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NUMERICAL ANALYSIS OF COOKING OVEN POWERED BY ENGINE EXHAUST GAS

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Abstract

Perfect heat exchangers (HXs) reduce waste heat by converting car exhaust gases to useful heat at an acceptable amount of pressure drop. In this study, HXs were used to supply heat for a cooking oven instead of using electrical heater to warm and girl meal in long trip the system can be reduce the waste heat and decrease the ambient temperature. Generally, the efficiency of HXs depends on the type of material and type of HX. Two different exhaust HXs were modelled, one is hollow shell and the other is shell equipped with baffles. By using computational fluid dynamics (CFD) programme, the two designs were improved to compare the back pressure and heat transfer in a perfect driving cycles of a car with a (1.2) Litter of Otto-cycle-engine. Results show that the rate of heat transfer in a shell equipped with four serial plates baffles reaches (370W). A maximum pressure drop of (140Pa) is achieved under the conditions of the driving in suburban. The CFD results of the shell equipped with serial fins were compared with an empty pipe. The empty pipe under the maximum power output provides a back pressure of less than (80kPa) which is acceptable under operation condition of the maximum output power. Therefore, the use of pressure valve with serial plate structure is important to bypass parts of the exhaust system.

Keywords: Baffles, Cooking oven, Engine exhaust gas, Heat exchanger.

1. Introduction

Waste heat recovery is intensively applied due to the energy crisis worldwide [1, 2]. In recent years, several studies have been conducted on exhaust gas recovery to reduce waste heat to the environment and carbon dioxide emissions and enhance the efficiency of internal combustion engines; these studies converted thermal energy into electrical energy by utilising thermoelectric generators or utilizing the thermal energy in a useful works [3]. Although cars are an important transportation mode, they produce considerable waste heat. Two-thirds of a car's engine energy generated from fuel combustion is transferred to the environment [4], a small percentage of a car's engine energy is used for heating its cabin rather than utilising its air-conditioning unit that consumes more engine energy, and other small parts of energy recovered are consumed to enhance powertrain efficiency.

Figure 1 shows the flow path of fuel consumption of an internal combustion engine, where 70% of the total fuel energy is lost to the environment, whereas only 25% of fuel consumption is used for vehicle operation [3-5].

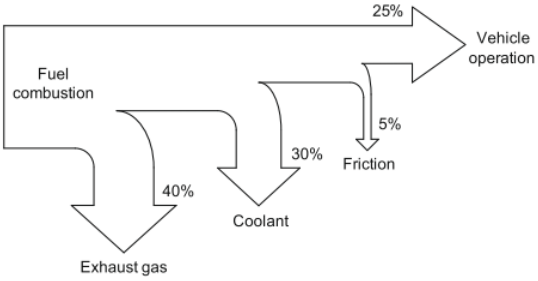


Fig. 1. Energy flow of an internal combustion engine.

Most researchers used heat exchangers (HXs) in thermoelectric generators to recover exhaust gas and produce electrical energy [5-8]. The shape, material and type of an exhaust gas HX were studied previously.

Abdulhamed et al. [9] designed and fabricated a shell and tube heat exchanger for portable solar powered water distiller system with four segmental baffles to increase the flow turbulent and Nusselt number.

Abdulhamed [10] presented a new system for flow turbulent by utilizing 20 rings with cross connection inserted in receiver tube of parabolic trough collector. Two geometries of exhaust HXs, equipped with inner fins, have shapes of cylinder and box, were utilized for car exhaust gas recovery.

Birkholz et al. [11] proposed a rectangular shape structure equipped with inner fins fabricated from (Hastelloy-X-alloy) to improve heat transfer. Crane and LaGrandeur [12] presented a stainless-steel shell with cylindrical shape equipped with internally bended fins and conducted computational fluid dynamics (CFD) simulations with geometry improvement to increase turbulent flow and heat transfer.

Martinez et al. [13] computed the pressure drop and thermal properties of a HX through CFD simulations. Determining the best or suitable HX for car exhaust gas recovery is difficult due to the large number of specifications, such as structure parameters, material types and operating conditions. Therefore, CFD is a suitable tool for comparing several HXs under the same boundary conditions [14-17].

The current study presented an empty pipe structure and an internal serial plate structure as an exhaust gas recovery device to power a cooking oven. The pressure drops and heat transfer of the two models under the same boundary conditions were compared by using improved CFD simulation models. The study focuses on benefiting from the waste heat energy from car exhaust in the cooking process, contributing to reducing the ambient temperature.

2. Aim and Objectives

Automobile's engines reject a high amount of waste heat to the surrounding. As a contribution, the study has considered a numerically design of heat exchanger powered by engine exhaust hot gas to as a heat supply to a cooking oven in the car, where the oven will be equipped with HX instead of using electrical heater. The heat transferred from HX to the inner space of oven can use to warm or girl meal in long trips. The study goal also, is to reduce ambient temperature by reducing the waste heat.

3. CFD Analysis

The limited range for allowable value of pressure drop of a car engine exhaust system is a large drawback for the use of HXs. An efficient HX must meet the application requirements and the vehicle operation level.

3.1. Design of exhaust HXs

In design of heat exchanger, it is necessary to identify the study limitations, such as the space to build the system, exhaust output temperature, and pressure drop. The study has considered design heat exchanger to place inside cooking oven, instead of electrical heater; therefore, the dimensions of HX are limitation based on actual oven dimensions.

Ansys-15 (Fluent) is used to simulate the current design. One empty shell and one box shell with internal plates arranged in serial were fabricated for comparison. The dimensions of these structures are (250 mm×200 mm×30 mm) as length, width, and high respectively, with 25.4 mm and 3 mm as inside diameter and thickness of the inlet and outlet pipes.

The external geometries of the internal serial plate are shown in Fig. 2. Half of the whole body was utilized to minimize the tetrahedral mesh quantity and increase the accuracy. The design was obtained by utilizing a symmetrical plane. With model complexity, the number of elements of mesh increased. The empty shell had smaller number of elements with 441,076, and the serial structure had higher number of elements with 739,485.

The number of elements of the serial structure was 40% higher than that in the empty cavity due to the use of fins, as shown in Fig. 3. The quantity and quality of a mesh for a physical model are used to determine the accuracy, robustness and scale of CFD simulation. The essential quality measure used for a mesh is skewness, which ranges from 0.25 to 0.3. These values represent a good mesh quality. Table 1 presents the mesh goodness values for the two designed shell.

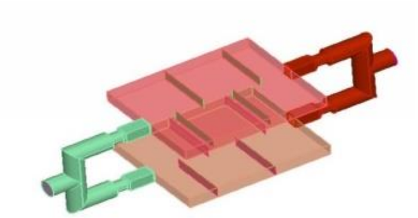


Fig. 2. HX with serial plate structure.

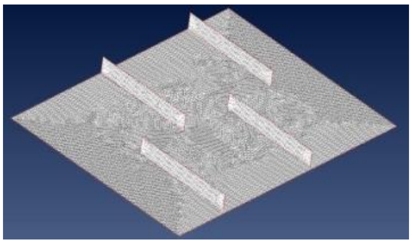


Fig. 3. Mesh of model.

Table 1. Mesh of each model.

Items	Empty shell	Serial plate
Nodes	134,428	220,843
Elements	441,076	739,485
Skewness	0.2626	0.2925

3.2. Simulation of operating conditions

Three variables, namely, exhaust temperature, mass flow rate and hot side temperature of HX, are used in the cooking oven HX powered by exhaust gas. These variables depend on the vehicle design, HX materials and operating conditions.

3.2.1. Calculation of exhaust gas flow rate

Determining the exhaust gas mass-flow-rate, which depends on vehicle engine configuration and operating conditions, is important to obtain the capacity of a vehicle exhaust gas HX. The automobile used in the test was supplied with a (1.2) Litter gasoline engine. Its specifications are listed in Table 2. The data of consumption fuel for the examined automobile based on the GB/T 19233-2008 measurement method were provided by the Ministry of Industry and Information Technology of the People's Republic of China, as listed in Table 3.

The exhaust gas flow rate is determined via using Eq. (1) [18].

$$\dot{V} = \rho . A . u \tag{1}$$

Heat energy removed from the engine exhaust system the exhaust gas flow rate by mass, was multiplied via the enthalpy variation at the inlet of HX and outlet of HX under the given boundary condition. The back pressure in the HX, that represents the difference in exhaust gas pressure between the inlet of HX and outlet of HX.

$$\Delta \boldsymbol{P} = \boldsymbol{P_1} - \boldsymbol{P_2} \tag{2}$$

Table 2. Vehicle specifications.

Type of Engine	P-TEC, LMU
Transmission	MT-5 4
Displacement (Volume) (cm^3)	1,206
Number of Cylinders	4
Number of Valves	16
Maximum power (kW/rpm) injection system	63/6,000 108/4,000
Maximum torque (N·m/rpm)	108/4,000
Type of Injection	Electric - controlled - injection

Table 3. Consumption of fuel.

Type of driving	Fuel Consumption, (L /100 km)	Exhaust flow rate, (g/s)
Urban	6.7	5.7
Suburban	5.1	14.4
Overall	5.7	8.53
Max. power output	-	80.14

3.2.2. Exhaust state

Exhaust gas is thermodynamically similar to air and is a summation of multiple gases. The temperature and pressure ranges are 500 °C-700 °C and 300-600 kPa, respectively, when exhaust gas leaves the cylinder of vehicle engine [19]. After passing the exhaust gas through silencing pipes, the pressure reduces to approximately of the ambient pressure, then the temperature drops to 150 °C due to frictional and local losses as well as heat leakage.

3.2.3. The Temperature of hot side in A HX

The HX transfers heat to the oven environment. Therefore, three typical operating conditions, namely, driving in urban, driving in suburban and driving with conditions of maximum output power, were considered, as shown in Table 4.

Table 4. The engine operating conditions.

Type of driving	Exhaust flow rate, (g/s)	Hot side HX (K)	Exhaust Temp. (K)
Urban	5.6	383.12	396.12
Suburban	13.8	393.14	413.14
Power output	78.7	383.15	423.15

3.3. Numerical method and boundary conditions

The overall calculating field involves a fluid section and a solid section. The flow and temperature fields are determined via calculating a set of numerical equations regarding to computational fluid and solid areas. In fluid areas, Eqs. (3) to (5), which represent governing equations, are calculated to simulate the transfer of heat and mass and fluid flow. In solid areas, the heat transfer is treated by using Eq. (6).

Therefore, the equation of continuity is

$$\frac{\partial\rho}{\partial t} + \nabla \times (\rho U) = 0 \tag{3}$$

The equation of momentum is

$$\frac{\partial(\rho U)}{\partial t} + \nabla\,(\rho UU) = -\nabla p + \nabla t + S_M \tag{4}$$

The energy equation is

$$\frac{\partial(\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + \nabla\,(\rho U h_{tot}) = \nabla(\lambda\nabla T) + \nabla(Ut) + US_M + S_E \tag{5}$$

The equation of energy conservation in solid area is

$$\frac{\partial(\rho h)}{\partial t} + \nabla\,(\rho U_S h) = \nabla(\lambda\nabla T) + S_E \tag{6}$$

The sound speed is 515 m/s under the presented exhaust temperature and pressure, which is higher than the actual velocity of exhaust flow, indicating that the working fluid models are incompressible. The type of exhaust flow, whether it is laminar or turbulent influences the viscosity of the model. The critical flow velocities of the serial and empty cavity structures are (0.89) and (0.43) m/s, respectively, which are record as lower as the actual flow velocity. (k-epsilon) turbulence pattern was used to imitate the engine exhaust system because it is the criteria for several well-known (CFD) designs [20, 21]. The exhaust fluid material was considered an ideal gas due to its thermodynamical similarity with air, and steel was used as solid material in the shell.

4. Results and Discussion

In this section, the serial plate and empty cavity structures are compared in terms of pressure drop and heat transfer under conditions of driving in city, driving in suburban and driving at maximum output power. The flow stream and temperature distribution were computed under conditions of driving in the suburban.

4.1. Comparison of performance under 3- operating conditions

Difference was found in the heat transfer rate between the two structures (Fig. 4). Under the three typical driving cycles, the maximum heat transfer rates in the serial plate structure were 530, 370 and 310 W, which were higher than the empty pipe by 1, 1.3 and 2.85 times, respectively. The heat transfer rate in the two structures increased from approximately 80% to 150% and to 300%, respectively, under the urban, suburban cycle and maximum power output.

The presented results are enough to warm and grill food in long trip comparing original electrical Oven and that definitely can be reduce the waste heat and decrease the surrounding temperature. With the increase in rate of heat transfer, the back pressure in the HX increases, therefore, the back pressure under the three operating conditions varies in the two structures, as shown in Fig. 5.

The variation order in pressure drop is decreasing, which is similar to the rate of heat transfer. The maximum pressure drops in the serial plate structure are 310, 140 and 90 kPa, which are 4, 2.7 and 2 times higher than the empty pipe under the three operating conditions, respectively. This outcome matches to the higher rate value of heat transfer in the two models. Two important points should be considered.

Firstly, the car’s engine may shutdown or fails if the bypass mechanism is unavailable and the pressure drop in the two structures reaches 80 kPa under conditions of the maximum output power. This condition was presented and experimentally verified by Crane and LaGrandeur [12], who reported 60 kPa of back pressure through a (BMW - X6) engine exhaust system. Thus, the use of the mechanism of a bypass with variable pressure valve is extremely important for the engine’s reliability and stability. Secondly, the large heat transfer rate for the presented HX usually corresponds to high pressure drop, thereby predicting the high limit of turbulent flow at an acceptable pressure drop.

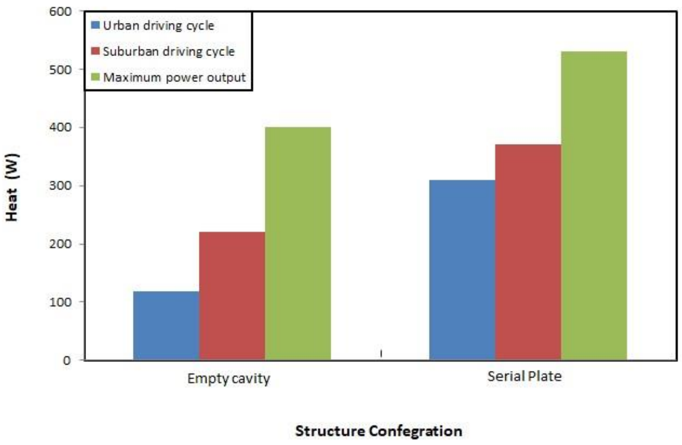


Fig. 4. Comparison between maximum output power, urban and suburban, driving cycles (heat transfer rate).

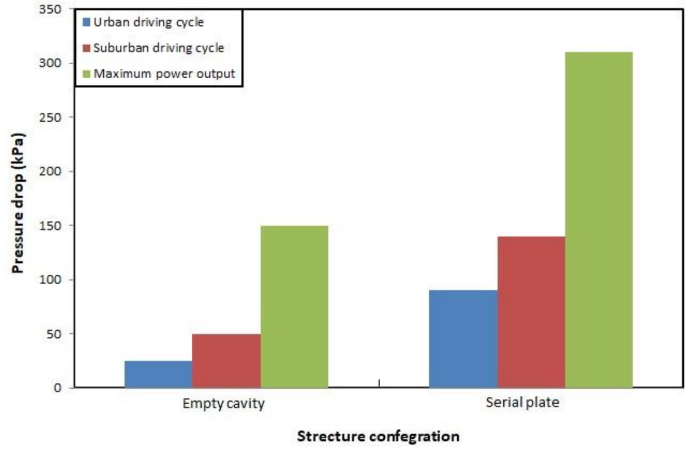
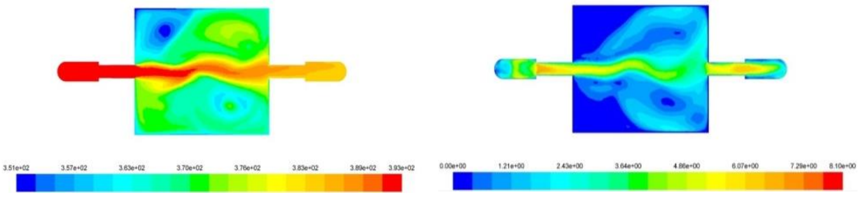


Fig. 5. Comparison between maximum output power, urban and suburban driving cycles (pressure drop).

4.2. Analysis of temperature and velocity fields

Various performances of thermal flow and aerodynamics were produced from the velocity and temperature fields of the HX. Computing the physical fields of the two models under the conditions of driving cycle in suburban is important. Therefore, a symmetrical plane along the shell thickness was produced in the model to determine the temperature and velocity fields of the engine exhaust system. The main flow area was the same from the entrance to the exit of the shell (Fig. 6), and the exhaust system gradually expanded because of the absence of fins in the empty pipe structure. Several swirls with depressed velocity and depressed temperature seemed on the top surface of the plain pipe, and (200W) was converted to the HX wall with small back-pressure of 50 Pa.

The pipe equipped with serial four fins (Fig. 7) broke a big swirl and allowed hot gas to squander and meet with the HX. walls, forcing the exhaust gas to flow back and forth. Therefore, heat was transferred by shell HX to the cooking oven environment, and the exhaust system gradually freed the heat to cool down. Several areas between two neighboring baffles provided hot sources for the cooking oven. Therefore, the heat transfer rate enhanced by approximately 75% compared with the empty pipe, and the pressure drop increased by 90%.



(a) Temperature contour. **(b) Velocity contour.**

Fig. 6. Flow distribution in a plain shell.

(a) Temperature contour. **(b) Velocity contour.**

Fig. 7. Flow distribution of a HX that equipped with internal serial plate.

5. Conclusions

In this study, CFD models with liquid field; solid field and liquid-solid interfaces were improved for two exhaust gas HXs to imitate the velocity and fluid temperature fields.

The curve order of back pressure for the empty cavity and serial plate models is the same as that for the curve order of rate of heat transfer under the three typical driving cycles. The four serial fins force the engine exhaust gas to flow back around and forth.

Therefore, heat is transferred by the HX shell to the cooking oven environment and reduces the exhaust temperature and waste heat. For the suburban driving cycle, the rate of heat transfer in the shell that equipped with internal serial plate reaches 370 W, enhancing by 75% compared with the empty pipe structure, and the pressure drop amount reaches 140 Pa, increasing by 90%.

The presented results are enough to warm and grill meal in long trip comparing original electrical Oven and the system can be reduce the waste heat and decrease the ambient temperature. The use of a bypass mechanism with variable pressure valve is extremely important in such cases to maintain the engine’s reliability and stability.

Nomenclatures

A	Cross section area of inlet pipe, m^2
h	Enthalpy, kJ/kg.K

P_1	Pressure in inlet pipe, Pa
P_2	Pressure in outlet pipe, Pa
u	Gas velocity, m/s
$\dot{V}$	Gas flow rate, m^3/s

Greek Symbols

ΔP	Pressure drop
ρ	Gas density, kg/m^3
θ	Semi-vertex angle of the conical nose (Fig. 1), deg.

Abbreviations

CFD	Computational fluid dynamics
HX	Heat exchanger

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