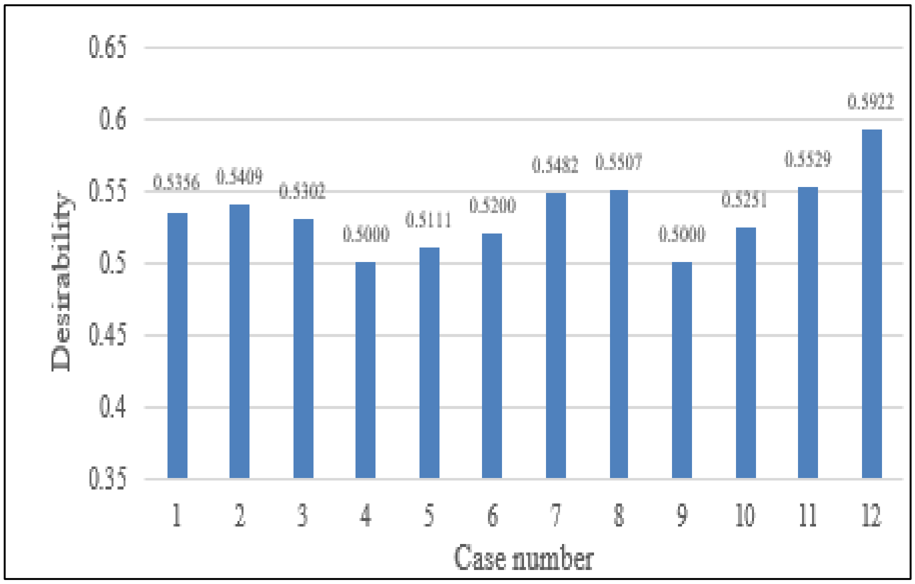

Fig. 10: Desirability chart of 12 cases of HEX

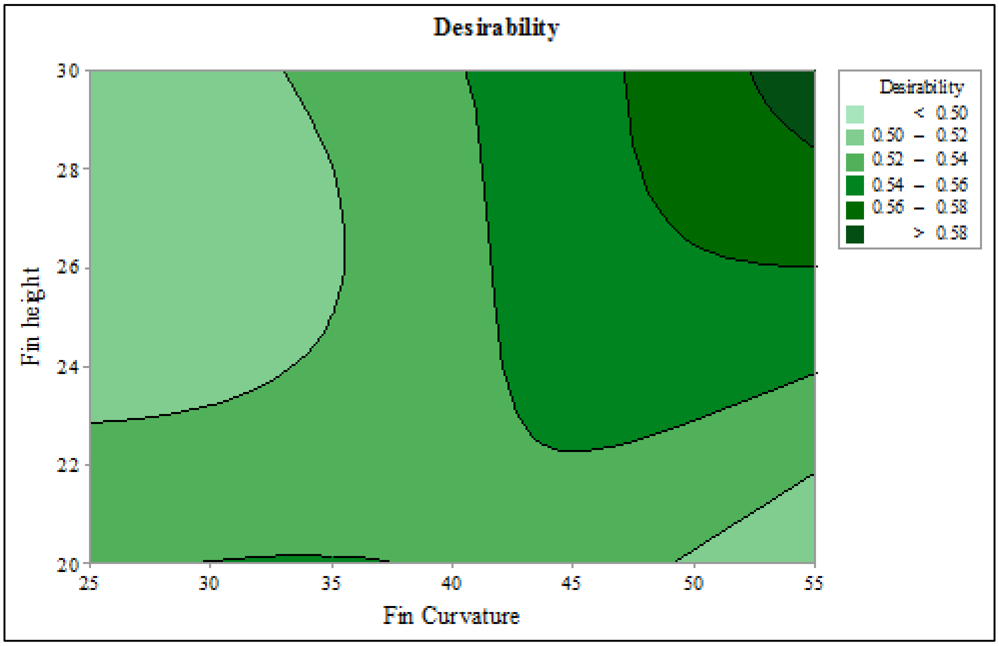

Fig. 11: Contour plot on effect of fin curvature & fin height on desirability

VI. CONCLUSION

In this study, the optimization of curved finned tube heat exchanger is done. For that 12, different models of heat exchanger are designed. Fin curvature and fin height are varied to obtain the maximum heat recovery. The increase in fin height and decrease in fin curvature (increase in curviness of fin), both increases the heat recovery & pressure drop. Increase in pressure drops is more sensible at higher fin heights and bigger curviness of fin. However, fin height has a more negative effect on pressure drop than fin curvature. The effect of fin height on heat recovered is slightly more sensible than that of fin curvature. It was observed that the heat recovered is maximum when fin height is maximum and when fin is more curved. But the pressure drops are also considerably high in such cases. The main objective of this work is to achieve maximum heat transfer within minimum pressure drop. In order to find the best optimum design of curved finned HEX, an optimization analysis is performed. Maximization of heat recovered and minimization of pressure drop was done by using the desirability approach. From the desirability test, it was found that case 12 having a geometry of fin curvature – 55mm and fin height – 30mm has the maximum desirability (0.592167143) and hence it is the best design among the 12 cases. Desirability is low at bigger curviness of fins. Except for low fin heights, desirability increases with increase in fin curvature (when fins become less curved).

REFERENCES

[1] M. Hatami, M. Jafaryar, D.D. Ganji, M. Gorji-Bandpy, “Optimization of finned-tube heat exchangers for diesel exhaust waste heat recovery using CFD and CCD techniques”, International Communications in Heat and Mass Transfer 57 (2014) 254–263
[2] M. Hatami, D.D. Ganji, M. Gorji-Bandpy, “A review of different heat exchangers designs for increasing the diesel exhaust waste heat recovery”, Renew. Sust. Energ. Rev. 37 (2014) 168–181.
[3] Vamsi Mokkapati, Chuen-Sen Lin, “Numerical study of an exhaust heat recovery system using corrugated tube heat exchanger with twisted tape inserts”, Int. Commun. Heat Mass Transfer (2014).
[4] V. Pandiyarajan, M. Chinna Pandian, E. Malan, R. Velraj, R.V. Seeniraj, ”Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system”, Appl. Energy 88 (2011) 77–87.
[5] S. Lee, C. Bae, “Design of a heat exchanger to reduce the exhaust temperature in a spark-ignition engine”, Int. J. Therm. Sci. 47 (2008) 468–478.
[6] H.G. Zhang, E.H. Wang, B.Y. Fan, “Heat transfer analysis of a finned-tube evaporator for engine exhaust heat recovery”, Energy Convers. Manag. 65 (2013) 438–447.
[7] M. Ghazikhani, M. Hatami, Gh. Shahi, A. Behravan, “Exergy analysis and experimental investigation on exhaust sound level in a DI diesel engine”, 7th international conference of internal combustion engine, Olympic international hotel, Tehran, Iran, 2011.
[8] M. Ghazikhani, M. Hatami, D.D. Ganji, M. Gorji-Bandpy, Gh. Shahi, A. Behravan, “Exergy recovery from the exhaust cooling in a DI diesel engine for BSFC reduction purposes”, Energy 65 (2014) 44–51.
[9] S. Mavridou, G.C. Mavropoulos, D. Bouris, D.T. Hountalas, G. Bergeles, “Comparative design study of a diesel exhaust gas heat exchanger for truck applications with conventional and state of the art heat transfer enhancements”, Appl. Therm. Eng. 30 (2010) 935–947.