Design and CFD Investigation of Exhaust Gas Recovery System for 4SSC Diesel Engine

Bibin P Varghese, V Hariganesh, Ajish Soman

Abstract*— With worldwide reserves of fossil fuels gradually diminishing and air pollution increasing, automotive engineers are constantly on the lookout for ways to make cars more fuel efficient and to reduce their carbon emissions. One of the most surprising places they've found wasted energy is in the car's exhaust. Actually, automotive designers have been tapping the hidden power of automobile exhaust since the early 1970s. Because this technology recycles the exhaust before it can exit the vehicle, it also helps reduce the emissions produced by a car and helps fight air pollution. Technologies made to maximize the efficiency of a vehicle's exhaust are known collectively as exhaust heat recovery and recirculation. There are several ways to use a vehicle's exhaust to increase its fuel efficiency and make it run with fewer emissions. For example, the heat of the car's exhaust can be used to warm the engine coolant to keep the engine running warm, even when the motor has been turned off for a significant length of time. Out of the total heat supplied to the engine in the form of fuel, approximately, 30 to 40% is converted into useful mechanical work; the remaining heat is expelled to the environment through exhaust gases and engine cooling systems, resulting in to entropy rise and serious environmental pollution, so it is required to utilized waste heat into useful work. This paper work presents design and CFD investigation of exhaust gas recovery for a 4SSC Diesel engine.

***Keywords* – CFD, 4SSC, Pollution, Fuel, Engine**

I. INTRODUCTION

In transportation, an exhaust heat recovery system turns thermal losses in the exhaust pipe into energy. This technology seems to be more and more of interest by car and heavy-duty vehicle manufacturers as an efficient way to save fuel and reduce vehicles' CO2 emissions. This technology can be used either on a hybrid vehicle or a conventional one: it produces either electric energy for batteries or mechanical energy reintroduced on the crankshaft. Even if current engines consume less fuel than they used to, the thermal efficiency of an internal combustion engine has not really increased since its creation. The peak efficiency reached by a 4-cycle Otto cycle engine is around 35%, which means that 65% of the energy contained in the fuel is lost as pumping losses, friction losses, cooling losses, exhaust losses and accessories.

Manuscript received May, 2015.

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High speed Diesel cycle engines fare a little better with around 45% peak efficiency, but are still far from their Carnot efficiency, and hence 55% of the fuel energy content is lost. Inside the exhaust pipe of an internal combustion engine, energy losses are various: thermal, kinetic, chemical and latent heat. Most important energy parts are located in the thermal and kinetic losses

1.1 Recovery System

A typical Rankine Cycle is a thermodynamic cycle that uses a fluid and works thanks to four reversible processes. In transportation, Rankine cycle systems vaporize a pressurized fluid, thanks to a steam generator located in the exhaust pipe. As a result of the heating by exhaust gases, the fluid is turned into steam/vapour. The pressure will then drive the expander of the Rankine engine, which could be a turbine as well as a volumetric expander. This expander can be either directly tied to the crankshaft of the thermal engine or linked to an alternator to generate electricity. The Fluid used in Rankine Cycle Engines can be a "humid" fluid (such as water) or "dry" organic fluids. The choice of the fluid depends in particular on the running temperature of the system. Researchers at Loughborough University and the University of Sussex, both in the UK, also have concluded that using waste heat from light-duty vehicle engines in a steam power cycle could deliver fuel economy advantages of between 6.3% and 31.7%, depending upon drive cycle, and that high efficiencies can be achieved at practical operating pressures. BMW is exploring two pathways for waste heat recovery in vehicles: one thermoelectric, the other thermodynamic. In 2005, BMW Group Research and Engineering announced it was developing a steam-powered auxiliary drive the Turbo steamer to use the waste heat present in the exhaust gases and cooling system from a conventional gasoline engine as its source of power. The long-term development goal articulated at the time was to have a system capable of volume production within ten years. At the recent SAE 2009 World Congress, BMW presented an analysis of two basic configurations of the Rankine cycle applied to a thermodynamic heat recovery system for a four-cylinder combustion engine. Based on bench test measurements, BMW has concluded that waste heat recovery can provide an additional power output of about 10% at typical highway cruising speeds Based on a quantitative analysis under constrained operating conditions, BMW determined that water delivered the highest thermal efficiency for system A, whereas ethanol is the preferable working fluid for system B (methanol was dismissed *a priori* due to health risks). BMW developed a simulation model with the tool Dymola to evaluate the two alternative systems for different engine types. The process for both systems consists of the expander, the pump, the condenser and heat exchangers. Based on the parametric analysis, BMW found that System B shows a higher potential at typical highway speeds (45-70 mph) for the engine type chosen (4-cylinder, stoichiometric combustion) and operating conditions. Nevertheless, the researchers cautioned, this cannot be interpreted as a general recommendation. Heat source parameters, which are deeply influenced by engine type and load profile, as well as operating parameters, which are limited by technical constraints (pressure level, ambient temperature), have significant effects on the net power output. Based on bench testing, BMW concluded that System B could show additional power outputs between 0.7-2 kW others are negligible. Kinetic losses can be recovered through a turbocharger or a turbo-compound.

1.2 Energy Loss in Automotives

The following figure shows the fuel power distribution for an engine.

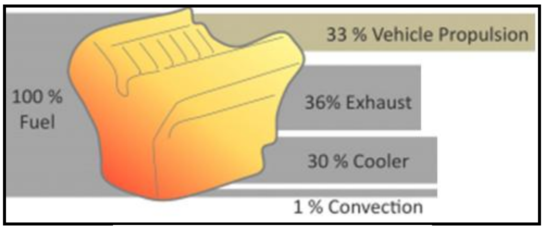

Fig.1 Fuel Power Distribution

Only one third at most of the energy produced is used for vehicle propulsion, the rest being lost through the exhaust and in the cooling system. By recovering part of this heat, our system produces electricity for hybrid vehicles and improves the dynamic performance levels of the engine: lower consumption, longer autonomy and greater respect for the environment.

1.3 Steam Formation

Steam is a vapour of water and is invisible when pure and dry. It is used as the working substance in the operation of steam engines and steam turbines. Steam does not obey laws of perfect gases, until it is perfectly dry.

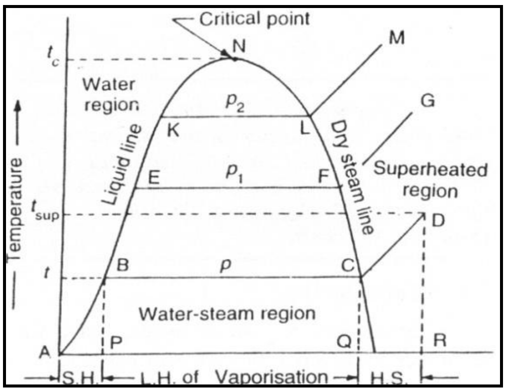

Fig.2 Temperature-Total heat graph during steam formation

The process of steam formation can be represented on a graph, whose abscissa represents the total heat and the vertical ordinate represents the temperature. The point A represents the initial condition of water at 0℃ and pressure p (in bar) as shown in figure. Line ABCD shows the relation between temperature and heat at a specific pressure of p (in bar). During the formation of the superheated steam, from water at freezing point, the heat is absorbed in the following three stages:

The heating of water up to the boiling temperature or saturation temperature (t) is shown by AB in figure 2.10. The heat absorbed by the water is AP, known as sensible heat or liquid heat or total heat of water. The change of state from liquid to steam is shown by BC. The heat absorbed during this stage is PQ, known as latent heat of vaporization. The superheating process is shown by CD. The heat absorbed during this stage is QR, known as heat of superheat. Line AR represents the total heat of the super heated steam. If the pressure is increased (say p1 bar), the boiling temperature also increases. The line passing through the points A, B, E, and K is known as saturated liquid line which forms boundary line between water and steam. Similarly, a line passing through dry steam points L, F, C is known as dry saturated steam line which forms boundary line between wet and superheated steam. When the pressure and saturation temperature increases, the latent heat of vaporization decreases, it becomes zero at a point (N) where liquid and dry steam lines meet. This point N is known as the critical point and at this point, the liquid and vapour phases merge, and become identical in every respect. The temperature corresponding to critical point N is known as critical temperature and the pressure is known as critical pressure. For steam, the critical temperature is 374.15℃ and a critical pressure is 221.2 bars.

II. LITERATURE REVIEW

Thermodynamic Analysis of a Diesel Engine Integrated with a PCM Based Energy Storage System [1], this work describes the energy and exergy analysis of a diesel engine integrated with a PCM based energy storage system, and provides more realistic and meaningful assessment than the conventional energy analysis. Design & Analysis of Waste Heat Recovery System for Domestic Refrigerator [2], presents the following, heat is energy, so energy saving is one of the key matters from view point of fuel consumption and for the protection of global environment. So it is necessary that a significant and concrete effort should be made for conserving energy through waste heat recovery too. The main objective of this paper is to study "Waste Heat recovery system for domestic refrigerator". An attempt has been made to utilize waste heat from condenser of refrigerator. This heat can be used for number of domestic and industrial purposes. In minimum constructional, maintenance and running cost, this system is much useful for domestic purpose. Design and Development of Low Cost I.C Engine Based Waste Heat Recovery System [3]. This study proposed a the new cost effective design of diesel exhaust waste heat recovery system (WHRS) for Bus rapid transport System (BRTS, Jaipur) and Stationary System and proposes a cost effective robust design that meets the principle design constraints for WHRS. In order to address various design constraints for WHRS while achieving the required performance of the system, numerical analysis and optimization was carried out using CFD software Ansys FLUENT and Ansys WB (Parametric Study).Possible waste heat recovery system geometries studied that meets both Indian Pollution control standard and geometries constraints. Based on the numerical analysis, author proposed a new kind of WHRS that meets the performance specifications but is outside of the space constraints of BRTS. The WHRS perform at approximately 0.3 to 0.6 efficiency; providing 10 kW at ideal conditions. The overall length of the system is 1200 mm and the overall width is 550 mm. The weight of the heat exchanger is 100 kg; therefore, it does not meet the weight constraint. The overall cost of the WHRS is INR 15000 which is within budget for BRTS, Jaipur. The results conclude with the following, both designs are good for use but circular tubes based WHRS are more feasible to manufacture. Parametric study shows that tube fluid velocity are best at 0.5 m/s to 1.0 m/s range for both designs of WHRS. WHRS can be used in movable and stationary I.C.engine with some small changes in the system. Cost of WHRS is also very less than commercial heat exchanger devices available. Review on Exhaust Gas Heat Recovery for Internal Combustion Engine [4]. The increasingly worldwide problem regarding rapid economy development and a relative shortage of energy, the internal combustion engine exhaust waste heat and environmental pollution has been more emphasized heavily recently. Out of the total heat supplied to the engine in the form of fuel, approximately, 30 to 40% is converted into useful mechanical work; the remaining heat is expelled to the environment through exhaust gases and engine cooling systems, resulting in to entropy rise and serious environmental pollution, so it is required to utilized waste heat into useful work. The recovery and utilization of waste heat not only conserves fuel (fossil fuel) but also reduces the amount of waste heat and greenhouse gases damped to environment. The study shows the availability and possibility of waste heat from internal combustion engine, also describe loss of exhaust gas energy of an internal combustion engine. Possible methods to recover the waste heat from internal combustion engine and performance and emissions of the internal combustion engine. Waste heat recovery system is the best way to recover waste heat and saving the fuel. Efficiency and exhaust gas analysis of variable compression ratio spark ignition engine fuelled with alternative fuels [5] presents the following, considering energy crises and pollution problems today, investigations have been concentrated on decreasing fuel consumption by using alternative fuels and on lowering the concentration of toxic components in combustion products. In the present work, the variable compression ratio spark ignition engine designed to run on gasoline has been tested with pure gasoline, LPG (Isobutene), and gasoline blended with ethanol 10%, 15%, 25% and 35% by volume. Also, the gasoline mixed with kerosene at 15%, 25% and 35% by volume without any engine modifications has been tested and presented the result. Experimental Analysis of Thermoelectric Waste Heat Recovery System Retrofitted to Two Stroke Petrol Engine [6], this paper presents the following, efficiency of the thermal power plants is only around 35% and the remaining 50 - 55% of energy is lost due to many losses. The major source of loss in the conversion process is the heat rejected to the surroundings due to the many inherent constraints. Also further losses of around 10-15% are associated with the transmission and distribution of electricity in the electrical grid. Therefore, the energy saving is one of the key issues, not only from the view point of fuel consumption but also for the protection of environment. So, it is imperative that significant efforts have been made for conserving the energy by recovering the heat dissipated to the atmosphere. The main objective of this paper is to study and analyse the feasibility of retrofitting the waste heat recovery system to a two stroke petrol engine. Finally, the potential of recovery of waste heat as a renewable energy source is assessed. The combined heat and power system offers additional benefits like reduction in the emission of carbon dioxide (CO2), sulphur dioxide (SO2) and oxides of nitrogen (NOx) for the same power and heat generation. This is achieved by using the waste heat recovery system and can be installed on any equipment which generates heat and needs heat dissipation to reduce the pollution during the operation of machines in addition to the auxiliary power generation. Review on Exhaust Gas Heat Recovery for I.C. Engine Using Refrigeration Systems [6] presents the following, Due to green house effect & changing environment and atmospheric effect, the air conditioning of the moving vehicle has become a necessity now a day. As the major percentage of heat energy is rejected by engine exhaust which can be recovered is approximately 30-40% of the energy supplied by the fuel depending on engine load. Waste heat recovery system is the best way to recover waste heat and saving the fuel. Although there are various methods are available for the recovery of waste exhaust gas such as direst methods in which the emf is directly induced by directly called the sea beck effect or indirect methods such as Rankine Cycle , Stirling Cycle & Refrigeration cycles. The present paper discusses the Exhaust Gas Heat Recovery for I.C. Engine using refrigeration systems. As continuous raise in fuel prices and manufacturing cost, the consumers getting many difficulties in maintain the automotive vehicles. Waste heat recovery system is the best way to recover waste heat and saving the fuel. Above papers shows the utilization of the waste heat into creating the refrigeration effect. For this purpose the vapour absorption system is most suitable. Experimental Simulation of a Heat Recovery Heat Pump System in Food Industries [7] presents the following; many opportunities for heat pumping technologies exist for recovering the waste heat generated by industrial processes. By using heat pump systems in the right way, the use of primary energy and CO_2 emissions as well as energy costs can be reduced. A laboratory flexible industrial scale heat recovery system is designed and built to carry out experimental simulations by reproducing the operating conditions of real case applications in food industries. The heat recovery system includes process integration technologies ranging from passive recovery like simple heat exchangers to technologies upgrading the waste heat like industrial heat pumps. The integrated heat pump is an electrically-driven vapour compression closed-cycle type, which can operate in a single-stage or in a 2-stage configuration and has a variable speed screw compressor. Several typical scenarios of food industry processes for low-temperature heat recovery (heat sources between 30°C and 50°C) and heat upgrading are experimentally simulated showing the overall energy savings and the environmental benefits of introducing heat pumps in this kind of industrial applications.

III PROBLEM IDENTIFICATION FOR SOLUTION

3.1 Problem Description

In transportation, an exhaust heat recovery system turns thermal losses in the exhaust pipe into energy. This technology seems to be more and more of interest by car and heavy-duty vehicle manufacturers as an efficient way to save fuel and reduce vehicles' CO_2 emissions. This technology can be used either on a hybrid vehicle or a conventional one: it produces either electric energy for batteries or mechanical energy reintroduced on the crankshaft. Even if current engines consume less fuel than they used to, the thermal efficiency of an internal combustion engine has not really increased since its creation. The peak efficiency reached by a 4-cycle Otto cycle engine is around 35%, which means that 65% of the energy contained in the fuel is lost as pumping losses, friction losses, cooling losses, exhaust losses and accessories. High speed Diesel cycle engines fare a little better with around 45% peak efficiency, but are still far from their Carnot efficiency, and hence 55% of the fuel energy content is lost. Quantity and quality of exhaust gas is vital in producing steam that is required for specific applications. The literature reviews showed the research gap in this particular sector and is an opportunity to do research on quality and quantity of exhaust gas for steam production.

3.2 Proposed Solution

The current research work proposes a design and prototyping of exhaust gas heat recovery system in the form of steam for a 4 stroke single cylinder Diesel engine. The design will be tested virtually using computational fluid dynamic analysis and presented for further proceedings, possibly into manufacturing.

IV METHODOLOGY

The following list shows the proposed methodology of the work.

- Objective Formulation
- Literature Review
- Problem Identification
- Proposed Solution
- Design of Recovery System
- CFD Simulation and
- Result Evaluation

The schematic drawing shows the discrete phases in the project work, the work begins with objective formulation followed by literature review, problem description and proposed solution. The design is followed by CFD simulation and prototyping finally experimental results compared against the CFD simulation to validate the performance of heat recovery unit.

IV DESIGN AND CFD ANALYSIS

4.1 Heat Recovery Unit Schematic Layout

The following figure shows the schematic layout of the heat recovery unit, the system contains a 4 stroke single cylinder diesel engine; the exhaust pipe is connected to a Plenum chamber where the pressure is recovered to avoid the back pressure to cylinder, which is then connected to a heat recovery unit, it is basically a steam generator form there the exhaust gas is released to atmosphere. The pipes are insulted using asbestos rope, this will maximize the heat recovery, the heat recovery unit contains inverted 'Z' type copper tubes and the recovery unit is made off mild steel box. Thermo couples will be used to record the temperature of the heat recovery unit, ambient temperature and exhaust gas temperature.

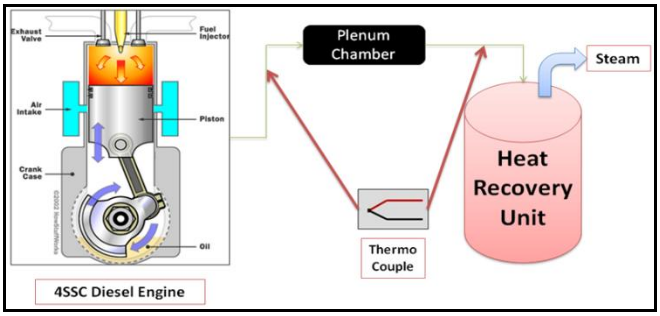

Fig.4 – Schematic Layout of Heat Recovery System

4.2 Exhaust Pipe Details

The following figures and details shows the specifications of exhaust piping system.

Diameter = 25.4 mm
Thickness = 2.6 mm
Material = GI
Length = 150 mm

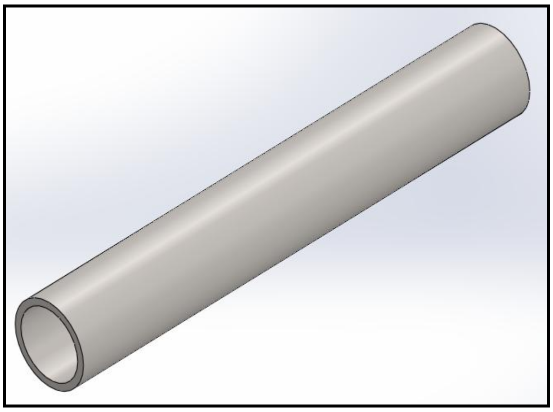

Fig.5 – GI Pipe for Exhaust Outlet

The following figure shows the piped plenum chamber for pressure recovery and eliminates back pressure to engine

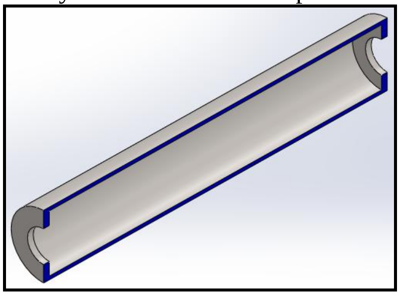

Fig.6 – Plenum Chamber Pipe

Diameter = 50.8 mm
Thickness = 2.6 mm
Material = GI
Length = 300 mm

The following figure shows the heat recovery inverted 'Z' type copper pipe, this pipe releases exhaust gas temperature to water in the heat recovery unit.

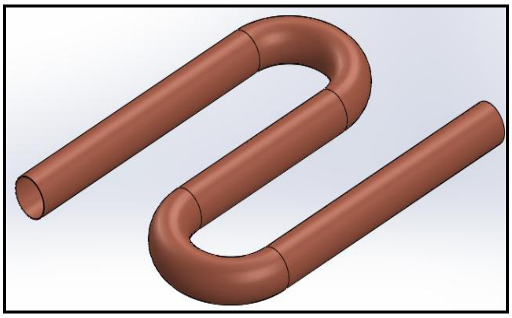

Fig.7 – Heat Recovery Pipe

Diameter = 50.8 mm
Thickness = 2.6 mm
Material = Copper
Type = Inverted "Z"
Container Size = 445 x 200 x 100 mm

The following figure shows the heat recovery box, which is made of mild steel and holds water and the heat releasing copper pipe in it. This unit takes heat from the exhaust pipe in conjugate heat transfer method where copper tube releases the exhaust heat to water. Over a period of time the water became steam and it continues to form.

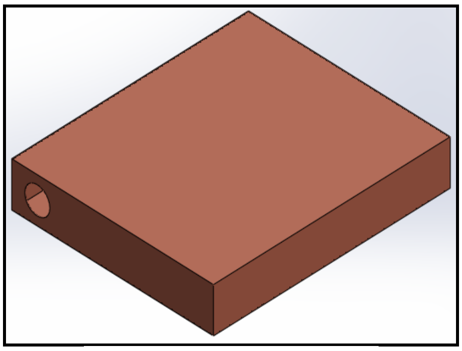

Fig.8 – Heat Recovery Unit

Volume = 18.8 lts
Thickness = 4 mm
Material = Mild Steel
Container Size = 470 x 400 x 100 mm

The following figure shows the schematic assembly unit of the heat recovery unit.

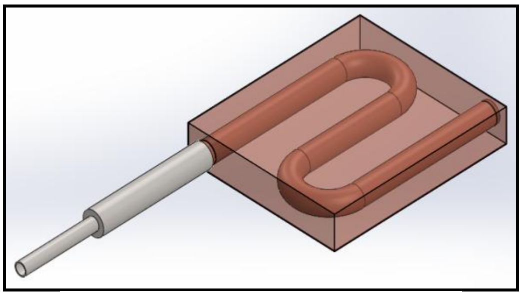

Fig.9 - Heat Recovery Unit Assembly

4.3 CFD Simulation

This section provide complete details of the computational fluid dynamic analysis of exhaust gas heat recovery system, the following figure shows the boundary conditions used in the simulation.

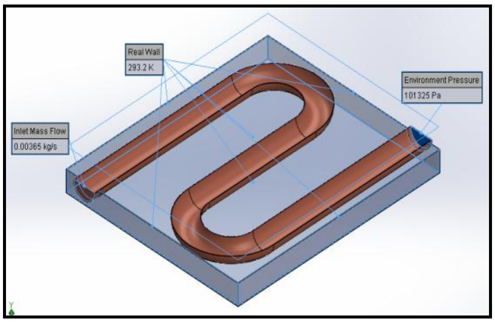

Fig.10 – Boundary Condition

Cosmos- Flow works 2010 is commercial CFD software used for many engineering flow simulations range from internal to external analysis, including heat transfer applications. This CFD software is used to perform this simulation under Solidworks environment. The boundary condition shows the inlet mass flow rate, outlet pressure and initial wall temperature of the heat recovery unit. The following figures show the pressure, velocity, fluid temperature and flow trajectory of the simulation.

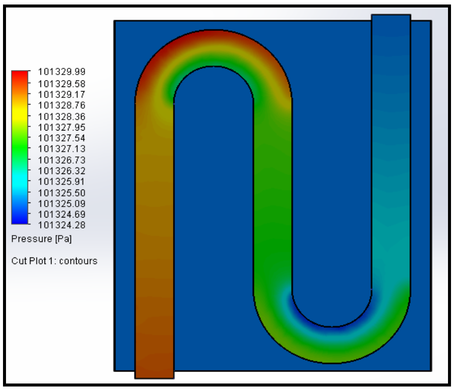

Fig.11- Pressure Plot

The pressure increases at the initial 'U' bend and continuously decreases afterwards and reaches atmospheric at the outlet.

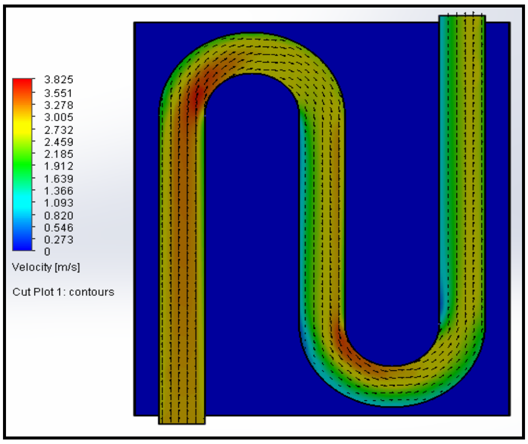

Fig.12 – Velocity Plot

The velocity plot shows the peak velocity observed at the inner radius of the 'U' bends where the pressure also high at the opposite (Outer Radius) end. The following figure shows the fluid temperature (Heat Recovery) of the system.

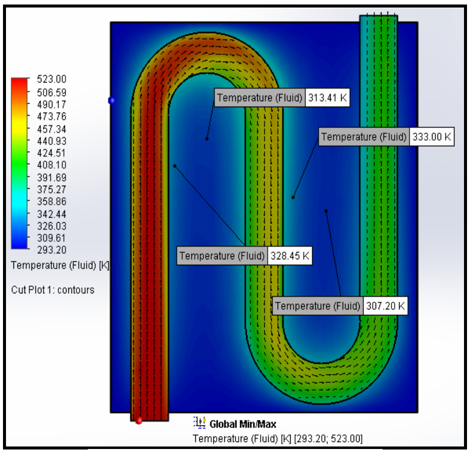

Fig.13 – Fluid Temperature

It is clear from the simulation result, the copper tube releases around 100°C to the fluid medium (Water) which is gradually reaching boiling point and then moves to steam phase, for every pass the copper tube releases the heat to the fluid medium, the exhaust gas is at peak temperature at the inlet of the copper tube at reduces at the exhaust. The flags in the figure show the fluid medium temperature is rising and it will change the fluid from liquid phase to steam. The following figure show the flow trajectory if the exhaust gas.

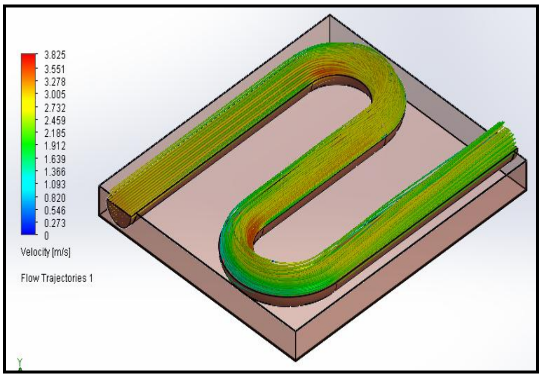

Fig.14- Exhaust Gas Flow Trajectory

V .CONCLUSION

The initial phase of the project work delivers the following, the objective formulation done successfully which is followed by the literature review which provided details of exhaust gas recovery system design, methods, type of heat recovery system, practical problems in heat recovery system, CFD simulation techniques for heat recovery system, engines used in the heat recovery system, this details provides the research gap in the literature review, where low powered diesel engines plays important role in exhaust gas recovery system which can be used for multipurpose operation in rural and urban areas. Based on this a proposed system is developed with research methodology which shows the systematic work involved in this project work. Design of heat recovery system is successfully done with CFD simulation to evaluate the heat recovery and the results are encouraging to go ahead with experimental results. The CFD results are detailed below. The fluid temperature (Exhaust Gas) at the outlet of the pipe and the velocity of the same is found from the CFD simulation, they are as follows.

Temperature (Fluid) [K] : 390.02°K
Velocity [m/s] : 2.272

The simulation shows that the heat recovery from the exhaust gas is around 117.15°K it shows that in continuous operation water in the heat recovery box will became steam in shorter time

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