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MODELING FOULING LAYER GROWTH IN EGR HEAT EXCHANGERS

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ABSTRACT

To meet strict emissions standards vehicle manufacturers utilized Exhaust Gas Recirculation (EGR), an efficient method of reducing nitrogen oxide (NOx) emissions. In this process, a small amount of exhaust is diverted into a cooler where its temperature is reduced before being re-introduced into engine cylinders along with fresh air. Fouling of these coolers is a significant issue as the large concentrations of particulate matter and unburned hydrocarbons in the exhaust can cause rapid formation of a fouling layer along the cooler walls. This fouling layer acts as an insulator between the cool wall and hot gasses, reducing the effectiveness of the heat exchanger (Abd-Elhady et al., 2011). A computer model has been developed in order to better understand the physical mechanisms driving the fouling layer formation and to explore methods of mitigating this process. Our model uses four coupled methods to model the fluid flow, heat transfer, particle motion and fouling layer growth. The fluid flow is modeled using the lattice Boltzmann method (LBM). The LBM is a mesoscopic method which uses the discrete Boltzmann equation to simulate flow of a Newtonian fluid instead of directly solving the Navier-Stokes equations (Succi, 2001; Ladd and Verberg, 2001; Aidun and Clausen, 2010). The method uses a fixed square lattice and simple boundary conditions, which allow for modeling of complex geometries and eliminate the need for re-meshing with moving boundaries. Additionally, the spatial locality of the method make is relatively simple to implement and highly parallelizable (Chen and Doolen, 1998). Heat transfer was simulated using an implicit finite-differences thermal model. This method was used because of its simple implementation and computational efficiency (Ozisik, 1994). The particle motion was simulated using a Brownian dynamics model. To include the effect of thermophoresis, we included a thermophoretic velocity component to the advection term in the model. A sticking probability model was incorporated for the wall boundary condition, which used the velocity and material properties of a particle as well as properties of the wall to determine if the particle rebounds or deposits when it impacts the wall (Dahneke, 1971). Additionally, in order to simulate the effects of the wall shear stress, a shear removal model was implemented to re-entrain particles into the flow when they experience sufficient shear stress at their deposit location. A custom fouling layer model (FLM) was developed and implemented to simulate the growth of the layer and its effects on the system. The FLM shifted the location of the surfaces defining the fluid-solid interface inward into the channel to simulate the growth of the fouling layer. Furthermore it altered the thermal conductivities used in the thermal model and the material properties used in the Brownian dynamics model to simulate the effects of the layer on the heat transfer and particle deposition occurring in the system. This software was programmed in C++ with the majority of the methods implemented using the OpenCL framework allowing for the use of GPUs as computational accelerators. The utilization of GPU accelerators has allowed for a greater than ten-fold increase in code execution speed.

We have begun using this model to investigate the ability of wavy walled channel geometries to mitigate the development of the fouling layer. The left image in Fig. 1 shows the layer growth in a channel with $A = a/h = 0.5$ and $L = l/h = 4$ and $P = h^3 p_x/(3\rho\nu^2) = 2500$, where p_x is the pressure gradient driving

the flow and ρ and ν are the density and viscosity of the fluid. It can be seen here that the deposit layer is thickest near the front side of the top and bottom peaks in the wall. This is a result of these locations having the largest temperature gradients leading to high thermophoretic velocities. An additional area of larger than average thickness is slightly beyond centers of the peaks. Although the thermal gradients at this location are not as large as those on the opposite side of the peak, this is the location of a separation point leading to minimal wall shear stresses. The small shear stresses are not only unable to shear deposited particles from the wall, but are also indicative of negligible fluid velocities which are unable to impart enough kinetic energy to the particle for it to rebound when impacting the surface. As the fouling layer grows, its high porosity results in the layer acting like an insulator reducing the rate of heat removal from the fluid (Lance et al., 2009). The right plot in Fig. 1 provides shows the Nusselt number and area of the deposit layer over the course of the simulation. In this plot, *T* is the length of the simulation, Nu is the Nusselt number and percent area indicates the percent of the total channel area filled by the deposit layer. Here we see that as the area of the deposit layer increases, Nu decreases indicating a reduction in the rate of heat transfer. This reduction in the heat transfer along the channel due to fouling is a symptom of all EGR heat exchangers. It is our goal to use this newly developed model to investigate a wide range of parameters in order to mitigate the growth of the fouling layer and therefore extend the lifespan of heat exchangers used in EGR systems.

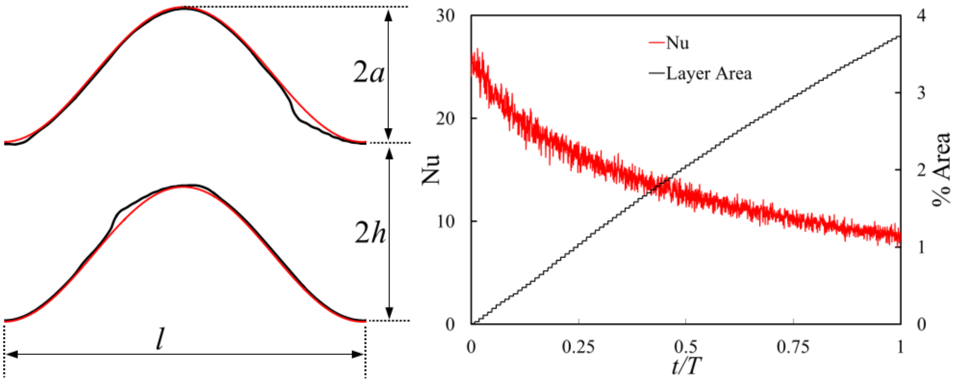

Figure 1. Fouling layer growth along a single period of a wavy walled channel (left) and the temporal distribution of Nusselt number and area of the fouling layer (right).

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