CFD Analysis of Exhaust Heat-Exchanger in Automobile Thermoelectric Generator

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Abstract: ***The world is facing a historical increase in energy demand and energy consumption. Regenerating energy sources are considered a solution of both environment issue and energy demand. A major part of the heat supplied in an internal combustion engine is not realized as work output, but dumped into the atmosphere as waste heat. If this waste heat energy is tapped and converted into usable energy, the overall efficiency of an engine can be improved. The percentage of energy rejected to the environment through exhaust gas which can be potentially recovered is approximately 30-40% of the energy supplied by the fuel depending on engine load. Thermoelectric modules which are used as thermoelectric generators are solid state devices that are used to convert thermal energy from a temperature gradient to electrical energy and it works on basic principle of Seebeck effect. Ideal heat exchangers recover as much heat as possible from an engine exhaust at the cost of an acceptable pressure drop. They provide primary heat for a thermoelectric generator (TEG), and their capacity and efficiency is dependent on the material, shape, and type of the heat exchanger Therefore in this work design of internal structure has been done to increase heat transfer and to reduce pressure drop.***

Keywords: Thermoelectric generator, Heat exchanger, Waste heat recovery, Heat transfer.

1. Introduction

Various thermodynamic cycles have been proposed and studied for low-grade waste heat recovery. An absorption cooling cycle in hybrid and electric vehicles transfers waste heat from the battery pack and exhaust gases into the boiler of ejector for cabin cooling. An open steam power cycle, combined thermoelectric generator and Organic Rankine cycle. Usually, the disadvantage of these cycles is the secondary fluid circuit composed of a pump, an evaporator, an expander and a condenser; the circuit increases vehicle weight and mechanical complexity and reduces available volume. The thermoelectric generator system takes the advantage of no moving parts, silent operation, and very reliable, therefore better suited waste heat recovery from automobile exhausts than the above cycles. [1]

Being one of the promising new devices for an automotive waste heat recovery, Thermoelectric generators (TEG) will become one of the most important and outstanding devices in the future. A thermoelectric power generator is a solid state device that provides direct energy conversion from thermal energy (heat) due to a temperature gradient into electrical energy based on “Seebeck effect”. The thermoelectric power cycle, with charge carriers (electrons) serving as the working fluid, follows the fundamental laws of thermodynamics and intimately resembles the power cycle of a conventional heat engine. The basic theory and operation of thermoelectric based systems have been developed for many years. Thermoelectric power generation is based on a phenomenon called “Seebeck effect” discovered by Thomas Seebeck in 1821. When a temperature difference is established between the hot and cold junctions of two dissimilar materials (metals or semiconductors) a voltage is generated, i.e., Seebeck voltage. In fact, this phenomenon is applied to thermocouples that are extensively used for temperature measurements. Based on this Seebeck effect, thermoelectric devices can act as electrical power generators.[1]

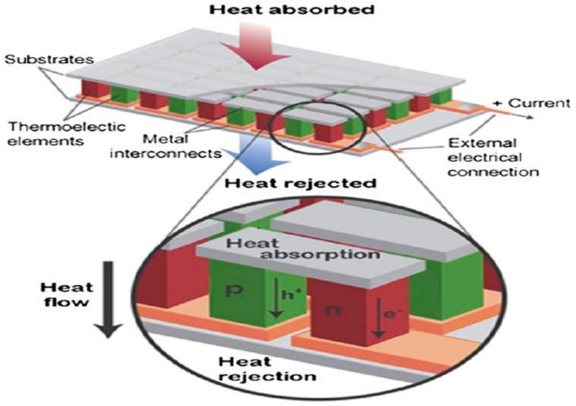

Figure 1: Thermoelectric module [17]

Thermoelectric systems can be easily designed to operate with small heat sources and small temperature differences. Such small generators could be mass produced for use in automotive waste heat recovery or home co-generation of heat and electricity. By converting the waste heat into electricity, engine performance, efficiency, reliability, and design flexibility could be improved significantly. Thermoelectric generator having number of thermoelectric modules arranged parallel to each other and electrically connected in series. The single thermoelectric module having P– Type & N – Type legs, Substrates the material above & below the legs & base material as shown in Figure 1. [16]

2. Literature Review

Ting Wu et al. [1] designed six different exhaust heat exchangers within the same shell, and their computational fluid dynamics (CFD) models were developed to compare heat transfer and pressure drop in typical driving cycles for a vehicle with a 1.2 L gasoline engine. For the purpose of comparison, 6 structures were made with a shell of 280mm X 110mm X 30mm with the inlet and outlet of 40mm in diameter for 5 of the structures. 6 structures are compared regarding heat transfer and pressure drop under urban driving, suburban driving and maximum power output. Among the 6 heat exchangers, the pipe structure has the 2nd greatest pressure drop and the 4th greatest heat transfer rate. The serial plate structure with 7 baffles had the maximum heat transfer rate of all the structures, at 1737W. The serial plate also had a maximum pressure drop of 9.7 kPa. Only the inclined plate and the empty cavity structure had pressure drops less than 80 kPa. They suggested that bypass mechanism with a differential pressure switch is necessary for the engine's stability and reliability if pressure is more than 80 kPa.

X. Liu at al. [2] built an energy-harvesting system which extracts heat from an automotive exhaust pipe and turns the heat into electricity by using thermoelectric power generators. The plate-shaped heat exchanger of TEG is connected to the exhaust pipe of diameter 36 mm on both sides. The section of the plate-shaped exchanger of 5 mm thickness is a 400mm long by 290 mm wide rectangle. Two three dimensional models of heat exchangers with different internal structures were designed are called fishbone-shaped and chaos-shaped heat exchangers. Heat exchanger thickness of 3 mm, 5 mm and 8mm were taken for simulation comparison, using the chaos-shaped structure and the same boundary conditions. 5 mm thickness heat exchanger is selected. To further verify 60 pieces of TMs were placed on the front and back surface of the heat exchanger, the maximum electrical power output of fishbone shaped TEG is 160.21 W while the chaos-shaped is 183.24 W. Considering the agreement between the experimental results and the CFD flow simulation results, a heat exchanger with chaos shape and thickness of 5 mm is selected to form hot side.

C.Q. Su et al. [3] studied about the thermal characteristics of heat exchangers such as internal structure, material and surface area. Computational fluid dynamics (CFD) software is used to simulate the exhaust gas flow within the heat exchanger. Internal structure, material and thickness of the heat exchanger are changed to obtain the ideal thermal field simulation results. The geometrical model of the heat exchanger including fishbone-shaped internal structure, accordion-shaped internal structure, and scatter-shaped internal structure are compared in terms of temperature distribution. These heat exchangers with different surface areas are designed, which are 598 mm X 250 mm, 660mm X 305 mm and 775mm X 365 mm. Pictures of the surface temperature field on the heat exchanger made of iron and brass with 5mm thickness of plate are taken by the infrared thermal imaging system. Modules on the brass exchanger have higher output power than those on the iron heat exchanger. According to the agreement between the infrared experimental results and the CFD simulation results, a brass heat exchanger with accordion shape and surface area (660mm X305 mm) was selected to form the hot side.

Y. D. DENG et al. [4] studied about thermal performance of the heat exchanger in exhaust-based TEGs. In terms of interface temperature and thermal uniformity, the thermal characteristics of heat exchangers with different internal structures, lengths, and materials are studied. CFD was used to simulate the exhaust gas flow within the heat exchanger. Three-dimensional models of plate-shaped and hexagonal prism shaped heat exchangers, are made of brass, were designed and compared. Volume of the hexagonal-prism-shaped heat exchanger is too large, which is not beneficial. Considering this factors, the plate-shaped heat exchanger is more suitable for TEG application. Thermal performances of the maze-shaped internal structure and the fishbone-shaped internal structure are relatively ideal. From CFD simulation results, the maze shape has slightly higher interface temperature at the front end but lower at the outlet. However, the fishbone design shows better uniformity. Thus, the heat exchanger with fishbone shape is more ideal for TEG application. Heat exchanger lengths of 480 mm, 560 mm, and 600 mm were taken for simulation comparison, using the fishbone shaped structure and the same boundary conditions. Considering the overall output powers of the TEG, the greater the length, the more modules can be arranged on the TEG. The CFD simulation results were verified by experiments. Considering the agreement between the infrared experimental results and the CFD flow simulation results, a brass heat exchanger with fishbone shape and length of 600 mm is selected to form the hot side.

C.Q. SU et al. [5] studied about the thermal characteristics of the exhaust gas tanks with different internal structures and thicknesses in terms of the interface temperature and the thermal uniformity. Computational fluid dynamics (CFD) software is adopted to simulate the exhaust gas flow within the gas tank. Different three-dimensional models of the internal structure of the gas tanks are designed by changing internal baffles arrangements. Among these, the temperature distribution in the first structure (the 非shape) and the second structure (the fishbone shape) of the gas tanks are relatively ideal. Considering even temperature distribution, the practical effect of the gas tank with the fishbone shape is much better than that with the 非 shape. The interior thicknesses of the gas tanks are 24 mm, 16 mm, and 12 mm, respectively; for simulation comparison, the internal structures of these three gas tanks are the fishbone shape and other boundary conditions are same. The temperature distributions of the three gas tanks are roughly the same: higher in the middle and lower in both sides. The temperature distribution in 12 mm thickness is relatively more uniform. Thermal imaging system is used to shoot the surface temperature distribution on the gas tanks with different internal structures and varied interior thicknesses. From infrared experimental results and the CFD flow simulation results, the gas tank, the internal structure of which is the fishbone shape and the interior thickness of which is 12 mm, was selected to form the hot box.

Shekhar R. Gulwade et al. [6] studied about the characteristic of the heat exchanger with enhancement features in order to achieve uniform temperature distribution and higher surface temperature. The different internal structures have been used in the heat exchanger to enhance heat transfer rate. The internal structure of the heat exchanger made up of aluminum of 5 mm thickness, fin thickness is also 5 mm and 20 mm height made up of aluminum. According to the position of the fins on the plate it is divided into number of internal structure such as inclined plate structure, Fishbone-shaped structure, Serial plate structure, Separate plate with holes, Dimple structure, and Accordion-shaped structure. Computational fluid dynamics (CFD) was used to simulate the exhaust gas flow within the heat exchanger, enabling simulation of the interface temperature distribution. Among these, the temperature distribution in the inclined-plate is relatively ideal, as compare to the fishbone shape.

G. Murli et al [7] modeled and compared four different configurations of heat exchange through Computational Fluid Dynamics (CFD) software. They are Fishbone shape, accordion shape, and serial plate and empty cavity heat exchangers. Comparing four different heat exchangers, the serial plate has maximum heat transfer 4062W compared with other heat exchangers.

X. Liu et al. [8] tried to vary the installation position of TEG and propose three different cases. In case 1, TEG is located at the end of the exhaust system; In case 2, TEG is located between CC and muffler; In case 3, TEG is located upstream of CC and muffler. In case 2, the heat exchanger obtained a relatively high surface temperature and an ideal temperature uniformity to improve the efficiency of the TEG. The pressure drop of catalytic converter, muffler and heat exchanger was relatively low, which met the requirement of the exhaust gas system. At the same time, the catalytic converter and muffler in case 2 can keep normal working. So they concluded that case 2 is the best.

Ting Wu et al. [9] combine exhaust heat exchanger with muffler in the form of 1-inlet 2-outlet, 2-inlet 2-outlet and the baseline empty cavity. Two exhaust heat exchangers with muffler-like internal structure were proposed as 1-inlet 2-outlet and 2-inlet 2- outlet based on the referenced structure: empty cavity. From this experiment they concluded that the symmetrical 1-inlet 2-outlet increased hydraulic disturbance and enhances heat transfer, resulting in the more uniform flow distribution than the 2-inlet 2-outlet and empty cavity.

Jins jose at al. [10] numerically modelled and analyses two cases of heat exchangers such as rectangular type and square type in exhaust of internal combustion engine to recover the exhaust waste heat. The heat exchangers made up of aluminum have inlet and outlet manifold diameters as 80mm, the width of the wall at inlet as110mm and at the outlet 130mm. The cross sectional area of the square heat exchanger is 110mm x 110mm. The wall thickness is about 5mm. The rectangular heat exchanger shows better surface temperature, an ideal temperature uniformity which improves TEG performance. Also the rectangular heat exchanger shows comparatively less pressure drop as well as better heat flux.

3. Simulation Analysis

3.1 Simulation operating condition

The fluid model is uncompressible. The viscous model depends on the flow type: laminar flow or turbulent flow. The k-epsilon turbulence model was employed to simulate the exhaust. This model has been proven to be stable and numerically robust. The fluid material for the exhaust uses a calorically perfect ideal gas because the two are near to one another thermodynamically, and the solid material for shell employs stainless steel.[1] Adopted convergence scale is under 10^{-3} for momentum balance, 10^{-6} for energy balance and relative error 0.1% for total energy conservation of system.[2]

Exhaust is a mixture of multiple compositions and is thermodynamically similar to air. Exhaust is approximately 300-500 kPa in pressure and 500-700^{o}C in temperature when discharged from the engine cylinder. After passing through the catalytic converter and several connecting pipes, the pressure drop nears to atmospheric pressure and the temperature decreases to 300-600^{o}C because of local and frictional losses and heat leaks.[1] The boundary conditions are defined on the geometry are given in Table 1.

Table 1: Boundary conditions on empty cavity structure

Fluid inlet	Mass flow rate 0.0144 kg/s at temperature 673.15K
Fluid outlet	Gauge pressure 0 Pa.
External wall	Convection Heat transfer co-efficient 15 W/m ^{2}K

3.2 Validation

To validate the CFD analysis results, Empty cavity structure will be used as an exhaust heat exchanger. Specification of Empty cavity structure proposed by Ting Wu et al.[1] is given in Table 2.

Table 2: Specifications of empty cavity structure [1]

Exhaust pipe diameter	40 mm
Heat exchanger length	280 mm
Heat exchanger width	110 mm
Heat exchanger height	30 mm
Material for heat exchanger	Stainless steel

The shell is of 280mm X 110mm X 30mm with the inlet and outlet of 40 mm in diameter. At both end of the shell, there were gradual enlargement and contractions of approximately 90 mm in length to distribute the flow. This empty cavity structure is shown in Figure 2.

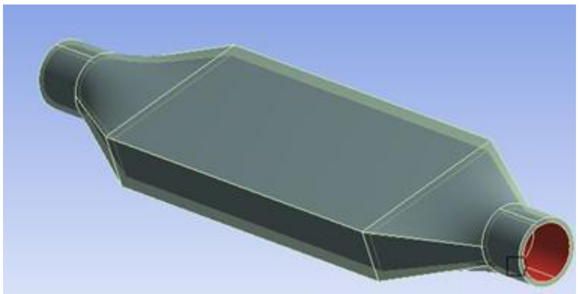

Figure 2: 3D model of Empty cavity structure

3.3 Grid independent test

In Grid independence test, different meshing sizes are taken; for which minimum size, maximum face size & maximum size are changed. At 116288 Number of elements Heat transfer from empty cavity structure is 2071.23 W. After increasing the number of elements there is very small change in amount of heat transfer. So 116288 number of elements are taken for simulation. The graph of number of elements vs. Heat transfer is shown in Figure 3.

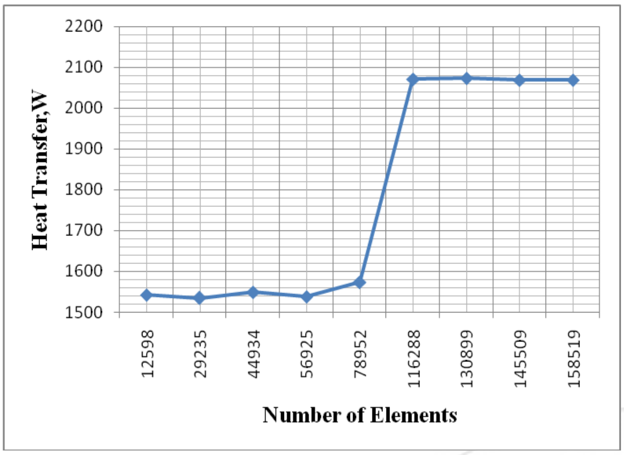

Figure 3: Grid independent test

3.4 Analysis of empty cavity structure

In experiment done by Ting Wu et al [1], for mass flow rate ranging from 0.0325 to 0.0600, amount of heat transfer and pressure drop in Empty cavity structure has been measured. Validation has been done with these experimental data for which the graph of mass flow rate vs. Heat transfer rate and mass flow rate vs. Pressure drop are shown in Figure 4 and Figure 5 respectively in which present CFD results and experimental data which is done by Ting Wu et al [1] are compared.

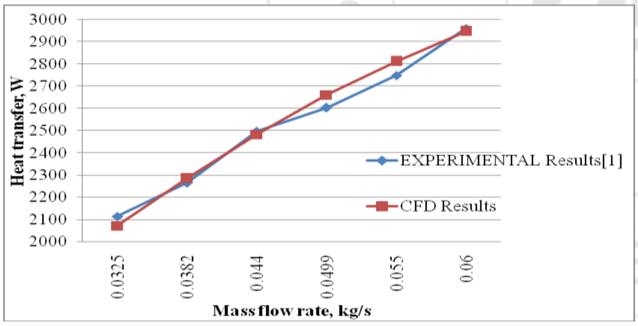

Figure 4: Variation of Heat transfer rate with mass flow rate at 673.15 K

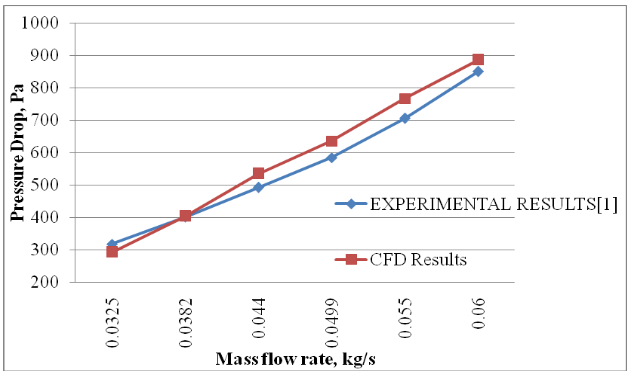

Figure 5: Variation of pressure drop with mass flow rate at 673.15 K

Average deviation between present CFD result and experiment work for heat transfer rate is 1.97% and for pressure drop is 7.13%. Good agreement of results found between the present work and that proposed by Ting Wu et al. [1].

4. CFD analysis of modified structure

4.1 Design of new internal structure

For the purpose of comparison structure is made with same dimension with shell of 280mm X 110mm X 30mm with inlet and outlet diameter of 40mm. Two different types of baffles are arranged having a dimension of 30mm X 10mm X 40mm and 30mm X 10mm X 50mm. Baffle having a dimension of 30mm X 10mm X 50mm is for to outwards and baffle having a dimension of 30mm X 10mm X 40mm is for to inwards. So that the exhaust gas can be fully in contact with the metal walls of the heat exchanger and stays longer in the cavity of the heat exchanger, which can increase the heat that airflow transfers to the fins.

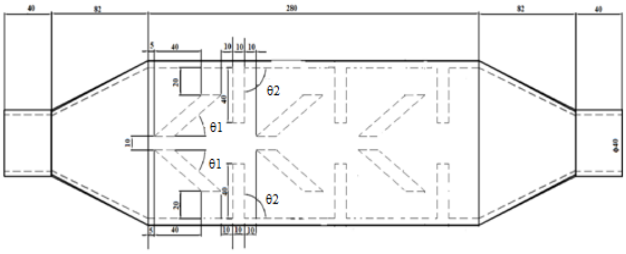

Figure 6: 2D model of a new geometry

Table 3: Effect of change in baffle angle on a heat transfer rate

θ_1	θ_2	Heat transfer rate, W
90	90	2056.37
80	90	2036.56
70	90	2017.57
60	90	1999.41
50	90	1965.34
40	90	2045.25
39	90	2058.68
38	90	2088.09
37	90	2096.14
37	85	2076.50
37	75	2049.46
37	70	2022.44
90	80	2042.61
90	70	2030.17
90	60	2020.38

Table 3 shows the change in heat transfer rate with change in angle of baffles. Based on the available space in a rectangular section of an exhaust heat exchanger, baffle angle has been changed as the only heat that will be absorbed in a rectangular section will be useful in TEG for power generation. At $\theta_1=37^o$ and $\theta_2=90^o$ Heat transfer is maximum which is 2238.64W.

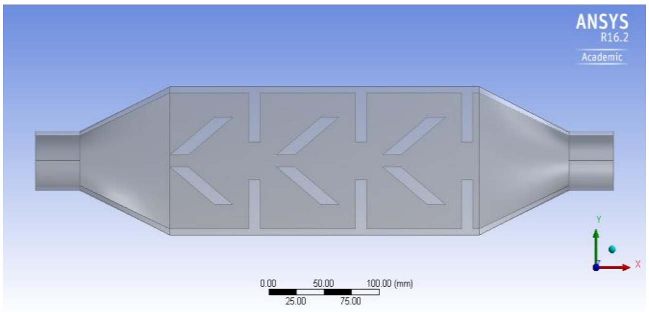

Figure 7: 3D model of a modified structure with optimum baffle angle combination

4.2 Grid independent test and meshing

In Grid independent test, different meshing sizes are taken; for which minimum size, maximum face size & maximum size are changed due to which the number of elements are changed from 24311 to 470422. For 251305 Number of elements Heat transfer new structure is 2096.14 W. Further increasing the number of elements shows very small change in amount of heat transfer. So 251305 numbers of elements are taken for simulation. The graph of number of elements vs. Heat transfer is shown in Figure 8. For 251305 number of elements,

Minimum size – 2 mm
Maximum Face size – 4 mm
Maximum size – 4.3 mm

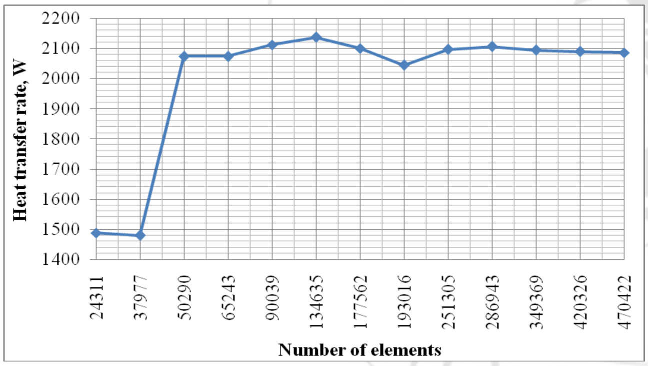

Figure 8: Graph of Grid Independent test of modified structure

4.3 Contours of modified structure

A symmetrical plane along the thickness of the shell was generated to obtain the temperature field and the pressure field of the exhaust. All the contours indicated are at constant mass flow rate 0.0144 kg/s and temperature at 673.15 K. Figure 9 shows the temperature contour of modified structure at the symmetrical plane along the thickness of the exhaust heat exchanger.

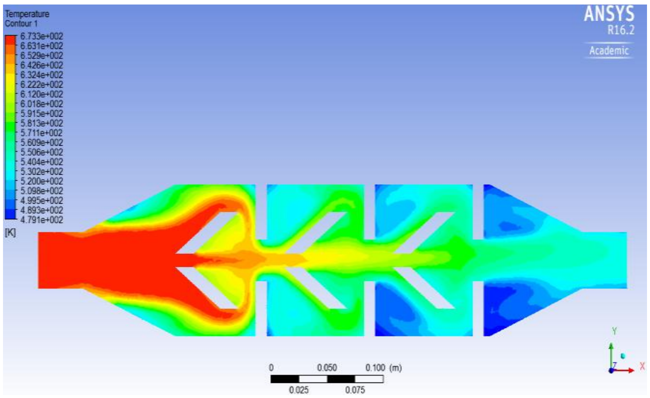

Figure 9: Temperature contour of a modified structure at XY plane

There are two fins set at the entrance for diverting the flow, so that the high-temperature exhaust gas is diffused in the entire lateral area rather than concentrating in the central region.

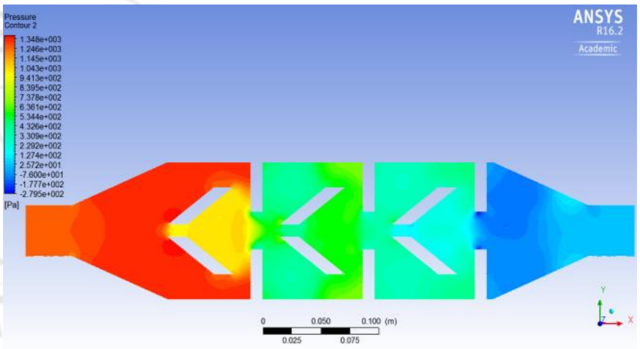

Figure 10: Pressure contour of a modified structure at XY plane

Another type of fins are set such that exhaust gas is concentrated at centre, so that the exhaust gas can be fully in contact with the metal walls of the heat exchanger and stays longer in the cavity of the heat exchanger, which can increase the heat that airflow transfers to the fins. Figure 10 shows the pressure contour of a modified structure.

4.4 Comparison of serial plate structure and modified structure

Serial plate structure was concluded as a best structure by Ting Wu et al. [1] in their case study. Comparison has been made under three different cycles which are Urban, Suburban and maximum power cycle. According to the range of the mass flow rate of exhaust gas, three typical operation conditions were considered as shown in Table 4 which are urban and suburban driving cycles and maximum power output.

Table 4: Operating conditions[1]

Driving cycle	Mass flow rate of Exhaust (g/s)	Hot side temperature of generator (K)	Exhaust temperature (K)
Urban	5.7	423.15	573.15
Suburban	14.4	473.15	673.15
Maximum power output	80.1	423.15	873.15

For Serial plate structure Heat transfer is 597 W, 1737 W and 14971 W for Urban, Suburban and maximum power cycle respectively. While in new structure, heat transfer is 673.61 W, 2096.14 W and 16345.60 W respectively. So in new structure heat transfer is increased by 12.83 %, 20.67% and 9.18% for the Urban, Suburban and maximum power cycles respectively.

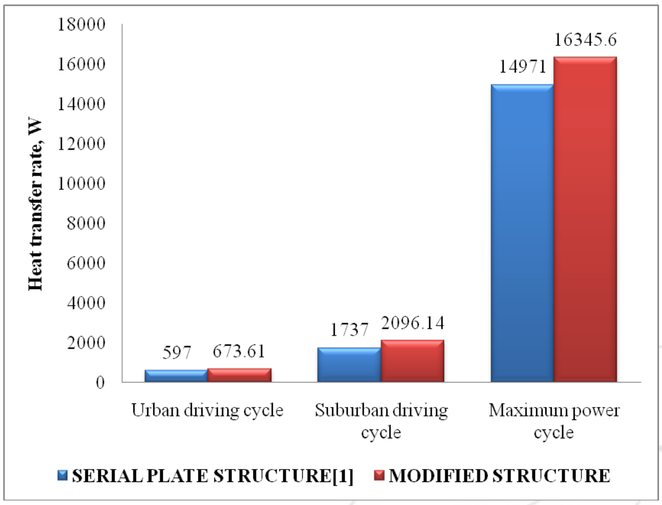

Figure 11: Comparison of Heat transfer rate of serial plate and new structure for different cycle

For Serial plate structure pressure drop is 1.3 kPa, 9.7 kPa and 190.7 kPa for Urban, Suburban and Maximum power cycle respectively. While in new structure, pressure drop is 0.16kPa, 1.239 kPa and 52.787 kPa respectively. So in new structure pressure drop is reduced by 71.25%, 68.29% and 26.12% for the Urban, Suburban and maximum power cycles respectively.

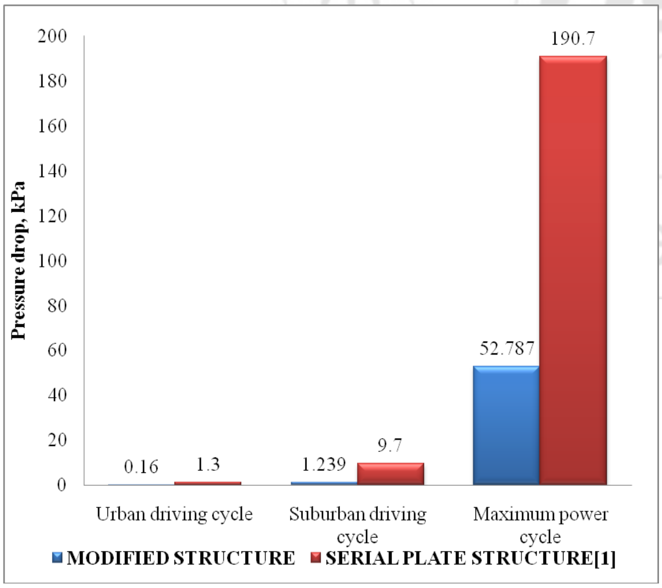

Figure 12: Comparison of pressure drop of serial plate and new structure for different cycle

Under the maximum power output condition, if the pressure drops is greater than 80 kPa, the automobile engine may fail to function or even shutdown if the bypass mechanism is not available.[1] In this modified structure, pressure drop under maximum power cycle is less than 80 kPa so it will not adversely affect the engine performance.

5. Conclusion

CFD models with a solid domain, liquid domain and fluid–solid interfaces were developed for exhaust heat exchangers to simulate the temperature field and pressure field. Under all the operating conditions modified structure shows better heat transfer performance compared to serial plate structure. In this modified structure, pressure drop under maximum power cycle is 52.787 which is less than 80 kPa. So it will not adversely affect the engine performance

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