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Research Paper

Numerical simulation of cooling performance of an exhaust gas recirculation (EGR) cooler using nano-fluids

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ABSTRACT

A numerical model is developed to predict the performance of an exhaust gas recirculation (EGR) cooler using nanofluid as the coolant. The model accounts for turbulent flow of coolant and hot smokes on an integrated computational domain. Thermal and hydrodynamic behavior of four nanofluids comprising water as the base fluid and SiO_2, TiO_2, Al_2O_3 and Cu nanoparticles, were compared over a wide range of Reynolds numbers and various particle concentrations. The accuracy of predictions was verified by experimental data available in the literature. The $Al_2O_3 - water$ nanofluid was found to provide the greatest heat transfer enhancement. Quantitatively, $Al_2O_3 - water$ nanofluid with a volume fraction of 5% and Reynolds number of 5000 improves the heat transfer coefficient by about 16% compared to pure water. However, it was found that the heat transfer enhancement was achieved at the expense of increased pressure drop due to greater viscosity of nanofluids compared to the base fluid. It was also found that the effectiveness of nanofluids in improving the heat transfer rate decreases as the Reynolds number increase.

1. Introduction

Emissions form internal combustion engines have a major role in environmental pollution. Engine exhaust gases release many dangerous pollutants to the atmosphere including nitrogen oxide (NOx) which has carcinogenic effects. Exhaust gas recirculation (EGR) coolers are heat exchangers that reduce the NOx emission by decreasing the temperature of the hot exhaust recirculated gases. The schematic diagram of an EGR cooler is depicted in Fig. 1. As shown in the figure, hot engine exhaust smokes run through the tubes and the coolant flows in the shell side in an arbitrary direction. After cooling process, a portion of gases recirculates to the combustion chamber and its temperature decreases. Therefore, the generation of NO_x diminishes due to the low temperature of the combustion gases [1]. In other methods, additional fuel is injected into the combustion chamber in order to achieve a richer mixture that results in smaller temperature rise and NO_x generation without loss of power. However, this approach, increases emission of CO and CO_2 and also increases the engine fuel consumption [2]. Temperature reduction of exhaust gases also helps to prevent the melting of catalyst coating which traps soot and reduces harmful emissions from diesel exhausts.

More efficient coolants like nanofluids, can increase the efficiency of cooling process, and allow for the use of smaller heat exchangers. Nanofluids with metallic particles have been considered as candidate heat transfer fluids with superior heat transfer [3]. Over the past few years, many theoretical and experimental studies have been conducted on convection heat transfer of nanofluids in laminar and turbulent flow regimes. Pak and Cho [4] found that increasing nanoparticle concentration led to improved heat transfer coefficients. Xuan and Li [5] presented a correlation for Nusselt number as a function of particle concentration. Besides experimental studies, numerical simulations have been employed to analyze the heat transfer behavior of nanofluids [6–11]. Nanofluids flow can be modeled using two different approaches. In the first approach, nanofluids are considered as a composition of two separate phases including base fluid and nanoparticles. Therefore it is possible to study the role of each phase in the heat transfer process. In the second approach, the mixture of the base fluid and nanoparticles is considered as a single phase fluid with effective thermophysical properties. It should be noted that in the second approach both phases are assumed to be in thermal equilibrium and share the same flow field. The simplicity and the less computational cost associated with the

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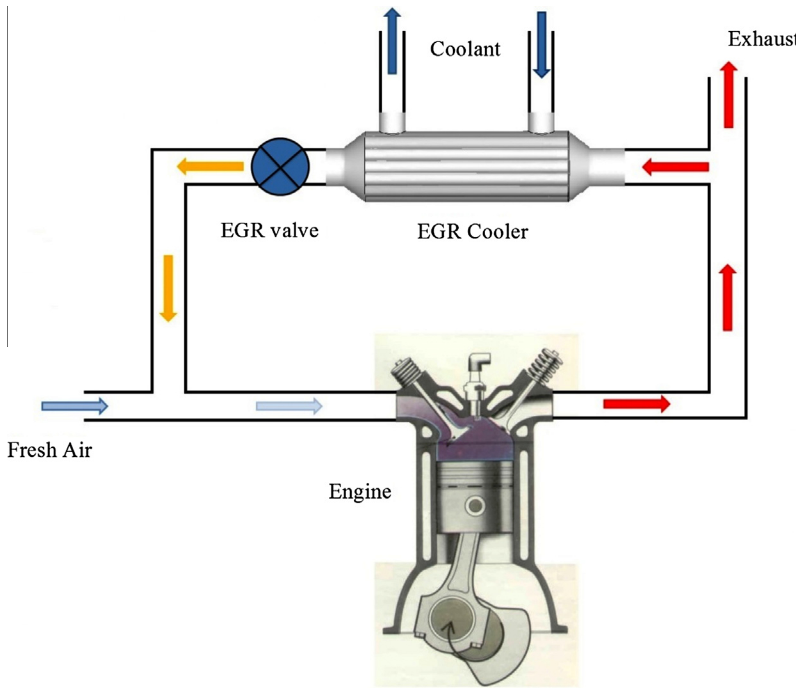

Fig. 1. Schematic diagram for the EGR cooler performance.

latter approach come with the penalty of less accurate predictions compared to the former approach. Behzadmehr et al. [12] performed a two-phase simulation of turbulent flow of nanofluids in tube using mixture model. Results of the other two-phase simulations proved the superiority of thermal properties of nanofluids in comparison with the base fluids [13–15]. Furthermore, Bianco et al. [16] showed that at high Reynolds number and low nanoparticle concentration, single phase simulations have acceptable accuracy in nanofluids simulations. Several studies investigated the efficiency of nanofluids as a coolant in heat exchangers. The results suggested that in industrial heat exchangers, especially in turbulent flows, substituting traditional fluids by nanofluids does not provide any advantage [17]. The outstanding property of nanofluids made the authors to investigate the effect of substitution of these fluids in EGR coolers. For example Kim et al. [18] considered the effect of carbon nanofluid on the cooling performance of an EGR Cooler. They found a little improvement in the cooling performance of nanofluid than that of water.

In this study, nanofluids with different particle concentrations at various Reynolds numbers are investigated numerically for use as heat transfer fluid of an EGR cooler. First, both the two phase mixture model and single phase model are used for the simulation of nanofluid flow in a circular tube with uniform heat flux on the wall. The Nusselt numbers obtained using both models are compared at different Reynolds numbers for various tube wall temperatures. The proposed numerical model of an EGR cooler is validated by comparison with experimental data related to a double pipe heat exchanger. Finally, the performance of nanofluids coolants is studied by a 3D numerical model (both exhaust gases and coolant side) of an EGR cooler.

2. Mathematical modeling

As previously noted, nanofluids are categorized as two phase fluids. However, it has been shown that in some special conditions such as turbulent flow or dilute mixture, single phase models perform well in thermal and hydrodynamic predictions [16].

2.1. Governing equation

Steady state, incompressible, turbulent, two phase and single phase flow are considered in the present study. The governing equations which represent the mathematical description of single phase and mixture model are listed below [16]. Continuity equations for single phase and two phase models are shown in Eqs. (1) and (2), respectively.

$$\nabla \cdot (\rho_m \vec{V}) = 0 \qquad \textit{Single phase} \tag{1}$$

$$\nabla \cdot (\rho_m \vec{V}_m) = 0 \qquad \textit{mixture} \tag{2}$$

where ρ and V are density and velocity, respectively, and subscript m is related to the mixture. Eqs. (3) and (4) are the conservation of momentum and energy for single phase whereas Eqs. (5) and (6) are related to two-phase simulations. In these equations, p, T and φ are pressure and temperature of fluid and particle volume concentration respectively and k relates to the k-th phase in the mixture. Also, c_p is the specific heat and λ refers to the thermal conductivity of the fluid. In addition, υ_t is turbulent viscosity and H is enthalpy of fluid in the energy equations.

$$\nabla \cdot (\rho_m \vec{V}\,\vec{V}) = -\nabla p + \nabla \cdot (\tau - \tau_t) \qquad \textit{Single phase} \tag{3}$$

$$\nabla \cdot (\rho \vec{V} c_p T) = \nabla \cdot (\lambda \nabla T - c_p \rho_m \bar{\upsilon}_t) \qquad \textit{Single phase} \tag{4}$$

$$\nabla \cdot (\rho_m \vec{V}_m \vec{V}_m) = -\nabla p_m + \nabla \cdot (\tau - \tau_t) + \nabla \cdot \left(\sum_{k=1}^{n} \varphi_k \rho_k \vec{V}_{dr,k} \vec{V}_{dr,k} \right) \qquad \textit{mixture} \tag{5}$$

$$\nabla \cdot \left(\sum_{k=1}^{n} \varphi_k \vec{V}_k (\rho_k H_k + p) \right) = \nabla \cdot (\lambda \nabla T - c_p \rho_m \bar{\upsilon}_t) \qquad \textit{mixture} \tag{6}$$

It should be noted that $V_{dr,k}$ in Eq. (5) is drift velocity for the nanoparticles (secondary phase of k) that is: