Experimental Investigation of Energy Harvesting at Outlet of IC Engine using Fire Tube Boiler.

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I certify that this research work titled "*Experimental Investigation of Energy Harvesting at Outlet of IC Engine using Fire Tube Boiler.*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

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Abstract

Energy plays a vital role in modern era. Many studies have been done to generate energy, to make ways to harvest energies and to make devices more efficient to energy as possible. IC engines are used widely in the world in many applications like vehicles, generators, aircrafts, etc. The efficiency of engine providing useful power ranges 20%-40% and a huge amount is wasted through exhaust gases. This work has been done to harvest energy through these gases. For this purpose, we fabricated a fire tube boiler using copper coil to transfer heat from exhaust gases to the water. A part of waste exhaust heat was absorbed by water and steam was generated using this boiler. It took 42 minutes for 300 ml of water to absorb heat from exhaust gases and raise its temperature from 25 ºC to 100 ºC and convert itself into steam. Using the amount of heat absorbed by water, it was observed that about 0.46%-2.31% of heat was recovered and mechanical system ought to be upto 70%, upto 1.617% of efficiency may be improved by using fire tube boiler to harvest energy.

Keywords: *Energy Harvesting; Diesel Engine; Waste Heat Recovery; Fire tube boiler*.

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CHAPTER NO. 01: INTRODUCTION

1.1 Introduction

Mechanical energy is essential to prime move the heavy machinery and provide rotational energy for pumping water, running vehicles, and generating electrical power. However, many types of prime movers are used (gas turbines, steam turbines and gasoline engines), but the most commonly used is the diesel engine. The autonomous energy is available in the form of few horse powers from few horse powers to 10,000 hp. If diesel engines are properly maintained, then they are powerful, inexpensive, small, extremely reliable and fuel efficient. Because diesel engines are used widely in power sector facilities, the fundamental knowledge about the diesel engine and its operation helps for the proper maintenance and operation where they are being used. Due to a wide range of engine sizes, services, and brands, it is compulsory to learn about the diesel engine theory of operation and fundamentals.

1.2 History

The history of diesel engine is extended to when Rudolf Diesel started his revolutionary work in the closing years of 19th century on air blast injected stationary engines, and it was being used in many leading positions which now embraces in many claims, e.g. land transport and marine propulsion, both rail and road, now a days it is the subject of severe growth and proficient of improvements. Diesel engine is considered one of the most powerful and efficient liquid burning prime mover derived yet. The diesel engines were used mostly in ship propulsion and stationary applications as four-stroke normally articulated engines at relatively low speeds in Hubert Ackroyd Stuart in the UK and Germany before 1914, which were built in the result of Rudolf Diesel work. The high-speed diesel engines were developed due to considerable motivation from 1914-18 war, which were capable of higher specific output, that were used in vehicles as their remarkable application. Although spark ignition engines were used undoubtedly in the first generation of road transport, the slightly later growth of the diesel engines which were working on the compression or self-ignition principle trailed shortly after the 1930 the high speed ordinarily articulated diesel engines were definitely recognized as the utmost effectual source of power for buses and trucks. In that years with the growing usage of turbochargers it started to move the extremely wasteful steam in the engine in railway trains while the future 1939 to 1945 war provided a main inspiration for the progress of highly supercharging diesel engines as an innovative aero plane engine, mostly in the Germany.[1]

Meanwhile in the 1939 to 1945 war each main manufacturing countries have established their individual variety of diesel engine. Its utmost market requirement has undeniably happened in the arena of substantial road transportation where at any amount in Europe, it is now leading. It is predominantly in this arena where progress, in the path of turbocharging in its several forms, has been fast throughout the previous twenty years, where abundant of the present investigation and progress struggle is focused. Though, a nonstop procedure of increasing and modification has been practiced from all of its arenas of application, after the very major low speed naval two-stroke engines, however average speed immobile engines to minor single cylinder engines aimed at process in distant zones with least presence. There is minute uncertainty that it will remain to live a principal location in the range of reciprocating engines, so to the extant as fossil fuels remain to be existing and, providing fuel quality can be less sensitive, however into the period of artificial or coal resulting fuels. IC engines are classified on a number of criteria given in the next section.[1]

1.3 Types of IC engines

There are a wide range of sorts of inner ignition Engine. They can be arranged by taking after parameters:

1.3.1 Applications

As indicated by the way of utilization and reason, vehicle, truck, train, light airplane, marine, versatile power framework, control era is the principal employments of IC Engine.

1.3.2 Basic engine design

Reciprocating engines, rotary engines (Wankel) are the basic types of Engines classified based on movement of piston in the cylinder. Both types have their own advantages and disadvantages.

1.3.3 Working cycle

According to working cycle IC engine may be two-stroke cycle, Four-stroke cycle, naturally aspirated, supercharged, and turbocharged.

1.3.4 Port or valve shape

Cross-scavenging porting, revolving valves, under head valves, overhead valves, circle loop porting and unidirectional stream scavenged.

1.3.5 Fuel

On the premise of fuel utilized the IC Engine might be Petrol Engine Diesel Engine Gas Engine Biodiesel Engine CNG Engine or Cross breed Engine.

1.3.6 Method of Mixture Preparation

According to method of mixture preparation the engine may be Carbureted engine, Engine with fuel injection into the intake railing fuel injection, direct injection method. Now-a-days some advanced methods of fuel mixture preparation are used.

1.3.7 Method of Ignition

There are two types based on method of ignition: spark ignition system and compression ignition. Spark ignition normally used for petrol engine, CNG engine, LPG engine and dual fuel engine, whereas compression ignition is used for diesel engine and biofuel engines.

1.3.8 Combustion Chamber Design

Open chamber, separated chamber (little and expansive secondary chambers; many plans: e.g., twirl chambers, pre chambers)

1.3.9 Loading Method

Airstream and throttling of fuel together so blend structure is basically unaltered, control of fuel stream alone, a mixture of them.

1.3.10 Cooling method

Substantial obligation vehicles have water cooled Engine, where as some light obligation Engine like engine bicycle Engine are air cooled, a few Engine are nearly un cooled.

1.3.11 Number of Cylinders

Engines may be single cylinder double cylinder or multi cylinder up to 16 cylinder or more. Engine having one chamber is termed as single cylinder and engine with more than one cylinder is called as multi cylinder engines.

1.3.12 Angular Position of cylinders

According to the angular position of cylinder the engine may be flat, inclined or V type engine.

1.4 Working principal of CI or Diesel Engine

In CI engines, the chemical energy of the fuel is altered into heat energy through ignition. The combusted gases increase the intensity of pressure within burning chamber which then transferred to the head of the piston and create motion of piston. There are main four processes in Diesel Engine. Intake valves are open during the intake stroke and air move in the ignition chamber and cylinder volume is enlarged by the piston movement. Now intake and exhaust valves are shut down and air is entrapped inside the cylinder. At the point when the piston is moving toward the top right on target, when the cylinder volume is minimum, diesel fuel is added into the ignition chamber. The highly compressed air is self-ignited by the injection of diesel droplets.

The amount of oxygen taken into Engine cycle is dependent upon the measure of fuel in the ignition chamber. When the fuel sum is expanded, accordingly more air is required for the ignition to build more power of engine. The rate of mass flow of air into the engine can be boosted by compressing the air before entering the chamber. Now a days, it is possible by introducing turbocharger and supercharger. Turbochargers consist of a turbine and a compressor coupled together by shaft. The turbine is compelled by the hot outflows gasses and drives the compressor which raises the pressure of the entering air into combustion chamber.

1.5 Diesel engine parts and terminologies

1.5.1 Injection nozzle

Injection nozzle sprays diesel fuel on the fully compressed air inside the cylinder of engine.

1.5.2 Hot bulb

Hot bulb is a pre-heater by which the temperature of piston and cylinder is maintained up to appropriate level to enhance the engine combustion process.

1.5.3 Piston

It is made of aluminum in shape of a cylinder which moves back and forth inside of engine cylinder.

1.5.4 Cylinder

Fuel is burned inside the cylinder and piston also move inside this cylinder.

1.5.5 Connecting rod

It is usually made of alloy steels which transfers motion from piston to crank shaft.

1.5.6 Crank shaft

Crank shaft is required to change over the reciprocating movement of piston inside the cylinder into rotational movement. This contains at least one driven and one driver component bit called crank.

1.5.7 Crank case

Crank case is a vessel of cylindrical shape which is use as a sump for the fresh air in the diesel engine and in petrol engine it used as a lubrication oil sump.

1.5.8 Cam shaft

The purpose of cam shaft in the diesel engine is to operate the inlet and exhaust valves of the engine.

1.5.9 Fuel pump

A diesel fuel pump or fuel infusion pump is utilized to infuse the fuel straightforwardly into the cylinder to start the start of dinner packed air in chamber.

1.5.10 Inlet port

Fresh air enters into the crank case through this port.

1.5.11 Outlet port

It is a passage for exhaust gasses when piston uncovers the exhaust port while moving from top dead center to the bottom dead center.

1.5.12 Fly wheel

It is a heavy wheel, mounted at one end of crank shaft. The function of this wheel is to store some energy in power stroke and then engine uses the energy during other processes. It also makes the speed at constant.

1.6 Types of Diesel Engines

There are lots of methods for classification of Diesel Engines. Two stroke Diesel Engines are C.I engines in which all the necessary processes of conversion of heat into mechanical work are just competed in one revolution and two strokes of piston. In a four stroke Diesel engine similar work is done in two crank revolutions and four individual strokes for each process needed for Diesel Cycle.

1.6.1 Working of two-stroke diesel engine

In a two stroke Engine, the four procedures of cycle are finished in just a single insurgency of wrench shaft and in two strokes of cylinder. In this engine the compression and intake take place in a single stroke. While the exhaust and expansion stroke take place in another stroke. Fig. 1.1 represent the basic components of a two stroke diesel engine.

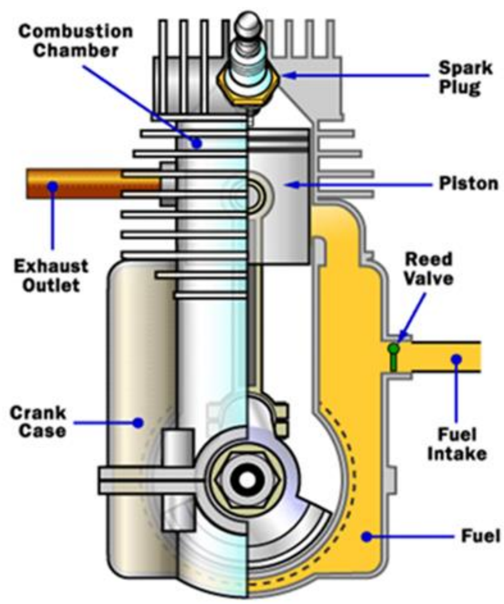

Figure 1 Basic components of a Two Stroke Diesel Engine

1.6.2 Working of four-stroke diesel engine

Today's immediate infusion diesel Engine are more rough, effective, tough, and solid than gas Engine, and utilize fuel substantially more productively, also. Diesels are workhorse Engine. That is the reason you discover them fueling substantial obligation trucks, transports, tractors, and trains, also expansive boats, bulldozers, cranes, and other development hardware. Previously, diesels fit the generalization of muscle-bound behemoths. They were messy and languid, malodorous and noisy. That picture doesn't make a difference to today's diesel Engine, in any case, and tomorrow's diesels will indicate significantly more prominent upgrades. They will be significantly more fuel effective, more adaptable in the powers they can utilize, and furthermore much cleaner in outflows

1.7 Main working processes of diesel engine

1.7.1 Suction

In this process, the piston while moving down towards B.D.C. uncovers the inlet port and outlet port. Due to which the fresh air enters into the cylinder from crank case because of pressure difference.

1.7.2 Compression

The piston while moving up towards the T.D.C. first uncovers the transfer port then the exhaust port. As the piston moves upwards to compress the air the inlet ports open and the fresh air enters in the crank case

1.7.3 Expansion

Shortly before the piston reaches the T.D.C the compressed air is injected with the fuel to burn when the compressed air is burn with a blat the piston is force back and hence, we get power.

1.7.4 Exhaust

Now the piston moves downward ant the exhaust port is uncovered the exhaust gasses flow out and the fresh air enters the chamber through transfer port. In 2 stroke engines a phenomenon named scavenging takes an important part for pushing out the burned exhaust gases from the combustion chamber.

1.8 Diesel Engine Performance Parameters

1.8.1 Brake torque

The resistance offered to the Engine by the pole/Fly wheel against turn or measure of constrain required to stop a pivoting shaft/fly of range "r' is named as Brake Torque additionally assigned as Load the units typically utilized for Brake Torque or Load are Nm. We require a measure of Force "N" Newton's to pivot the pole, Pulley or Fly wheel of Radius "m". The term Brake shows the estimation technique for Torque utilizing Prony Brake framework. The Brake Torque Brake torque increments with speed up to a most extreme esteem named as Max Brake Torque then it gets lower as at higher speeds as it gets to be distinctly troublesome for Engine to consume a full Charge of air. Fig. 1.2 indicates the Engine power and torque curves.

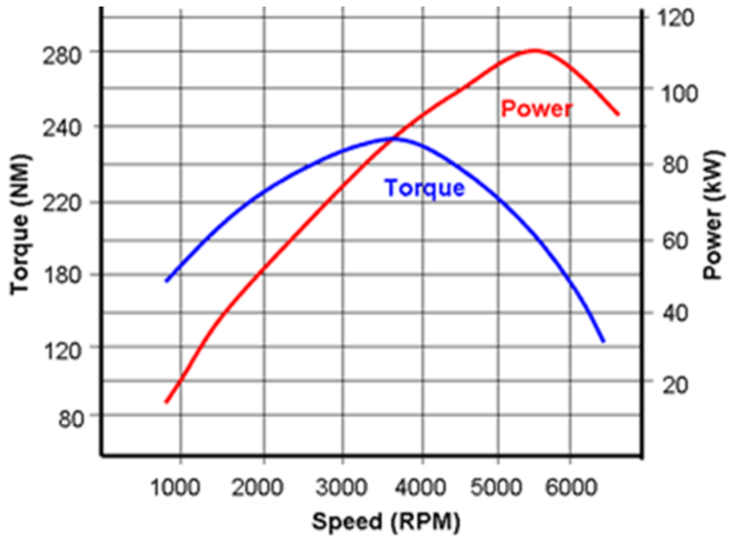

Figure 2 Engine power and torque

1.8.2 Brake power

The measure of mechanical work "w" in time "t" accessible at the yield shaft of Diesel Engine is called Brake Power. Ordinarily Given as kW different units are Horse power and kilo Watt hours. Brake Power relies on upon Brake torque and Engine Speed (rpm). Brake is lower at lower speeds where as it gets on higher at speed increments. It gets bring down after the temperate range at rapid of 6000 rpm where the torque diminishes significantly due lesser admission of air/fuel blend.

Brake Power =$2\pi TN/60$ (watt)

1.8.3 Brake mean effective pressure

While torque is a valuable measure of a particular engine's ability to do work, it depends on engine size. A more useful relative engine performance measure is obtained by dividing the work per cycle by the cylinder volume displaced per cycle. The parameter so obtained has units of force per unit area and is called the mean eflective pressure (mep).

1.8.4 Brake specific fuel consumption

Measure of fuel expended is another parameter of Diesel Engine. This parameter is identified with the economy of fuel. As the manageability of vitality is under serious dangers so the utilization of fuel is taken as key parameter while plan of Diesel Engine. Measure of fuel in given time is named as particular fuel utilization while the particular fuel utilization per unit Brake power is given as Brake Specific fuel utilization.

$BSFC = mf/Pb$ (g/kWh)

1.8.5 Brake thermal efficiency (BTE)

Brake thermal efficiency is the measure of how efficiently engine converts the thermal energy in the fuel supplied into useful power that is obtained at the output shaft or crank shaft of the engine. It is the ratio of brake power to equivalent heat energy that is supplied to the combustion chamber.

1.8.6 Loss power

All the power Developed accordingly of fuel utilization is not changed over into mechanical work or Brake Power 60-70% of this power is lost as warm troubles. These loses are as exhausts temperature, increment in interior energy of framework and increment in the entropy of universe. It is regularly ascertained as a distinction of IP and BP;

FP=IP=BP

1.8.7 Air-fuel ratio

For burning to occur, the best possible proportion of air and fuel must be available in the chamber. The air-fuel proportion is characterized as

A/F = ma/mf

The perfect AF is around 15:1, with homogenous burning conceivable in the scope of 6 to 19. For a SI Engine the AF is in the scope of 12 to 18 contingent upon the working conditions. For a CI Engine, where the blend is very non-homogeneous and the A/F is in the scope of 18 to 70.

1.8.8 Swept volume

Perfect most extreme cylinder volume secured by the cylinder from TDC to BDC is named as cleared volume or dislodging volume Vs or Vd. The BP, IP, and Thermal productivity of Engine fluctuates straightforwardly with this parameter, so the size and rating of Diesel Engine is portrayed by this parameter.

$Vd = \pi/4 D^2 L$

1.8.9 Clearance volume

The volume in between TDC and cylinder head that is used to compress the air-fuel mixture and start the ignition is called clearance volume.

1.8.10 Volumetric efficiency

Due to very fast reciprocation of pistons inside engine, very little time is obrtained for intake of fresh air into the combustion chamber. The capability of an engine to intake the fresh air into the chamber is evaluated by the volumetric efficiency which is the ratio of actual air enhaled and the designed volume of the chamber. Commonly, volumetric efficiency for wide open throttle varies in the range of 75-90% and decreases when the throttle is closed.

1.9 Advantages of diesel engines

Diesel fuel (longer HC chains) is more protected than gas in numerous applications. In spite of the fact that diesel fuel will smolder in outside utilizing a wick, it won't detonate and does not discharge a lot of combustible vapor. The lower pressure of diesel vapors is particularly worthwhile in underwater applications, where the gathering of unstable fuel/air blend is specific liability. For a similar reason, diesel Engine are invulnerable to vapor bolt. At specific load fractional load the fuel productivity (mass smoldered per Energy delivered) of a C.I engine remains almost consistent, instead of petrol and turbine Engine which utilize relatively additional fuel with halfway power yields. They create less waste warmth in cooling and fumes. Diesel Engine can acknowledge super-or turbo-charging pressure with no characteristic farthest point, compelled just by the quality of Engine segments. Biodiesel is an effortlessly orchestrated, Biofuels fuel (through trans esterification) which can run straightforwardly in numerous diesel Engine, while gas Engine either require adjustment to run engineered energizes or else utilize them as an added substance to gas e.g., ethanol included.

1.10 Diesel engine performance parameters and challenges

1.10.1 Power to Pressure Ratio

The ability to pressure proportion of Diesel Engine on the substantially lesser side than alternate sorts of interior burning Engine.

1.10.2 Cost

Because of less energy to pressure proportion and less warm productivity the Diesel Engine are moderately more expensive than Petrol Engine of comparable determinations.

1.10.3 Tolerances on Valves and VVT

The design of valves and seats of a 4-stroke diesel is much more difficult and standardized than diesel engine. So, it is difficult to obtain the variable valve timing in case of modern 4-stroke diesel Engines

1.10.4 Noise

Diesel are having wide body structure so on working at various loads and speed they generate more vibration and noises, which sometimes lead to the failure. The intensity of shock waves due abnormal combustion is another reason higher noise level in diesel Engines

1.10.5 Emission and Pollution Level

The combustion of compressed air due to atomization of fuel is not so effective and normal so combustion remains incomplete. The incomplete or partial combustion of fuel leads a large amount of toxic and nontoxic emission which heavily contributes to the global pollution and warming.[2]

CHAPTER NO. 02:LITERATURE REVIEW

2.1 Literature review

Energy plays a vital role in modern era. The development of modern age depends on energy. Due to its acute importance, many efforts have been made to use energy more efficiently and produce maximum amount of work from the available energy. Hence, a lot of work has been done in past few years to manufacture more efficient machines and devices. An example of this effort includes the increase in efficiency of an internal combustion engine using different methods. A literature review has been done in this regard and here are the details of efforts made to improve the efficiency an engine.

Thermal energy can be recovered in two ways: thermoelectricity and Rankine cycles. Due to its higher cycle efficiency when compared to the present state-of-the-art thermoelectric materials' intrinsic conversion ratio, the Rankine cycle has the most opportunity.[3]

According to Peter Heidrich, in urban traffic conditions, the thermal efficiency of a modern internal combustion (IC) engine is predicted to be confined to 20–40%, whereas 33 percent of the fuel energy from a typical medium-size passenger vehicle is taken away by exhaust gases and 33 percent by engine cooling water. Consequently, 60-80% energy is lost during the typical operation of an IC Engine.[4]

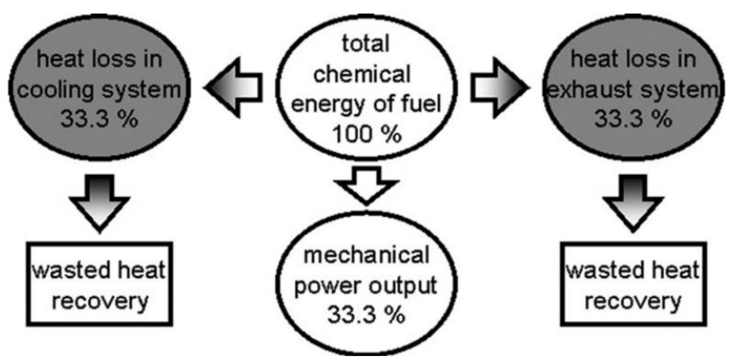

Figure 3 Typical Heat balance diagram of an IC Engine

A Swiss engineer, Alfred Buchi, introduced the first prototype to increase the power of IC engine. After those continuous efforts have been made to get more power and make the engine more efficient.[5]

Energy storage devices can be used in hybrid automobiles to decouple the engine from the vehicle's driving wheels. The engine can now be run closer to its optimal operating condition, but fuel energy is still dissipated as heat through the exhaust system. A turbogenerator on the exhaust line solves this problem by recovering and converting some of the otherwise wasted heat into useful electrical energy. Briggs was involved with modelling the engine of a diesel-electric hybrid bus, as well as a hybrid powertrain model that analyzed a hybrid vehicle's performance over a drive cycle. The influence of the turbogenerator power distribution on the bus's fuel consumption was investigated. This revealed that using the turbogenerator reduced fuel usage by 2.4 percent over a typical drive cycle.[6]

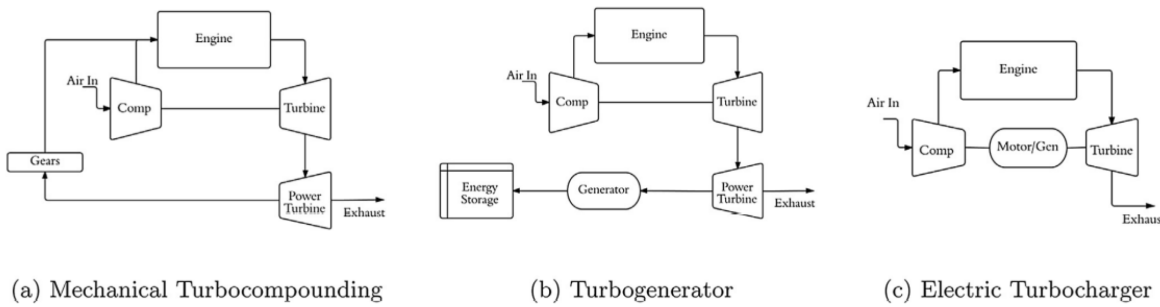

Figure 4 Briggs whole diesel-vehicle modelling for energy recovery

Range extenders have shown to be a viable solution for extending the driving range of electric vehicles (EVs) while also reducing harmful emissions in the automotive sector. Fenzhu Ji investigated the use of Micro-Gas-Turbine-based Range Extender (MGTRE) instead. The Micro-Gas-Turbine-based Range Extender (MGTRE) emitted less pollutants and had a greater power-to-weight ratio, around 0.48–0.8 kW/kg, than the traditional Diesel-Engine-based Range Extender (ICERE).[7]

Mohd Asjad Siddique used the LiBr-H2O Absorption refrigeration cycle, which was powered by engine exhaust heat, to recover energy from waste heat and put it to good use.[8]

Gaurav Sharma carried out an experiment in which TEG technology was employed to recover waste heat from a diesel engine's exhaust gas. Thermoelectric modules were mounted on the surface of a square-section stainless steel pipe. It was discovered that as the engine load increased, the thermoelectric generator's power output increased. TEG's highest electrical power output was measured at 37 W with a maximum load of 6 kg. The inclusion of a TEG type waste heat recovery system boosted the overall thermal efficiency of the diesel engine.[8]

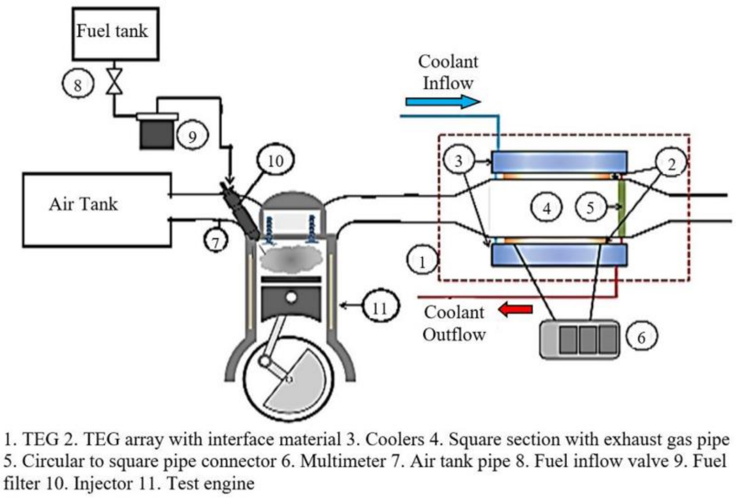

Figure 5 Use of TEG in Diesel Engine to improve efficiency

Pranay Raut conducted an experimental inquiry with a TEG module (TEC1-12715) integrated with a waste heat recovery module using an Aluminum heat sink on one end and a Copper heat sink on the other. This entire waste heat recovery module was connected to the exhaust system of the Honda GX120 engine and was applied for conversion and storage. Using a pair of TEGs (TEC1-12715), the greatest voltage achieved is 1.4 V at 3000 rpm.[9]

Francesco Catapano used experimental and numerical approach to investigate the performance of a diesel Engine by coupling a Stirling Engine. Stirling Engine was coupled at exhaust to recover waste heat. The results revealed that the heater collected 42.9 percent of the waste heat rate, producing 0.350 kW of mechanical power, corresponding to a SE efficiency of 15.8 percent.[10]

Qi Liu used an approach based on in-cylinder steam–air expansion, which had simpler design but higher practicality than previous methods. The high-temperature steam generated by engine waste heat was injected into the steam expansion cylinder, in which it expanded together with air and produced effective work.[11]

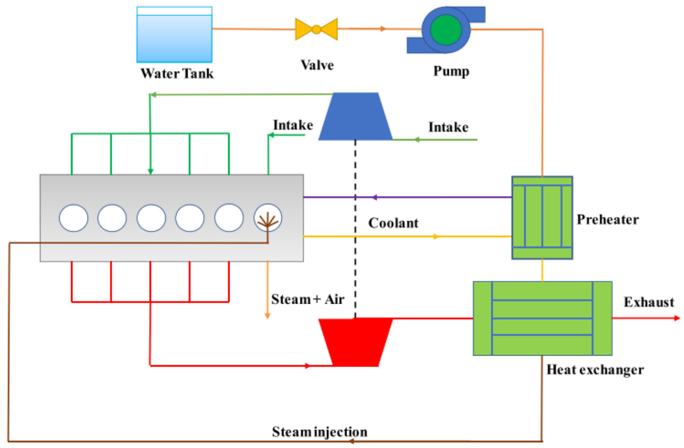

Figure 6 Schematic diagram of cylinder steam air expansion using waste heat recovery

Ding Lou investigated numerically waste heat recovery at exhaust of IC engines by using thermoelectric generators at COMSOLE. The results indicated that the conversion efficiency and power output of the automobile using thermoelectric generators was 1.53% and 38.07 W, respectively.[12]

Jelmer Rijpkema experimented on turbo-charged heavy duty truck engine to recover energy from waste heat using typical Rankine cycle. Cross counter flow heat exchanger was used during this experimentation to convert water into steam. The findings of the experiments were used to calibrate and validate steady-state models of the cycle's principal components, including the pump, evaporator, bypass valve, condenser, and expander.[13]

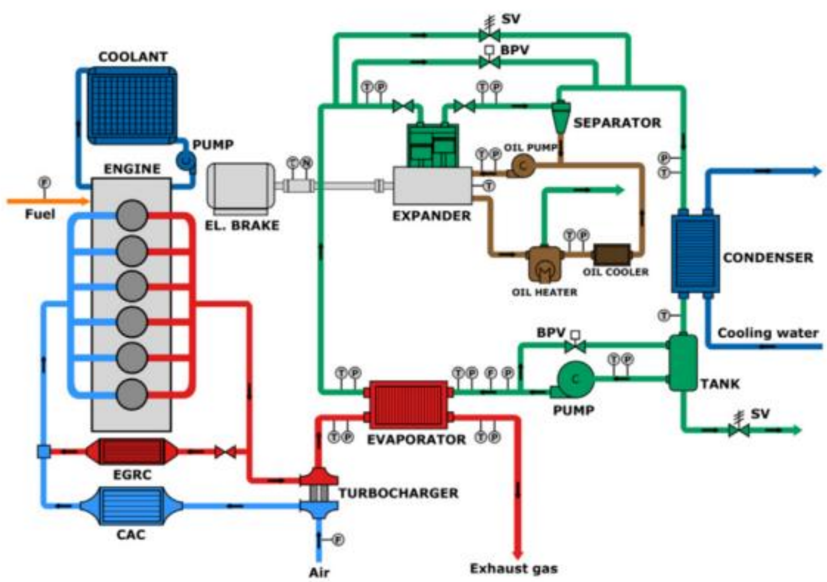

Figure 7 Experimental Setup Heat Recovery of Turbo Charge Heavy Truck Engine

E. Galloni examined the feasibility of an ORC-based heat recovery system sized for a light-duty car with a SI engine. The system's major components were louvred heat exchangers and a scroll expander. In two operational scenarios, the integrated system was modelled with the vehicle cruising at different speeds. To explore the influence of the system control elements, parametric analyses were done. Results of this study proved that the recovery system's functioning must be properly regulated according to the engine's operating point. On average, over 6% of the heat carried by exhaust gases might be recovered under ideal conditions. This improved the overall power delivered by the powertrain by around 3.5%. In terms of integration on board vehicle, the powertrain fuel consumption increased for each driving scenario, but the overall energy balance improved.[14]

Lixia Kang strived to optimize the design of the ORC waste heat recovery system (WHRS) for multi-source, multi-period operations. An industrial case study is used to validate the proposed method's application and effectiveness, and the results are expected to provide guidelines for the design of multi-period and multi-source waste heat recovery processes in practical.[15]

Jelmer Rijpkema conducted study to extract energy from low temperature regions. An organic Rankine cycle with R1233zd(E) as the working fluid recovered heat from the coolant of a heavy-duty Diesel engine was used for the experiment. Experiments at various engine operating points revealed that the maximum operating cycle pressure was 8 bar, and the temperature was 92°C. With a thermodynamic efficiency of 1.1 to 1.8 percent, between 0.1 and 0.7-kW net shaft power was generated, producing the highest expander power of 0.7 percent relative to the engine power. Experimentally, a simple empirical model predicted that about 0.7 percent of the engine's energy could be recovered throughout a driving cycle, rising to 1.3 percent if a high efficiency pump and expander were installed.[16]

Alberto A. Boretti discussed the pros and cons of using Rankine cycle as waste heat recovery system for IC engines.[17]

Norbert Lümmen investigated for waste heat recovery from a 900-kW fast passenger ferry using organic Rankine cycle (ORC). Different means of ORC were investigated which led to different amount of heat recovered.[18]

The complete heat exchanger, which can transfer entire heat between flue gas and air, is a crucial component of waste heat recovery systems. Yiyu Men investigated the primary causes of the performance difference between two total heat exchangers (double spray towers and an enthalpy wheel) in a quantitative comparison. When comparing the enthalpy wheel to the two spray towers, the experimental results showed that the enthalpy wheel performed better. The enthalpy wheel had a greater total heat efficiency of 88.4%, which aided in improving a boiler's waste heat recovery efficiency.[19]

To recover waste heat, Xilong Kang created extremely efficient pyroelectric generators using nanocomposite. P(VDF-TrFE-CFE) and barium strontium titanate (BST) nanoparticles, as well as boron nitride (BN) nanosheets, were used to create the nanocomposite, which has high thermal conductivity and polarity. The output current density of PEG devices can attain 1.7 A/cm2, which is a considerable improvement.[20]

Peter Heidrich investigated the properties of an internal combustion engine based on a passenger car. The characteristic of available waste heat overload and speed was evaluated using exhaust gas temperatures and exhaust gas mass flows. An ideal, water-based Rankine cycle was created and compared to several organic Rankine cycles based on this trait. Finally, the projected waste heat recovery under typical passenger car operation conditions was calculated by balancing the waste heat recovery characteristics against the new European driving cycle operation criteria (NEDC). Only roughly 0.2 kW of power may be recovered in the NEDC scenario. Between 2.5 and 4.0 kW could be recovered by transitioning to range extender conditions.[4]

D. Di Battista attempted to integrate various methods in order to achieve more efficient waste heat recovery results. Power units based on organic Rankine cycles are the most promising technology (ORCs). Regrettably, their actual efficiency differs significantly from that expected by thermodynamic calculations: low efficiencies of small-scale machines, severe off-design environments, and the backpressure effect are the root drivers. This research proposed a combined strategy to improve conversion efficiency by combining two thermodynamic cycles: Joule-Brayton and Rankine-Hirn. The top cycle employed supercritical CO2 as the working fluid, whereas the bottom cycle utilised an organic fluid (R1233zDe, bottom cycle). The combined recovery unit enhanced the complexity to the system, but it achieved a 3–4% higher overall net efficiency than a single ORC-based recovery unit.[21]

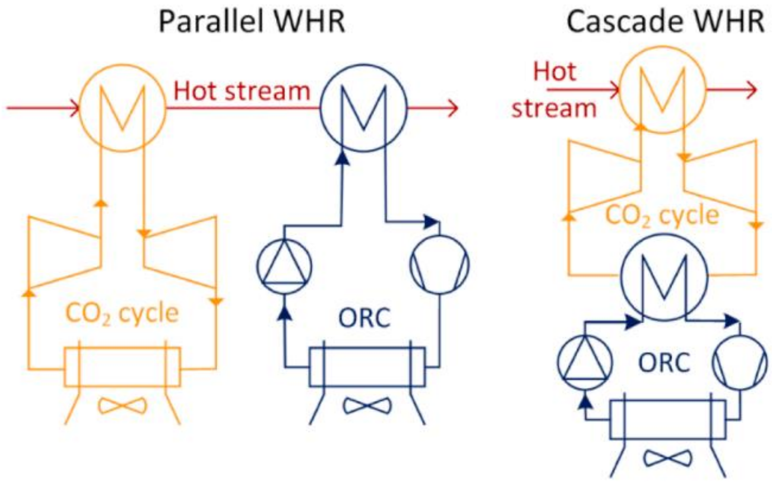

Figure 8 Schematic of combined technologies to recover waste heat

Dariusz Butrymowicz developed a prototype heat recovery system for small and mid-sized naval combustion engines with nominal loads ranging from 100 to 250 kW. The unique low-pressure steam indirect heat transfer subsystem was covered by the waste heat recovery system. The recovered heat was utilized by the prototype and a heating system. The waste heat recovery system also delivered nearly 60 kW of heat recovered from the engine block's water jack cooling, which was utilized to provide heating capacity for space heating and tap water. Almost all small and mid-sized boats' thermal energy objectives had been achieved. Two independent maritime classification groups had given its approval to the prototype design.[22]

During on-road operation, Stijn Broekaert investigated waste heat recovery for heavy - duty vehicles. A Class 5 Heavy Lorry (Tractor) with a waste heat recovery system was examined on the chassis dyno and on the road under realistic conditions, with waste heat recovery enabled and disabled through every test cycle. Waste heat recovery reduced fuel usage by 3.1 percent in the World Harmonized Vehicle Cycle (WHVC), 2.5 percent in the Regional Delivery Cycle (RDC), and 1.9 percent in on-road journeys. Because more exhaust energy was accessible during the RDC on the chassis dyno than during on-road journeys, the WHR system was able to deliver more power output, leading in a more significant reduction in fuel consumption. There was no statistically significant reduction in pollutant emissions. The Vehicle Energy Consumption Calculation Tool (VECTO) was used to simulate on-road excursions, and the fuel consumption was predicted with an error of less than 1.5% for individual trips and less than 0.5% when averaged over several repeats. These data indicated VECTO's capacity to accurately model cars with Waste Heat Recovery in real-world settings.[23]

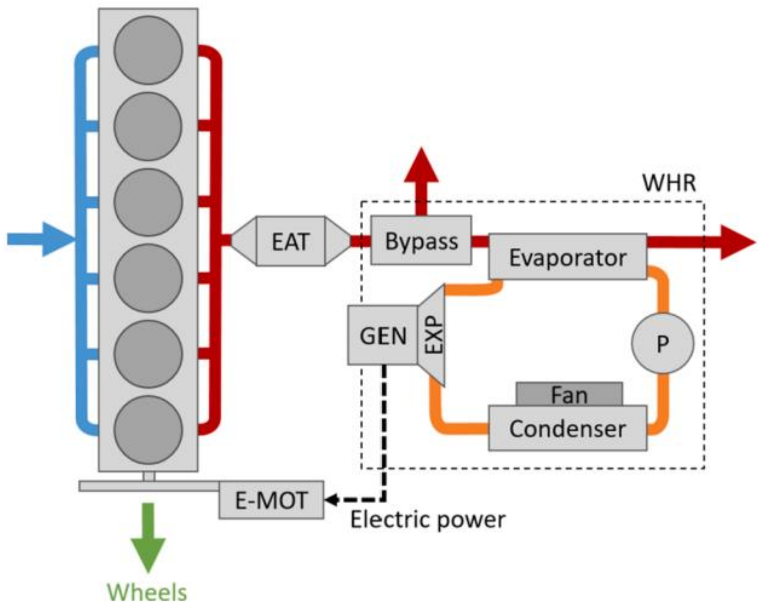

Figure 9 Schematic of Waste heat recovery (WHR) System

Diego A. Arias investigated waste heat recovery from IC engines in hybrid automobiles theoretically. A Rankine cycle operating with exhaust gases, a cycle operating with the engine coolant system, and a combined exhaust-engine coolant system were all explored. The criteria and restrictions for each of the configurations, the most effective fluids, and the geometries and sizes of the components were all determined throughout the development of these strategies.[24]

V. Dolz examined alternative bottoming Rankine cycles with water-steam and/or ORC configurations in both traditional and novel settings, such as a waste heat recovery system in a Heavy-Duty Diesel (HDD) engine. This work is broken into two halves. The model of the researched HDD engine and the available waste energy sources in this HDD Engine are discussed in the first part. Finally, two configurations were chosen as the most suitable, balancing external irreversibility and technological complexity, and they were studied to identify global efficiency, power increments, and necessary adjustments to implement these cycles in the HDD engine.[25]

Edward Doyle analyzed the performance of class 8 truck after installation of ORC with the diesel engine. In preparation for a one-year test program, a Class 8 vehicle was equipped with a diesel-organic Rankine compound engine. The compound engine was made up of an organic Rankine bottoming cycle system that was directly connected to a Mack diesel engine and used the waste heat in the exhaust fumes to generate electricity. The bottoming cycle system's components were discussed, and their testing was aimed at confirming the expectations of a 15% fuel economy gain that were previously obtained through engine dynamometer testing and extensive engineering research.[26]

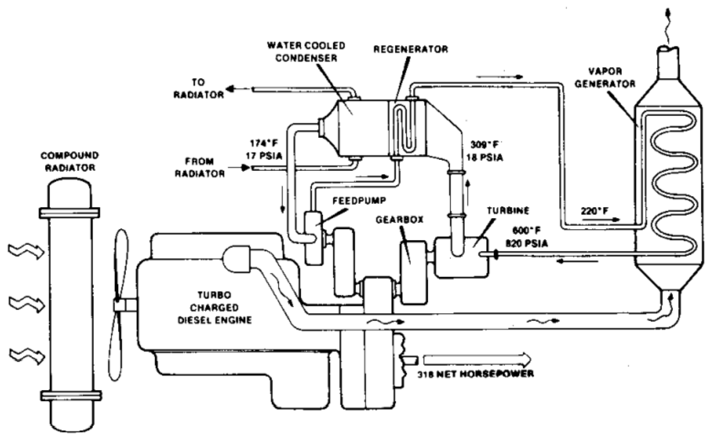

Figure 10 Schematic of ORC coupling with Class 8 truck diesel engine

Takatoshi Furukawa worked on heavy duty HV truck to recover heat from exhaust using Rankine cycle. The primary heat source in this study was engine coolant, which collected energies via engine cooling, EGR gas, and exhaust gas to capture as much steady energy as feasible. The flow of the heat source was also increased by raising the coolant temperature to 105 degrees Celsius. To increase system efficiency, the saturation temperature difference was improved by boosting the heat exchanger's performance and employing a high-pressure turbine. To recover the heat of the working fluid at the turbine generator, a recuperator was fitted, which transfers heat in the working fluid between the expander output and the evaporator intake. The system's power usage was then reduced by improving a working fluid pump. Hydro-fluoro-ether was chosen as a suitable working fluid for the vehicle system. The Rankine cycle generating system, which consists of each of the components listed above, was tested under highway cruising conditions using the created downsizing engine. Consequently, the efficiency was elevated by 7.5%.[27]

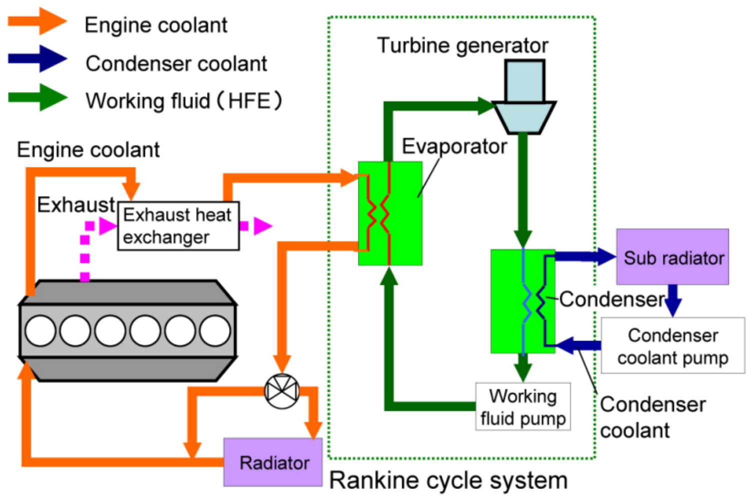

Figure 11 Rankine cycle generating system collecting energies recovered

Cheng-Ting Hsu worked on harvesting to harvest energy on low temperature waste using TEGs. In this case study, a waste heat recovery system was built using 24 thermoelectric generators (TEG) to convert heat from an automobile's exhaust pipe to electrical energy. To assess the feasibility of these applications, simulations, and experiments for the thermoelectric module in this system were conducted. Based on simulation results, a sloping block was created to uniform the internal thermal field, which contributed to the effectiveness of TEG modules. The system is created and assembled in addition to simulations. The system was connected to the middle of an exhaust pipe, and measurements were taken. The system's open circuit voltage and maximum power output were defined as a function of temperature difference. The power generated using a commercial TEG module is illustrated through these simulations and experiments. In this case study and prior work, the findings establish the fundamental development of a low-temperature waste heat thermoelectric generator system that improved vehicle TEG efficiency.[28]

The ORC's productivity to harvest energy from waste heat is mostly influenced by two factors: the cycle's working conditions and the thermodynamic parameters of the working fluids. Tzu-Chen Hung analyzed the performance of ORC using dry fluids. Benzene (C_6H_6), Toluene (C_7H_8), p-Xylene (C_8H_{10}), R113, and R123 were the working fluids under examination. p-Xylene was the most efficient of the working fluids studied, whereas benzene was the least efficient. The irreversibility was proven to be extremely dependent on the type of heat source. In general, p-Xylene had the lowest irreversibility when it went for recovering high-temperature waste heat, whereas R113 and R123 performed better when it came to recovering low-temperature waste heat.[29]

Matthew Read was involved in the development of Screw Expanders for Low-Grade Heat Recovery. The power output of systems for recovering energy from low-grade heat sources that use twin screw machines to expand wet vapors is determined by the competing requirements of high heat recovery and high working fluid temperatures, the dryness fraction of the fluid entering the expander, the rotor diameter and profile, the speed, and the built-in volume ratio. Optimization methods and associated numerical procedures can be used to find the ideal combination of these for maximum power production per unit flow of a given heating medium. The goal of this study was to optimize the geometry of a twin-screw machine for the expansion of wet steam to maximize power output. The procedures utilized to design the machine were discussed, as well as representative machine operating circumstances. The projected performance was compared to experimental data for the improved machine, and the predicted and observed values for power output, mass flow rate, and efficiency were found to be quite close.[30]

According to Parimal S. Patel, the heat from the exhaust gases of a truck diesel engine is used to power an organic Rankine-cycle system (ORCS). Over the course of a normal duty cycle, adding an ORCS to a long-haul diesel vehicle can improve fuel economy by 15%. This could result in a reduction of 1.8 billion gallons per year (120,000 barrels per day) in transportation fuel requirements soon. Emission levels will be decreased by the same amount as the efficiency improvement. The potential fuel savings also give an economic incentive for the fleet operator to invest in the additional cost of a bottoming cycle system at current diesel fuel prices. The results of studies using an organic Rankine bottoming cycle (not specifically designed for this use) and a Mack 676 diesel engine are reported. Without any additional fuel, 36 additional horsepower was produced at peak power, an increase of 13% in power.[26]

According to the findings of Ho Teng, the composite fuel savings with this EGR WHR system over the ESC 13-mode test is up to 5%. If charge air cooling is also included in the Rankine cycle loop, the fuel economy gain can be increased even more. By running the Rankine cycle with two distinct working fluids, R245fa and ethanol, the effect of working fluid characteristics on WHR efficiency is investigated. The temperature-entropy and enthalpy-entropy diagrams for both subcritical and supercritical cycles compare the two working fluids. The subcritical cycle outperformed the supercritical cycle for R245fa. In the case of ethanol, the supercritical cycle outperforms the subcritical cycle. According to the comparison, ethanol might be used instead of R245fa.[31]

Ho Teng also worked on using Rankine cycle to harvest energy from HD Diesel engine by installing compact heat exchanger. This study helped him recover 5% more energy.[32]

Chuang Yu used thermoelectric generators to collect heat from the exhaust of IC engines which was then regulated using maximum power point tracking.[33]

Tianyou Wang conducted experiments and used modelling techniques to analyze heat recovery from exhaust light duty petrol engines. According to the findings, the efficiency of engine increased up to 3% to 8% by implementing heat exchange to extract energy. It was also claimed that under some condition the efficiency might increase up to 34%.[34]

Et al. Noboru Yamada[35] gave the concept of using pumpless Rankine cycle to generate power from low temperature heat sources. For this purpose, he used Switching Valve Method (SVM) to control the cycle. The experimental results proved that the cycle works.

Et al. X. Rui analyzed[36] the feasibility of using steam water supercharger instead of using mechanical pump for Rankine cycle. Slider crank mechanism was used to realize the automatic control of steam intake and steam exhaust for this purpose.

Et al L. Gkimisis[37] worked on modelling and numerical simulation of a novel pumpless Rankine cycle. He used a greater number of valves (6 Valves) for actuation, that made the system more efficient, but complexity of the system increased.

2.2 Research Gap:

After reading several research articles comprehensively, following points have been concluded:

- A lot of work has been done and being done to make systems as efficient as possible.
- Rankine Cycle is a good option to harvest energy from the exhaust of IC Engines.
- Many studies have been found using ORC rather than standard Rankine cycle, but a few studies have been done using water as working fluid, too.
- Due to the fact that ORC generates less power than steam, is combustible in nature and can cause environmental hazards upon leakage have encouraged me to use water as working fluid.
- During the entire literature review, it was also found that no experimentation has been done to recover energy using boiler as component in standard Rankine cycle (Steam) from Diesel engine.

- Boiler (Heat exchanger) provide us the opportunity to implement pumpless Rankine cycle.

CHAPTER NO. 03: MATERIALS AND METHODS

3.1 Overview:

The primary objective of the study is to investigate that how much energy can be extracted from exhaust of Diesel engine using boiler and water. This water would be converted to steam which can be further uses to produce energy (Rankine Cycle). To harvest maximum amount of energy, the experimental setup and techniques should be as ideal as possible. For this purpose, material selection plays a vital role while designing. Although, there are several types of boilers available but according to findings, fire tube boiler might be the best suited to produce maximum efficiency which would be investigated in our experimentation.

3.2 Materials:

Material selection plays a crucial role in the performance and efficiency of any procedure. So, the basic purpose of every component was analyzed, and keeping in view the desired property of the applications, materials were selected. The details of materials selection are as follows:

3.2.1 Boiler:

Boiler is closed structure in which steam is produced. Its definition suggests that following properties of materials should be kept in mind while selecting the material of boiler.

3.2.1.1 Heat Resistant

The purpose of boiler is to contain heated water until it is turned in to steam up to a specified pressure for the application. By keeping this in mind, it is evident, that the material used for the boiler should have high heat resistance and conduct very less heat to the environment for boiler to work efficiently. So, the material should have high heat resistance while fabricating boiler.

3.2.1.2 Strength

A boiler should have high tensile strength due to its purpose of storing water and high-pressure steam unless distributed for application.

3.2.1.3 Creep

The fabrication of boiler is not a simple procedure so we should opt a material that would have high creep life.

3.2.1.4 Thermal Fatigue

Components may face cycling or thermal shocks during the operation of boiler. Hence, the material should also have high thermal fatigue.

3.2.1.5 Thermal Expansion

The material should have very low thermal expansion coefficient so that the structure of show minimal deformation during the operation.

3.2.1.6 Material Selected:

By going through the properties of different materials, we found that stainless steel has following properties[2]:

Table 1 Properties of Stainless Steel

Material		**Stainless Steel**	
Serial No.	**Property**	**Value**	
1	Tensile Strength	621 MPa	High
2	Thermal Conductivity	25 W/m.K	Low

Other properties of stainless steel are also feasible for it to work as boiler. Hence, stainless steel was selected for the fabrication of boiler.

Figure 12 Stainless Steel Sheet Used

3.2.2 Exhaust Coil (Fire tube):

The objective of exhaust coil or fire tube is to carry out exhaust gases from outlet of engine to the atmosphere while transferring heat to the water present in boiler. For this purpose, this should be kept in mind that material should have high conductivity while other parameters would be as same as material for boiler. For this purpose, properties of different materials were observed, and it was observed that copper could be the optimized selection for the coil. The materials of copper are as follows[2]:

Table 2 Properties of copper

Material		Copper	
Serial No.	**Property**	**Value**	
1	Tensile Strength	210 MPa	Fairly Enough
2	Thermal Conductivity	385 W/m.K	High

Due to these properties, copper was selected for coil as material.

Figure 13 Copper Coil

3.2.3 Connector:

For the experimentation, a connecting pipe is also needed to connect the outlet of IC engine to the boiler. This pipe should withstand heat and should be insulator to prevent leakage of heat energy as much as possible. PVC pipe was used for this purpose which has very low thermal conductivity. The length of this connector was kept as minimum as possible to prevent heat losses before harvesting.

Figure 14 PVC Pipe

3.3 Methodology:

The methodology for our experimentation is that exhaust gases having ample amount heat should enter the coils of boiler, transferring heat to the water inside the boiler. This water would be heated up and ultimately would be converted to steam. The main schematic of our procedure is given below:

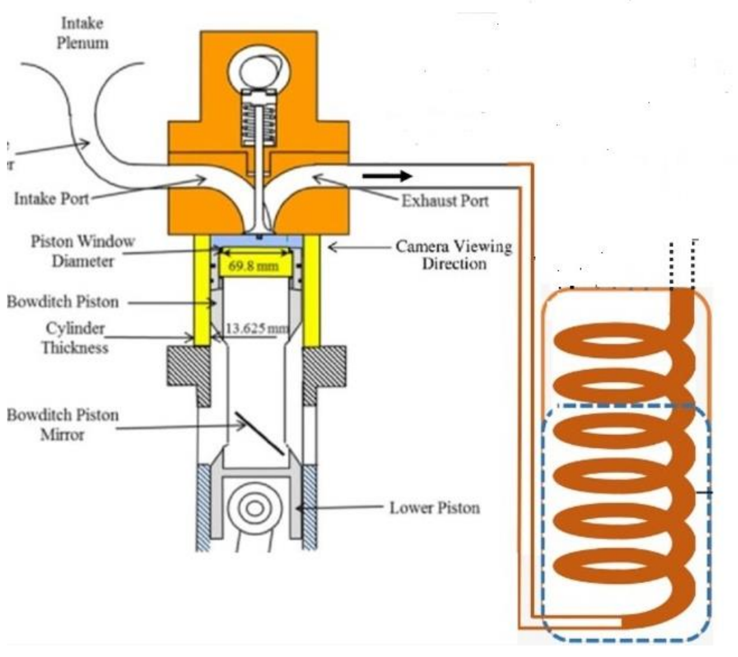

Figure 15 Schematic of energy harvesting using fire tube boiler

To analyze the results, we need different components in this experimentation. The key components of our procedure are:

1. Engine Test Bed
2. Diesel Engine
3. Thermocouple

4. Glass Beaker
5. Dynamometer
6. Stopwatch
7. Anemometer

The details of each component are as follows.

3.3.1 Engine Test bed:

An engine test bed is the equipment used to test the performance of engine by finding and calculating different parameters. For our experimentation, engine test bed is coupled with diesel engine (as experimentation to be done on diesel engine). After that diesel oil is injected in fuel cylinder to make engine work. Then engine is turned ON to observe the performance of engine. As engine is turned ON, engine test bed shows the readings of exhaust gas temperature, engine speed in RPM and torque, which can be utilized to find brake power of the engine that engine speed. The values obtained will be further used in our calculations.

Figure 16 Engine Test Bed

3.3.2 Diesel Engine:

Diesel engine has to be used in our experiment to investigate the amount of heat recovered by implementing fire tube boiler to the engine. The details of engine that we used are as follows:

Table 3 Specifications of Engine

Engine Type	**Four Stroke Diesel Engine**
Model	**LDF 170F**
Bore	**70 mm**
Stroke	**55 mm**
Displacement	**0.211 L**
Compression Ratio	**20:01**
Engine Speed	**3000-3600 RPM**
Rated Power	**2.8 kW-3.1 kW**

Figure 17 Diesel Engine LDF 170F

3.3.3 Thermocouple:

Thermocouple is the sensor used to measure the temperature accurately. So, thermocouple and vapor pressure thermometer are used to observe temperature of gases at outlet of diesel engine and temperature of water in the boiler. These temperatures will be used in our experimentation for calculations.

Figure 18 K type thermocouple

3.3.4 Glass Beaker:

Glass beaker is used to measure the amount of water poured into the boiler for steam conversion. To know the amount or volume of water to be boiled is very necessary to calculate the amount of heat gained by water. So, Glass beaker is also used in our experimentation.

Figure 19 Beaker

3.3.5 Dynamometer:

Dynamometer is also mounted in engine test bed near the shaft of engine to measure the torque. This torque will then be used in calculating the brake power of the engine.

Figure 20 Dynamometer

3.3.6 Stopwatch:

Stopwatch is used the measure the time to calculate that how much fuel has been consumed in how much time, which will help in finding the indicated power (power produced in the engine).

3.3.7 Anemometer:

Anemometer is the device that is used to measure the velocity of the fluid, which help us finding the flowrate of the fluid. By measuring the value of velocity, we may extrapolate our results of how much mechanical work can be obtained using this methodology.

Figure 21 Anemometer

3.4 CAD Model:

CAD model was prepared on Solidworks software for our convenience. While designing, it was kept in mind that the size of boiler should be optimum. It should contain the optimal amount of water to harvest maximum energy possible. If the amount of water is too much large, then it would take very long time to generate steam. If the size of boiler is too short, then a little amount of energy would be extracted, remaining would be lost. So, it was analyzed that observing at the rated power of the engine and estimated time to generate steam as approximately 30 minutes, 300 ml of water would be optimum to contained in the boiler for steam generation.

By keeping above points in mind, fire tube boiler was designed with following dimensions.

Table 4 Dimension of the components of Fire tube boiler

Material	**Stainless Steel (For Boiler)**
Dimensions	
Outer Diameter (d_O)	7.3 cm
Thickness (t)	3 mm
Inner Diameter (d_i)	6.7 cm
Height (h)	12.58 cm
Material	**Copper Coil**
Dimensions	
Outer Diameter (d_O)	6 mm
Thickness (t)	1.2 mm
Inner Diameter (d_i)	3.6 mm
No of turns in coil	07
Material	**PVC Pipe**
Dimensions	
Outer Diameter (d_O)	3.35 cm
Thickness (t)	2.9 mm
Inner Diameter (d_i)	2.77 cm

3.4.1 2D Views (Multiple Views):

The multiple or 2D views of the designed model are as follows:

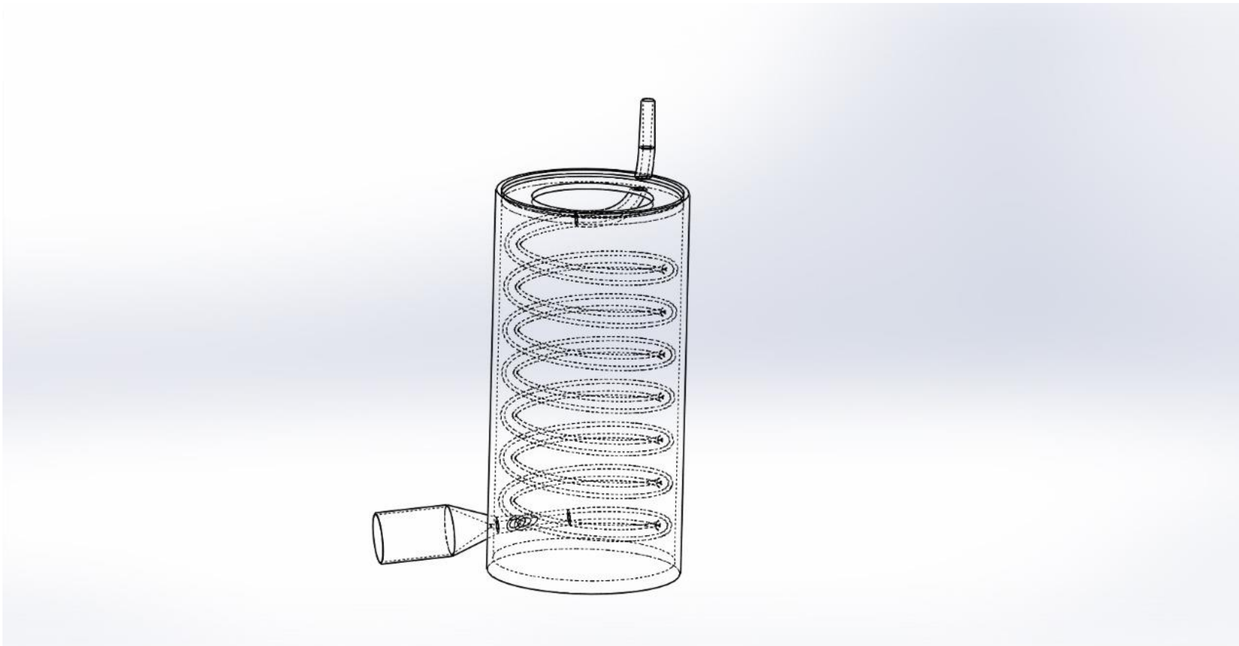

Figure 22 Front view of Fire tube boiler

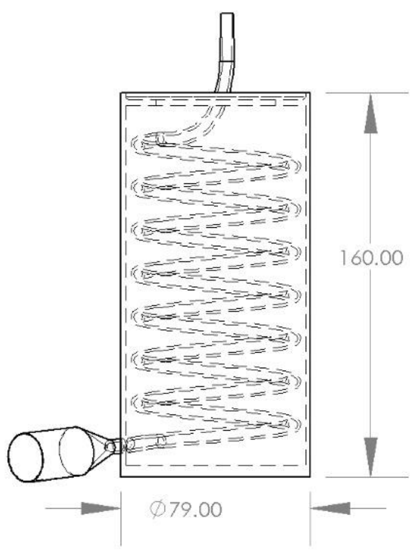

Figure 23 Side View of Fire Tube Boiler

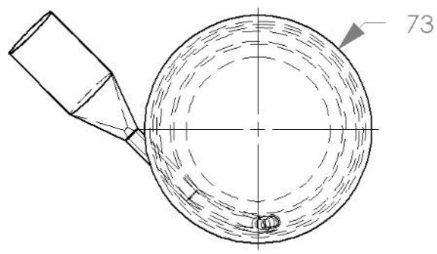

Figure 24 Top View of fire tube boiler

3.4.2 Isometric View:

The isometric or 3D view of our model is as follows:

Figure 25 Isometric View of fire tube boiler

3.4.3 Actual Model:

After manufacturing of fire tube boiler, here is the picture of actual fire tube boiler to be put for experimentation.

Figure 26 Fire Tube boiler for testing

3.5 Experimental Setup:

For our experimentation, diesel engine was coupled with engine test bed. We connected our specimen (fire tube boiler) with outlet of engine via PVC pipe. We also inserted K-type thermocouple at the outlet of engine and in the boiler to note down the temperatures. The experimental setup of our study has shown in the figures below:

Figure 27 Experimental Setup (i)

Figure 28 Experimental Setup (ii)

3.4 Design of Experiment:

The primary objective of the study is to investigate that how much maximum energy can be extracted from exhaust of Diesel engine using boiler and water. This water would be converted to steam which can be further uses to produce energy (Rankine Cycle). To harvest maximum amount of energy, the experimental setup and techniques should be as ideal as possible. For this purpose, design of experiment, response surface technique, was applied to harvest maximum possible energy for the specific case.

Response surface method was used to optimize the conditions of operations and then experimentation was done on those conditions to observe the results for conclusions.

CHAPTER NO. 04: DESIGN OF EXPERIMENT

4.1 Design of Experiment:

The primary objective of the study is to investigate that how much maximum energy can be extracted from exhaust of Diesel engine using boiler and water. This water would be converted to steam which can be further uses to produce energy (Rankine Cycle). To harvest maximum amount of energy, the experimental setup and techniques should be as ideal as possible. For this purpose, design of experiment, response surface technique, was applied to harvest maximum possible energy for the specific case.

Efficiency improved (Energy Harvested) depends on the following factors: Speed, Torque, and volume. So, speed, torque, and volume being the input parameters and efficiency being the output parameter, our objective is to optimize the conditions of engine and volume of water to being able to harvest maximum energy. For this purpose, different readings of improved efficiencies were taken by changing the values of speed of engine, torque, and volume. The variables are as follows:

Table 5 Factors affecting the response

Factor	Name	Unit	Min	Max
A	Speed of Engine	RPM	1500	3000
B	Torque	Nm	1.9	2.7
C	Volume	cm^3	250	300

The response of interest in our study is as follows:

Table 6 Response Parameter

Response	Name	Unit	Min
R	Efficiency Improved (Energy Harvested)	No Unit (%)	0

Several experiments were done by changing the values of factors and their effect on response. The readings are as follows:

Table 7 Data of input factors and response value

Run	A	B	C	R
1	2250	1.9	250	1.12%
2	1500	1.9	275	1.65%
3	2250	2.7	250	1.34%

4	3000	1.9	275	1.23%
5	2250	2.7	300	1.59%
6	2250	2.3	275	1.39%
7	1500	2.3	300	2.10%
8	3000	2.3	250	1.41%
9	1500	2.3	250	1.52%
10	3000	2.3	300	1.42%
11	2250	2.3	275	1.39%
12	2250	1.9	300	1.36%
13	3000	2.7	275	1.20%
14	2250	2.3	275	1.39%
15	1500	2.7	275	2.25%

Using the above data, response surface method of DOE was applied using Minitab to obtain the regression model.

Table 8 Analysis of Variance of Response Surface method for regression model

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	9	0.000129	0.000014	11.82	0.007
Linear	3	0.000091	0.00003	25.04	0.002
A	1	0.000064	0.000064	52.46	0.001
B	1	0.000013	0.000013	10.69	0.022
C	1	0.000015	0.000015	11.98	0.018
Square	3	0.00002	0.000007	5.47	0.049
A*A	1	0.000019	0.000019	15.53	0.011
B*B	1	0	0	0.35	0.582
C*C	1	0	0	0	0.95
2-Way	3	0.000018	0.000006	4.94	0.059
A*B	1	0.00001	0.00001	8.15	0.036
A*C	1	0.000008	0.000008	6.67	0.049
B*C	1	0	0	0	0.966
Error			5	0.000006	0.000001
Lack-of-Fit	3	0.000006	0.000002		
Pure Error			2	0	0
Total				14	0.000136

Table 9 Model Summary

S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
0.001103	95.51%	87.43%	28.17%

Table 10 Coded Coefficients of Response Surface regression

Term	Effect	Coef	SE_Coefficient	T-Value	P-Value	VIF
Constant		0.0139	0.000637	21.82	0	
A	-0.00565	-0.002825	0.00039	-7.24	0.001	1
B	0.00255	0.001275	0.00039	3.27	0.022	1
C	0.0027	0.00135	0.00039	3.46	0.018	1
A*A	0.004525	0.002263	0.000574	3.94	0.011	1.01
B*B	-0.000675	-0.000337	0.000574	-0.59	0.582	1.01
C*C	-0.000075	-0.000037	0.000574	-0.07	0.95	1.01
A*B	-0.00315	-0.001575	0.000552	-2.86	0.036	1
A*C	-0.00285	-0.001425	0.000552	-2.58	0.049	1
B*C	0.00005	0.000025	0.000552	0.05	0.966	1

The regression equation obtained after all processing is:

R= -0.0678 + 0.000011A + 0.0240B + 0.000252C + 0.000000 AA - 0.00211 BB -0.000000 CC - 0.000005 AB -0.000000 AC + 0.000002 BC

Using this equation, we predicted the values and compare them with the experimental values, we have:

Table 11 Comparison between predicted and experimental values

Run	A	B	C	R (Experimental)	R (Predicted)
1	2250	1.9	250	1.12%	1.29%
2	1500	1.9	275	1.65%	1.48%
3	2250	2.7	250	1.34%	1.39%
4	3000	1.9	275	1.23%	1.55%
5	2250	2.7	300	1.59%	1.83%
6	2250	2.3	275	1.39%	1.58%
7	1500	2.3	300	2.10%	1.81%
8	3000	2.3	250	1.41%	1.34%
9	1500	2.3	250	1.52%	1.37%
10	3000	2.3	300	1.42%	1.78%
11	2250	2.3	275	1.39%	1.58%
12	2250	1.9	300	1.36%	1.73%
13	3000	2.7	275	1.20%	1.55%
14	2250	2.3	275	1.39%	1.58%
15	1500	2.7	275	2.25%	1.68%

The plot between both readings is as follows:

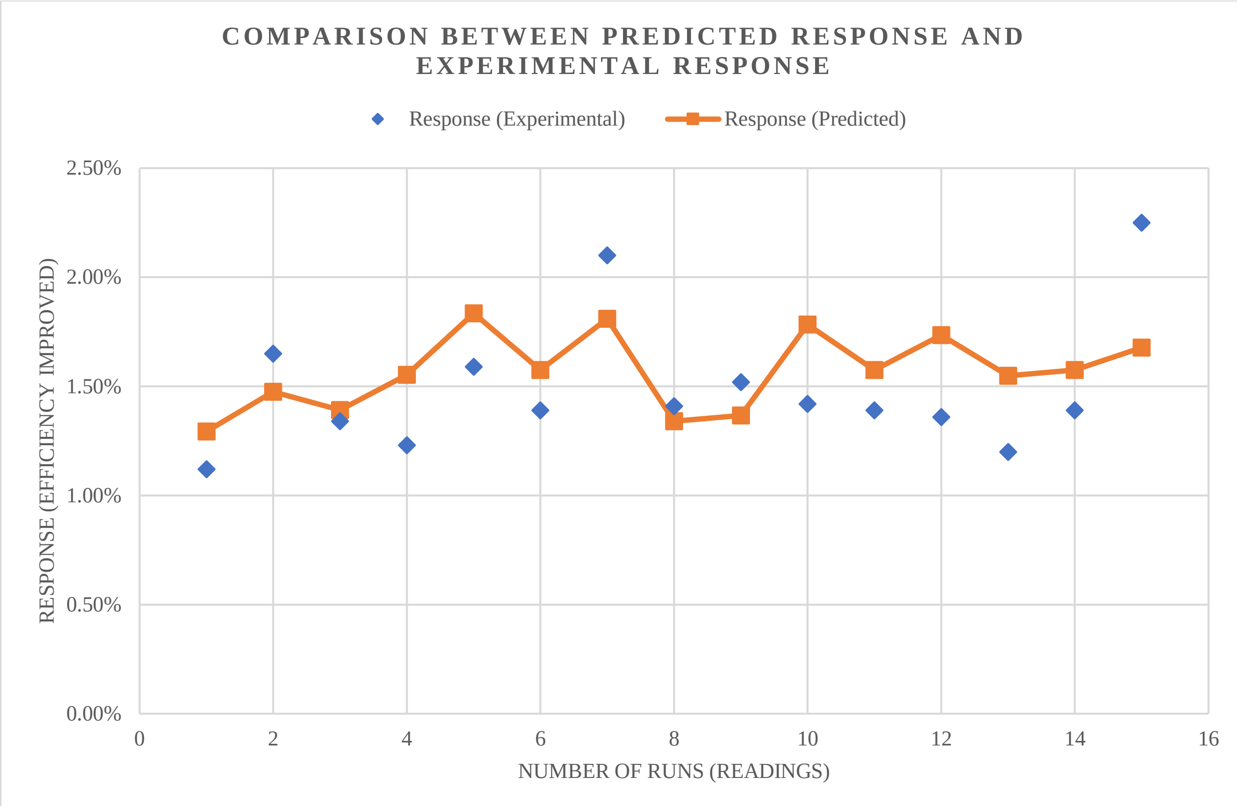

Figure 29 Comparison between experimental and predicted response

It can be seen in the graph that the regression model obtained after applying DOE (Response Surface Method), the model is good enough to predict the values and analyze.

4.1.1 Optimization:

To optimize the scenario for our study, DOE response surface method was further used to predict the conditions on which the setup would give maximum output. For optimization:

Table 12 Optimized Settings for Response Surface Method

Response	**R**
Goal	Maximize
Lower Bound	0
Upper Bound	-

During the experimentation and readings obtained it was observed that as the power of engine increases the optimum values the efficiency of energy harvesting decreases. This is due to the reason that high power yields to higher flowrate leaving us very less time to harvest energy.

Similarly, when the volume of water was low, a lot of heat was wasted, and a little amount of energy was harvested. The behavior of all input factors (Speed, torque and volume of water) on response (energy harvest) can be seen in the following plots.

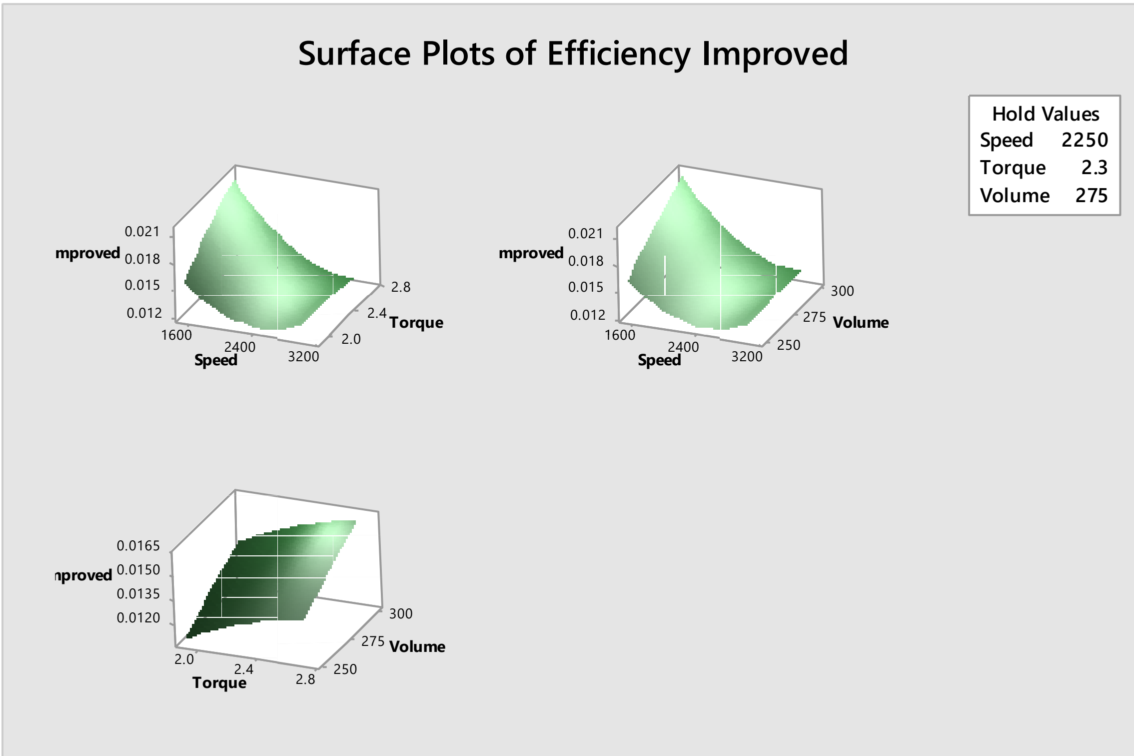

Figure 30 Surface plots of comparison between efficiency improved and other input parameters

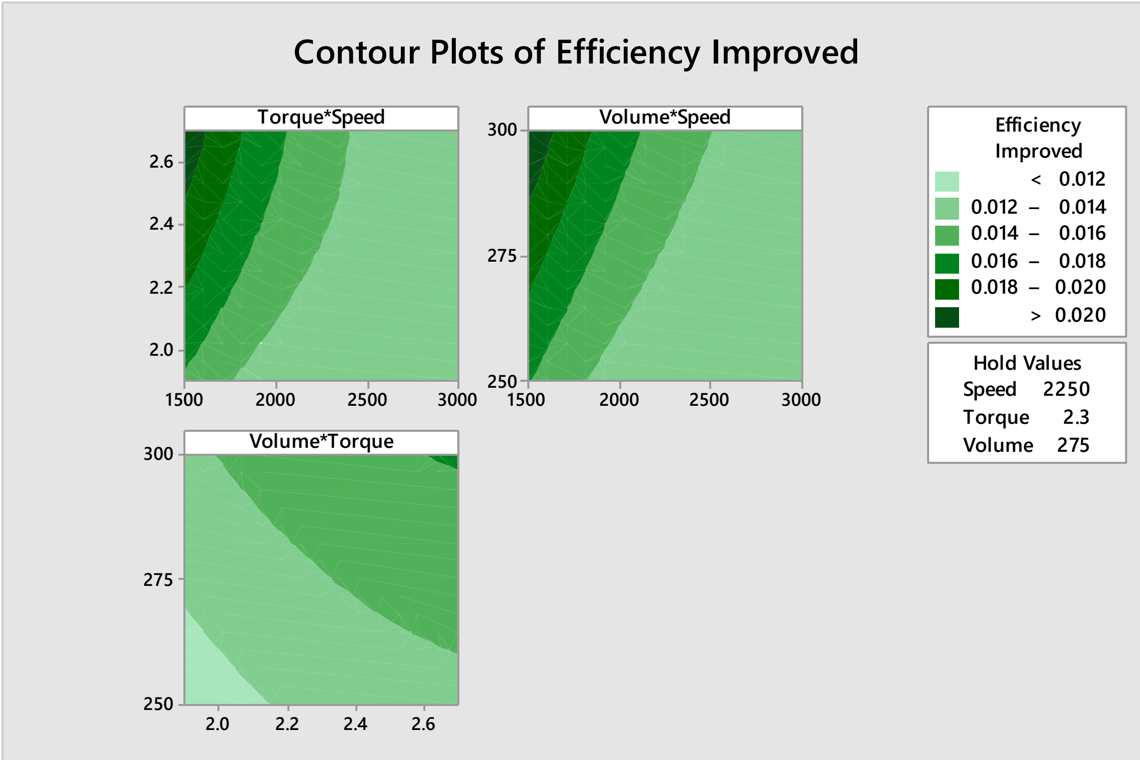

Figure 31 Contour plots of comparison between efficiency improved and other input parameters

At the end, the response optimizer was applied on our model to get the conditions on which the experimental setup would have given the maximum output, which are as follows:

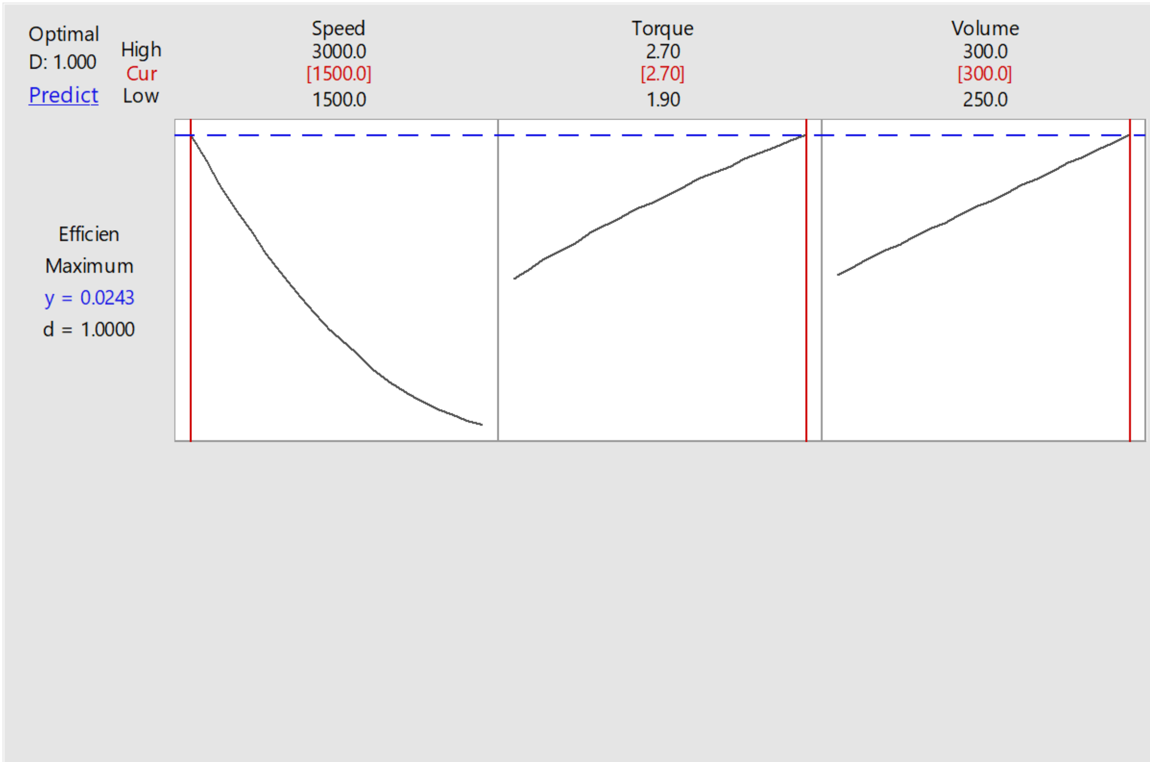

Figure 32 Response Optimization for maximum efficiency (Energy Harvesting)

From the response predictor, it was clear that for experimental setup under study, the maximum energy could be harvested at the following conditions.

Table 13 Optimized Conditions for maximum response

Factor	**Value**	**Unit**
A	1500	RPM
B	2.7	Nm
C	300	Cm^3

So, we applied these conditions for long period of time to completely comprehend the results.

CHAPTER NO. 05: RESULTS AND DISCUSSION

The primary objective of the study is to investigate that how much energy can be extracted from exhaust of Diesel engine using boiler and water. So, the engine test bed was turned ON. Stopwatch was also clicked to note down the time and how much fuel was used during that to find fuel consumption. This will lead to calculate indicated power of the engine. We will also calculate amount of heat energy present in exhaust gases and how much of it was extracted.

5.1 Fuel Consumption:

During the whole time while engine was running, we observed that how much fuel was consumed in how much time. This was done by observing the initial and fin

$$Volume\ of\ fuel\ consumed = V_f = 500\ ml = 0.211\ l$$

$$Time\ take\ by\ engine\ to\ consume\ this\ much\ fuel = t = 56\ min = 3360\ sec$$

$$Density\ of\ diesel = \rho_f = 0.85\ kg/l$$

$$Mass\ of\ fuel\ consumed = m_f = \rho_f \times V_f = 0.85 \times 0.211\ kg = 0.17935\ kg$$

So, 0.17935 kg or 179.35 g of diesel oil was used during the whole experimentation.

5.2 Indicated Power:

By using the amount of fuel consumed and specific lower heating value (LHV) of diesel, we can find the amount of heat and power produced in the engine.

$$Indicated\ Power = Q_i = m_f \times LHV$$

As, m_f=0.17935 kg,

Lower Heating value of diesel, LHV=42.6 MJ/kg

Now,

$$Q_i = 0.17935 \times 42.6 = 7.64\ MJ$$

In order to find the average power developed in engine, we will divide indicated energy to the time of operation, i-e;

$$P_i = \frac{Q_i}{t} = \frac{18.105}{3360} = 2.274\ kW$$

This amount of power is developed in the engine.

5.3 Brake Power:

Dynamometer is couple in engine test bed near the shaft of the engine to measure the torque. As per our observation, the average amount of torque and engine speed noted are as follows:

$$Torque = \tau = 2.7\ N.m$$

$$Speed\ of\ Engine = N = 1500\ RPM$$

Using these values, we can find the brake power of the engine.

$$Brake\ Power = P_b = \frac{2\pi N\tau}{60} = \frac{2\pi \times 1500 \times 2.7}{60}$$

$$P_b = 424.115\ W$$

The brake power of the engine operating is 424.115 W. The brake efficiency can also be found by using the relation:

$$\eta_b = \frac{P_b}{P_i} = \frac{424.115}{2274} = 0.3108 = 18.65\%$$

Brake efficiency of the engine is 18.65% which means that an average of 18.65% energy has been utilized in mechanical work. Rest is lost in friction, via coolant, and exhaust gases.

5.4 Power taken by exhaust gases:

As the engine starts, the power taken by exhaust gases in less but increases up to some time and then almost become constant. When the temperature difference of exhaust gases at outlet of the engine and ambient temperature of air was measured, this helped us finding the heat content in the exhaust gases. To calculate the amount if heat, properties of exhaust gases were needed, which were as follows:

Table 14 Properties of Exhaust gases

Properties for Exhaust Gases		
Property	**Value**	**Unit**
Specific Heat of exhaust gases, C_p	1.006	KJ/kg.K
velocity of exhaust at outlet valve, V_e	8	m/s
Diameter of outlet valve, d	0.0277	M
density of exhaust gases ($ƒ_e$)	1.3	kg/m3

Using the above data, we can find the mass flow rate of exhaust gases, and then use the for our observation regarding power taken exhaust gases.

$$\dot{m}_e = ƒe \times A \times V_e = ƒe \times \frac{\pi d^2}{4} \times V_e$$

$$\dot{m}_e = 1.3 \times \frac{\pi 0.0277^2}{4} \times 8$$

$$\dot{m}_e = 0.00627 \frac{kg}{s}$$

To find the heat carried by exhaust, this relation will be used:

$$P_e = \dot{m}_e \times c \times \Delta T = \dot{m}_e \times c \times (T_e - T_a)$$

T_a=Ambient temperature of air

During experimentation, it was observed that the ambient temperature of was around 36 ^oC. With time, temperature of the exhaust gases changed which was observed continuously in regular interval of time. Using the above data and the equation, these results were found during our experiment.

Table 15 Power Lost Engine through Exhaust Gases

Time (sec)	Exhaust Temperature (Te, C)	Water Temperature (Tw, C)	Power Gain by water (W)
120	34	26	10.5
240	54	28	21
360	88	31	31.5
480	141	34	31.5
600	207	37	31.5
720	254	41	42
840	271	45	42
960	298	48	31.5
1080	269	52	42
1200	284	57	52.5
1320	290	61	42
1440	261	65	42
1560	277	68	31.5
1680	253	73	52.5
1800	280	77	42
1920	279	80	31.5
2040	291	85	52.5
2160	266	89	42
2280	263	93	42
2400	273	97	42
2520	280	100	31.5

It can be observed from above table that almost 60% power of engine was carried by exhaust gases which is a huge amount of energy.

5.4.1 Trend of exhaust gases temperature with time:

According to the values observed, it was evident that initially the temperature of exhaust gases was low but was increasing with time of operation of IC Engine. Almost after 10-15 minutes of operation, the exhaust temperature of the gases was almost remained the same wiggling at around temperature of 260-270 ^{o}C. The trend of the temperature gained by exhaust gases with time is as follows:

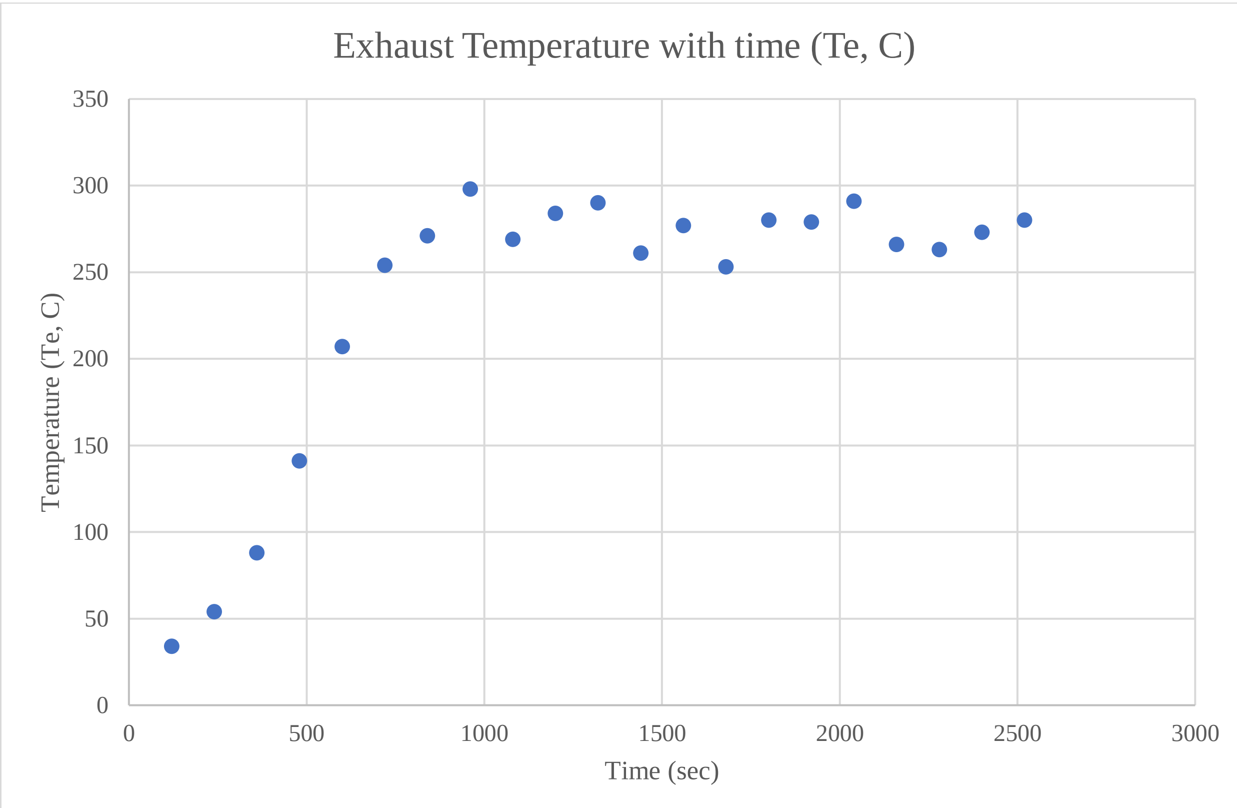

Figure 33 Trend of exhaust gases temperature with time

5.5 Power harvested by Fire Tube Boiler:

In our experimentation, fire tube boiler has been coupled at the outlet of engine with PVC pipe. The purpose of using fire tube boiler is the absorb some amount of heat carried by exhaust gases. The heat lost by exhaust gases during this process is absorbed by water in the boiler. By absorbing this heat, the temperature of the water began to rise, and a time came when it became more than 100 ^{o}C and we observed the steam coming out of the boiler. The details of temperature raise in the water present in the boiler, amount heat absorbed, and percentage of energy harvested are as follows:

5.5.1 Trend of temperature of water with time:

When exhaust gases passed through copper coil in the boiler, copper being a good conductor conducted heat to water which started to rise its temperature as shown in the table below:

Table 16 Trend of water temperature in boiler with time

Time (sec)	Water Temperature (Tw, C)
120	26
240	28
360	31
480	34
600	37
720	41
840	45
960	48
1080	52
1200	57
1320	61
1440	65
1560	68
1680	73
1800	77
1920	80
2040	85
2160	89
2280	93
2400	97
2520	100

The table shows that the temperature of water continued to increase with time. Due to limitation of experimentation capability of engine, we could not run engine further, but it was observed that steam was converted into steam. If engine were run further, this steam could be converted to super-heated steam which could be utilized for running turbine.

The trend of temperature of water in the boiler with time shown in the fig. below:

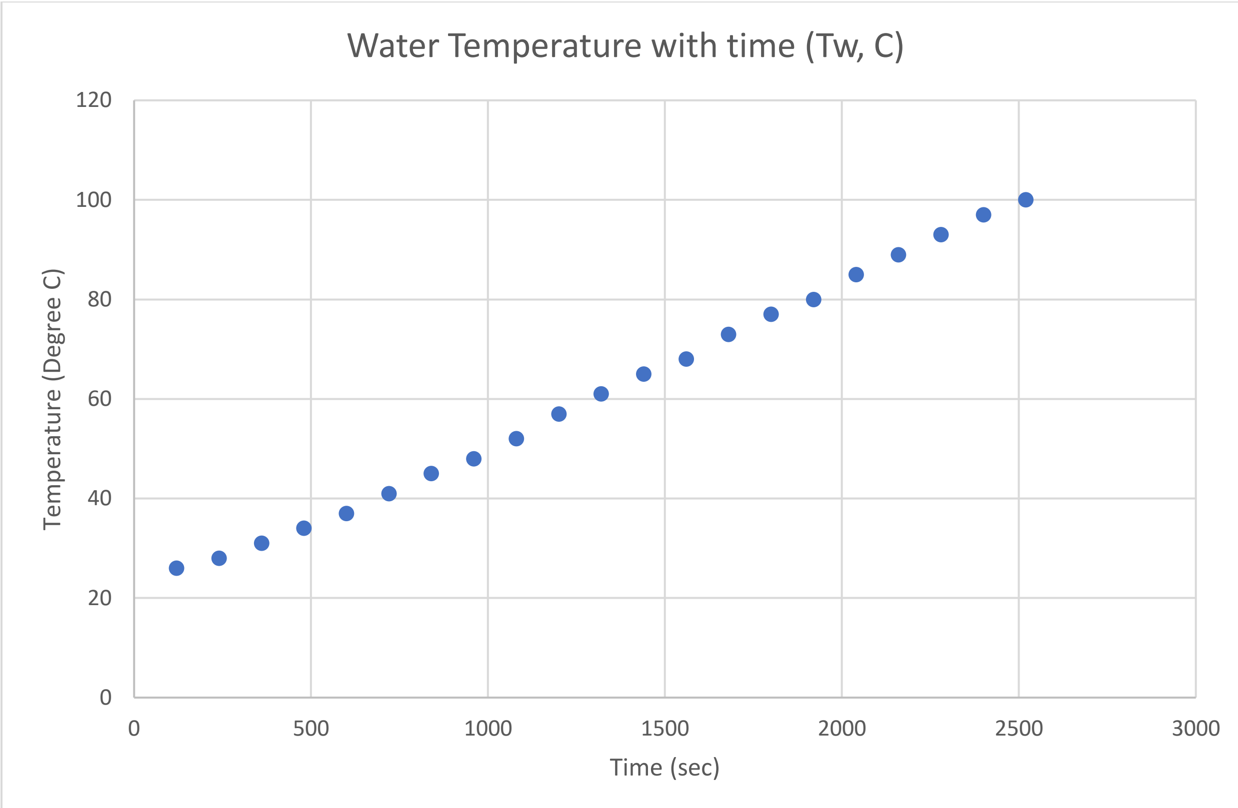

Figure 34 Trend of water temperature in boiler with time

5.5.2 Trend of power absorbed by water with time:

We had poured 300 ml of water in the cylinder using beaker. At normal temperature and pressure, the value of density of water is almost 1000 g/l. So, in other words, 300 g water was poured in the boiler. We also know that the specific heat of water is 4.2 g/J.K. We observed the data after almost 2 minutes. This data can be utilized to observe the amount of power absorbed by water by using this formula:

$$P_w = \frac{m \times c \times \Delta T}{t}$$

Data to be used for calculations is as follows:

Table 17 Data for Boiler

Data for Boiler (Values)		
Mass of water (g)	300	g
Cp(Water)	4.2	J/g.K

This formula was put in excel to get power absorbed by water at different occasions. The details of power absorbed by water are as follows:

Table 18 Amount of power absorbed water with time

Time (sec)	Power Gain by water (W)
120	10.5
240	21
360	31.5
480	31.5
600	31.5
720	42
840	42
960	31.5
1080	42
1200	52.5
1320	42
1440	42
1560	31.5
1680	52.5
1800	42
1920	31.5
2040	52.5
2160	42
2280	42
2400	42
2520	31.5

The behavior of the power absorbed by water with time is shown in the figure below:

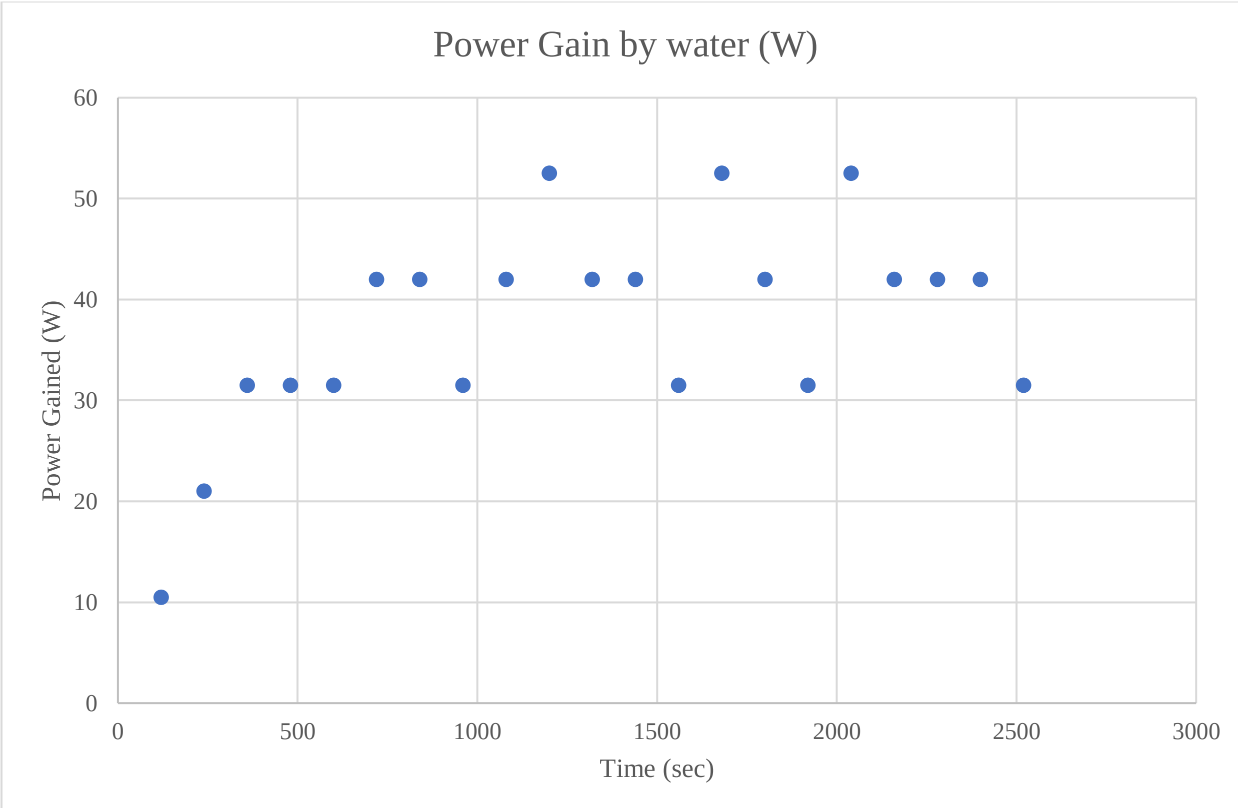

Figure 35 Trend of power absorbed by water with time

The graph shows that there are some wiggles in the graph, but general behavior indicates that the power absorbed by water increased with time.

5.6 Mathematical Modeling:

Mathematical calculations were done in order to validate our experimental results. To calculate heat transfer, we need to calculate overall heat transfer coefficient using the dimension of coil and other properties of operations. Dimension of coil are given below:

Table 19 Dimension of Copper Coil

Dimensions of Coil		
di	3.6	mm
t	1.2	mm
L	132	mm

Properties of material and operating conditions are as follows:

Table 20 Properties of material and other operating Conditions

Properties of Materials and other Parameters		
Cp(Exhaust)	1.006	KJ/kg.K
velocity of exhaust	8	m/s
di	0.006	m
density of exhaust gases	1.3	kg/m3
Ɛ (Exhaust Gases)	0.8	
k	0.0231	W/m.K
µ	0.0000165	Pa.s
k(copper)	385	W/mK
Ta	36	C
Tf	270	C

In order to calculate overall heat transfer (conduction and convection), following equation will be used:

$$q = UA\Delta T_{LM}$$

Where,

q = heat transfer rate (W)

U = overall heat transfer coefficient (W/(m2·K))

A = heat transfer surface area (m2)

T_{LM}= logarithmic mean temperature difference (K).

To find UA, following relation be used:

$$\frac{1}{UA} = \sum \frac{1}{hA} + \sum R$$

Where;

R = Resistance(s) to heat flow in pipe wall (K/W)

h=coefficient of convective heat transfer

Also,

$$R = \frac{t}{k}$$

t = the wall thickness (m)

k = the thermal conductivity of the material (W/(m·K))

At the end heat transfer due to radiation using Stefan Boltzman law will be added to evaluate overall heat transfer rate.

Stefan Boltzman Law states:

$$q = \sigma\left(T_f^4 - T_a^4\right)$$

Using above equations and data, we found that at start the value of heat transfer would be as follows:

Table 21 Calculation of Heat Transfer

Calculations for "Total Heat Transfer Rate"		
Area of coil	0.001492284	m^2
h (exhaust)	35.64975465	W/ m^2.K
Overall Heat Transfer Coefficient	11.4	w/ m^2.K
Heat Transfer Rate (Conduction and Convection)	3.980817293	W
Heat Transfer Rate through radiation (Exhaust Gases)	5.27	W
Heat Transfer Rate through radiation (Copper)	0.329	W
Total heat Transfer	**9.579817293**	**W**

Now, comparing the calculated value with experimental value, we have:

Table 22 Comparison between experimental and mathematical values

Comparison Between Experimental and Theoretical Values			
Heat Transfer (At Start)	Mathematical Modelling	Experimental Values	Difference (%)
Initial	9.579817293	10.5	8.76%

The above table indicates that the values obtained by experimentation is comparable with the mathematical values and hence is validated. With time, heat transfer rate changes in experimentation, that is, increases up to a certain value which is also valid. At initial the water was at rest, hence its rate of heat transfer due to convection was almost negligible but as with the time, temperature of water increased enhancing the motion of water particles and hence overall heat transfer rate.

5.7 Percentage of Efficiency improved:

After performing experiment, measuring all the required readings, and applying all related formulas, we observed that by coupling a diesel engine with fire tube boiler, the efficiency of the engine can be improved from 0.46% to 2.31%. The details of which are as follows:

We divided the heat absorbed by water in boiler to the indicated to observe that how much percentage of total power was recovered and how much efficiency of the engine was improved. For this purpose, we used the formula given below and put it in the excel to observe the results.

$$Percentage\ of\ Heat\ recovered = \frac{P_w}{Q_i}$$

Using this formula and putting in excel, we obtained the following results:

Table 23 Percentage of heat recovered with time

Time (sec)	Power Gain by water (W)	Efficiency Improved (%)
120	10.5	0.46%
240	21	0.92%
360	31.5	1.39%
480	31.5	1.39%
600	31.5	1.39%
720	42	1.85%
840	42	1.85%
960	31.5	1.39%
1080	42	1.85%
1200	52.5	2.31%
1320	42	1.85%
1440	42	1.85%
1560	31.5	1.39%
1680	52.5	2.31%
1800	42	1.85%
1920	31.5	1.39%
2040	52.5	2.31%
2160	42	1.85%
2280	42	1.85%
2400	42	1.85%
2520	31.5	1.39%

During our operation we observed that the percentage of heat absorbed by water was varying continuously within a specified range.

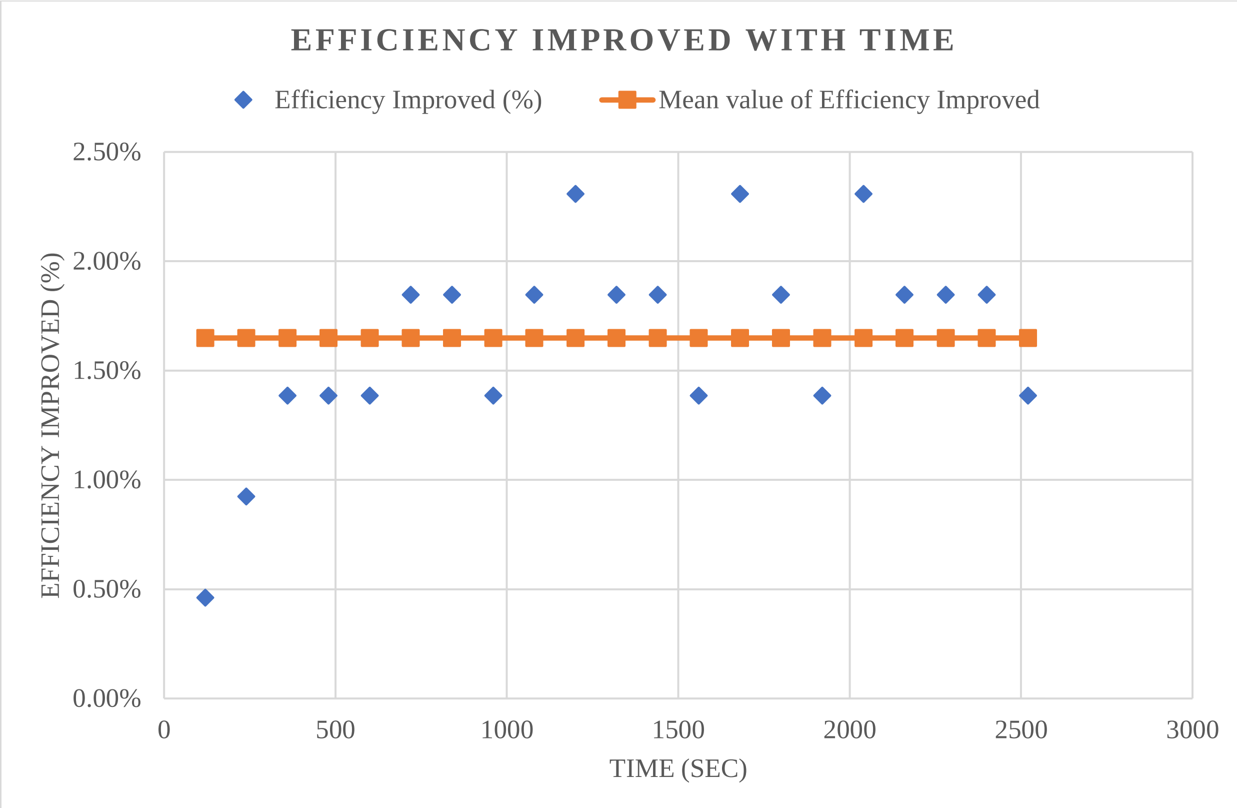

Figure 36 Efficiency of Engine Improved with time

Now, if we couple this boiler with tesla turbine (feasible to run at low flow rate and has an efficiency of almost 70%), then the mechanical power can be improved by 0.322% to 1.617%. This much efficiency of a diesel engine can be improved by implementing fire-tube boiler and Rankine cycle at the outlet of diesel engine.

CHAPTER NO. 06: CONCLUSIONS

6.1 Conclusions

An experimental study was conducted on an air-cooled single cylinder four stroke diesel engine to investigate the energy harvesting using a copper coiled fire tube boiler. For this purpose, a known amount water was poured in the boiler, the boiler was coupled with the engine using PVC pipe, and engine was turned ON. We used different equipment to measure different parameters like, thermocouple, dynamometer, fuel tank cylinder, stop-watch, and anemometer to find temperature of exhaust gases before injection to the boiler and water in boiler, torque at the shaft of engine, amount of fuel used, periodically note down the parameters, and velocity of exhaust gases to measure calculate the flow rate, respectively. Vernier caliper was used to measure all the required dimensions. After doing whole experimentation, we had the following findings:

- At start, the temperature of exhaust gases was low but after 10-15 minutes engine achieved steady operation and the temperature of exhaust gases was almost similar after that time.
- As the temperature of exhaust gases increased, the amount heat absorbed was also increased until steady state of engine after which the power absorbed gases was almost constant.
- It was observed that a huge amount of power generated was taken by exhaust gases and very less amount of brake power produced.
- Up to 70.698% (1607.67 W) of the power produced was going with the exhaust gases which was the huge amount of loss through exhaust gases via an engine.
- It was also observed that the water continuously absorbed heat from exhaust gases and kept rising its temperature.
- As water in boiler kept absorbing heat continuously, hence its temperature kept on increasing linearly with time. We also observed that it took 56 minutes for water to achieve a temperature of 109 ^{o}C. So, it can be deduced that it can work more efficiently in the vehicle that run their engines for longer periods.
- It was observed that about 10.5 W-52.5 W of power was harvested by using fire tube boiler at the outlet of IC engine.
- Results also showed that efficiency of the engine was also improved by 0.46% to 2.31%.

- Concluding we can say that using fire tube boiler at the outlet of an engine is an economical and simple method to harvest energy and improve the efficiency of the engine.

6.2 Future recommendations

Here are some suggestions for future work:

- We estimated theoretical that if this fire tube boiler is coupled with tesla turbine, then almost 0.322% to 1.617% of the power of engine can be harvested and stored in batteries. This can be done experimentally in future to validate our deduction.
- In future, a plan can be devised to combine fire tube boiler with another energy harvesting technique like using TEGs to harvest more energy by compound two different schemes.
- This study was done on a diesel engine test model. In future, a real engine of heavy vehicles can also be coupled to get the results which might vary slightly from these results.

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