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Optimizing Design of EGR Cooler in Vehicle by Numerical Simulation

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Abstract

Exhaust Gas Recirculation (EGR) is a technology used in internal combustion engines to reduce the formation of nitrogen oxides (NOx) emissions. Numerical simulation method is used to study the flow field and temperature distribution of the fluids inside the EGR cooler. In this study two models of EGR cooler have been compared. Model A is a standard shell and tube heat exchanger having baffles and seven plain tubes which are in staggered arrangement. Model B having a same geometry as well as same tube arrangement similar to model A, but the surface of the tube of heat exchanger is coated with Nickel chromium (NiCr). The inlet temperature of hot gases and cooled water are same in both the models. Then the both models are analysed in ANSYS FLUENT software. The results shows that coating enhances the heat exchanger rate and also increases overall efficiency of the shell and tube heat exchanger. In conclusion model B which is coated with Nickel chromium shows better overall performance than the standard model.

Keywords: CFD; heat exchangers; shell and tube; baffle spacing; turbulence models

Introduction

A diesel engine is an internal combustion engine that uses diesel fuel to generate power. Diesel engines are commonly used in various applications, including vehicles, generators, and heavy machinery. They are known for their fuel efficiency, durability, and high torque output. However, diesel engines also produce emissions, particularly nitrogen oxides (NOx), which contribute to environmental pollution and health issues. Emissions from diesel engines, including NOx, pose significant environmental and health concerns. To mitigate these emissions, various technologies have been developed, such as exhaust gas recirculation

(EGR), selective catalytic reduction (SCR), and lean-burn combustion. EGR is a technique that recirculates a portion of the engine's exhaust gas back into the combustion chamber, reducing the combustion temperature and NOx formation.

The EGR system includes components like an EGR valve, EGR cooler, and EGR control system. The EGR cooler is a heat exchanger that cools the recirculated exhaust gas before it enters the combustion chamber. Cooling the exhaust gas reduces the combustion temperature and subsequently lowers the NOx emissions. EGR coolers need to transfer a large amount of heat efficiently and withstand engine vibrations.

Soot and hydrocarbon deposition in the EGR cooler decrease heat transfer efficiency, increase emissions, and cause pressure drop. Pre-ignition and detonation can harm the engine and reduce overall output. In this project, the aim is to address these issues and improve the thermal efficiency and lifespan of the EGR cooler. One approach is to coat the inner tubes of the EGR cooler with nanomaterials to prevent fouling and enhance thermal conductivity. The objectives of this project include: Optimizing the design of the EGR cooler through parameter variations and analyzing thermal and fluid dynamics behaviour; Comparing the performance of the optimized EGR cooler to the original design, quantifying improvements in engine temperature reduction and efficiency. "A comprehensive review on micro/nanoscale surface modification techniques for heat transfer enhancement in heat exchangers" (June 2021) - This paper discusses the importance of improving heat exchanger efficiency and the use of nanotechnology for surface modification. It provides an overview of micro/nano surface modification techniques in both single-phase and phase-change heat exchangers; "Numerical investigation of helical baffles heat exchanger with different Prandtl number fluids" (May 2013) - This paper presents numerical simulations of helical baffles heat exchangers with different fluids and tilt angles. The study analyzes the effects of helical baffles on fluid flow and heat transfer. These literature sources contribute to understanding heat exchanger efficiency enhancement through surface modification techniques and the impact of design parameters on heat transfer in heat exchangers. They provide valuable insights for optimizing the EGR cooler design and assessing the potential benefits of coating the inner tubes with nanomaterials.

1. Modelling Details

CREATION OF GEOMETRY & MATERIALS USED

A Geometry of seven tubes shell & tube type EGR cooler is made using Ansys Space claim.

The geometry has the following dimensions:

Sr no.	Dimension	Value
1	Tube length	440mm
2	Tube diameter	15mm
3	Tube thickness	1mm
4	Shell length	400mm
5	Shell diameter	76mm
6	Shell inlet diameter	30mm
7	No of baffles	7
8	Baffles thickness	1mm

Table 1: Dimensions of CAD Model

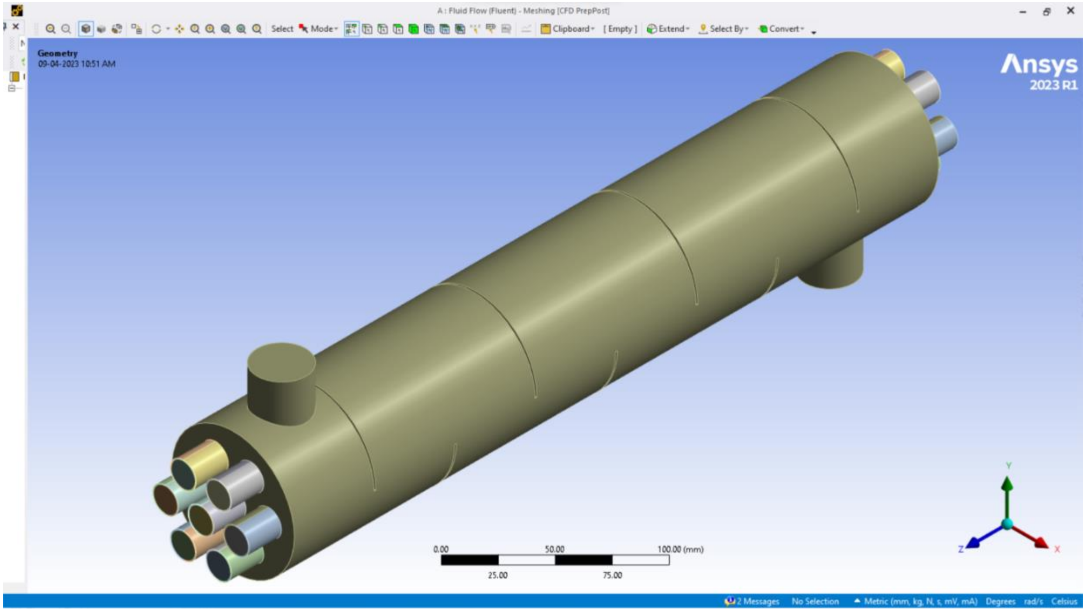

Figure 1: CAD Model

The entire CAD model is made in such a way that it has the following CAD bodies:

1. Exhaust Gas which is portrayed as a fluid domain.
2. Coolant Domain which is also portrayed as another fluid medium.
3. Pipe which is solid body made up of aluminum.
4. Outside Shell and Baffles which are also solid bodies made up of aluminum.

(Outside shell and baffles are neglected and have been suppressed as they are not taking part in heat transfer)

Two models have been created for Analysis. Model A is a standard Shell and Tube Heat Exchanger with no change in the geometry while the Model B is coated with Nickel-Chromium alloy (Ni-Cr) on the internal surface of the tubes. The properties of the coating material are as follows: Nickel Chromium Alloy Nanoparticles, nanodots or nano powders are high surface area nanoscale Nickel chromium alloy particles. American Elements manufactures nickel chromium alloy nanoparticles and Nano powder with standard particle size <100 nanometers (nm) and specific surface area (SSA) in the 5-50 m2/g range. They are also available as a dispersion through the AE Nanofluid production group. Nano dispersions are generally defined as suspended nanoparticles in solution either using surfactant or surface charge technology. Nanofluid dispersion and coating selection technical guidance is also available. Surface functionalized nanoparticles allow for the particles to be preferentially adsorbed at the surface interface using chemically bound polymers.

Properties of Nickel Chromium Alloy

1. Chemical formula - Ni-Cr
2. Molar mass - 101.96 g/mol
3. Density - 5600 kg/m3
4. Melting point - 1400°C
5. Thermal conductivity - 30 W/m°C
6. Nanoparticle size - 30 nm
7. Thermal expansion - 0.000008 1/°C
8. Poison ratio - 0.2
9. Youngs modulus - 46000 Mpa

2. GOVERNING EQUATIONS

The set of equations that describe the full flow behavior – the Navier-Stokes equations – are now described:

Mass Conservation Equation:

$\partial p/\partial t + \nabla \cdot (\rho \vec{u}) = S_m$

This equation is applicable for both compressible and incompressible flows and it is time dependent, being Sm the mass source term. It defines the mass variation inside a control volume, executing the balance between mass leaving and entering this last one (Oliveira, 2012).

Momentum Equation

The momentum conservation lies on the principles of the second Newton's law: the momentum variation in all directions is equal to the summation of all the forces acting in the same directions. The microscopic momentum fluxes across a surface are the forces due to pressure and stress that these surfaces are subjected to, from a molecular perspective.

$\partial / \partial t \, (\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \cdot \vec{u}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho g + F$

This Equation is the set of Navier-Stokes equations that describe the momentum conservation

$\bar{\bar{\tau}} = \mu \, [(\nabla \vec{u} + \nabla \vec{u}^{\,T}) - 2/3 \, \nabla \cdot \vec{u} \cdot \bar{\bar{I}}]$

being p the static pressure, $\bar{\bar{\tau}}$ the tensor that describes the molecular rate of transport of momentum (specified in equation X), ρg the term corresponding to the gravitational body force, and F an external body force.

Energy Conservation Equation

The conservation of energy is based on the physical law that the rate of change of energy in one control volume equals the balance of energy transferred to and from the particle by heat and work. The following equation describes the energy transport along the fluid flow:

$\partial / \partial t \, (\rho E) + \nabla \cdot (\vec{u} \, (\rho E + p)) = \nabla \cdot (k_{eff} \nabla T - \sum h_j J_j + (\bar{\bar{\tau}}_{eff} \cdot \vec{u})) + S_h$

in which k_{eff} stands for the effective conductivity (altered by the turbulence model), h_j corresponds the enthalpy of species j and J_j is the diffusion flux of species j. The term E corresponds to the internal energy of an element:

$E = h - p/\rho + u^2/2$

The three terms in brackets on the right-hand side of equation correspond to, respectively: energy transfer by conduction, species diffusion and viscous dissipation; the last term stands for all of the volumetric heat sources.

This equation is essential for any problems having heat transfer or compressible flows in their scope.

3. BOUNDARY CONDITIONS

In the setup of the fluent solver, the boundary conditions for the model are applied. The inlets are of type mass flow, and the outlets are of type pressure. The walls for the model are no slip and stationary type.

The following boundary conditions are applied to the model at cold and hot inlets and outlets respectively:

1	Exhaust gas inlet mass flow rate	0.08 kg/s
2	Exhaust gas inlet gauge pressure	0 pa
3	Exhaust gas outlet gauge pressure	0 pa
4	Exhaust gas inlet temperature	642 K
5	Coolant(water) inlet gauge pressure	50000 pa
6	Coolant (Water) outlet gauge pressure	0
7	Coolant inlet mass flow rate	0.000714 kg /s
8	Coolant inlet temperature	353 K

Tabe 2: Boundary conditions

4. Mesh selection

Mesh generation is performed using Ansys Meshing. The surfaces of the model are meshed using tetrahedral elements. The shell volume is meshed using tetragonal-hybrid elements. Two different mesh sizes are used in the six-baffle case: the coarse mesh with approximately 700,000 elements; and a finer mesh with approximately 8164370 elements. Computations were performed on a PC with Intel Core i5-1135G7 CPU, 2.40GHz and 8 Gb Ram.

5. Turbulence Model

Turbulence modelling is the construction and use of a model to predict the effects of turbulence. A turbulent fluid flow has features on many different length scales, which all interact with each other. A common approach is to average the governing equations of the flow, in order to focus on large-scale and non-fluctuating features of the flow. However, the effects of the small scales and fluctuating parts must be modelled.

k-ε model

This model is based on model transport equations for the turbulence kinetic energy k and the corresponding dissipation rate ε. There are three versions of the k-ε model: Standard, Realizable and RNG; they allow the determination of a turbulent length and time scale, by solving two different equations (ANSYS, 2016b). The main difference between the Standard and Realizable models lies on the fact that the first determines the k variable from exact equations and ε from empirical ones, and the latter derives them both from exact equations. The Realizable k-ε model allows a more precise result regarding the separation of the boundary layer flows depicting a high swirling component, adverse pressure gradients and recirculation areas. It also predicts very accurately the spreading rate of both planar and round jets.

For turbulent kinetic energy k

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right]+2\mu_t E_{ij}E_{ij}-\rho\varepsilon \quad \ldots\ldots.1$$

For dissipation

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad \ldots\ldots\ldots..2$$

Where,

u_i represents velocity component in corresponding direction.

E_{ij} represents component of rate of deformation

t represents eddy viscosity

7. RESULTS OF MODEL A

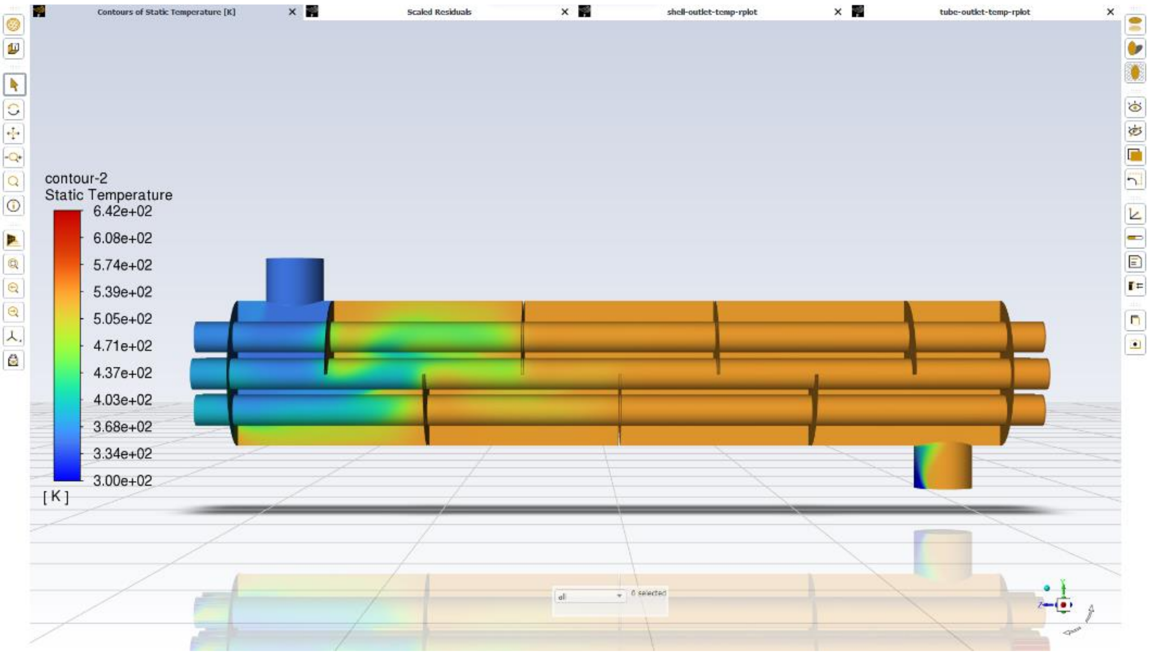

Fig. 2 Contour of static temperature of model A

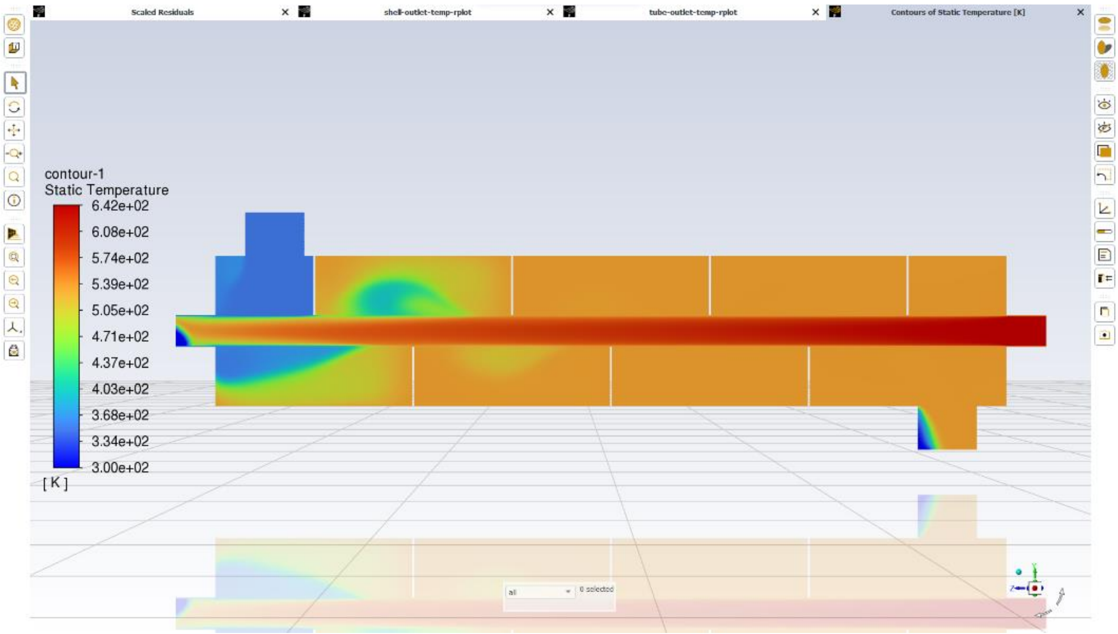

Fig. 3 Contour of static temperature of model A in a mid-plane

8. RESULTS OF MODEL B

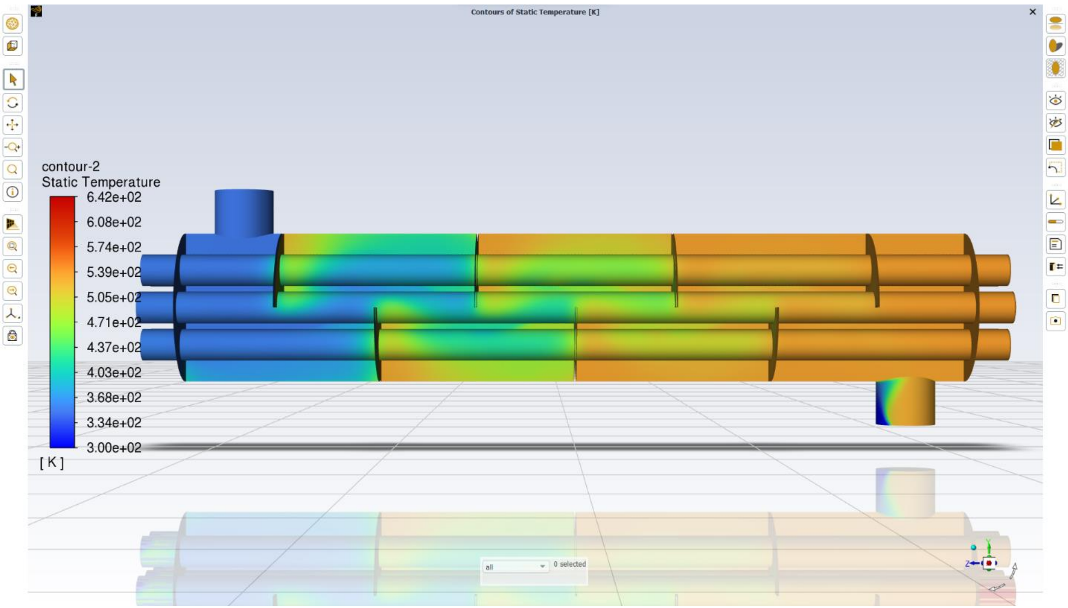

Fig. 5 Contour of static temperature of model A

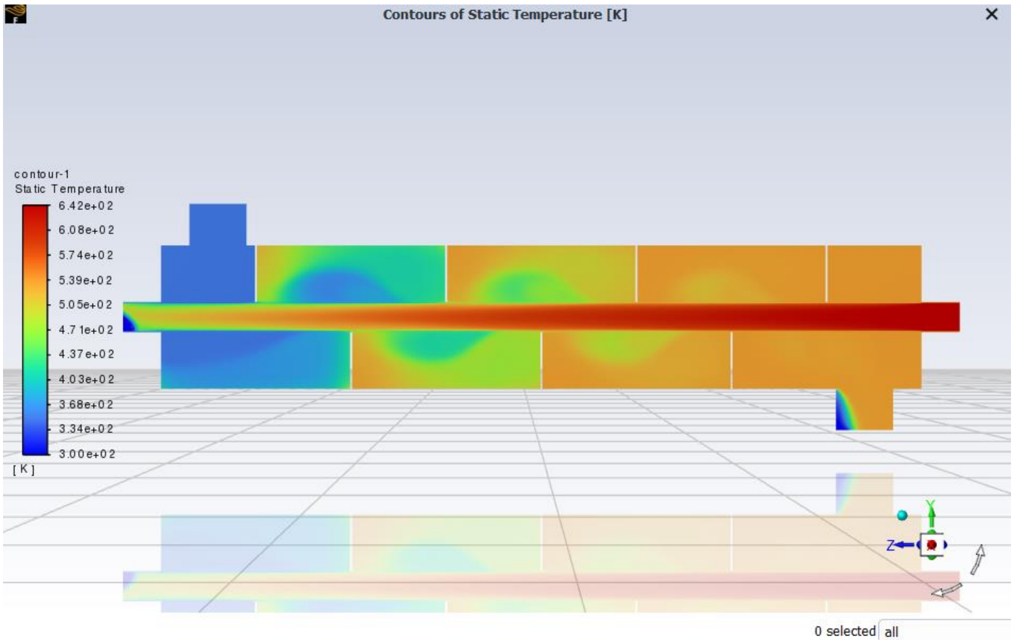

Fig. 6 Contour of static temperature of model B in a mid-plane

9. RESULT TABLE

Standard EGR cooler (MODEL A)	
Shell inlet temp.	353 K
Shell outlet temp	481 K
Tube inlet temp.	642 K
Tube outlet temp	371 K
Overall Heat transfer (Q)	304.9 W

Nano-coated EGR cooler (MODEL B)	
Shell inlet temp.	353 K
Shell outlet temp	467 K
Tube inlet temp.	624 K
Tube outlet temp	360 K
Overall Heat transfer(Q)	327.15 W

10. CONCLUSION

This research project focused on computational simulations of an Exhaust Gas Recirculation (EGR) cooler, comparing a standard EGR cooler with one featuring nano-coated tubes made of nickel chromium. The aim was to assess the heat transfer capacity and efficiency of the nano-coated EGR cooler. The hypothesis that the nano-coated tubes would improve effectiveness was proven true. The heat transfer rate of the nano-coated EGR cooler was higher, attributed to enhanced heat capacity and changes in surface area due to nanoparticles. Nickel chromium nanoparticles yielded favorable results, but alternative nanoparticles like Magnesium Zirconium Oxide or Al2O3-SiO4 could be considered. Nanoparticle coating eliminates fouling issues and improves corrosion resistance, benefiting durability. The improved EGR cooler design shows promise for implementation in commercial vehicles, reducing toxic NOx emissions and contributing to a sustainable future. In conclusion, this research demonstrates the enhanced heat transfer capabilities of nano-coated EGR coolers, supporting their use for improved efficiency and performance in emission control technologies.

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