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Metal foams as gas coolers for exhaust gas recirculation systems subjected to particulate fouling

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ABSTRACT

This paper presents experimental results indicating the benefits and challenges associated with the use of metal foams as Exhaust Gas Recirculation (EGR) coolers. Fouling of such heat exchangers is a critical issue and, as such, special attention has been paid to address this very issue in the present study where a soot generator has been employed to simulate the engine running condition. Effects of aluminium foam PPI and height as well as gas velocity are investigated. It has been noted that proper design of the foam can lead to significantly higher heat transfer rate and reasonable pressure drop compared to no-foam cases. More interestingly, it is demonstrated that the foams can be cleaned easily without relying on expensive cleaning techniques. Using simple brush-cleaning, the foams can be reused as EGR gas coolers with a performance penalty of only 17% (compared to a new or clean foam).

1. Introduction

Modern diesel engines are equipped with EGR (exhaust gas recirculation) coolers to reduce NO_x emissions. The system, known as external EGR, works by recirculating a portion of the exhaust gases into the combustion chamber after cooling them in an EGR cooler. Abd-Elhady et al. [1,2] demonstrated that cooled EGR is favourable as it showed a greater NO_x reduction compared to the hot EGR counterparts. The EGR cooler removes the heat from the exhaust gas which contains dominantly particulate matter consisting of a soluble organic fraction (SOF), sulfates (mostly carbon) and solid fraction commonly referred to as soot which makes up the core of the particulate matter. To some extent, the particulate matter will deposit on the walls of the EGR cooler leading to formation of a deposit layer which in turn results in significant deterioration of the cooler thermal effectiveness and increased pressure drop across the cooler. With EGR flow driven by the exhaust-intake manifold pressure difference, an increase in flow resistance across the EGR cooler would compromise the desired EGR rate. A major drawback of utilising EGR coolers is the excessive production of particulate matter. Agrawal et al. [3] showed that improper (very low) combustion temperature would lead to incomplete combustion process and more soot particles are generated. Besides, a significant pressure drop results in decreased fuel efficiency due to increased pumping power while the exit gas temperature will exceed that of the initial EGR cooler design, thus reducing the EGR efficiency [4]. Hence, one needs to understand the transport and deposition mechanisms of soot particles in EGR coolers that lead to deposition. These are primarily thermophoresis (particle motion in the presence of a temperature gradient), eddy diffusion, turbulent impaction and gravitational drift.

Not all the particles that come into contact with the surface will deposit. Kern and Seaton [5] proposed a model of the deposit removal by defining an average removal rate caused by shearing action of the stream at the surface. Deposits are sheared off in chunks rather than individual particle removals. The average removal rate over the whole tube is roughly proportional to the shear stress and thickness of the deposit layer. According to visualization tests conducted by Yung et al. [6], fluid drag force is the dominant re-entrainment force and when it exceeds the adhesion force for small particles, removal occurs. Abd-Elhady et al. [1] reported that particulate fouling can profoundly be suppressed if the gas velocity is above a critical value defined as the bulk velocity above which rolling of the deposited particles occurs. Warey et al. [7] offered a 1-D model for soot particle deposition, particle removal and condensation of six (HC) species between C15–C24 alkanes in a circular pipe at constant wall temperature in the turbulent flow regime.

Most of the above studies are focused on circular pipes mainly because the first EGR cooler design was a shell and tube one which later evolved into corrugated tubes, and rectangular corrugated

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tubes with housing to optimize the EGR cooler volume and thermal efficiency to match EURO 5 standard and later, the designs considered internal fins to be attached to different geometries e.g. tubes or plates to meet the requirements of EURO 6 standard [3].

This paper, however, investigates a different class of heat exchangers being open cell metal foams; interconnected pores formed by bone-like ligaments. Foams are characterized by their pore number density PPI (pore per inch), porosity as well as ligament and pore diameter. Such heat exchangers offer significantly higher compactness and heat transfer compared to conventional heat exchangers; see for instance [8–13]. However, fouling of metal foam heat exchangers is not well understood yet. Most of the past studies into the topic are conducted numerically [14–17] with no experimental data was available for validation. Hooman et al. [18] offered a theoretical model which assumed uniform deposition in the pores and on the ligament surfaces; again with no experimental data to compare the results with. Hence, the aim of this paper is to fill this gap in the literature. This work presents experimental results pertinent to fouling of a metal foam heat exchanger applied as an EGR cooler.

2. Experiments

The test rig that has been used for the current EGR experiments is described by Abd-Elhady et al. [2] and is designed to flow hot gas through an EGR cooler. Additional Eicosane [$C_{20}H_{42}$], water as well as soot can be injected (at controlled rates) to simulate diesel exhaust gas with different compounds [19,20]. The gas flow rate is controlled by a flow controller and can be varied from 0.1 slm up to 500 slm. Soot is added by oxidization of ethylene in a special burner. Nitrogen is used to make sure that the flame keeps burning homogeneously with no jittering. The particle size is analysed using DMS500 Fast Particulate Analyser to note that the mean particle size is 130 nm. All experiments were conducted with a soot concentration of 90–100 mg/m^3. Once the soot is generated, preheated (using tape heater) then clean air is injected. Gas inlet pressure and temperature are measured using a pressure transducer and K-type thermocouples, respectively. The test set up is schematically shown in Fig. 1.

Parameters are selected to represent engine conditions. For instance, 250 °C inlet temperature represents a slow driving vehicle at about 50–60 km/h or low engine speed. At full throttle, the exhaust gas of a diesel vehicle has a soot concentration of about 80 mg/m^3 which is close to the soot concentration attempted in the present study. The counter-current heat exchanger, illustrated in Fig. 2, has dimensions similar to those currently used in EGR gas coolers. It is 195 mm long in the stream-wise direction and has a rectangular cross section with 8 mm height extended 30 mm in the transverse direction. Foam samples occupy either 3 mm or 4 mm of the height allowing a portion of the hot gas to bypass the foam. Cooling water flows outside the rectangular section which its flow rate has always been kept sufficiently high to lead to only 0.5 °C rise in the water temperature (at the outlet) leading to almost isothermal cooling condition. Two different PPI values for aluminium foams are tested, namely 20 and 40 PPI. The samples with 40 PPI have smaller pore sizes and, with the same foam height, will have almost twice as many pores in the normal direction compared to those of 20 PPI. A total of four foam samples were tested all made of aluminium and glued (using a thermal paste) to a 0.5 mm thick stainless steel plate which separates the hot gas from cooling water. The samples were provided by Bekaert and are similar to those used in [14]. Benchmark tests were conducted with no foam, i.e. with only a (0.5 mm thick) stainless steel flat plate separating the two fluid streams. All samples were initially tested under no-fouling conditions, i.e. with the soot generator turned off with only hot air transferring heat to the cooling water. Tests were repeated three times to make sure about repeatability and an uncertainty analysis was conducted to realize that the

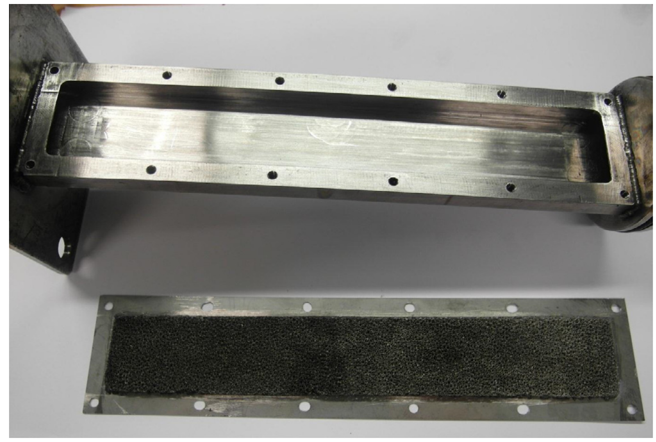

Fig. 2. The EGR gas cooler used in this study.

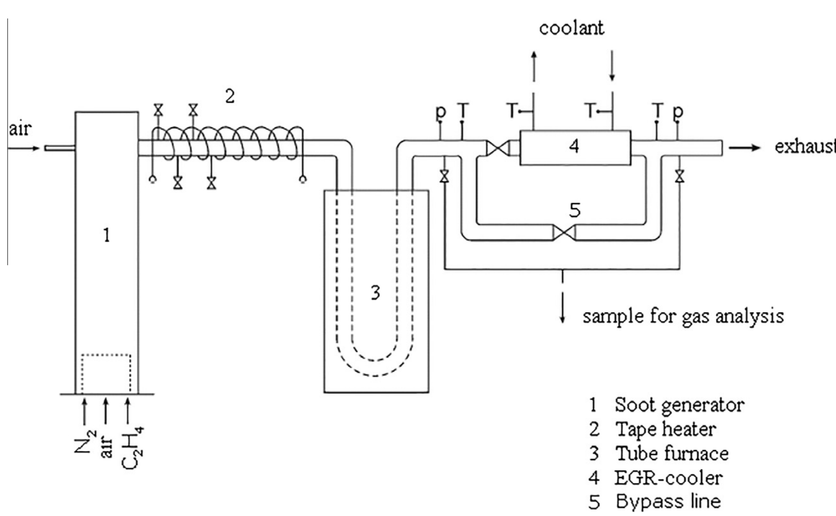

Fig. 1. Schematic description of the test set up.