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

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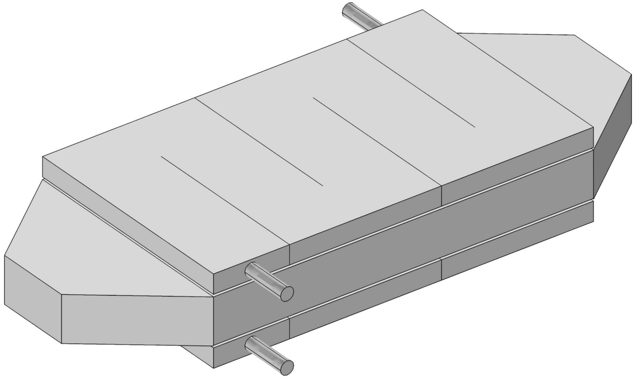
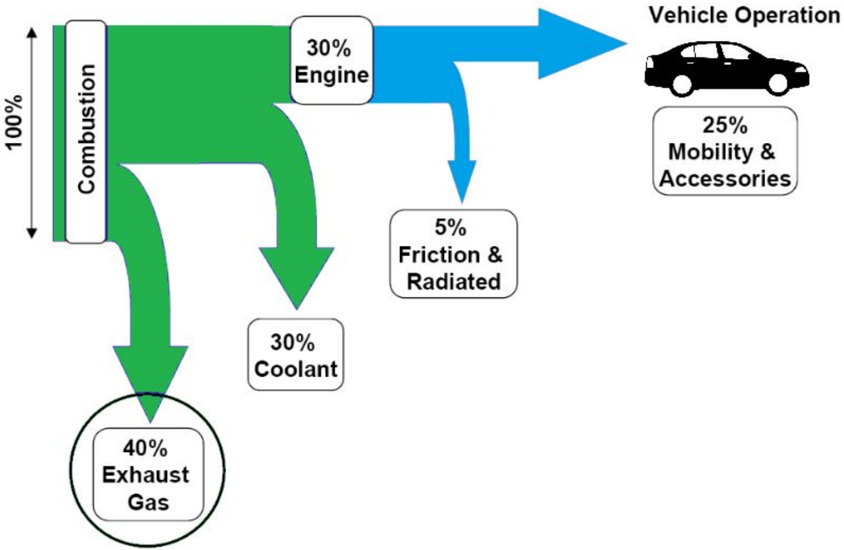


Introduction & Objectives

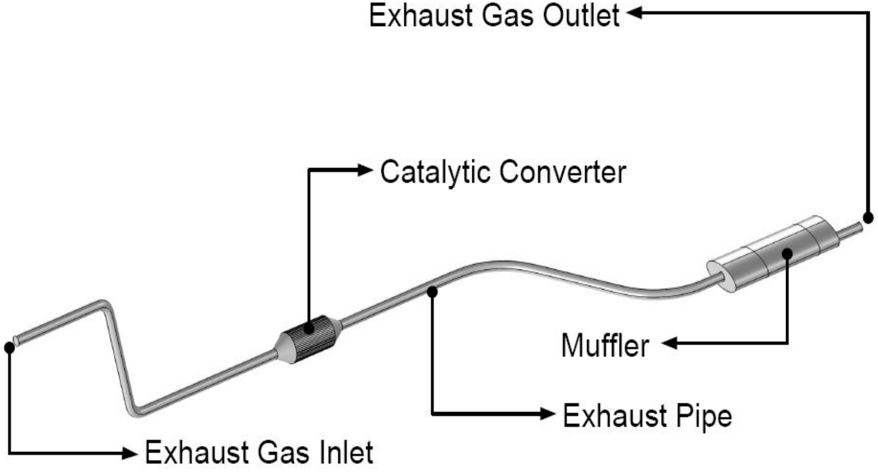
- Internal combustion engines are mechanical devices that produce work from fossil fuel combustion.
- Approximately 70% energy is wastage while remaining 30% used for vehicle operation.
- Huge loss in terms of fuel efficiency.
- Exhaust heat recovery technologies are used improve fuel efficiency indirectly by converting waste heat into useful energy.
- In this work a heat exchanger model is designed for efficient heat recovery from exhaust gas.



(Fig 1: Automotive Energy Flow, Sankey Diagram)

Automotive Exhaust System

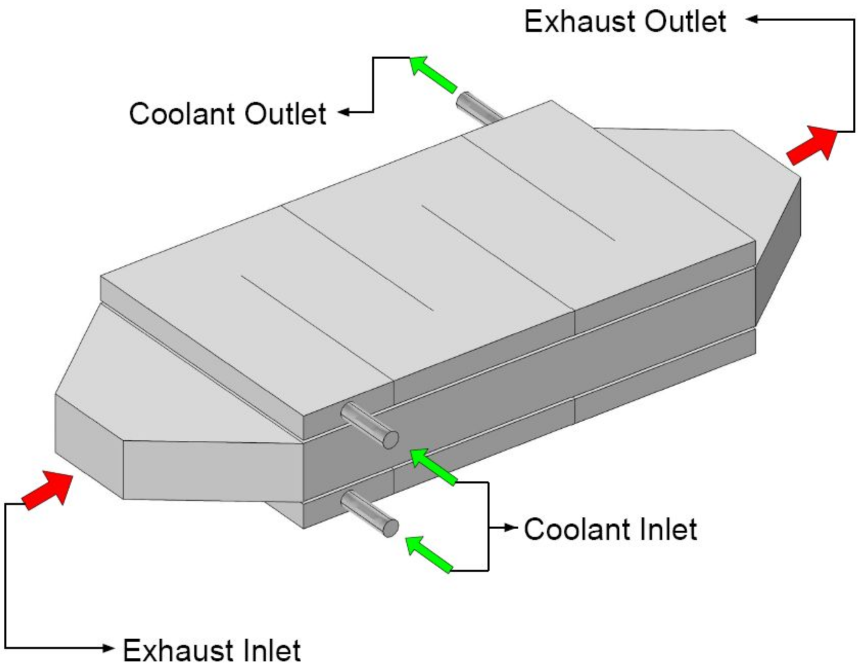
- It guides the toxic gases from engine to the atmosphere.
- The responsibility and the job of an exhaust system is grown.
- Modern Exhaust Systems plays vital role to increase fuel efficiency
- Major Components
    - Exhaust Manifold
    - Manifold Pipe and Connector
    - Exhaust Pipe and Elbows
    - Catalytic Converter
    - Muffler
- Complex and challenging for exhaust heat recovery.



(Fig 2: Automotive Exhaust System)

Heat Exchanger

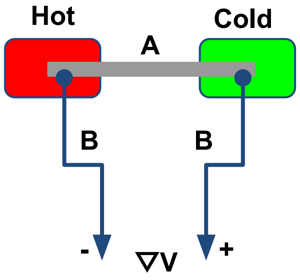
- It is a mechanical device used to transfer heat between two fluids with different temperatures.
- Fluids are separated by metal walls to prevent direct contact and mixing.
- Heat exchanger design in this experiment for automotive exhaust heat recovery is given in figure 3.
- The heat exchanger is designed suitable for Thermoelectric application where proper temperature differential is needed for electric power generation.



(Fig 3: Heat Exchanger)

Thermoelectric Generator (TEG)

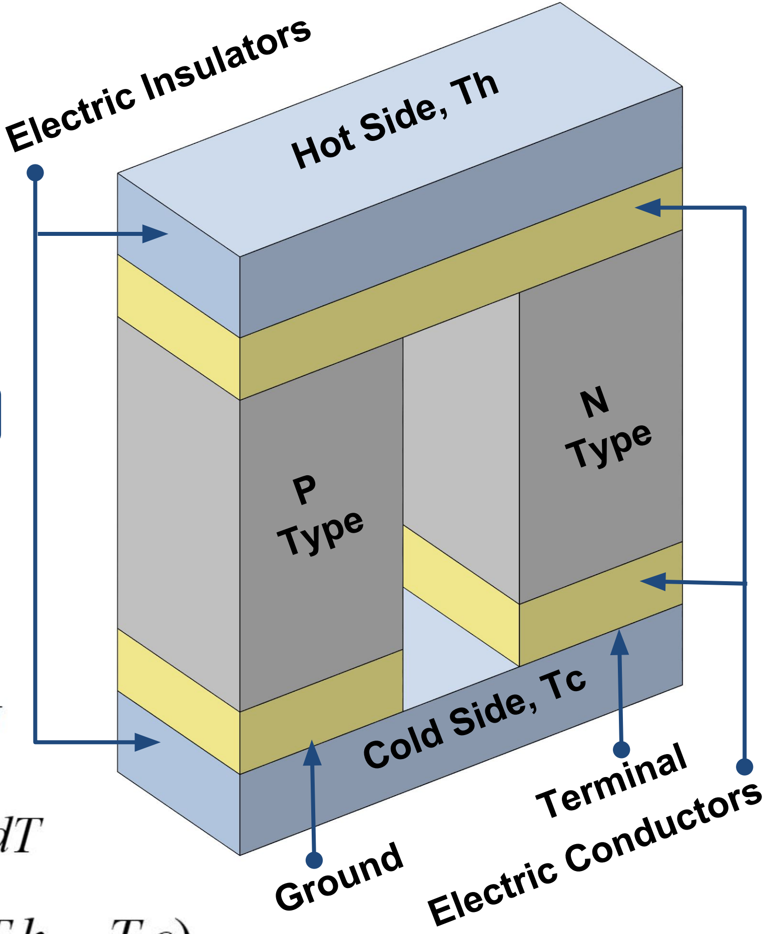
- Energy harvesting device.
- Convert temperature difference (Th-Tc) into electrical energy (Voltage).
- Thermoelectricity.
  - Seebeck effect.
- Thermoelectric materials
  - Bismuth Telluride (Bi_2Te_3)
  - Lead telluride (PbTe)
  - Silicon Germanium (SiGe)
  - Skutterudite ($CoAs_3$)
- Seebeck Coefficient (α)
- Thermal Conductivity (k)
- Figure of Merit (ZT)



$$\alpha = \alpha_P - \alpha_N$$

$$V_{OC} = \int_{Tc}^{Th} \alpha(T)dT$$

$$\nabla V \ or \ V_{OC} = \alpha(Th - Tc)$$

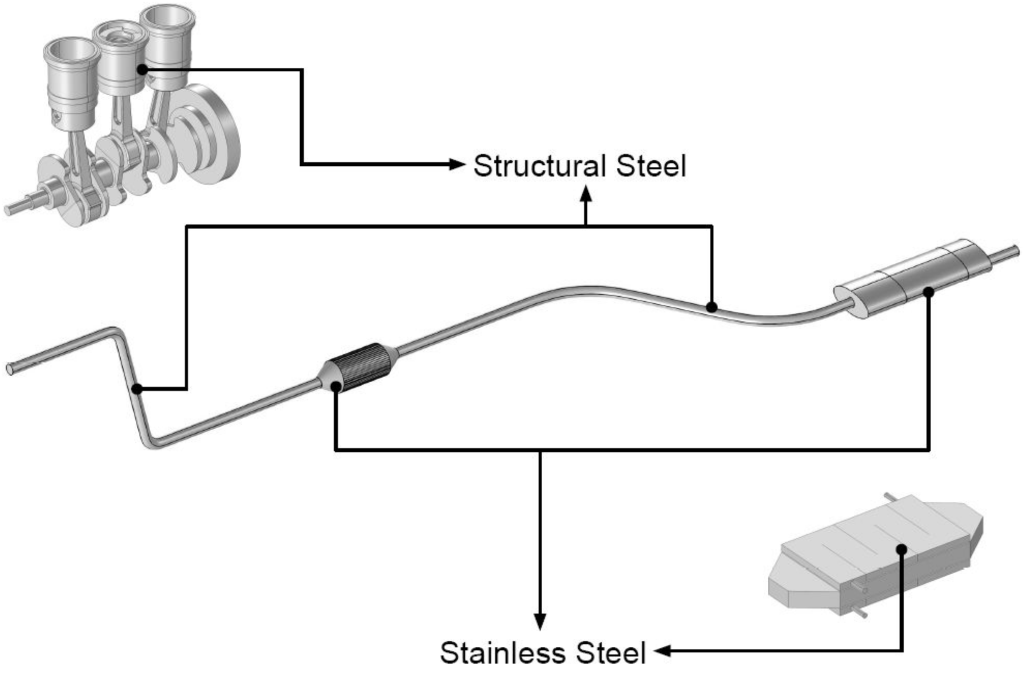


(Fig 4: TEG Module)

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 6.
- 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.

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



(Fig 6: Exhaust System Material Properties)

Comsol Simulation

Governing Equations

Turbulent Fluid Flow

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

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

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

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

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

$$\epsilon = ep$$

$$\mu_T = \rho C_\mu \frac{\kappa^2}{\epsilon}$$

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

Heat Transfer in Solid

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

Heat Transfer in Fluid

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

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)

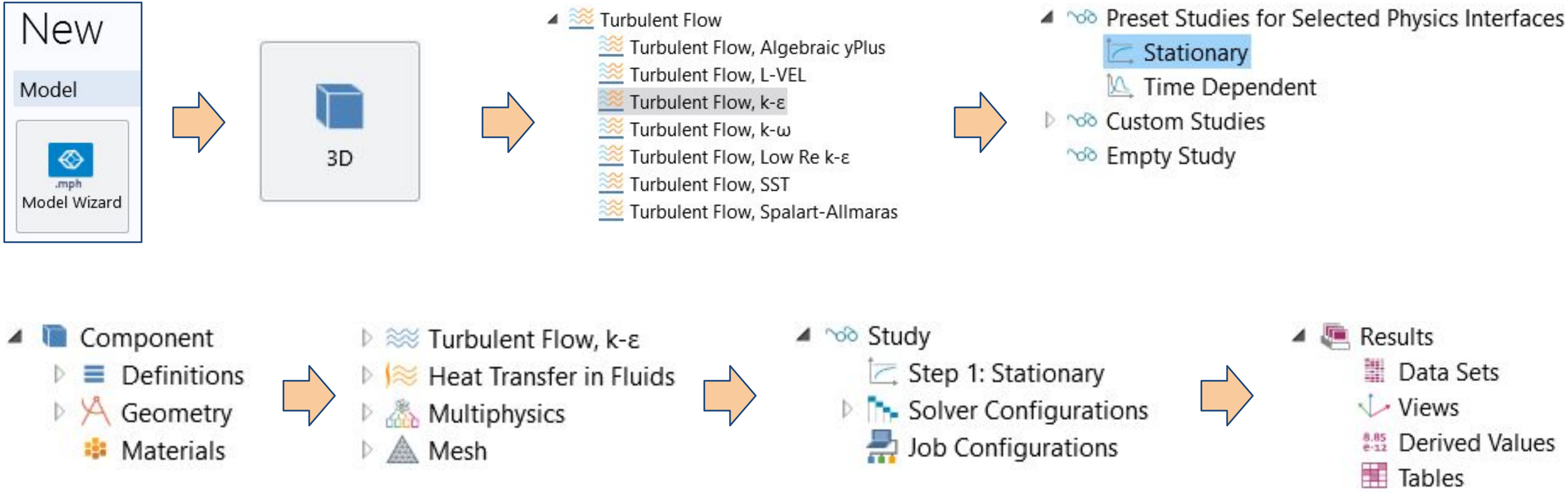
F = Volume force vector (N/m^3)

V = Velocity (m/s)

ep = Turbulent dissipation rate

Simulation in Comsol

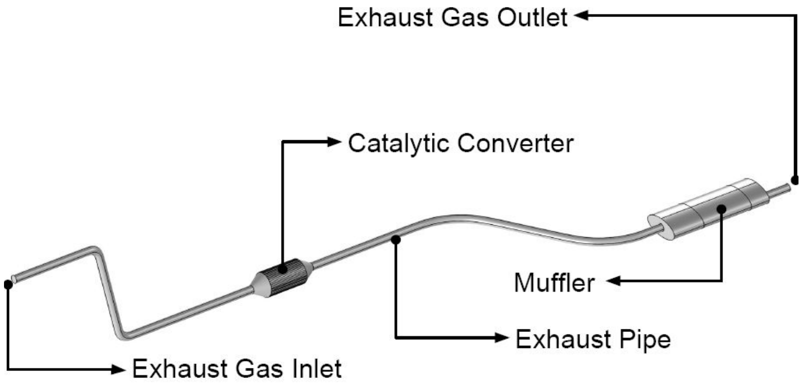
Steps



Automotive Exhaust System

Comsol Model

- A multiphysics cae model for the automotive exhaust system is developed using COMSOL.
- The computational model of the exhaust system is developed as shown in figure 1.8.
- The turbulent fluid flow, heat transfer in fluid and heat transfer in solid interfaces are coupled numerically.
- The exhaust gas temperature predicted from the fuel combustion (400^C) is taken as inlet exhaust temperature.
- A fully coupled, direct, stationery study is implemented to the automotive exhaust system.

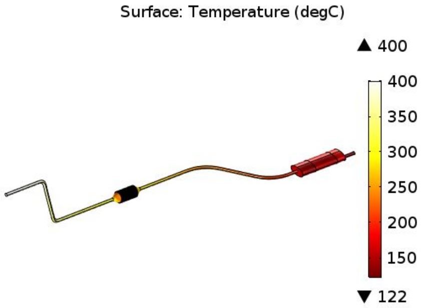


(Fig 7: Exhaust System, Comsol Model)

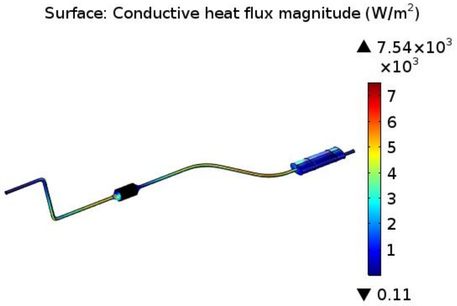
Simulation Results

Exhaust System, Contour Plots

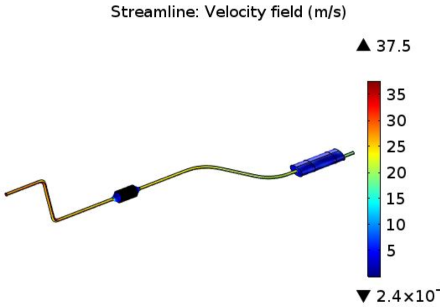
- The temperature distribution, exhaust pressure and fluid velocity magnitudes are plotted graphically as shown in contour plots.
- The maximum temperature occurence is predicted to be nearer the engine while lesser at the tailpipe
- From the temperature distribution results in exhaust system the desired position for heat exchanger is predicted to be in between catalytic converter and muffler.



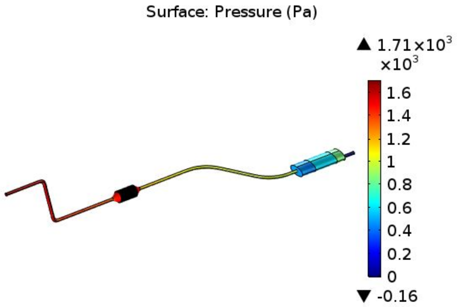
Temperature (degC)



Conductive Heat Flux (W/m^2)



Fluid Velocity (m/s)

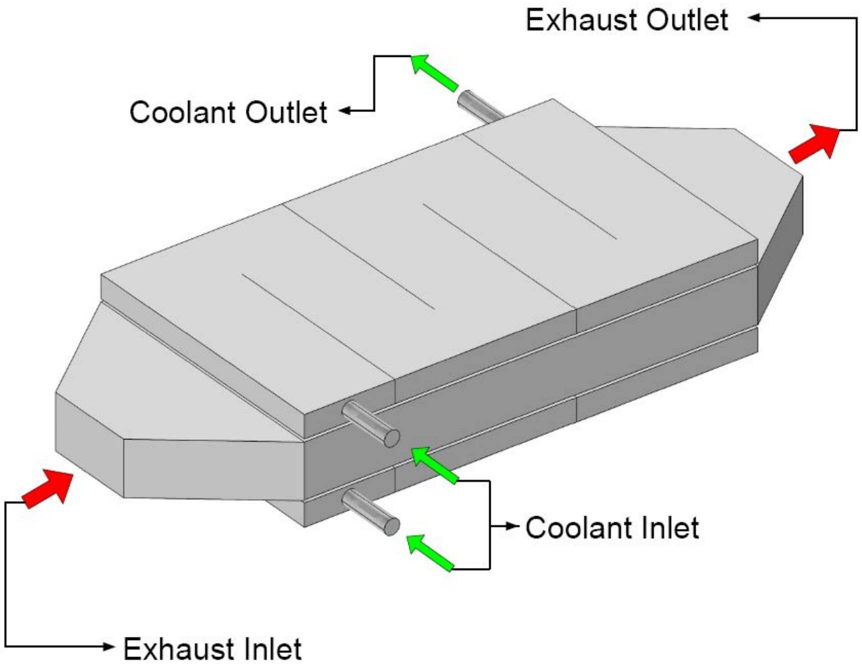


Fluid Pressure (Pa)

Heat Exchanger Simulation

Comsol Model

- An optimized heat exchanger model is designed in COMSOL.
- It will be attached to exhaust system in between catalytic converter and muffler.
- Two coolant chamber attached opposites to each other as shown in figure 8.
- Numerical boundary definition for heat exchanger model is defined as in figure 8.
- Exhaust gas temperature predicted from exhaust system (250^C) is taken as exhaust inlet temperature and coolant as 13^C.
- Corrugated chambers are designed to recover more heat from the exhaust gas.

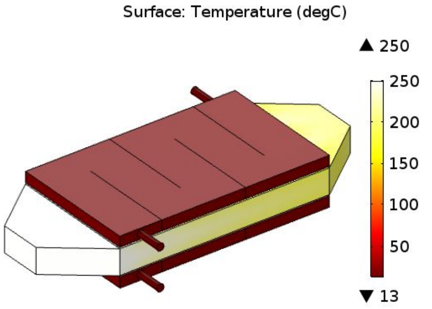


(Fig 8: Heat Exchanger, Comsol Model)

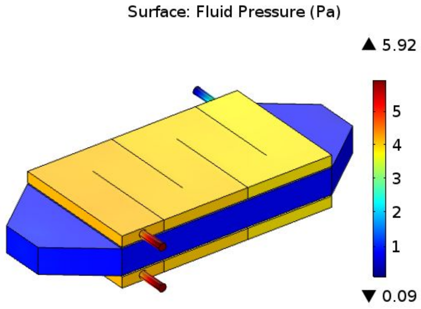
Simulation Results

Heat Exchanger, Contour Plots

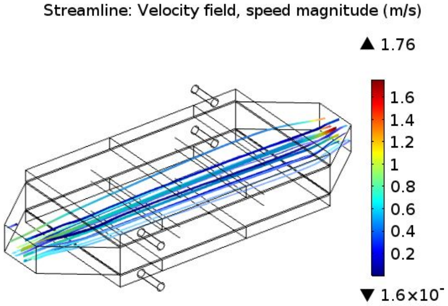
- Temperature distribution, exhaust pressure and fluid velocity magnitudes are plotted graphically as shown in contour plots.
- Maximum temperature occurence is predicted to be at the entrance of the heat exchanger.
- Temperature distribution in the heat exchanger as shown is suitable for thermoelectric power generation.
- Thermoelectric modules can be attached safely in between exhaust chamber and coolant chamber to produce electric power.



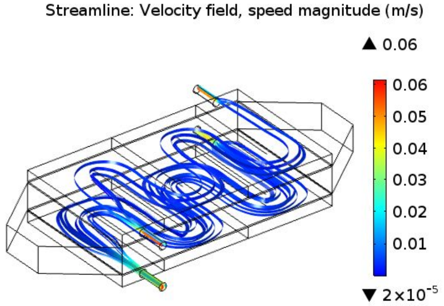
Temperature (degC)



Fluid Pressure (Pa)



Exhaust Flow Velocity (m/s)



Coolant Flow Velocity (m/s)

Conclusion and Future Work

- 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 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.

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