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Experimental investigations of cooling methods on the performance of TEG Module in an exhaust heat recovery system of an agricultural Diesel engine

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ABSTRACT

Diesel engines are fuel efficient and have better part load characteristics than their counterpart petrol engines. Approximately thirty percent of heat is rejected in the exhaust gases of diesel engine. Many research works have been carried out to recover this waste heat for the utilization of power generation and other applications. The most notable one is the turbocharger, with others being various types of heat exchangers. All these devices have worked well in recovering heat. They also have their drawbacks. The present work is about recovering waste heat using thermoelectric devices to generate power directly. But the problem was how effectively this waste heat could be recovered. In this present work an exhaust passage has been designed to extracts maximum amount of heat from the exhaust and supplies it to the thermoelectric module. The passage has two main components. The central passage which extracts heat from exhaust and supplies it to the thermoelectric generator. The heat sink ensures the continuous absorption of heat from the thermoelectric module. Two types of designs were developed. One passage uses air for cooling the heat sink. The other passage uses water for cooling the heat sink. Then testing was carried out by connecting the passage to the exhaust pipe of the single cylinder diesel engine. Testing was carried out separately for air cooling and water cooling. A comparison was made on theoretical heat transfer, actual heat transfer, module power in both air- and water-cooled setups. Efficiencies based on heat transfer and module power were also calculated. It showed around 9% of heat had been converted to electricity by the module.

Keywords: Diesel engine, TEG Module, waste heat recovery, seebeck effect

1. INTRODUCTION

Diesel engines are fuel efficient and have the highest thermal efficiency against gasoline engines due to higher compression ratio. Low-speed diesel engines often have a thermal efficiency that exceeds 50 percent. Nearly 75% of fuel energy is rejected to the environment and ultimately becomes waste heat in motor vehicles (Aljaghtham & Celik, 2020). In a direct injection diesel engine, the energy balance indicates that approximately 30% of the fuel energy input is lost to the environment through heat transfer, another 30% is expelled as exhaust heat, and only about 30% is effectively converted into useful shaft work. While the percentages vary between engines, this seems to be the accepted rule of thumb. Energy is supplied to the engine through the combustion of fuel and leaves as energy in the exhaust, cooling water, brake power, and heat transfer. Heat losses must be minimized to improve the engine efficiency. Therefore, it is essential to know the fraction of the heat loss mechanisms.

Depending on the loading conditions, the percentage of the unaccounted losses ranged between 1 and 23%. Waste heat is the heat that is rejected to the surrounding during the combustion of fuel or chemical reaction. The key characteristic of heat lies not in its quantity but in its quality or usefulness. The approach to recovering waste heat is determined by the temperature of the exhaust gases and the associated economic feasibility.

Thermoelectric devices (thermoelectric modules) can convert electrical energy into a temperature gradient (Jaziri et al., 2019). This phenomenon was discovered by Peltier in 1834, but its practical application in cooling and heating remained limited until the advent of semiconductor materials. With the development of semiconductor materials, the utilization of waste heat using thermoelectric modules for refrigeration applications has become feasible. Thermoelectric refrigeration occurs when direct current flows through one or more pairs of n-type and p-type semiconductor materials. In the cooling mode, direct current passes from the n-type to the p-type semiconductor material.

The temperature of the interconnecting conductor drops as it absorbs heat from the surrounding environment. This cooling effect takes place when electrons transition from a lower energy level in the p-type material to a higher energy level in the n-type material through the interconnecting conductor. A thermoelectric generator is shown in Figure 1.

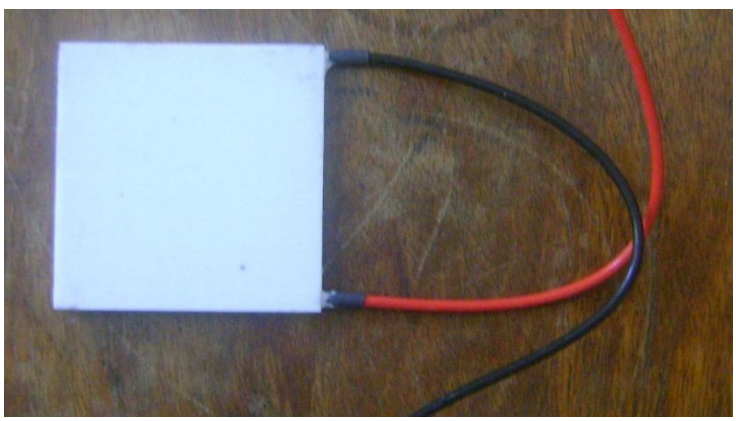

Figure 1 Thermoelectric Generator

Hsu et al., (2011) in a case study on a system to recover waste heat. The system consisted of 24 thermoelectric generators (TEGs) designed to convert heat from an automobile's exhaust pipe into electrical energy. Simulations and experimental studies were conducted on the thermoelectric module to evaluate the feasibility of such applications. Crane et al., (2004) investigated thermoelectric waste heat recovery systems with advanced heat exchangers. Talom & Beyene (2009) used a 10.55 kW absorption chiller modified for hot gas intake and matched to a 2.8 L V6 internal combustion engine. The mathematical model and experimental results indicated that the concept was thermodynamically viable and had the potential to improve system performance, particularly under part-load engine conditions significantly. Vázquez et al., (2002) explored the application of thermoelectric generation by utilizing the heat from exhaust gases produced during an automobile's combustion process. Karri & Thacher (2011) reported predictions of the power and fuel savings created by thermoelectric generators (TEG) placed in the exhaust stream of a Sports Utility Vehicle (SUV) and a stationary, compressed-natural gas-fuelled engine generator set (CNG).

Chen et al., (2010) analyzed the system efficiency of TEG in thermal energy systems, especially Combined Heat and Power production (CHP). Riffat & Xiaoli (2003) discussed the basic knowledge of thermoelectric devices and gave an overview of their applications. Also, the applications of the thermoelectric devices were discussed. Suzuki et al., (2004) studied a prototype system for thermoelectric power generation as a potential heat recovery system from spent nuclear fuel at a fast breeder reactor (FBR) cooled by liquid sodium.

Generally, a thermoelectric generator exhibits low efficiency due to the relatively low figure of merit of currently available thermoelectric materials. For low-power generation, the low efficiency of thermoelectric generators is not a significant drawback. But for high power generation, low efficiency is a disadvantage and has limited its application to specialized areas. Utilizing waste heat as an energy source, especially at temperatures below 140°C, greatly enhances the commercial viability of this electrical power generation method. In this present work, a thermo-electric module has been developed and tested to utilize the waste heat from a single-cylinder agricultural diesel engine.

2. MATERIALS AND METHODS

2.1. Design

2.1.1. Air Cooled Passage

An exhaust passage of 8 x 6.5 cm is designed as shown in Figure 2. It is designed to the size of outside diameter of the exhaust pipe of an agricultural diesel engine. Fins are designed for the size of 10 x 3.7 cm and are placed on the plate. All the fins are placed at the intervals of 1 cm. Because increasing the intervals may lead to decreased heat transfer. The heat sink on the cooling side of the thermoelectric generator is designed with a size of 8 x 7.5 cm. The height of fins is designed to match the height of the fan because placing the fin equivalent to the fan height may lead to maximum heat transfer. Holes are drilled in the plates for placing the thermoelectric generator between the central passage and the cooling side and the heat side.

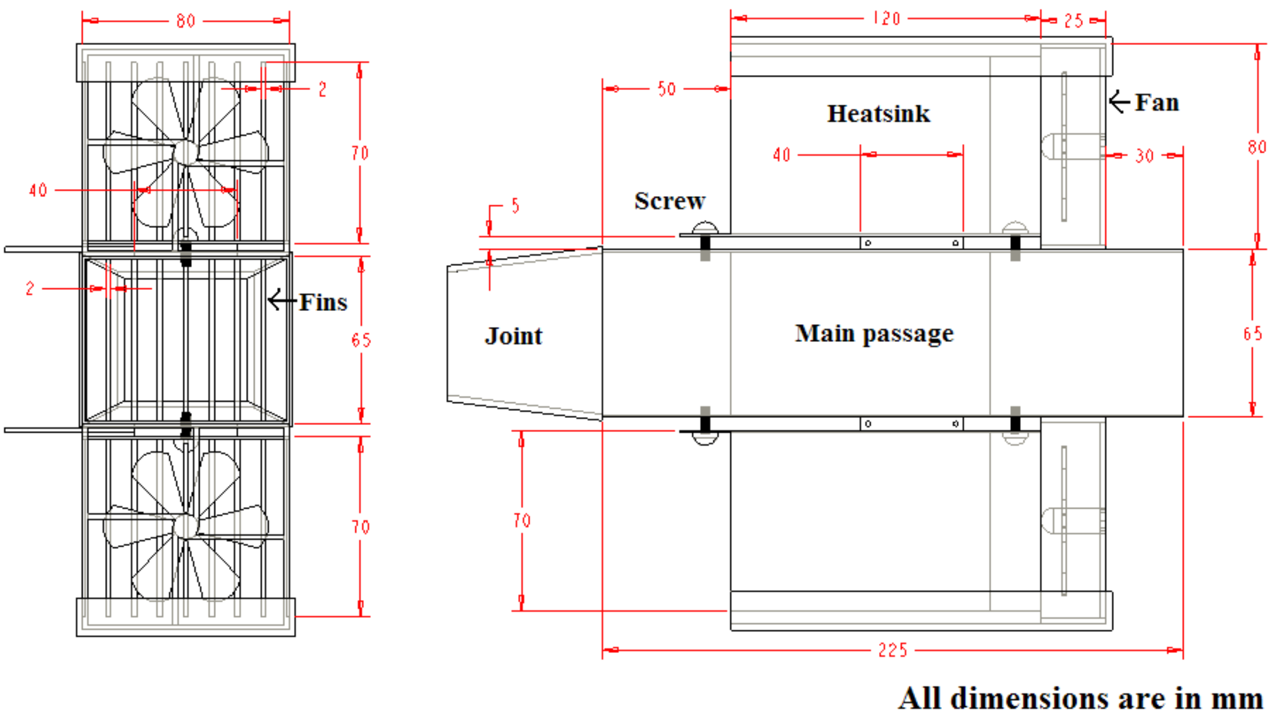

Figure 2 Air Cooled Passage Layout

Covers are designed (Figure 3) to allow the specified path to air and exhaust gas. Two covers of size 8 x 12 cm are preferred for closing the sides of the exhaust passage. Another two covers are designed for the size of 10 x 8 cm to close the passage of air passing through the fins of the heat sink on the cooling side.

The height of fins is designed depending up on the height of the fan because placing the fin equivalent to fin height may lead to maximum heat transfer. Holes are drilled in the plates for placing the thermoelectric generator between the main passage and the cooling side heat side. All the fins are placed at intervals of 1 cm.

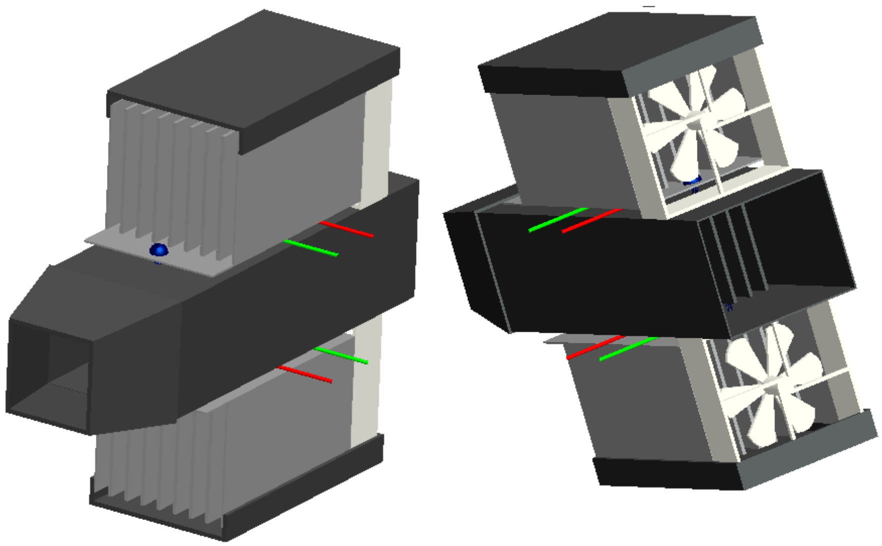

Figure 3. Air-cooled passage Design

2.1.2. Water Cooled Passage

An exhaust passage of 8 x 6.5cm is designed as shown in Figure 4. It is designed as per the outside diameter of the exhaust pipe of the engine. Prominent passage Fins are designed to 10 x 3. 7 cm fins are placed on the plate. All the fins are placed at intervals of 1 cm. Increasing the intervals may lead to a decrease in heat transfer. The heat sink on the cooling side of the thermo electric generator is designed to 8 x 7.5 cm.

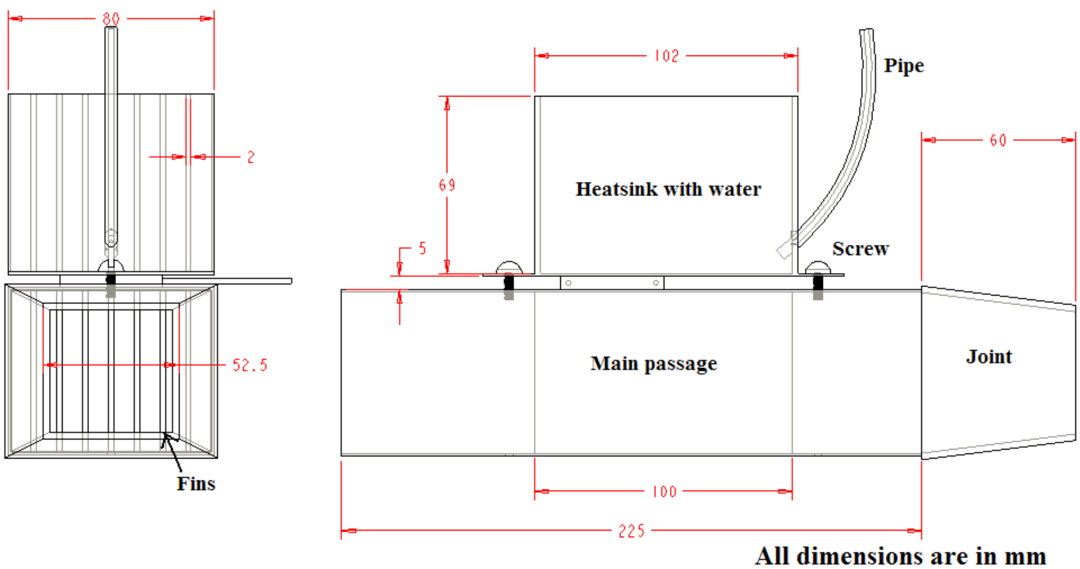

Figure 4. Water-Cooled Passage Layout

The heat sink is sealed on all four sides, ensuring no water leakage. A separate extension on the plate is screwed to attach it to the central passage, as shown in Figure 5. The module is placed in between these two setups and it is tightly screwed. A 5mm hole is drilled at the base of the plate for draining water. A tube is attached to the hole facing upward to avoid leakage. Once water gets heated up, the tube is lowered and, hot water is drained. At the same time, cold water is added to the tank from the top.

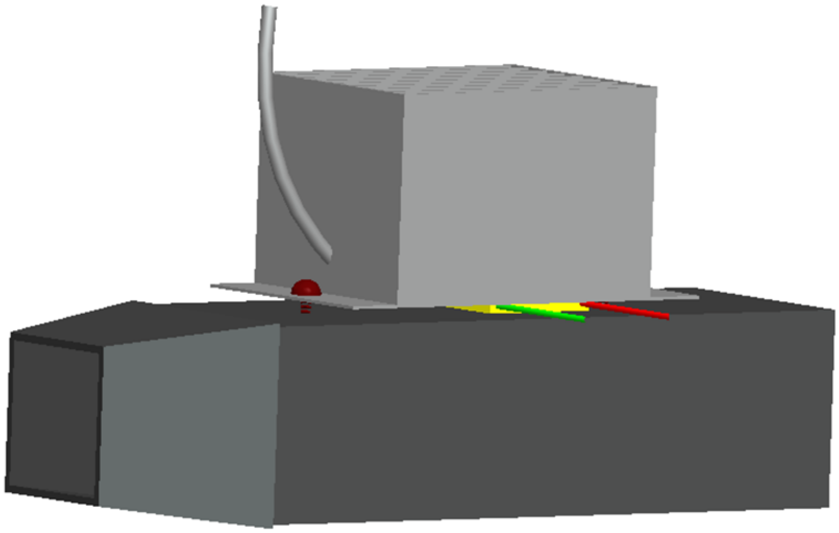

Figure 5 Water-Cooled Passage Design

2.2. Materials Used

For efficient heat transfer, aluminium has been chosen as the material for passage. Aluminium has good thermal conductivity, rigidity and high melting point. Two thermoelectric generators (50W rating) to generate electricity. A 12 Volt fan has been chosen for cooling the heat sink. An adapter is used to supply current to the fan. The power rating of the fan in 1.5 Watt. Thermocouples for measuring the hot side and cold side temperatures of the thermoelectric module have been installed. Also, they are used for measuring the inlet and outlet temperature of the exhaust

- A digital display for the purpose to display the temperatures
- Araldite, a resin hardener epoxy adhesive, to bind aluminium sheets
- Mseal to seal leakage of water from gaps in the passage
- Asbestos rope 10mm diameter of length 1m
- Tube 5mm diameter
- Four M10 screws with nut for temporary locking of the heat sink and the central passage
- Aluminium rivets for permanently joining the aluminium sheets

2.3. Experimentation

The fabricated setup was to be attached to the exhaust passage of the engine. Before that, required thermocouples were arranged as needed. The wires from the module were to be given a load. The load was taken to be a bulb. For measuring current, the ammeter and voltmeter were connected in series. To ensure the rigidity of the setup, it was tested initially for heat resistance. Fins were tested for shear resistance. The entire setup was tested for tensile resistance.

To ensure that the thermoelectric generators on both sides don't fall, it was stuck to the passage using adhesive tape. It was taped on all four sides to ensure rigidity. This was to ensure that the module did not vibrate. The setup was also cleaned before being tested in the engine.

2.3.1. Air Cooling

The exhaust passage of the engine was attached to the setup using the joint designed. For rigidity, the asbestos rope was wound over the joint. The wires from the module were connected to a load (bulb) through an ammeter and voltmeter. Thermocouples were attached to a display device. The experimental setup has been shown in Figure 6. The engine was turned on and run at no load condition.

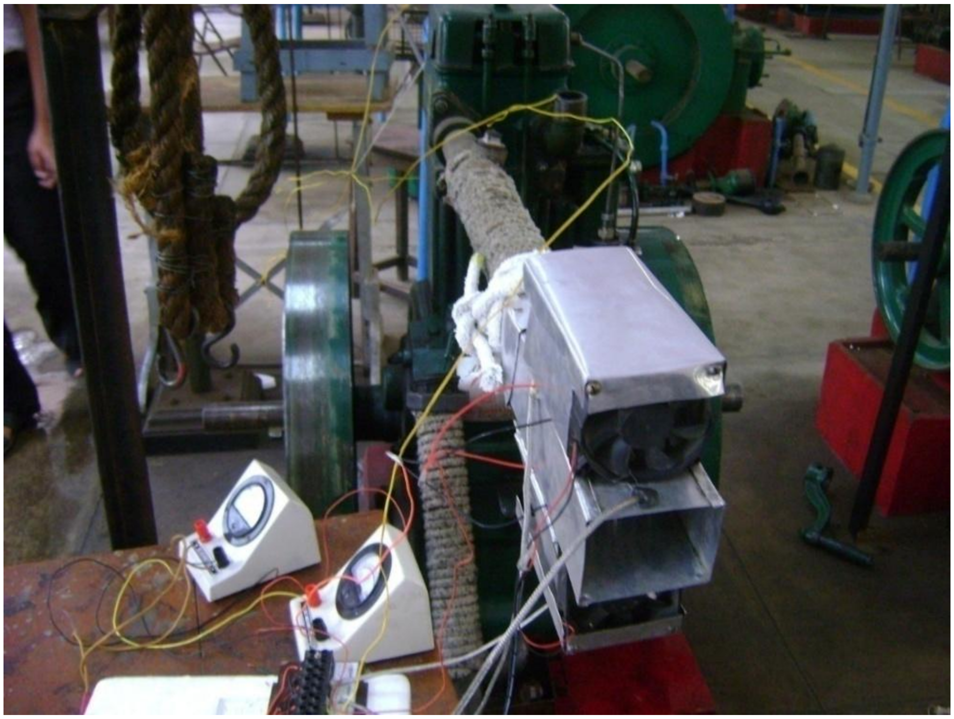

Figure 6 Experimental Setup – Air Cooling

Once steady state was reached reading were taken. Temperatures at hot side, cold side, exhaust inlet and exhaust outlet were noted. Exhaust velocity, voltmeter reading, ammeter reading was also noted. No load condition reading was taken to see the least possible power. Then, the load was increased to 1kg. At this load, the engine was allowed to run for some time until a steady state was reached. At this load again the temperatures at hot side, cold side, exhaust inlet, exhaust outlet, exhaust velocity, voltmeter reading and ammeter reading were reported. The same procedure was done till a load of 9 kg. A total of ten different observations were made (Table 1). All the results were noted and tabulated.

Table 1 Air cooled passage-Data collection

Load (kg)	Exhaust temperature (Celsius)		Temperature (Celsius)		dT/dt (K/s)	Module		Velocity (m/s)
	Inlet	Outlet	Hot side	Cold side		Current (A)	Voltage (V)	
0	82	50	53	35	0.1	0.4	1	7.5
1	95	71	67	42	0.15	0.4	1.2	11.6
2	104	98	78	56	0.18	0.5	1.3	12.5
3	124	113	92	65	0.21	0.6	1.5	13.6
4	150	140	113	73	0.26	0.6	1.8	14.5
5	175	151	134	95	0.3	0.6	2.5	14.6
6	201	175	157	112	0.34	0.8	3.6	15.8
7	226	187	178	134	0.37	0.8	4.5	16.3
8	240	203	187	140	0.4	1	6.6	16.9
9	253	217	198	161	0.42	1.1	8.9	17.3

2.3.2. Water Cooling

Now, the air-cooling setup was removed from the engine. The water-cooling setup was attached to it. The design of the water-cooling setup has already been shown. It has only one heat sink. Two modules were placed one over the other and sandwiched between the heat sink and the central passage. To ensure rigidity, module was taped on all sides to the heat sink. The other module was taped on all sides of the central passage. Both were kept together and screwed. To avoid vibration, a nut was also placed on the other sides. The thermocouples were placed at different locations, such as in air cooling. The setup was rigidly attached to the central exhaust passage using asbestos rope. Just like in air cooling, readings like temperatures at hot side, cold side, exhaust inlet and exhaust outlet were noted (Table 2).

Table 2 Water cooled passage-Data collection

Load (kg)	Exhaust temperature (Celsius)		Temperature (Celsius)		dT/dt (K/s)	Module		Velocity (m/s)
	Inlet	Outlet	Hot Side	Cold side		Current (A)	Voltage (V)	
0	88	57	55	32	0.2	0.4	1	8
1	101	88	64	36	0.25	0.5	1.2	10.5
2	113	94	72	45	0.27	0.7	1.3	12
3	141	114	88	52	0.31	1.2	1.5	13.2
4	158	134	104	60	0.34	1.4	1.8	14
5	185	151	128	64	0.37	1.7	2.5	15
6	210	174	147	68	0.4	1.7	3.6	16.5
7	235	199	166	72	0.42	1.8	4.5	17.2
8	251	211	179	78	0.45	2	6.6	18
9	268	225	191	80	0.5	2.3	8.9	19.2

Also exhaust velocity, voltmeter reading, ammeter reading was observed. Initially, readings were taken under no load conditions. Then load was increased from 1kg to 9kg. The setup is shown in Figure 7.

Figure 7 Experimental Setup – Water Cooling

3. RESULT AND DISCUSSION

For calculating the theoretical heat transfer in the passage, the following formula was used

$$Q_t = h \times A \times (T_\infty - T_b) \quad \ldots\ldots (1)$$

The heat transfer coefficient is multiplied with the area of cross section of the pipe and the temperature difference between walls and the exhaust gas.

For calculating the actual heat transfer, the following formula was used

$$Q_a = m \times \frac{dT}{dt} \times C_p \quad \ldots\ldots (2)$$

The mass of aluminium that is being heated is multiplied by the rate of change of temperature concerning to time and the specific heat value of aluminium at constant pressure.

For calculating the heat transfer coefficient, the following formula was used.

$$h = \frac{Nu \times k}{L} \quad \ldots\ldots (3)$$

It is the ratio of the product of Nusselt number and thermal conductivity of aluminium to the Length of the passage.

For calculating the Nusselt number, the following formula was used.

$$Nu = .332 \times Re^{0.5} \times Pr^{0.333} \quad \ldots\ldots (4)$$

This formula was taken from heat transfer data book under the condition of flow over flat plate with constant wall temperature.

For calculating the Reynolds number, the following formula was used.

$$Re = \frac{uD}{v} \quad \ldots\ldots (5)$$

It is the ratio of product of velocity of the exhaust and equivalent diameter to the kinematic viscosity of the exhaust gas.

For calculating the equivalent diameter, the following formula was used It is the ratio of four times the area to the perimeter of the exhaust passage

$$D = \frac{4 \times A}{P} \quad \ldots\ldots (6)$$

For calculating the equivalent diameter, the following formula was used.

$$\dot{m} = \rho \times A \times u \quad \ldots\ldots (7)$$

It is the product of the density of the exhaust, the area of cross section of the exhaust passage, and the velocity of the exhaust.

The power of the thermoelectric generator is calculated by the following formula

$$Q = V \times I \quad \ldots\ldots (8)$$

It is the product of current and voltage.

Air Cooling

The value of Reynolds number, Nusselt number is calculated based on the formula and values taken from data book. Prandtl number is directly taken from the Databook. The heat transfer coefficient is calculated using the Reynolds number, Nusselt number, and Prandtl number. Theoretical heat transfer is calculated based on the heat transfer coefficient value. The various values are shown in Table 3.

Table 3 Performance parameters-Air-cooled

Load (kg)	Reynolds number	Nusselt number	Heat Transfer Coefficient (W/m²K)	Q $_{theoretical}$ (W)	Q $_{actual}$ (W)	power (W)
0	26363.66	47.639	14.901	34.571	11.2	0.4
1	40775.80	59.246	18.532	41.512	16.8	0.48
2	43939.44	61.502	19.238	40.015	20.16	0.65
3	47806.11	64.151	20.066	51.370	23.52	0.9
4	50969.75	66.239	20.720	61.330	29.12	1.08
5	51321.26	66.467	20.791	68.195	33.6	1.5
6	55539.45	69.145	21.629	76.133	38.08	2.88
7	57297.03	70.231	21.968	84.358	41.44	3.6
8	59406.12	71.511	22.369	94.844	44.8	6.6
9	60812.18	72.353	22.632	99.581	47.04	9.79

The comparison between theoretical heat transfer and actual heat transfer is shown in Figure 8. Similar trend was reported by Huu et al. (2018)

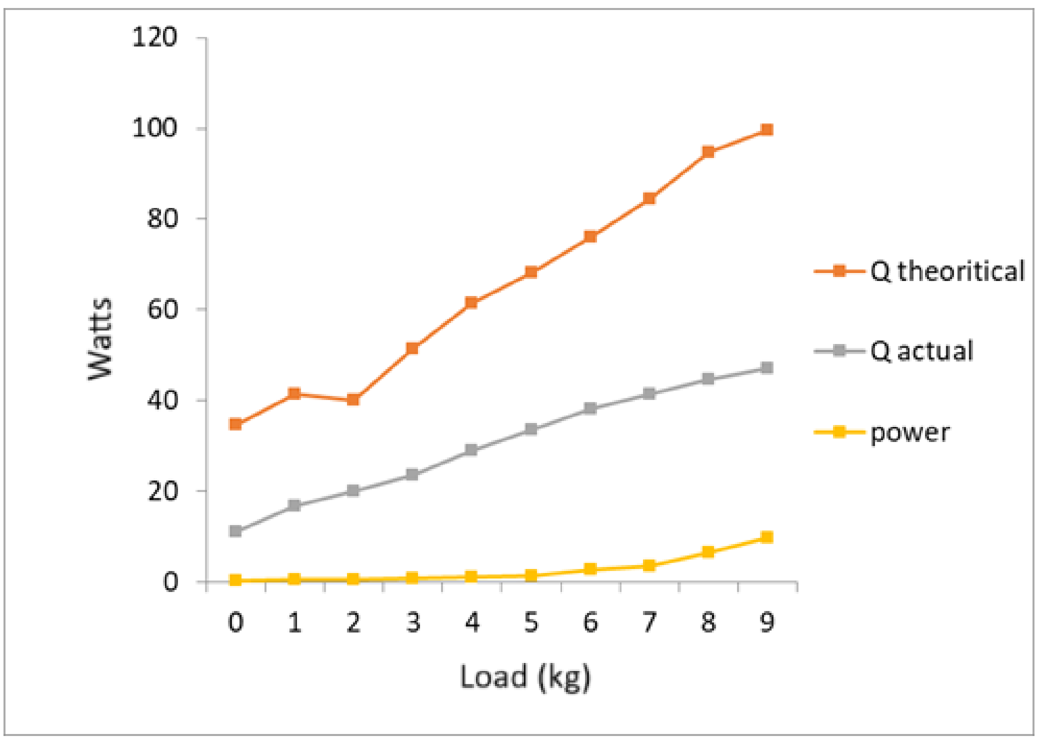

Figure 8 Variation of various powers for load in air cooling

Water Cooling

The value of the Reynolds number and the Nusselt number is calculated based on the formula and values taken from the data book. The Prandtl number is directly taken from the data book. The heat transfer coefficient is calculated using the Reynolds number, Nusselt number, and Prandtl number. Theoretical heat transfer is calculated based on the heat transfer coefficient value. The actual heat transfer is calculated based on the formula given before. The various values are listed in Table 4.

Table 4 Performance parameters- Water-cooled

Load (kg)	Reynolds number	Nusselt number	Heat Transfer Coefficient (W/m^2K)	$Q_{theoretical}$ (W)	Q_{actual} (W)	power (W)
0	28121.24	49.201	15.390	40.630	22.4	0.4
1	36909.13	56.367	17.632	52.190	28	0.6
2	42181.86	60.259	18.849	61.825	30.24	0.91
3	46400.05	63.200	19.769	83.821	34.72	1.8
4	49212.17	65.087	20.359	87.952	38.08	2.52
5	52727.33	67.372	21.074	96.097	41.44	4.25
6	58000.06	70.660	22.102	111.397	44.8	6.12
7	60460.67	72.143	22.566	124.567	47.04	8.1
8	63272.79	73.802	23.085	132.971	50.4	13.2
9	67490.98	76.222	23.842	146.869	56	20.47

The graph showing various powers is shown in Figure 9.

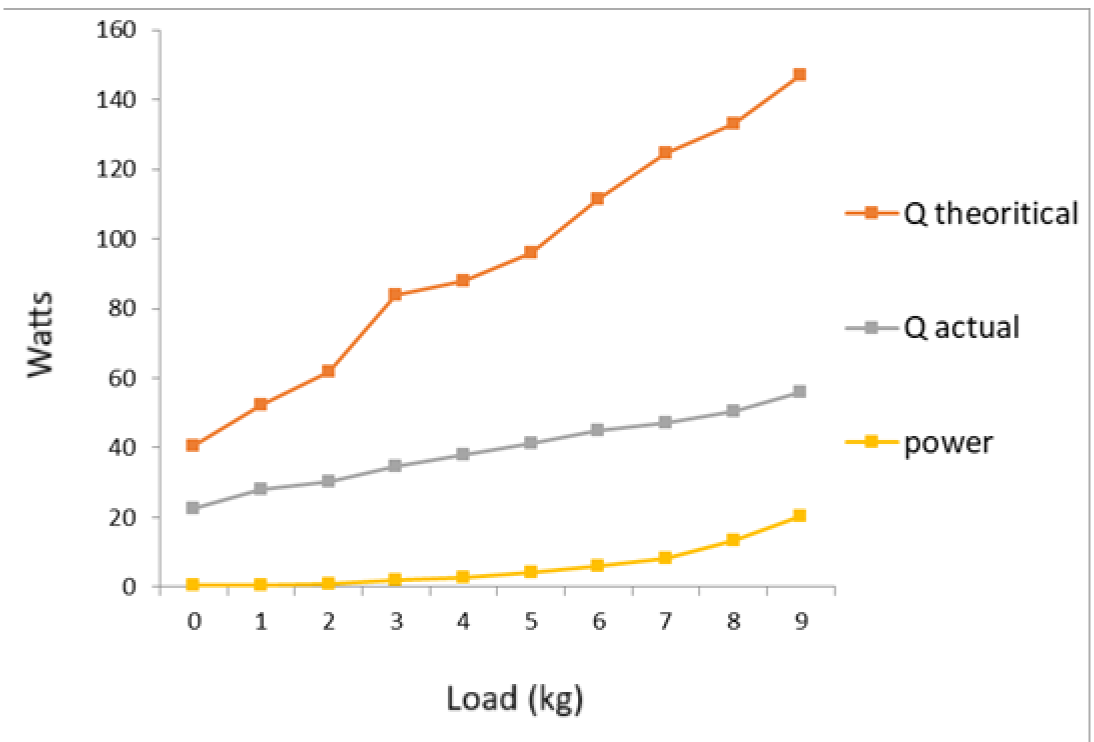

Figure 9 Variation of various powers for load in water cooling

Various comparisons were made based on the two values of air and water cooling. The comparison for theoretical heat transfer in air cooling and water cooling was made first.

Theoretical heat transfer

From the graph, it is observed that the heat transfer is almost the same in no load condition. As the load increases, the heat transfer in water cooling gets better than in air cooling. This is because the exhaust temperature increases at higher loads and cooling is effective in water. The comparison of theoretical heat transfer is shown in Figure 10.

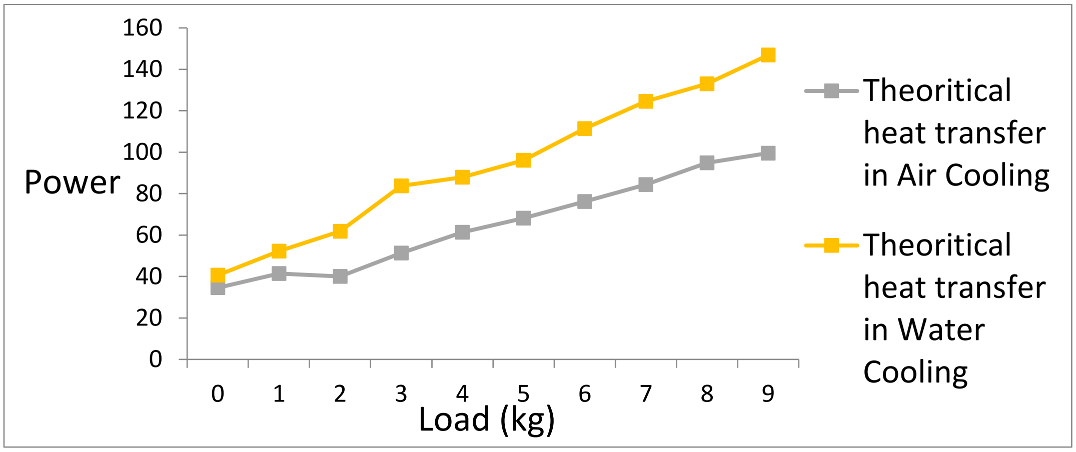

Figure 10 Variation of theoretical heat transfer in air and water cooling for load

Actual heat transfer

From the graph, it is observed that the heat transfer is highly different at no load condition. As the load increases, the heat transfer in water cooling tends to move towards the heat transfer in air cooling. This is because the exhaust temperature increases at higher loads and cooling is effective in under water. The comparison of actual heat transfer is shown in Figure 11.

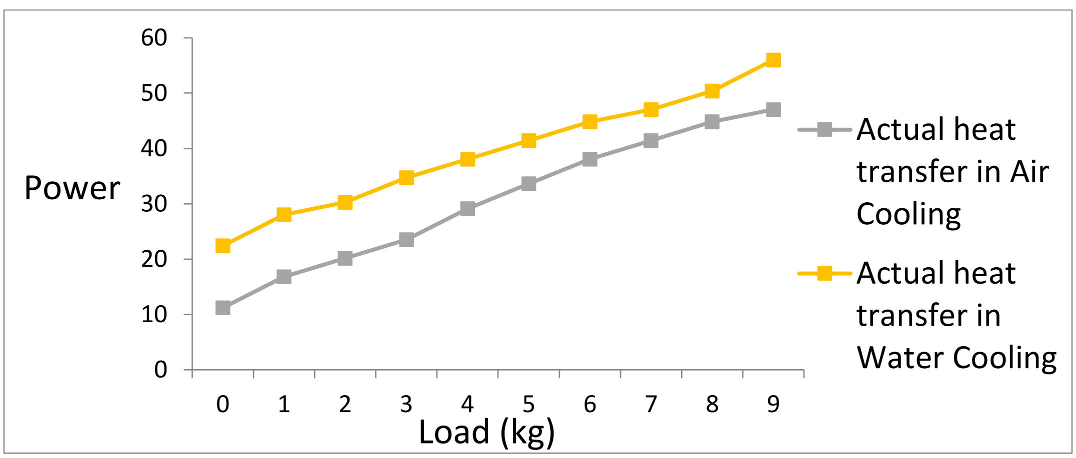

Figure 11 Variation of actual heat transfer in air and water cooling for load

Module power

The final comparison was based on module power. From the graph, it is observed that the heat transfer is almost the same as at no load condition. As the load increases, the heat transfer in water cooling was better than the heat transfer in air cooling. This is due to the fact that exhaust temperature increases at higher loads and cooling is effective in under water. Similar trend was reported by Yulong et al., (2021). The comparison of module power is shown in Figure 12.

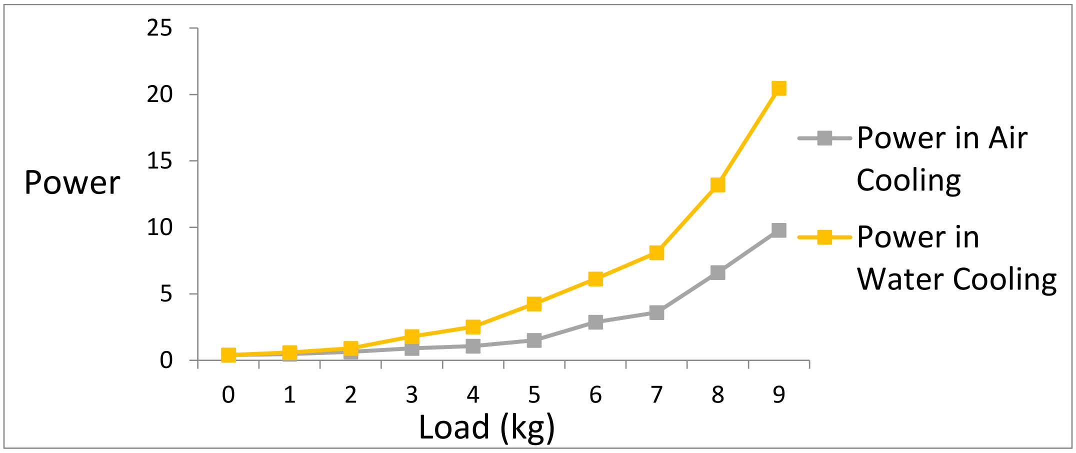

Figure 12 Variation of module power in air and water cooling for load

Module Efficiency

The heat transfer efficiency is calculated based on the ratio of actual heat transferred to the theoretical heat transferred. The conversion efficiency is calculated based on the ratio of power produced in the module to the actual heat transferred. The efficiency of air and water cooling is tabulated in Tables 5 and Table 6, respectively.

Table 5 Air Cooling Efficiency

Load (kg)	Q theoretical	Q actual	power (W)	Heat transfer Efficiency (Effectiveness) - Air	Conversion efficiency - Air
0	34.571	11.2	0.4	32.397	1.157
1	41.512	16.8	0.48	40.470	1.156
2	40.015	20.16	0.65	50.382	1.624
3	51.370	23.52	0.9	45.786	1.752
4	61.330	29.12	1.08	47.481	1.761
5	68.195	33.6	1.5	49.271	2.200
6	76.133	38.08	2.88	50.018	3.783
7	84.358	41.44	3.6	49.124	4.268
8	94.844	44.8	6.6	47.236	6.959
9	99.581	47.04	9.79	47.238	9.831

Table 6 Water Cooling Efficiency

Load (kg)	Q theoretical (W)	Q actual (W)	power (W)	Heat transfer Efficiency (Effectiveness)- Water	Conversion efficiency - Water
0	40.630	22.4	0.4	55.132	0.984
1	52.190	28	0.6	53.650	1.150
2	61.825	30.24	0.91	48.912	1.472

3	83.821	34.72	1.8	41.422	2.147
4	87.952	38.08	2.52	43.296	2.865
5	96.097	41.44	4.25	43.123	4.423
6	111.397	44.8	6.12	40.217	5.494
7	124.567	47.04	8.1	37.763	6.503
8	132.971	50.4	13.2	37.903	9.927
9	146.869	56	20.47	38.129	13.938

Effectiveness

The heat transfer efficiency shows a unique trend. For air cooling the efficiency initially increases and then decreases as the load is increased. For water cooling, the heat transfer efficiency initially increases and then it decreases at a lower rate. It is shown in Figure 13.

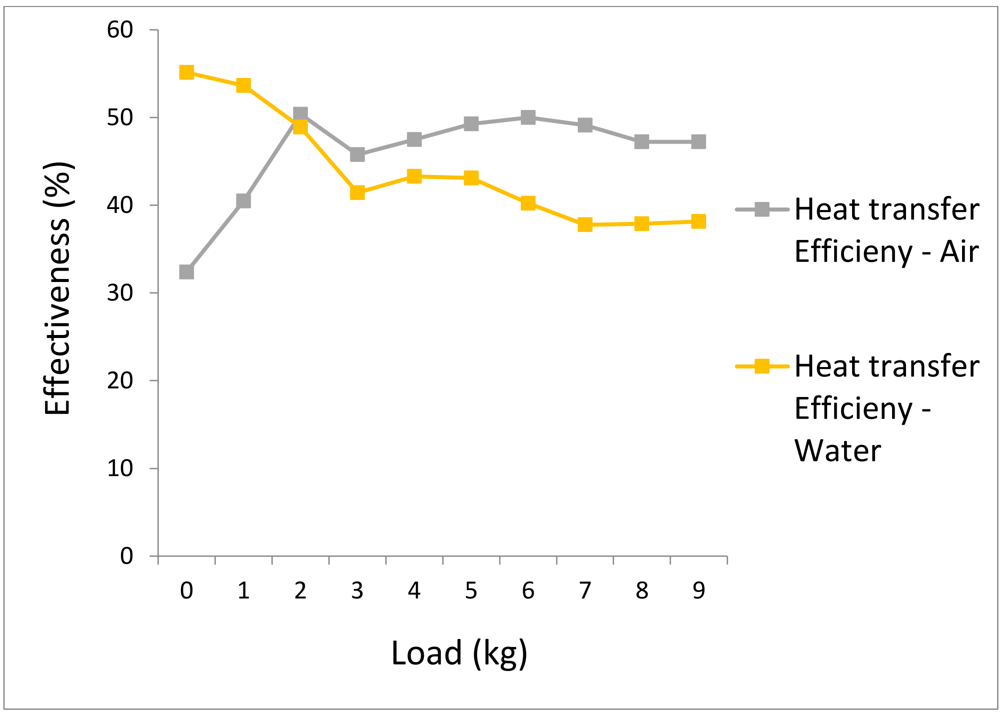

Figure 13 Variation of effectiveness in air and water cooling for load

Conversion efficiency

The conversion efficiency of air cooling initially remains constant and then gradually increases. The conversion efficiency of water cooling keeps on increases. The comparison shows that initially the conversion efficiency of air cooling is higher. However, as the load increases, the conversion efficiency of water cooling is greater than that of air cooling (as reported by Fernández-Yáñez et al., 2021). It is shown in Figure 14.

The conversion efficiency can be increased by insulating the other parts of the engine. Water cooling has far higher conversion efficiency than air cooling because water has a higher specific heat than air. This means water can absorb more heat than air at the same temperature before rising to a higher temperature. The degree of uncertainty (error) analysis for various measuring instruments used in the experiments is shown in Table 7.

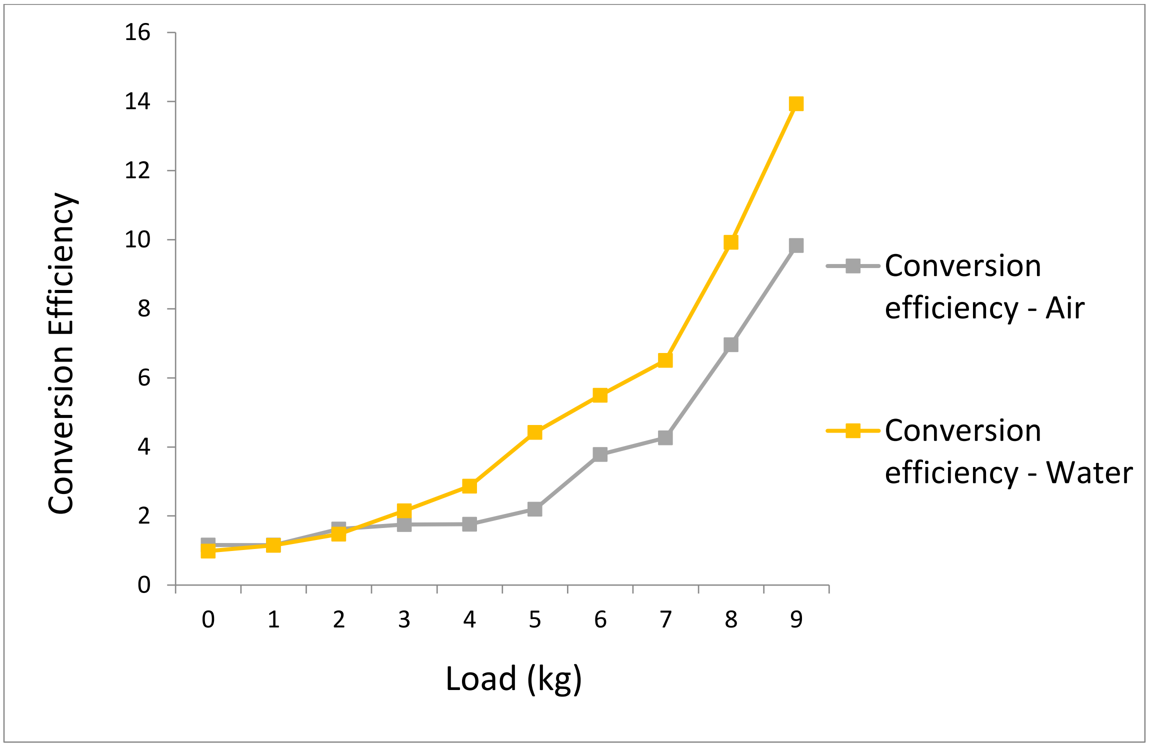

Figure 14 Variation of conversion efficiency in air and water cooling for load

Table 7. The uncertainties of measured and calculated parameters

Sl No	Parameter	Maximum errors [± %]
1	Power	0.19
2	Voltage	0.33
3	Current	1.01
4	Exhaust gas temperature	0.28
5	Efficiency	1.01

4. CONCLUSION

An exhaust heat recovery system was designed and fabricated successfully, and the waste heat from a single-cylinder diesel engine was recovered and converted to electricity using a pair of thermoelectric power generator modules. Based on the experimental results, several conclusions can be drawn. Firstly, a maximum of 9% of the heat convected to the module from the exhaust was successfully converted into electricity. Secondly, it was observed that heat transfer is significantly more effective in water cooling compared to air cooling, with an increase of about 19%. Furthermore, the efficiency of the thermoelectric generator improves at higher temperatures in both air- and water-cooling methods. Lastly, the fabricated exhaust heat recovery system demonstrates potential for application in low heat rejection (LHR) engines. Such engines are expected to generate more electricity since the amount of exhaust heat energy is greater in LHR engines than in conventional diesel engines.

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Author Contributions

Author 1: Conceived and designed the analysis, Wrote the paper

Authors 2: Collected and contributed the data

Ethical issues
Not applicable.

Informed consent
Not applicable.

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Conflict of Interest
The author declares that there are no conflicts of interest.

Data and materials availability
All data associated with this study are presented in the paper.

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