Journal of Engineering
journal homepage: www.joe.uobaghdad.edu.iq
Number 3 Volume 26 March 2020

***Mechanical and Energy Engineering***

# Thermal Performance Analysis of Compact Heat Exchangers for Thermoelectric Generators

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## ABSTRACT

The efficiency of internal combustion engines (ICE) is usually about thirty percent of the total energy of the fuel. The residual energy is lost in the exhaust gas, the lubrication, and the cooling water in the radiators. Recently much of the researcher's efforts have focused on taking advantage of wasted energy of the exhaust gas. Using a thermoelectric generator (TEG) is one of the promising ways. However, TEG depends entirely on the temperature difference, which may be offered by the exhaust muffler. An experimental test has been conducted to study the thermal performance of a different muffler internal design. The researchers resort to the use of lost energy in an ICE using TEG, which is one of the ways to take advantage of energy lost, which depends on the difference in temperature. TEG needs a heat exchanger and the muffler one of its types. In this work, four different types of mufflers will be designed and studied. The results showed that the thermal performances of the studied models compared to the empty cavity were as follows, the serial plate structure 56.11%, the central Box structure 52.73%, and the central curvature structure 29.61%. The highest thermal performance is on the serial plate structure relative to the other types.

**Keywords:** Exhaust heat exchanger, TEG, heat transfer.

# تحليل الاداء الحراري للمبادلات الحرارية المدمجة لمولدات الكهروحرارية

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## الخلاصة

عادة ما تكون كفاءة محركات الاحتراق الداخلي (ICE) حوالي ثلاثين بالمائة من إجمالي الطاقة للوقود. تضيع الطاقة المتبقية في غاز العادم ، التشحيم ومياه التبريد في المشعات. ركزت معظم جهود الباحث مؤخرًا على الاستفادة من الطاقة المهدرة لغاز العادم. يعد استخدام مولد حراري (TEG) أحد الطرق الواعدة. ومع ذلك ، يعتمد TEG تماماً على اختلاف درجة الحرارة الذي قد يتم توفيره بواسطة كاتم الصوت العادم. تم إجراء اختبار تجريبي لدراسة الأداء الحراري للتصميم الداخلي المختلف لكاتم الصوت . يلجأ الباحثون إلى استخدام الطاقة المفقودة في ICE باستخدام TEG ، والتي تعد واحدة من الطرق للاستفادة من الطاقة المفقودة ، والتي تعتمد على الفرق في درجة الحرارة. TEG يحتاج إلى مبادل حراري وواحد

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2020.03.03

Article received:27/2/2019
Article accepted:22/5/2019
Article published:1/3/2020

من انواع كاتم الصوت. في هذا العمل ، سيتم تصميم ودراسة أربعة أنواع مختلفة من كاتم الصوت . أظهرت النتائج أن الأداء الحراري للنماذج المدروسة مقارنة مع Empty Cavity كان على النحو التالي ، Serial Plate Structure 56.11٪ ، Central Box Structure 52.73٪ ، وCentral Curvature Structure 29.61٪. أعلى أداء حراري هو Serial Plate Structure بالنسبة للأنواع الأخرى.
**الكلمات الرئيسية:** مبادل حراري العادم، المولد الكهروحراري، انتقال الحرارة.

## 1. INTRODUCTION

An internal combustion engine (ICE) is one of the important prime movers driving many of the automobiles today. The exhaust gas from an internal combustion engine carries away approximately 30% to 40% of the combustion heat (**J.S.Jadhao, 2013).** However 60% to 65% of thermal energy of the used fuel is wasted without converting it into useful energy or work. There is a lot of heat energy goes out the engine to the atmosphere in the form of waste heat. It is important to find a method to recover this heat, which is, in turn, leads to enhance the efficiency of the engine. There are different techniques used to recover the wasted energy of the exhaust, some of these techniques are charging like turbocharging, small scale Rankin cycle, and thermoelectric generator (TEG). In general, heat exchangers are important devices used for different processes such as utilization, transferring and exchanging the thermal energy in varied applications. Any heat exchanger is considered as one of the devices to transfer heat, its transfer the thermal energy between fluids at different temperature **(Basma, and Hawraa, 2019)**. The exhaust heat exchangers of (ICE) can be selected as the significant type of heat exchangers which can be used with TEG. To achieve this purpose, proper heat exchanger design should be selected to give high-temperature deference. **(C. Q. Su, Zhan, and Shen 2012)** studied the thermal characteristics of exhaust gas, designed two different internal structures and thicknesses; the two rows of fins in two sides shape and the Fishbone shape as shown in **Fig.1** by changing the internal baffles order. The researcher used CFD software to simulate the exhaust gas flow. The researcher found that the Fishbone shape is better than the two rows of fins in two sides' shape.

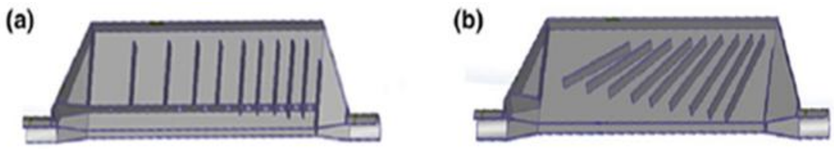


**Figure 1.** The two rows of fins in two sides shape and the Fishbone shape heat exchanger.

**(Quan et al. 2012)** designed a novel heat exchanger, and they used it in AETEG. The researcher analyzed the interior structure Fish-bone heat exchanger. ANSYS software used to simulate the surface temperature distribution; it was more uniform for fish-bone heat exchanger compared with cavity heat exchanger. **(C. Su et al. 2013)** studied the temperature distribution and heat flux distribution for two cases of heat exchanger whence the position of TEG: model with the TEG first and model with the three-way catalyst first are studied. The researcher concluded that a front three-way catalytic converter was better than another type. **(Bai et al. 2014)** designed six configurations of heat exchangers, which are inclined plate, parallel plate structure, and separate plate with holes, serial plate structure, and novel pipe structure. The researcher designed it with the same dimensions of the shell and compared it whence the heat transfer rate, pressure drop, and maximum output power with each other using computational fluid dynamic (CFD). The results showed that the serial plate structure with seven baffles was the best. **(Gupta 2014)** used the heat exchanger with thermoelectric generators (TEGs), to produce power about 1KW. They proved that using TEG automotive had enhanced vehicle performance and fuel efficiency, and it reduced the NOx Emission. They found that using TEG with heat exchanger gives better efficiency and more amount of work. **(T.Venkateshan1 et al., 2015)** designed six exhaust heat exchangers types. The researcher compared it with each other by CFD software, compared the heat transfer and pressure drop. The researcher found that the serial plate with seven baffles had maximum heat transfer and maximum pressure drop so, it was the best heat exchanger compared with other types. **(Kiran R. SonawaneNilesh C. Ghuge 2015)** designed a fishbone heat exchanger to achieving regular temperature distribution and compared this structure with the cavity heat exchanger whence the thermal performance by CFD software. The results proved that the thermal performance of fishbone is better than that of cavity heat exchanger. **(Murali 2016)** tried to get benefit from the exhaust gas by designing four heat exchangers with different internal structures. The four modeled heat exchangers were compared with each other by computational fluid dynamics software (CFD). The four structures are fishbone shape, serial plate, accordion shape, and cavity shapes. The researcher ordered the four structures as follows, serial plate had heat transfer rate about 4062 W, accordion plate had 3468W, fishbone had a 3092W, and empty cavity had 1568W of heat transfer rate. **(Ravi Bhatt et al.2017)** designed and analyzed the exhaust heat exchanger. The researcher used CFD simulation done by ANSYS V.14.to compared pressure distribution, heat exchanger, and to simulate the exhaust gases flowing inside the heat exchanger. The results showed that the rectangular-shaped with gradual increasing cross-sectional area had better uniform temperature distribution than the rectangular shaped with equally cross-sectional area. So the heat exchanger with a gradual increasing cross-sectional area of a rectangular shape is ideal for TEG.

In the present work, four different types of the muffler with different internal structures are proposed and the temperatures are measured along the surface of different types of muffler and compare them with the empty cavity one relative to the best and worst in terms of the highest rate of heat transfer and less pressure drop.

## 2. EXPERIMENTAL TEST RIG DESCRIPTION

The muffler is a part of the exhaust system that has a function of noise damping. Generally, automotive mufflers consist of an inlet and outlet pipe separated by a chamber that is cylindrical in geometry. There are four types of this chamber in commercial use, these are:

- An empty cavity: The internal structure of this type is empty from the inside.
- Muffler with an internal structure: This type contains internal plate fins arranged in a serial form.
- Muffler with an internal structure: This type contains a central box open from the top and from the other side which is considered as the base of the box is welded.
- Muffler with an internal structure: This type contains a central curvature fin with two plate fins putting from each side of the central fin. **Fig.2** shows different types of mufflers.

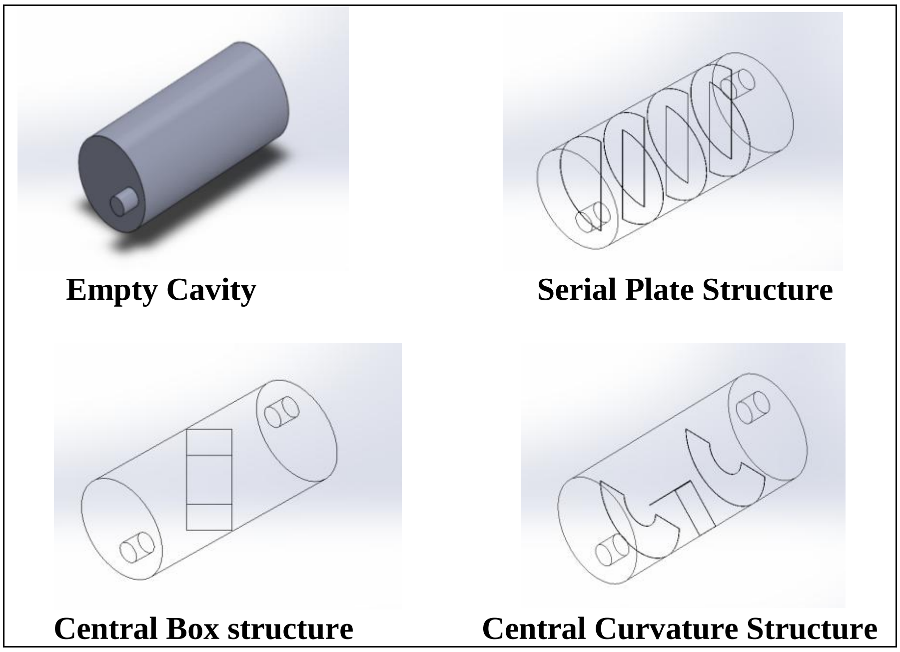


**Figure 2.** Four types of exhaust heat exchangers.

A galvanized iron muffler with 54 cm x 25 cm x 0.1 cm (Length x width x Thickness) had been manufactured was used as a test section. The inlet and outlet diameters equal to 5.08 cm. Ten thermocouples are soldered on the outer upper surface muffler along the test section with an equal distance between them; thermocouples heads are well insulated. The experimental apparatus scheme is shown in **Fig.3**. It consists of the following parts:

- The exhaust system.
- The measuring devices.
- The test section.

The measured variables during the experimental test rig are listed as follows:

- The inlet and outlet exhaust temperatures.
- The pressure drop across the test section.
- The temperatures along the muffler surface.

The devices used to measure these variables are thermocouples, digital thermometer, digital manometer, Pitot - static tube.

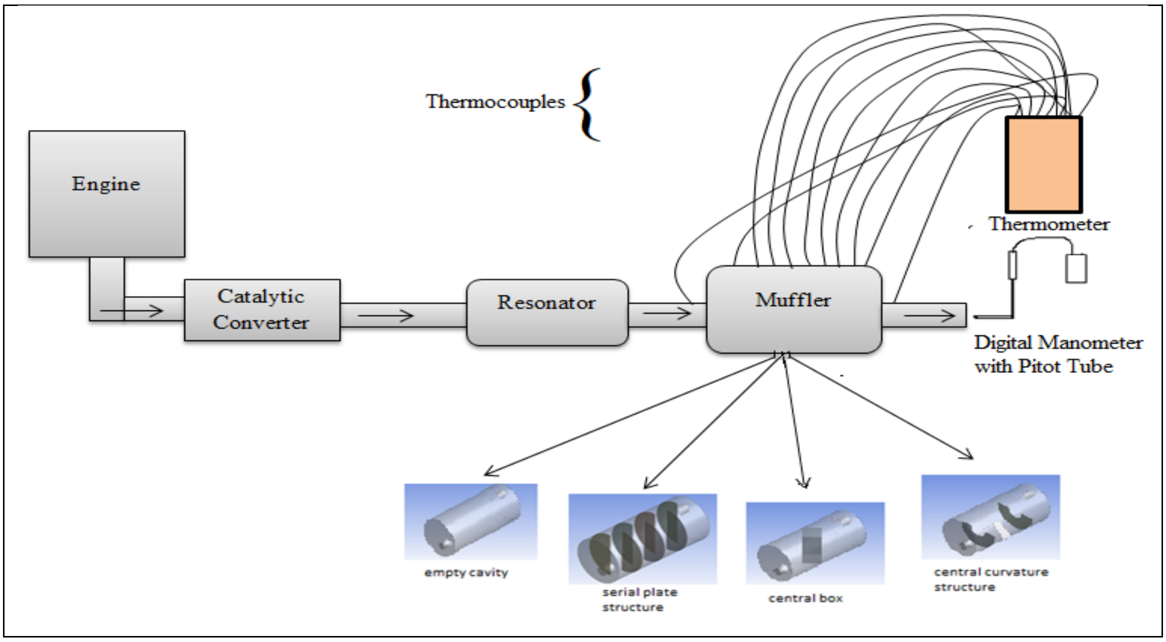


**Figure 3.** Schematic diagram of the experimental test rig.

## 3. EXPERIMENTAL PROCEDURE

After installing the test rig and the measuring devices, experimental work has been done following these steps:

1- Start the engine and waited for ten minutes until the steady-state condition was achieved. At this point the temperature along the surface of the muffler is recorded, and the pressure drop is measured at the inlet and exit of the muffler using the digital manometer and the pitot-static tube.

2- Replacing the tested muffler with the other manufactured one to repeat the same procedure of running specified in point 1 above to take the readings and collect the required data.

3- The above procedure was repeated for all the fabricated mufflers.

**Table 1.** The temperatures °C Readings at (46°C, 47.5°C and 50.1°C)

| **At 46°C** | | | | **At 47.5°C** | | | | **At 50.1°C** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Case1 | Case2 | Case3 | Case4 | Case1 | Case2 | Cas3 | Case4 | Case1 | Case2 | Case3 | Caes4 |
| 46 | 46.5 | 46 | 46.5 | 47.5 | 47.3 | 48 | 48 | 50.1 | 50.4 | 50.5 | 50.7 |
| 45.5 | 45.5 | 45.5 | 46 | 46.6 | 46.5 | 47.5 | 47.5 | 49.6 | 49.5 | 49.4 | 50.1 |
| 44.8 | 44.6 | 44.8 | 45.8 | 46 | 45.8 | 46.6 | 47.1 | 49.4 | 48.8 | 48.5 | 49.4 |
| 44.6 | 44.2 | 44.1 | 44.5 | 45.5 | 44.5 | 46.2 | 46.6 | 48.8 | 47.5 | 48.1 | 48.5 |
| 43.7 | 43.8 | 43.6 | 44.1 | 45.1 | 44.1 | 45.7 | 46.3 | 48.5 | 46.6 | 47.5 | 48.2 |
| 42.5 | 43.3 | 43.2 | 43.4 | 44.5 | 43.6 | 45.4 | 45.5 | 8 | 45.5 | 46.6 | 47.5 |
| 42 | 42.5 | 43 | 43.2 | 44.2 | 42.3 | 44.6 | 45 | 47.6 | 44.5 | 46.2 | 47 |
| 41.5 | 41.7 | 42.5 | 42.5 | 44 | 41.5 | 44.2 | 44.5 | 47.1 | 43.1 | 45.5 | 46.7 |
| 41.3 | 40.5 | 41.4 | 41.8 | 43.4 | 40.7 | 43.8 | 43.8 | 46.6 | 42.5 | 45.1 | 45.5 |
| 40.8 | 39.4 | 41.1 | 41.2 | 42.8 | 40.1 | 43.1 | 43.1 | 46.4 | 41.8 | 44.7 | 45 |
| 40.5 | 39.08 | 40.2 | 40.8 | 42.5 | 39.5 | 42.7 | 42.9 | 46.21 | 40.0 | 44.6 | 44.9 |

## 4. METHOD OF CALCULATIONS

The experimental data includes the measured temperatures and pressure drop. The air thermophysical properties were taken at 25℃. The heat transfers from the exhaust gases to the muffler and then to the ambient was calculated by using the below equation. It is used when the heat gained or lost by cold or hot fluid should be calculated and only for one type of fluid:

$$Q = \dot{m}\ \mathrm{Cp}\ \Delta T \tag{1}$$

Velocity can be calculated by pitot tube law as follows:

$$V=\sqrt{\frac{2(P_t-P_s)}{\rho}} \tag{2}$$

The Reynolds No. is a dimensionless number can be defined according to the diameter inlet section and the fluid velocity at the inlet divided by viscosity as follows:

$$Re=\frac{inertia\ forces}{viscous\ forces} \tag{3a}$$

So the Reynolds number of air **(Dhaiban 2013)** is obtained by the following equation:

$$Re=\frac{\rho\ v_{in.}\ D}{\mu} \tag{3b}$$

The effectiveness method offers many advantages to analyze the problems in which the comparison between different types of heat exchangers. The effectiveness of the heat exchanger can have been calculated **(j_Holman)** as:

$$\eta_1=\frac{Q_{act.}}{Q_{max.}} \tag{4}$$

$$\eta_2=\frac{\Delta p_{act.}}{\Delta p_{max.}} \tag{5}$$

So the thermal performance factor for any heat exchanger system can be calculated as:

$$\boldsymbol{\eta}=\frac{\eta_1}{\eta_2}*100\% \tag{6}$$

## 5. RESULTS AND DISCUSSION

The results of experiments are presented and discussed the problem of heat transfer inside the muffler. The experimental work includes the velocity of the exhaust at the inlet of the muffler, temperature along the muffler surface, pressure, heat transfer rate, and the test section performance.

**Fig. 5** shows the temperature distribution for the mufflers with empty cavity, serial plate structure, central box structure and central plate structure along their outer surface for inlet temperature, $T_i$ = 46℃. This figure illustrates that the mufflers with the serial plate structure have a higher temperature distribution compared to the other three mufflers. The temperature difference between the inlet and the outlet of the muffler of empty cavity, serial plate structure, central box structure and central curvature structure are 5.5℃, 7.42℃, 5.8℃ and 5.7℃ respectively.

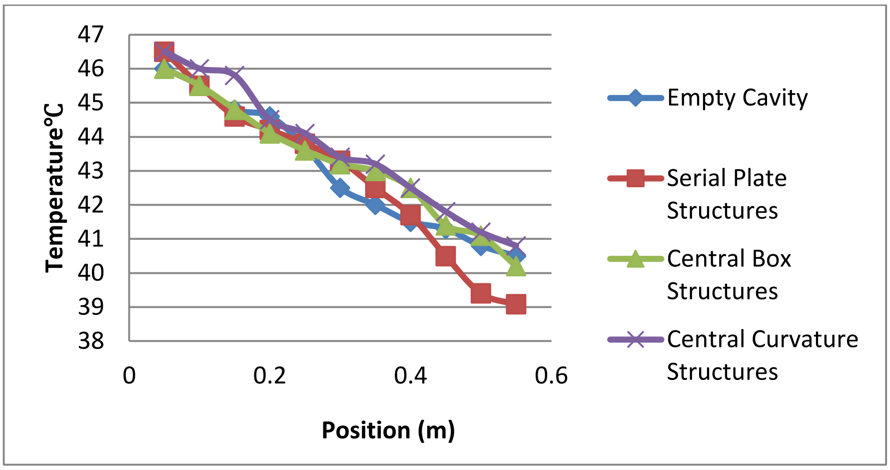


**Figure 5.** Temperature distribution for the four studied mufflers along its surface at 46 ℃ inlet temperature.

**Fig. 6** shows the temperature distribution for the mufflers with the empty cavity, serial plate structure, central box structure and central plate structure along their outer surface at 44.5℃. This figure illustrates that the serial plate structure has a higher temperature distribution compared to the other three mufflers. It conforms to the previous figure result. The temperature difference between the inlet and the outlet of the muffler of empty cavity, serial plate structure, central box structure and central curvature structure are 5℃, 7.8℃, 5.3℃ and 5.1℃ respectively.

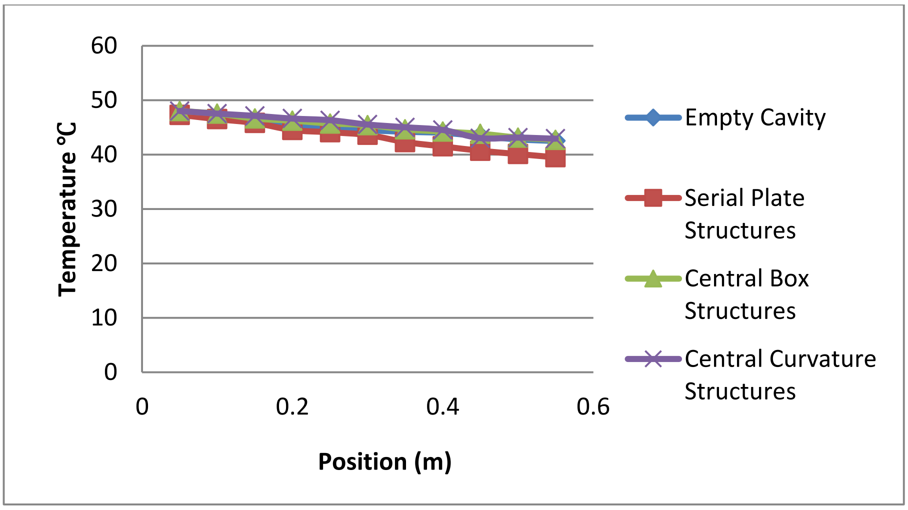


**Figure 6.** Temperature distribution for the four studied cases along the muffler surface at 47.5℃ inlet temperature.

**Fig. 7** shows the temperature distribution for the mufflers with empty cavity, serial plate structure, central box structure and central plate structure along their surface at 50.1℃. This figure also clarifies that the serial plate structure has a higher temperature distribution compared to the other three mufflers. The temperature difference between the inlet and the outlet of the muffler of empty cavity, serial plate structure, central box structure and central curvature structure are 3.89℃, 10.33℃, 5.9℃ and 5.8℃ respectively.

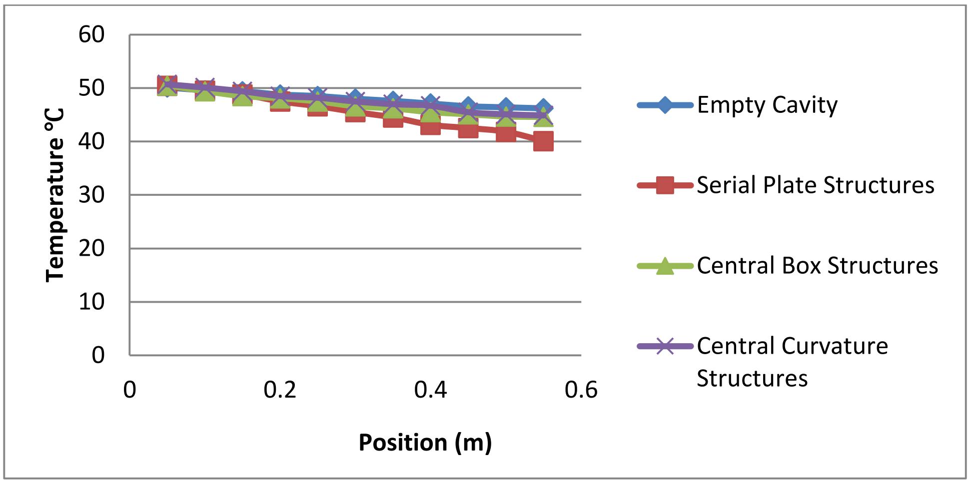


**Figure 7.** Temperature distribution for the four studied cases along the muffler surface at 50.1℃ inlet temperature.

**Fig. 8** shows the pressure drop along with the muffler for the four types at 46℃. From this figure, it's evident that the pressure drop for the muffler with the central curvature structure is the maximum pressure drop, which is around 280 Pa while the serial plate structure, central box structure, and empty cavity have 190 Pa, 160 Pa, and 80 Pa respectively.

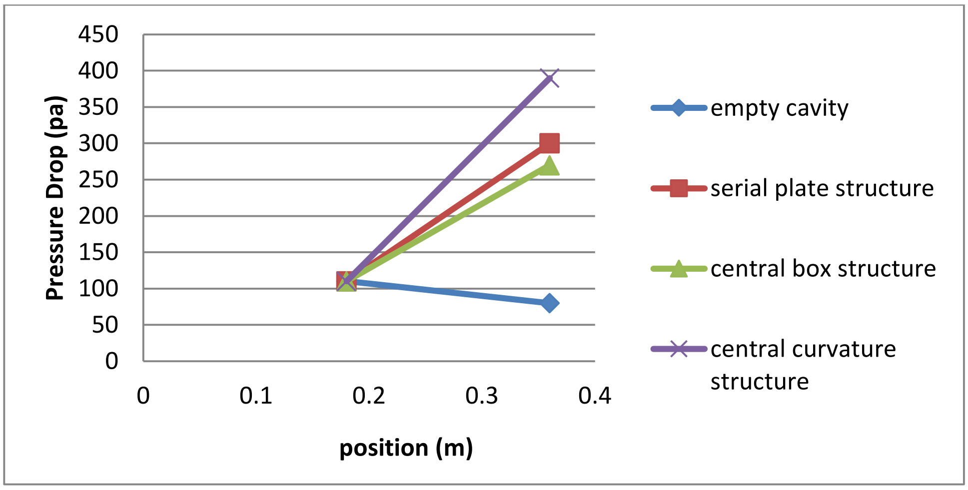


**Figure 8.** Pressure distribution for the four studied mufflers along its surface at 46 ℃ inlet temperature.

**Fig. 9** shows the pressure drop along with the muffler for the four types of muffler at 47.5℃. This confirms the previous figure result. It's clear that the pressure drop for the muffler with the central curvature structure is the maximum pressure drop, which is around 210 Pa while the serial plate structure, central box structure and empty cavity have 143 Pa, 110 Pa, and 70 Pa respectively.

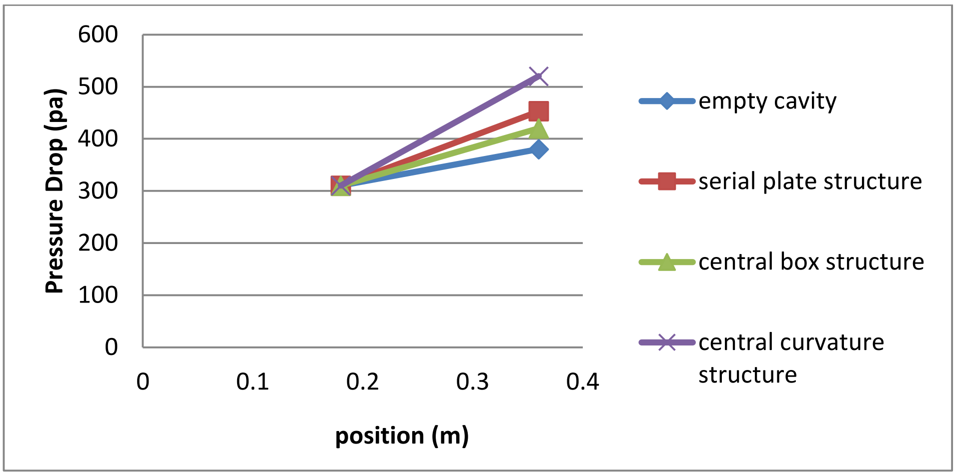


**Figure 9.** Pressure distribution for four mufflers along its surface at 47.5℃.

**Fig. 10** shows the pressure drop along with the muffler for the four types of muffler at 50.1℃. It also displays that the pressure drop for the muffler with the central curvature structure is the maximum pressure drop, which is about 220 Pa while the serial plate structure, central box structure, and empty cavity have 140 Pa, 80 Pa, and 20 Pa respectively.

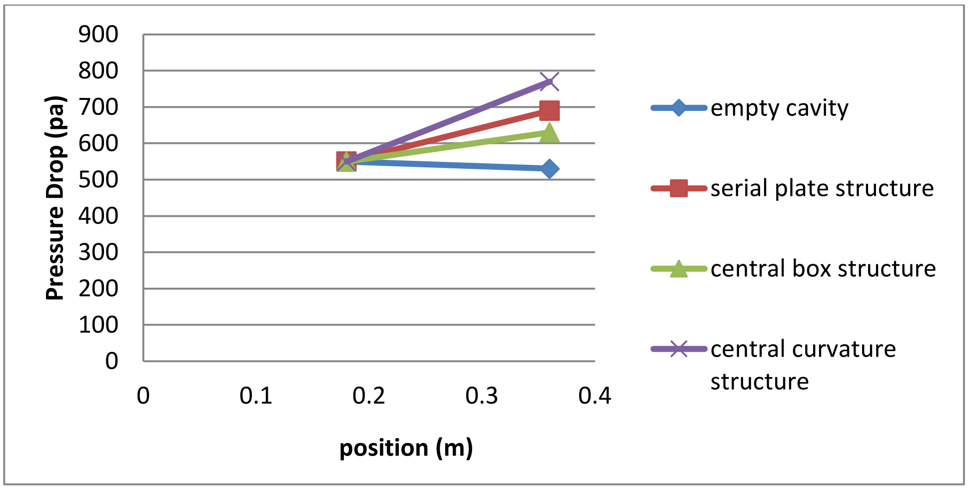


**Figure 10.** Pressure distribution for the four studied mufflers along its surface at 50.1℃ inlet temperature.

**Fig. 11** shows the variation of the thermal performance with the inlet temperature for the four types of mufflers. When the temperature increases, the thermal performance of the muffler increases, it is evident from this figure that the serial plate structure has the maximum thermal performance compared to the empty cavity muffler, which is 56.11%. The central box structure and central curvature structure have 52.73% and 29.61%, respectively.

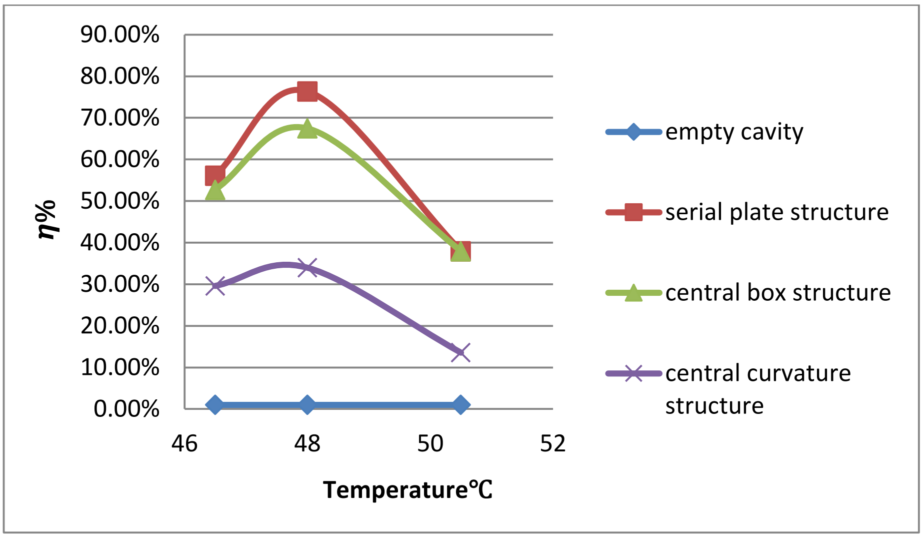


**Figure 11.** A variation of the thermal efficiency with the inlet Temperature for the Four studied Mufflers.

**Fig. 12** shows the variation of the thermal performance with the heat transfer rate at 46℃, 47.5℃, and 50.1℃. From this figure, it is evident that the serial-plate structure has the maximum thermal performance and the maximum heat transfer rate followed by the central box structure, the central curvature structure, and at last the empty cavity.

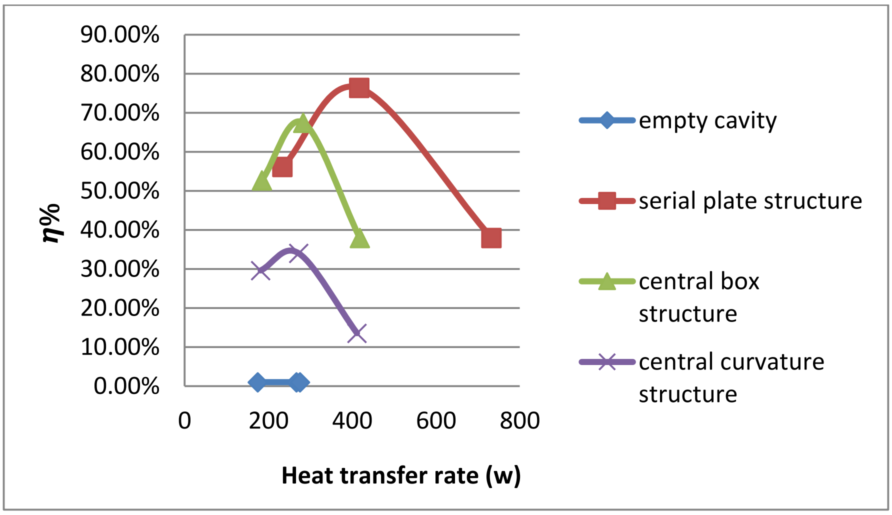


**Figure 12.** Variation of heat transfer for the four studied mufflers with the thermal performance at 46℃, 47.5℃ and 50.1℃ inlet temperatures.

**Fig. 13** shows the variation of the pressure drop with the heat transfer for the four types of the muffler at 46℃, 47.5℃, and 50.1℃. From this, figure it is obvious that the serial-plate structure has the maximum heat transfer rate, which is 233.51W with the second-highest pressure drop which is about 190 Pa. While the central box structure has the second-highest heat transfer rate 184.79W and pressure drop 160 Pa. The central curvature structure has maximum pressure drop 280 Pa with heat transfer rate 181.602W followed by empty cavity has the minimum heat transfer rate 175.23W and the minimum pressure drop 80 Pa.

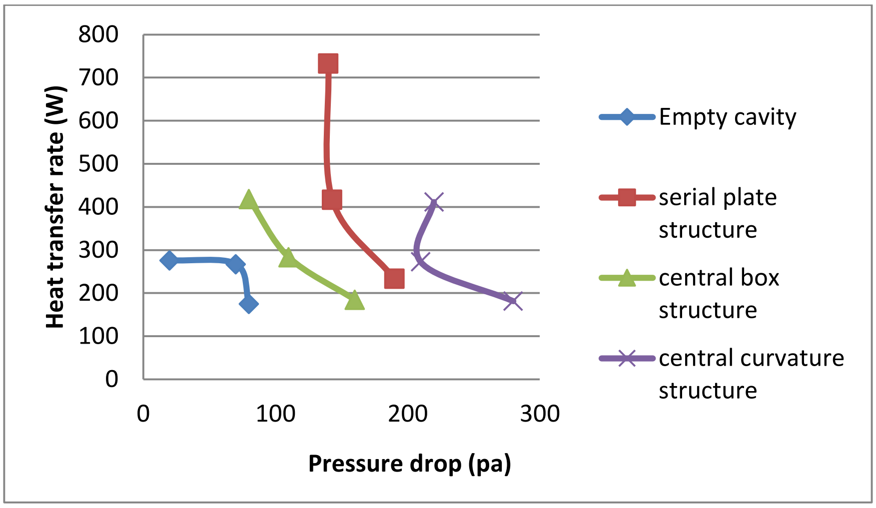


**Figure 13.** Variation of Heat Transfer for the Four Studied Mufflers with the Thermal Performance at 46°C, 47.5°C, and 50.1°C inlet temperatures.

**Fig. 14** shows the relationship between the pressure drop and the mass flow rate for the four mufflers at inlet temperature, $T_i$ = 46°C, 47.5°C, and 50.1°C. This figure shows that the pressure drop decreases when the mass flow rate increases, this for empty cavity and central box structure. While at the central box structure and the central curvature structure can note that at a mass flow rate 53.47 kg/s and 70.95 kg/s pressure drop is starting to reduce to 110 Pa and 210 Pa, and then rise to 80 Pa and 220 Pa, that's for central box structure and central curvature structure respectively, this is because of the internal structure of this two muffler.

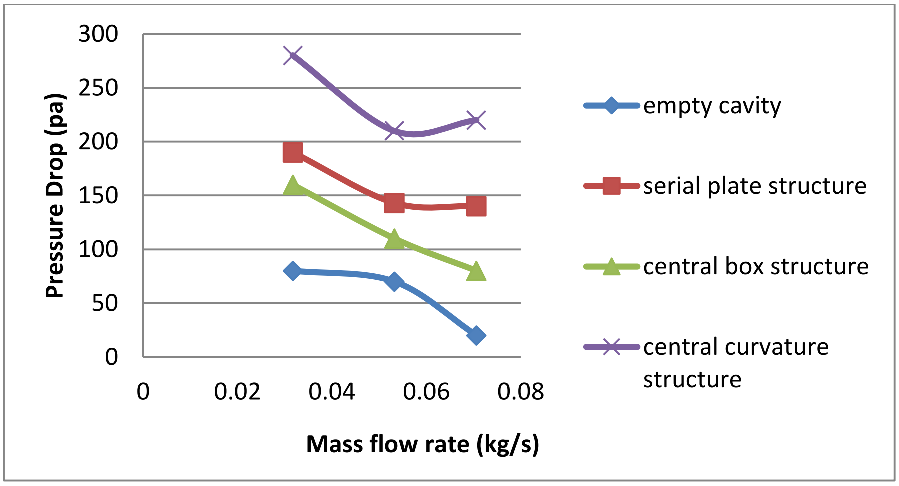


**Figure 14.** the relationship between the mass flow rate and the pressure drop at 46°C, 47.5°C, and 50.1°C inlet temperatures.

**Fig. 15** shows the variation of heat transfer for four mufflers at, $T_i$ = 46°C, 47.5°C, and 50.1°C. The four mufflers differed in heat transfer; it can be regulated by the reduction of heat transfer as follows; serial-plate structure 233.51W, central box structure 184.79W, central curvature structure 181.602W and empty cavity, this at 46°C. While at 47.5°C the heat transfer for four mufflers for the same order is 417.07W, 283.39W, 272.69W, and 267.35W respectively. At 47.5°C the heat transfer for four mufflers for the same order is 732.91W, 418.65W, 411.51W and 275.99W, respectively. From this figure it's evident that the serial-plate structure has the maximum heat transfer compared to the other three mufflers.

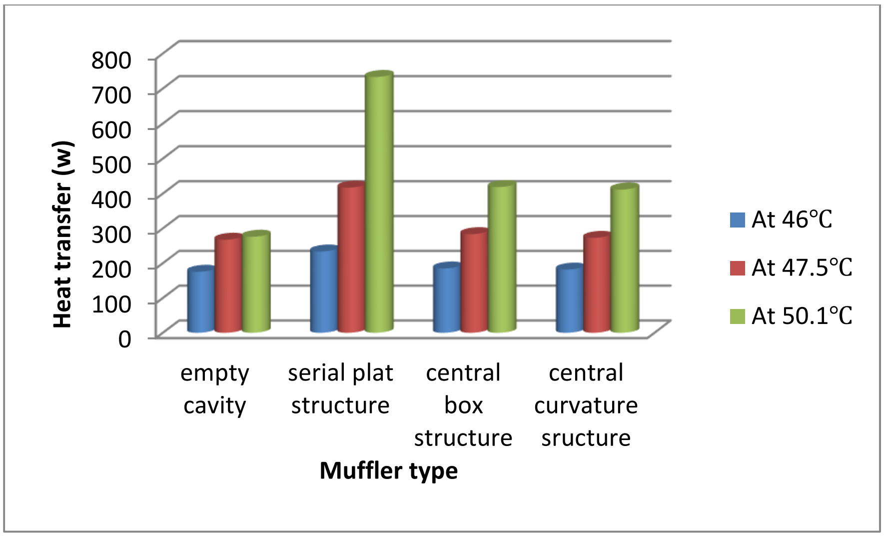


**Figure 15.** Variation of Heat Transfer for the Four studied Mufflers at 46℃, 47.5℃ and 50.1℃ inlet temperatures.

## 6. CONCLUSION

The following conclusions can be given: The performance of the muffler is highly affected by the insertion of the internal structures. By comparing the collected data in the four cases (empty cavity, serial plate, central Box and central curvature structures), it is found that the insertion of those internal structures caused the highest heat transfer rate and highest pressure drop. The heat transfer improvement is finding for muffler with serial plate structures compare with the other three types. So, the serial plate structure is the best design since it has maximum heat transfer rate and second maximum pressure drop.

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## NOMENCLATURE

AETEG = automobile exhaust thermo-electric generator
CFD = computational fluid dynamic
ICE = internal composition engine.
TEG = Thermoelectric Generator.
A= Cross sectional area of air passage in test section $m^2$.
Cp = Specific heat capacity of air at constant temperature and at atmospheric pressure J/Kg.K.
D = the inlet diameter (0.05m).
$P_t$ = total pressure, Pascal.
$P_s$ = static pressure, Pascal.
$Q_{act.}$= The heat transfer rate in the studied model.
$Q_{max.}$ = The heat transfer rate in the standard model.
Re = Reynolds number, dimensionless.
$V_{in}$ = flow velocity of air at inlet m/s.
$\boldsymbol{\eta}$ = Thermal performance, dimensionless.
$\eta_1$= Effectiveness of heat transfer rate.
$\eta_2$= Effectiveness pressure difference.
$\dot{m}$= Mass flow rate of air Kg/s.
$\Delta p_{act.}$ = pressure drop in the studied model.
$\Delta p_{max.}$ = pressure drop in the standard model.
$\Delta T$= Temperature difference K.
$\rho$ = Mass density of the air Kg/$m^3$.
$\mu$ = the dynamic viscosity of fluid N.S/$m^2$.