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Research Paper

Design, simulation, and testing of a novel micro-channel heat exchanger for natural gas cooling in automotive applications

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HIGHLIGHTS

- A microchannel heat exchanger with two heat sinks was designed for cooling CNG.
- An extrapolation method for pressure drop gave significant computational savings.
- Pin structures in the design provided even flow distribution into microchannels.
- A symmetry method used for heat transfer greatly reduced the computational load.

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ABSTRACT

Micro-channel heat exchangers offer potential for a highly compact solution in heat transfer applications that have space limitations. Mobile applications such as automotive vehicles are one such area. This work presents the design, modeling, simulation and testing of a two-region micro-channel heat exchanger, employing both engine coolant and R134a, for use in an engine that compresses natural gas for on-board refueling at pressures up to 250 bar. The novel design of the micro-channel heat exchanger is presented. Numerical simulations were performed using ANSYS Fluent utilizing extrapolation techniques to estimate the pressure drop as a function of flow rate and symmetry methods to investigate heat transfer. Pressure drop was determined experimentally, and heat transfer was investigated through system tests employing the novel engine. Experimental results showed good comparison with corresponding numerical simulations which demonstrated the validity of the applied extrapolation and symmetry methods, enabling considerable reduction in computational cost. The pressure drop, flow distribution, and heat transfer characteristics of the heat exchanger are discussed.

1. Introduction

Natural gas is emerging as a promising alternative to liquid hydrocarbon fuels for transportation applications as a result of production increases from directional drilling and hydraulic fracturing, lower cost than gasoline, reduced reliance on imported oil, and environmental benefits [1]. However, a key challenge to overcome is the lack of refueling infrastructure. To this end, a novel bi-modal engine has been developed that allows on-board refueling of natural gas (NG) [2,3]. Engine development, implementation and packaging are the focus of current efforts [4]. Utilizing cylinder de-activation, some cylinders of a multi-cylinder internal combustion (IC) engine perform two stages of natural gas compression, while an external engine driven compressor performs an additional third stage compression, all with the engine working near idle speed. The process is being developed with the aim of filling an 11.5 gasoline gallon equivalent (GGE) tank to about 250 bar (3600 psi) in less than an hour using a low pressure (~0.25 psi) residential natural gas supply.

The compression process results in considerable heating, which is undesirable [2,3,5] because of increased specific volume necessitating increased work input, potential damage to engine seals and valving, changes in engine performance resulting from fuel preheating, and thermal cooking of oil in the gas stream [6]. Micro-channel heat exchanger technologies are emerging as a promising cooling solution offering high performance, compact size and lower pressure drops compared to conventional cooling technologies [7]. A micro-channel heat exchanger test performed by Cetegen [8,9] demonstrated a heat transfer coefficient of

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130,000 W/m^2 K using the non-aqueous refrigerant HFE-7100. The decreased dimensions of micro-channels result in more compact heat exchangers and higher heat transfer coefficients as a result of increased surface area per unit volume. Micro-channel heat exchangers may achieve surface area per unit volume as high as 1500 m^2/m^3 [10]. Micro-channels have been successfully applied in automotive air conditioning systems [11], fuel cells [12], and microelectronics [13]. Automobile radiators with channels on the scale of micrometers to millimeters enable the use of less refrigerant without increasing size or weight of the refrigerant system [14]. Further development of micro-channel heat exchanger technology has been motivated by requirements of specific process conditions such as low flow rate and high operating pressures. Conventional plate type heat exchangers are typically rated to maximum pressures of 40 bar [15] and have an average area density of approximately 200 m^2/m^3 [16]. Tests of micro-channels conducted by Wu [17] applied pressures of more than 40 bar. The diffusion-bonding process typically used in the construction of micro-channel heat exchangers allows operating pressures as high as 1000 bar [18]. Therefore, the use of a micro-channel heat exchanger is especially attractive for the 3rd stage cooling in the present application given the stringent volume constraints and high operating pressures (of up to 250 bar).

This work presents details of the heat exchanger design process along with the selected heat sinks, the final configuration, and dimensions. Steady flow tests were conducted to evaluate the pressure drop in the heat exchanger pathways. Numerical simulations of the flow field were conducted using ANSYS FLUENT and findings were correlated with the steady-flow measurements. Air compression tests were carried out on an engine setup utilizing the micro-channel heat exchanger for cooling. Numerical simulations of the heat transfer process were performed and findings from experiments and simulations were correlated.

2. Heat exchanger design

2.1. Cooling requirements and heat sink configuration

The 3rd stage heat exchanger working requirements are presented in Table 1 [4].

Air, engine coolant (EC), and refrigerant (R134a) were considered as heat sinks since they are present onboard the vehicle. Atmospheric air is freely available, but would require a blower onboard the vehicle. Further, the low specific heat capacity of atmospheric air results in a large heat exchanger volume, and is thus not a viable option for this application. EC and R134a are available onboard the vehicle, in the engine cooling and air conditioning (a/c) systems respectively.

EC alone is not capable of cooling natural gas to the required exit temperature because high EC temperature (around 90 °C) is required for optimum engine combustion performance [19]. The cooling capacity of the a/c system alone is also less than the total cooling load. An energy flow model indicated that the total cooling capacity available using both the engine coolant and air-conditioning circuits was only slightly less than the total cooling load for natural gas (see Table 1) and engine cylinder heat transfer is expected to make up for this small difference [5].

Table 1
Specifications for the 3rd stage micro-channel heat exchanger.

	Unit	NG	EC	R134a
Mass flow	g/s	24.4	105	36
Inlet temperature	°C	145	80	9
Outlet temperature	°C	25	90	13
Heat load	kW	9.6	3.8	5.7

2.2. Micro-channel heat exchanger overall design

By utilizing the EC and R134a available onboard the vehicle, it appears possible to have a self-contained system for natural gas cooling employing a two-region micro-channel heat exchanger with EC in the first region and R134a in the second region. Since counter-flow plate heat exchangers with both fluids enclosed within internal passages are generally more compact than parallel flow heat exchangers and size is the biggest constraint driving the current design process, the micro-channel heat exchanger was configured as counter-flow. Fig. 1 depicts the micro-channel heat exchanger discussed in this work.

2.3. Micro-channel heat exchanger shim design

The micro-channel heat exchanger consists of a bottom plate, cover plate, and 32 pairs of shims. Each pair of shims contains a NG shim and heat sink shim as shown in Fig. 2. Stainless steel was used for its superior anti-corrosion, thermal and mechanical properties.

A novel shim design as shown in Fig. 2(a) was developed that incorporates flow paths of the two regions into a single heat sink shim. The 1st region accommodates EC flow and the 2nd region provides flow passage for R134a. The R134a and EC channel heights and widths are the same. Fig. 2(b) shows the shim design for natural gas flow. The shims contain 22 channels in the 1st region and 17 channels in the 2nd region. The design dimensions of the micro-channel heat exchanger are shown in Table 2. In this work, the layer closest to the top of the heat exchanger (where the inlet pipes enter the heat exchanger) was defined as the 1st layer, and the channels were numbered starting at the inlet and increasing in the direction of the outlet. The last channel of each region has a smaller width than the other channels.

2.4. Fabrication of the micro-channel heat exchanger

The micro-channel heat exchanger was fabricated in two steps. The individual shims were fabricated using photo-chemical etching for the pin and rib structures followed by laser machining of the through holes and perimeter. The shims, along with the cover plate and bottom plate, were then diffusion bonded in a vacuum furnace under an applied force at high temperature conditions resulting in the final device [20].

2.5. Actual dimensions of the micro-channel heat exchanger

When the heat exchanger was fabricated from the shim plates the total height of the heat exchanger decreased from 98.6 mm to 89.5 mm, while the total width of the heat exchanger increased

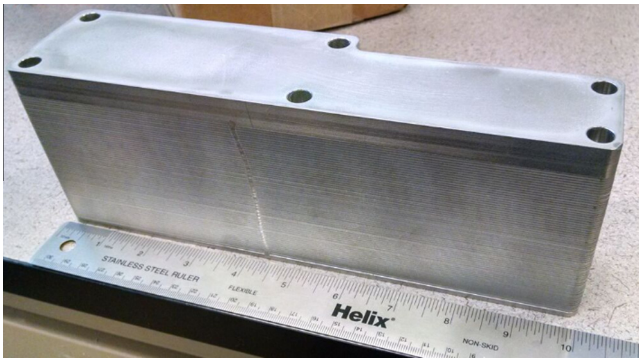

Fig. 1. Overall design of the micro-channel heat exchanger for this work.