International Journal of Thermal Sciences 112 (2017) 118–128

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Turbulence induced structures in Exhaust Gas Recirculation coolers to enhance thermal performance

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ARTICLE INFO

Article history:
Received 21 February 2016
Received in revised form
5 October 2016
Accepted 5 October 2016
Available online 14 October 2016

Keywords:
Thermal performance
Exhaust gas recirculation coolers
Structured surfaces
Soot deposition

ABSTRACT

While the utilization of Exhaust Gas Recirculation (EGR) coolers in diesel driven cars gathers pace, the degradation of the thermal performance of EGR coolers due to soot deposition becomes a matter of much concern. In-situ change of surface structure would potentially be a promising approach to stem the deposition process by changing local shear stresses for the same inlet exhaust gas velocity. The present study focuses on the deposition of soot particles as primary precursors in four structurally different EGR coolers. The investigated surfaces included grooved and straight/inclined ribbed plates as well as smooth flat plate for the sake of comparison. The experimental results showed that the ribbed plates particularly the straight ribbed plate improved the thermal performance of the EGR cooler by approximately 10% while the deposition rate reduced by 9% compared to the smooth flat plate. More importantly, the orientation of ribs with respect to the direction of gas inlet flow had a profound impact on the thermal performance due to the variation in the flow stream structure and its turbulence level. Similar results were not obtained for the grooved surface, due to rapid soot deposition of grooves.

1. Introduction

Reduced NO_x emission in diesel (CI) engines through the utilization of Exhaust Gas Recirculation (EGR) systems has been proven to be one of the most promising technologies to meet the environmental regulations [1–3]. This can be done internally by returning directly a portion of the exhaust gas to the combustion chamber or externally as an efficient way through cooling down the exhaust gas across an EGR cooler before returning it to the combustion chamber, i.e. cylinder. As for the latter, the efficiency may though be compromised due to the build-up of the deposit layer in the gas-side flow paths of the cooler which may mainly be a mixture of soot particles and unburned hydrocarbons causing a thermally insulating layer [4].

The deposition in the EGR cooler could lead to several drawbacks such as; i) deterioration of its thermal performance as a result of deteriorated overall heat transfer coefficient, ii) increased pressure drop that could have a detrimental impact on engine efficiency, and iii) operational failure [4–6]. Many parameters would influence the process of soot deposition, i.e. i) physical/chemical properties in terms of nature and size of the particles and their composition and concentration, ii) operating conditions in terms of exhaust gas flow velocity and temperatures of inlet exhaust gases and cooling working fluid; iii) surface properties in terms of shape, texture, and surface energy and finally vi) particle-particle cohesion forces. To combat fouling, among other solutions, there are two approaches that are gaining increased attention namely i) change of surface properties to reduce the rate of deposition due to change of surface energy [7], and ii) modification of the geometry of EGR coolers with the aim of enhancing the removal rate of deposition layer through the improvement of the wall shear stress causing higher turbulence mixing [4,8–10]. These approaches are known as environmentally-friendly since the requirement for the use of usually detrimental anti-fouling agents or local burn of deposit layer in the EGR cooler would be minimized.

Ref. [11] investigated experimentally different EGR cooler geometries, i.e. shell-and-tube heat exchanger and plate-fin heat exchanger. They concluded that the plate-and-fin heat exchangers EGR cooler turned out to be more efficient than shell-and-tube heat exchangers in terms of thermal effectiveness. This finding was consistent with that of [12] who showed that EGR coolers with

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.10.005
1290-0729/

higher heat transfer surface area are less sensitive to the impact of fouling on thermal effectiveness. Similarly [13], found that the utilization of corrugated tubes EGR cooler would decrease the loss in thermal effectiveness compared to plain tubes of the same size. They concluded that corrugations would develop a secondary flow that could break the boundary layer and consequently increase the flow velocity close to the tube wall. Malayeri et al. [4] also showed that the presence of spiral grooves in corrugated cooler initially helped to increase local shear forces. Nevertheless, their advantages deteriorated as soon as the grooves were fouled by soot particles. Most recently [9], simulated various structurally different surfaces and found that shear forces which are required to increase the removal rate can increase up to 350% compared to that on the smooth flat plate under the same operating conditions, i.e. a given inlet gas velocity. Moreover Kim et al. [11], found that heat transfer effectiveness of the stack-type EGR cooler is 25–50% higher than that of the shell & tube type due to increased surface area and a better mixing of the exhaust gas flow.

Overall, surface modification in terms of protuberances can be considered as passive heat transfer augmentation method which would develop boundary layers or stream fluctuations, creating vortices and flow instability or turbulence intensification. As for the utilization of such surfaces Mohammadi and Malayeri [9] proposed that the following criteria should be considered in order to enhance wall shear stresses:

- Increased flow instabilities or abrupt change of flow path for increased average wall shear stress.
- Uniform distribution of wall shear stress and minimization of flow dead-zones. The latter, if existed, would result in intensified deposition.
- Geometrical changes should be done carefully to minimize the ineffective heat transfer area.
- Any geometrical change should result in minimum increase of pressure drop across the cooler in order to meet engine operating limitations.

In this study, a set of experiments was performed to demonstrate the possibility of modifying EGR cooler geometries by introducing turbulence induced structures. The primary aim was to increase the flow instabilities and enhance the wall shear stress of EGR coolers for the same inlet gas velocity. To do so, four different geometries were constructed for installation in a rectangular channel of an EGR cooler which were 1) smooth flat, 2) grooved, 3) straight ribbed and 4) inclined ribbed plates. The smooth flat plate was also intended to serve as baseline surface to compare the performance of various structurally different surfaces. The selection of these four geometries was basically based on the promising theoretical results obtained by Ref. [9].

2. EGR modified geometry surfaces

The EGR cooler investigated in this study was a simple shell type heat exchanger, where the hot exhaust gases passed through a rectangular channel while counter-flow cooling water was passing through the shell side. The channel had a rectangular shape with a cross sectional area of 30 mm width, and of 8.5 mm height, with a maximum length of 210 mm as depicted in Fig. 1. The rectangular shape allowed accommodation of different structured surfaces.

To investigate the influence of different types of turbulence-induced structured surfaces on soot deposition, the rectangular cooler was designed such to have a removable stainless steel 304 flat plate of thickness of 0.5 mm at its bottom side with the dimensions of 45 mm × 210 mm. The modified EGR surfaces included:

- Smooth flat plate;
- Ribbed plate with a rectangular ribbed shape of dimensions of 26 × 3 mm, and thickness of 1 mm. The ratio of rib height to channel height is 0.3529. Two ribbed plate configurations were selected with respect to its angle of attack (α) which defines as the angle between a reference line on a body and the oncoming flow. Two different types of ribbed surfaces were also:
  - Straight ribbed plate: The ribs were arranged vertically with respect to inlet flow direction with an angle of attack (AoA) of 90°;
  - Inclined ribbed plate: The ribs were arranged with respect to inlet flow direction where the angle of attack was 135°.
- Grooved plate-EGR cooler with 30° V-shape structure of dimension of 0.2 × 0.2 mm.

The turbulence-induced surfaces were fixed to the cooler itself by utilizing a gasket and bolts. It is worth mentioning that the turbulence-induced surfaces, e.g. ribbed plates created an additional increase to the effective heat transfer surface area by approximately 10% compared to that of smooth flat plate. The geometrical specifications of the structured surfaces are fully described in Table 1.

3. Experimental apparatus and procedure

The experimental test facility included a soot generator to provide live soot particles similar to those of exhaust gases in diesel engines with the advantage of individually controlling the intake conditions for the EGR heat exchanger, e.g. exhaust gas flow rate, exhaust gas composition, exhaust gas and coolant temperatures. Full description of the experimental setup has been reported by Ref. [14] and only a brief description is provided here for the sake of brevity. The experimental setup, as shown in Fig. 1, consisted of a soot generator [1], gas particle heater [2 and 3] and EGR cooler [4] and an exhaust system including gas analyzer facilities.

The main functionality of the soot generator was to produce the particulate matter of the exhaust gases that simulated those produced in a heavy-duty vehicle through the burn of a rich mixture of ethylene (C_2H_4) and air. The range of the generated soot particle diameter was between 10 and 300 nm with an average value of 130 nm at a constant mass flow rate of about 2 g/h. The experimental apparatus was designed to perform EGR fouling experiments at accelerated conditions in a short period of time through: i) changing the mass flow rate of exhaust gas by controlling the amount of the injected air mass flow rate, and ii) controlling the exhaust gas temperature before entering the EGR cooler by adjusting the temperatures of the tape heater and the tube furnace. The generated exhaust gas firstly passed through a bypass line until achieving the steady-state conditions where the temperature of both of the exhaust gas and the cooling water remained constant. Afterwards, the exhaust gas had to be redirected to the EGR cooler (tube side), while a counter-flow deionized water flowed in the shell side with a possibility to control the cooling temperature between 25 and 95 °C by using a thermostat.

Table 2 provides the range of operating conditions that were attempted in this experimental study. It should be noted that in heavy duty diesel engines, the exhaust gas velocity usually ranges from 6 to 30 m/s though the engine tends to work at higher loads close to the upper limit of exhaust gas velocity [14]. In addition, the cooling medium, here water, for EGR coolers is mainly supplied from car radiator with a temperature of 80 °C which is being considered as baseline cooling temperature in practice [14,15]. Lower cooling temperatures are favorable for further reduction of NOx but at the expense of possibly higher thermophoretic velocities which would, in turn, lead to more soot deposition as a result