Multiphysics Modeling and Optimization of Automotive Heat Exchanger for Exhaust Heat Recovery.

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1.0 Introduction:-

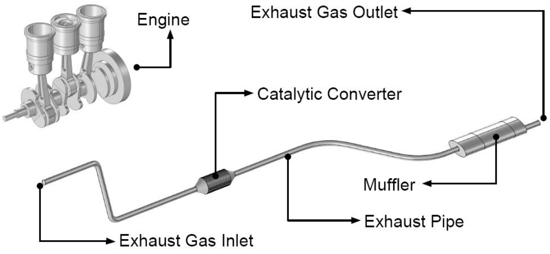
An Internal Combustion Engine (IC Engine) is a heat engine where combustion of air-fuel mixture occurs in a combustion chamber. The combustion of chemical fuels produces energies in form of heat and pressure. The pressure energy then converted to mechanical work through piston, connecting rod and crankshaft while the heat energy is exhausted to atmosphere. The Internal Combustion Engine (ICE) does not efficiently convert chemical energies to mechanical energy. A majority of this energy is dissipated to engine coolant and atmosphere as heat. Approximately 70% energy is wastage while remaining 30% used for vehicle operation which is a huge loss in terms of fuel efficiency. Rather than directly increasing fuel efficiency of the engine, exhaust heat recovery technologies are proposed to improve fuel efficiency indirectly by converting waste heat to electrical energy. Developing an optimized exhaust heat exchanger for automobiles is a challenging task in automotive industry. The advancement in multiphysics cae simulation technologies makes it possible to design complex exhaust heat exchanger for efficient heat recovery, which energy can later be used to produce useful work. In this work a heat exchanger model is developed for efficient heat recovery from exhaust gas while reducing the heat energy dissipated to atmosphere. The heat transfer, cfd and design modules of COMSOL Multiphysics software is used to develop the optimize exhaust heat exchanger for exhaust heat recovery.

Keywords:- Heat Exchanger, Exhaust Heat, Heat Recovery.

1.2 Automotive Exhaust System:-

The exhaust system is a very vital component of an automotive. Initially it was developed as a simple duct system to prevent toxic exhaust gases entering to the cabin. Over the years the responsibility and the job of an exhaust system is grown. The modern exhaust system not only guides the toxic gases to the atmosphere but also reduces engine noise and play a vital role by increasing fuel efficiency. The recent development is numerical modelling and heat recovery technologies makes it possible to design efficient exhaust systems for better fuel efficiency. In recent findings of energy conversion and energy transmission its is estimated that a lots of energy is lost to atmosphere as waste heat through the exhaust system. More research is focused on developing efficient exhaust system which can reduce toxicity of exhaust gas, attenuate engine noise and also harvest useful work from waste energy. The major parts of conventional automotive exhaust system are

- Exhaust Manifold
- Manifold Pipe and Connector
- Exhaust Pipe and Elbows
- Catalytic Converter
- Muffler

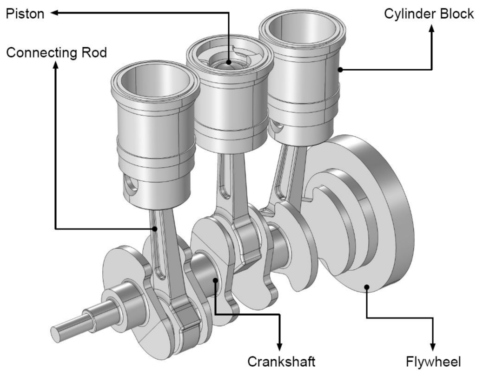


(Figure 1.1 : Conventional Automotive Exhaust System)

1.3 Internal Combustion Engine:-

Internal combustion engines are mechanical devices that produce work from fossil fuel combustion. Internal combustion engines are most commonly used in automobiles due to its portability and high power to weight ratio. The internal combustion engine is designed in a manner that produced high pressure from fuel combustion which can converted into kinetic energy. The production of heat and toxic gases from fuel combustion is released to the atmosphere. The major components of an internal combustion engine are

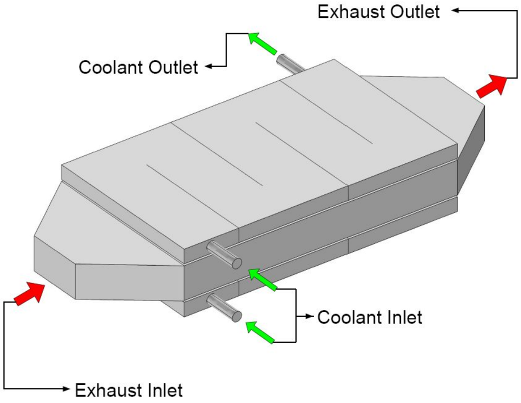
- Cylinder Block
- Piston
- Connecting Rod
- Crankshaft
- Crankcase
- Camshaft
- Sparkplug
- Fuel injector
- Flywheel



(Figure 1.2 : Automotive IC Engine)

1.4 Heat Exchanger:-

The heat exchanger is a mechanical device that used to transfer heat between two fluids with different temperatures. In a conventional heat exchanger the fluids are separated by metal walls to prevent direct contact and mixing. Heat exchangers are most commonly used in power plants, chemical plants, electronic cooling, air-conditioning, refrigeration and automotive applications. The heat exchanger design in this experiment for exhaust heat recovery is given in figure 1.3. The heat exchanger is designed suitable for Thermoelectric application where temperature differential is needed for electric power generation. In this paper more importance is given to the heat exchanger design and optimization for maximum waste heat recovery suitable for thermoelectric effects.

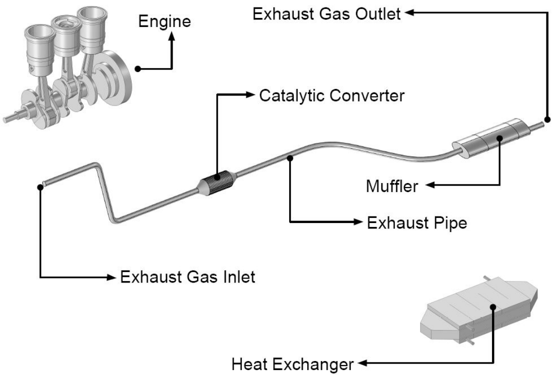


(Figure 1.3 : Heat Exchanger)

2.0 Numerical Simulations:-

2.1 Exhaust System Numerical Simulation:-

A conventional computational model for exhaust system heat recovery is designed in COMSOL Multiphysics as shown in figure 1.4. The exhaust system computational model is consist of exhaust pipe, catalytic converter and muffler. The engine model is an additional simulation where we can find the exhaust flow parametres which later can be used to perform multiphysics cae simulation on the exhaust system. The optimized heat exchanger model is designed suitable for thermoelectric power generation while recovering waste heat energy and improving fuel efficiency. The initial boundary conditions for heat exchanger is taken from the simulation results of exhaust system. The temperature distribution in exhaust system and heat exchanger will help to find optimize location of heat exchanger for thermoelectric power generation. Thermoelectric power generation works on the principle of Seebeck effects, where the thermoelectric semiconductor materials have temperature dependent seebeck coefficient, thermal conductivity and electrical conductivity. The thermoelectric materials have a certain temperature range while producing electricity. The desired temperature range is required for the thermoelements to produce electricity without failure. A high temperature may leads to melting of thermoelements while in working condition, hence the optimization and placement of heat exchanger is performed for efficient power generation without any failure.



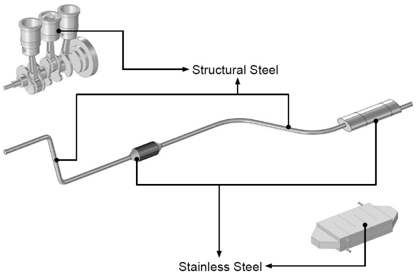
(Figure 1.4 : Exhaust System Computational Model)

2.3 Model Material Properties:-

The material properties such as Density, Thermal Conductivity, Heat capacity for engine and exhaust system components are given in the below table. The material definition for engine and exhaust system is shown in figure 1.5. Exhaust pipes are defined as structural steel. Catalytic converter body and Muffler bodies are defined as stainless steel. The Catalyst elements in catalytic converter are defined as platinum. The fluid domains for the couple physics are defined as carbon dioxide for exhaust gas and water as coolant. The materials used in the simulation model are taken from the comsol material library.

Materials	Cp (J/kgK)	K (W/mK)	ρ (kg/m^3)
Structural Steel	445	44.5	7850
Stainless Steel	530	17	8.07E-6
Platinum	133	71.6	21450

(Table 1 : Material Properties)



(Figure 1.5 : Material Definition)

2.4 Physics and Governing Equations:-

Multiple physics couple numerically are heat transfer in solid, heat transfer in fluid and turbulent fluid flow on the domain of exhaust gas, coolant and components by help of comsol multiphysics. The physics involved in computational model are mentioned with equations as belows.

(1) Heat Transfer in Solid:-

The heat transfer in solid interface is used to model heat transfer in solids by conduction, convection and radiation. The temperature equation defined in solid domains corresponds to the differential form of the Fourier's law that may contain additional contributions like heat sources.

$$\rho C_p u.\nabla T + \nabla.q = Q + Q_{ted},\ q = -k\nabla T$$

(2) Heat Transfer in Fluid:-

The heat transfer in fluid interface is used to model heat transfer in fluid by conduction, convection and radiation. The temperature equation defined in fluid domains corresponds to the convection-diffusion equation that may contain additional contributions like heat sources.

$$\rho C_p u.\nabla T + \nabla.q = Q + Q_p + Q_{vd},\ q = -k\nabla T$$

(1) Turbulent Fluid Flow:-

The Turbulent Flow, Low Re k-ε (spf) interface is used for simulating single-phase flows at high Reynolds numbers. The physics interface is suitable for compressible flows and incompressible flows at low mach numbers. The equations solved by the Turbulent Flow, Low Re k-ε interface are the Reynolds-averaged Navier-Stokes (RANS) equations for conservation of momentum and the continuity equation for conservation of mass.

$$\rho(u.\nabla)u =$$

$$\nabla.[-pI + (\mu + \mu T)(Vu + (\nabla u)^T) - \tfrac{2}{3}(\mu + \mu T)(\nabla.u)I] + F$$

$$\nabla.(\rho u) = 0$$

$$\rho(u.\nabla)\kappa = \nabla\left[\left(\mu + \tfrac{\mu_T}{\sigma_\kappa}\right)\nabla\kappa\right] + P_\kappa - \rho \in$$

$$\rho(u.\nabla)\kappa = \nabla\left[\left(\mu + \tfrac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + C_{\varepsilon 1}\tfrac{\varepsilon}{\kappa}P_\kappa - C_{\varepsilon 2}\rho\tfrac{\varepsilon^2}{\kappa}$$

$$\varepsilon = ep$$

$$\mu_T = \rho C_\mu \tfrac{\kappa^2}{\varepsilon}$$

$$P_k = \mu_T\left[\nabla u : (\nabla u + (\nabla u)^T - \tfrac{2}{3}(\nabla.u)^2\right] - \tfrac{2}{3}\rho\kappa\nabla.u$$

Where

ρ = Density (kg/m^3)

Cp = Specific heat (J/kg.K)

Q = Heat source (W/m^3)

Qted = Thermoelastic effects

Q_p = Work done by pressure changes

Q_{vd} = Viscous dissipation in fluid

q = Heat flux by conduction (W/m^2)

k = Thermal conductivity (W/m.K) (Heat Transfer)

k = Turbulent kinetic energy (Turbulent Flow)

T = Absolute temperature (K)

p = Pressure (Pa)

u = Velocity Vector (m/s)

μ = Dynamic Viscosity (Pa.s)

F = Volume force vector (N/m^3)

V = Velocity (m/s)

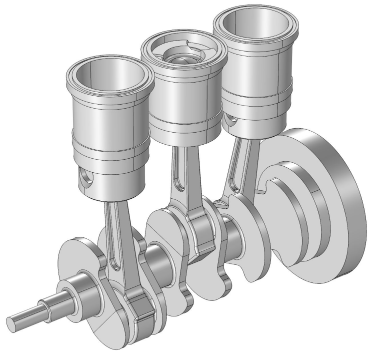
ep = Turbulent dissipation rate

3.0 Automotive Engine Heat Transfer Simulation:-

A 1.5 litre, inline 3 cylinder diesel engine from a hatchback passenger car is considered for this simulation. The exhaust temperature produced from the engine is taken as initial values for the exhaust system. The temperature distribution in the exhaust system is predicted as given in section 4.1. The engine cad model from comsol model library is included in this simulation.

3.1 Boundary and Physics Definition-

The heat transfer in engine model is solve using the heat equation in comsol. The temperature value of 450C is applied at the inner chambers of the engine and an atmospheric natural convection heat transfer coefficient (10 Watt) is applied to remaining boundaries of the engine. The materials for the engine component is defined as structural steel. Material properties for structural steel can be found from table 1 in section 2.3.



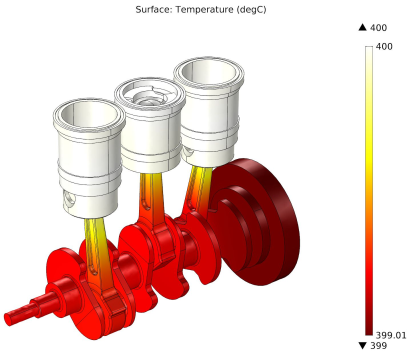
(Figure 1.6 : Automotive engine model)

3.2 Numerical Solver:-

A fully coupled, direct, stationery study is implemented to the automotive engine heat transfer model to predict the temperature distribution.

3.3 Result Evaluation:-

The temperature distribution contour plots are plotted graphically as shown in figure 2.8.



(Figure 1.7 : Engine temperature distribution)

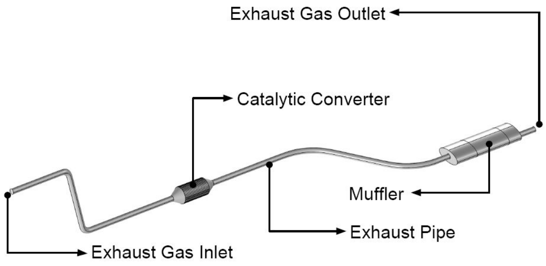
A maximum temperature of 400C is obtained inside the combustion chamber, which is released to atmosphere through the exhaust system. The results from the engine thermal simulation will help to define the boundary condition for exhaust heat recovery system.

4.0 Exhaust System Multiphysics Simulation:-

A multiphysics cae model for the automotive exhaust system is developed using COMSOL Multiphysics software package. The computational model of the exhaust system is developed as shown in figure 1.8. The included components in numerical model are exhaust pipe, catalytic converter and muffler.

4.1 Boundary and Physics Definitions:-

The numerical coupling of heat transfer and fluid flow physics is implemented on the exhaust system. The model consisting of fluid domain as exhaust gas and solid domains as metal component. The turbulent fluid flow, heat transfer in fluid and heat transfer in solid interfaces are coupled numerically to perform multiphysics cae simulation. The material definition for the model can be found from figure 1.5 and the material properties from table 1 in section 2.3. The exhaust gas temperature predicted from the fuel combustion (400^C) is taken as inlet exhaust temperature. Turbulent flow Reynolds Averaged Navier Stoke and heat transfer in fluid equations solved for the fluid domain while heat transfer in solid equations are defined to solid domains. The governing equations for the involved physics can be found from section 2.4.



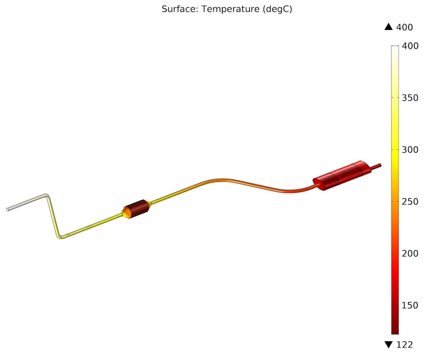
(Figure 1.8 : Computational Model of Exhaust System)

4.2 Numerical Solver:-

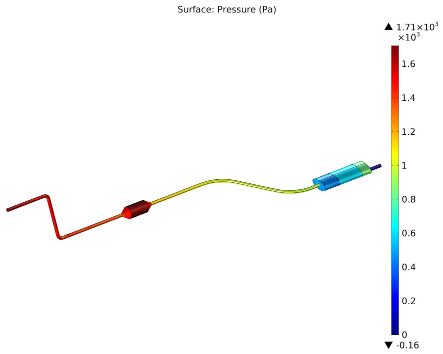
A fully coupled, direct, stationery study is implemented to the automotive exhaust system to predict the temperature distribution. The Non-Isothermal physics node is added to the model for coupling of multiple physics as mentioned in section 4.1.

4.3 Result Evaluation:-

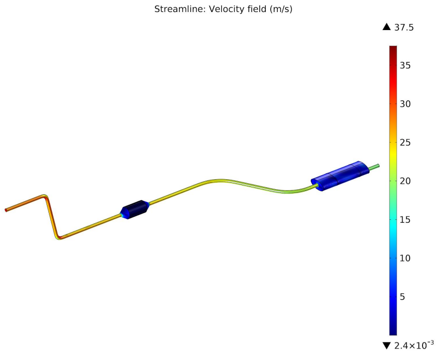
The temperature distribution, exhaust pressure and fluid velocity magnitudes are plotted graphically as shown in below contour plots.



(Figure 1.9 : Exhaust System Temperature Distribution)



(Figure 2.0 : Exhaust System Pressure Distribution)



(Figure 2.1 : Exhaust Gas Velocity Magnitude)

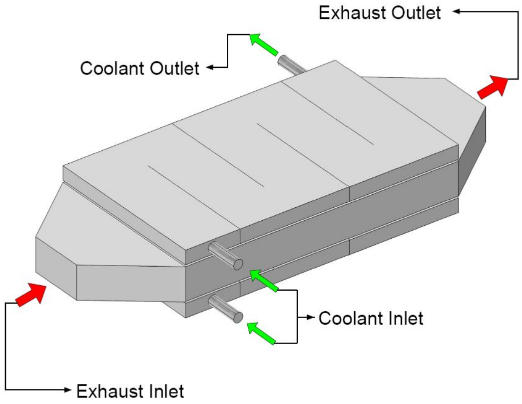
The maximum temperature occurence is predicted to be nearer the engine while lesser at the tailpipe. There is a fluctuation in temperature propagation predicted at catalytic converter, which shows, how external devices attached to exhaust system can play a role in temperature distribution. From the temperature distribution results in exhaust system the desired position for heat exchanger is predicted to be in between catalytic converter and muffler.

5.0 Automotive Heat Exchanger Multiphysics Simulation:-

An optimized heat exchanger model is developed in COMSOL. The heat exchanger will be attached to exhaust system in between catalytic converter and muffler. The heat exchanger's body is made of stainless steel sheets to prevent mixing of coolant and exhaust gas as well as prevent corrosion. There are two coolant chamber attached opposites to each other as shown in figure 2.2.

5.1 Boundary and Physics Definition-

The numerical boundary definition for heat exchanger model is defined as in figure 2.2. The exhaust gas temperature predicted from exhaust system (250^{C}) is taken as inlet exhaust temperature and the normal temperature value for water is taken as 13^{C}. The corrugated chambers are designed to increase coolant flow distance and increase flow time for better thermal management. The Turbulent flow Reynolds Averaged Navier Stoke and heat transfer in fluid equations solved for the fluid domain while heat transfer in solid equations are defined for solid domains. The governing equations for the involved physics can be found from section 2.4.



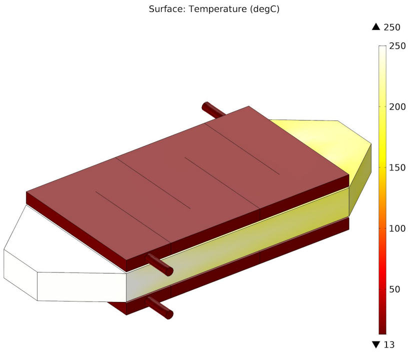
(Figure 2.2 : TEG Device Boundary Definition)

5.2 Numerical Solver:-

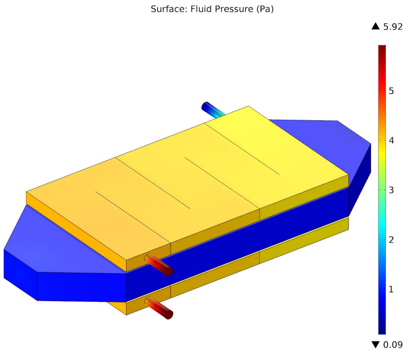
A fully coupled, direct, stationery study is implemented to the heat exchanger model to predict the temperature distribution.

5.3 Result Evaluation:-

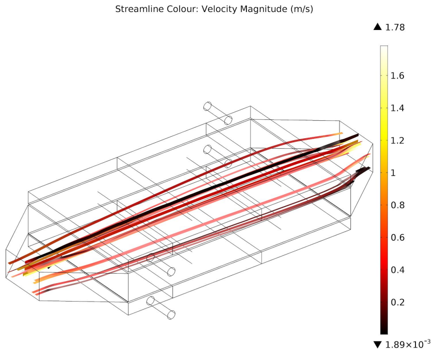
The temperature, pressure and velocity field contour plots are plotted graphically as shown in below pictures.



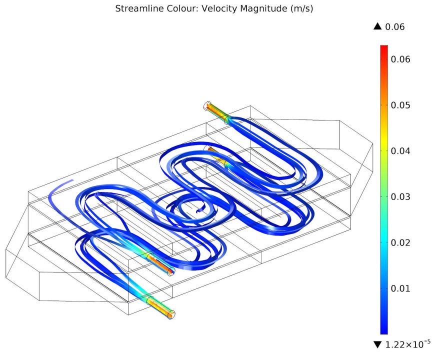
(Figure 2.3 : Heat exchanger temperature Distribution)



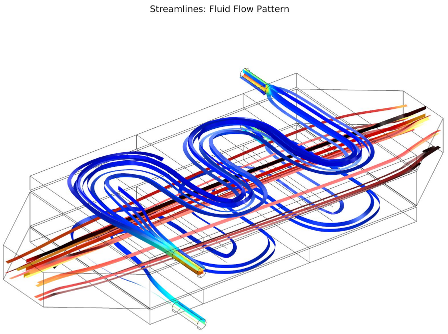
(Figure 2.4 : Heat exchanger pressure distribution)



(Figure 2.5 : Exhaust flow streamline)



(Figure 2.6 : Coolant flow streamline)



(Figure 2.7 : Heat exchanger fluid flow streamlines)

The maximum temperature occurence is predicted to be at the entrance of the heat exchanger. The temperature distribution in the heat exchanger as shown in figure 2.3 is suitable for thermoelectric power generation. The thermoelectric modules can be attached safely in between exhaust chamber and coolant chamber to produce electric power which can improve fuel efficiency.

6.0 Conclusion and future work:-

Waste heat is an inevitable process in automotive internal combustion engine. Most of heat is lost to atmosphere through the exhaust system as waste heat. The waste heat produced during vehicle operation decreases fuel economy. In this paper a solution of waste heat recovery technology and method for better fuel economy is proposed by help of numerical simulation. The numerical model of automotive heat recovery exhaust system and heat exchanger is designed using comsol multiphysics. The predicted temperature distribution in the exhaust system and heat exchanger shows potential in maximum exhaust waste heat recovery. Simulation results of heat exchanger found to be a suitable condition for thermoelectric power generation. The predicted simulation results can further be helpful in optimized design and placement of heat exchanger for maximum heat recovery.

6.1 References:-

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6.2 Acknowledgement:-

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