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A Second Generation Heat Transfer Simulator for Single-Cylinder Engines to Replicate Multi-Cylinder Engine Dynamics

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Abstract: Researchers in the Powertrain Control Research Laboratory (PCRL) at the University of Wisconsin-Madison have developed single-cylinder engine transient test systems that control the instantaneous dynamic cylinder boundary conditions of these engines to replicate those in the target multi-cylinder engine performance and dynamics. The overall goal is to exploit the benefits of the single-cylinder engine, while eliminating the negative aspects of this device, and to have the single-cylinder "think" it is dynamically operating at any location within a multi-cylinder engine, with the same transient operation.

This paper describes the latest developments in controlling the heat transfer geometry and dynamics of the single-cylinder engine to meet these goals. This is a second generation heat transfer simulator (HTS2) that addresses challenges and issues raised from the experimental operation of the original HTS, and that significantly simplifies the control strategies. There is a brief introductory section explaining the overall transient test system and HTS2's role in this system, a presentation of the operational analysis of the heat transfer system, the design and construction of the HTS2, and preliminary performance results.

Keywords: Powertrain, transient testing, internal combustion engine, heat transfer, multivariable control

1. INTRODUCTION

Single-cylinder test engines (SCE) are used extensively in engine research, and sparingly in engine development, as an inexpensive and convenient way to test or evaluate new concepts or to understand in-cylinder motion or combustion. They allow good access to the cylinder for instrumentation, and in almost all cases they are a surrogate for the multi-cylinder engine (MCE) which will ultimately be used in a vehicle. However, these single-cylinder engines differ significantly in operation from their target multi-cylinder engines, in rotational dynamics, gas intake dynamics, heat transfer dynamics, dynamic coupling between cylinders, and in other areas. Charge motion within the SCE cylinder, even during the closed period differs from the MCE because of the differences in both instantaneous intake flow and momentum, and in-cylinder emission production is impacted by the differences in heat transfer. Even the heat transfer around the cylinder in the SCE is different than the MCE, and each cylinder within the MCE is different from the next. As a result, data gathered from the SCE does not necessarily represent operation of the MCE target engine, and there can be significant differences.

1.1 The Heat Transfer System

A SCE transient test system that addresses these shortcomings and replicates the MCE transient dynamics has been developed, built and tested. Several U.S. patents on various aspects of this new system have been filed and issued (Moskwa & Lahti 2004), (Moskwa, Lahti & Snyder 2006), (Moskwa, Klick Krosschell & Marty 2009). An overview of the SCE test system is shown in Figure 1. In the figure, the Intake Air Simulator (IAS) is also visible (Snyder, 2005).

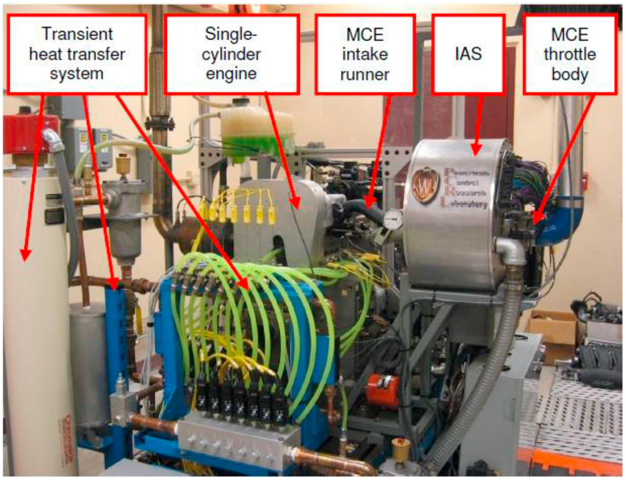

Fig. 1. Single-cylinder engine (SCE) transient test system

A subsystem of this SCE transient test system is the heat transfer system (HTS), which is the subject of this paper. To replicate the cylinder heat transfer of the MCE when using a

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SCE, a new heat transfer system must be developed that has the flexibility to simulate the heat transfer performance and details of any particular MCE cylinder. Figure 2 shows the custom HTS block that surrounds the cylinder, in order to accomplish these goals.

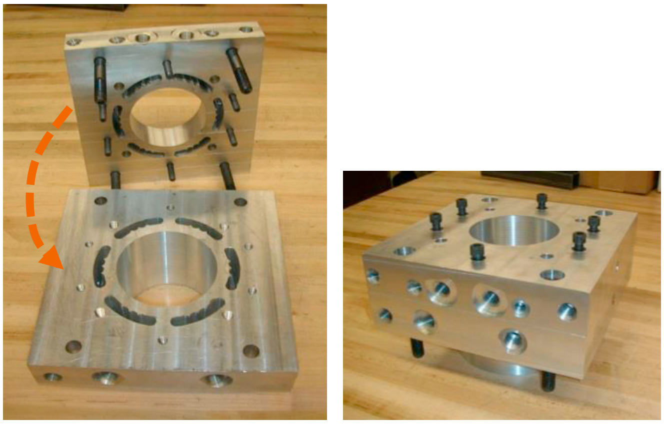

Fig. 2. Interior of block showing six coolant zones (left), and assembled exterior with coolant & thermocouple access (right)

A production cylinder liner is inserted vertically in this block, following final machining. This assembled block and passages allow the temperature and heat transfer around the circumference of the cylinder to vary, and for this distribution to be carefully controlled to represent a cylinder in a MCE.

In addition to this cylinder block, there is a heating and cooling system to individually control the heat transfer in each of the six zones shown in Figure 2, as well as a seventh zone in the cylinder head. This system of hot and cold manifolds, valves, thermocouples, and flow meters was designed to individually control both the flow and temperature in each of the seven zones, thus replicating the MCE heat transfer performance. The green tubing in Figure 1 distributes the individually controlled coolant to/from these seven zones. This paper describes a new HTS2 that allows better control of heat transfer distribution, while being significantly easier to control.

2. ANALYSIS AND CONTROL OF THE HTS

While the goal of the HTS is to accurately replicate the instantaneous cylinder heat transfer of a MCE, the *modelling goal* in this paper is to guide decisions regarding the construction and control of the HTS2. The modelling includes appropriate assumptions for a simplified cylinder model that is used to explore the basic functionality of the cooling system. These assumptions are shown, later, to be appropriate in the experimental data from this system. A basic radial heat transfer model for a single passage was found sufficiently accurate for use in the coolant system design. In the modelling process, it was assumed that the flow in each zone and the overall coolant temperature can be commanded.

The cooling liquid is a 50/50 mix of ethylene glycol and water, commonly used for the cooling system of internal combustion (IC) engines. The coolant has a freezing point of -37 °C (-34 °F) and its atmospheric boiling point is at 107 °C (225 °F). In the pressurized cooling system of an IC engine the boiling point is around 120 °C (248 °F). This is sufficiently high for the system's purposes.

2.1 Static Model

The static model was developed to estimate the attainable cylinder wall temperatures in each coolant passage. Figure 3 shows how the cylinder block is divided into six passages and how the cross sectional area is obtained. It is assumed that every segment has the same heat transfer behavior. The figure shows how the heat, q, flows from the cylinder inside through the cylinder wall to the coolant passages.

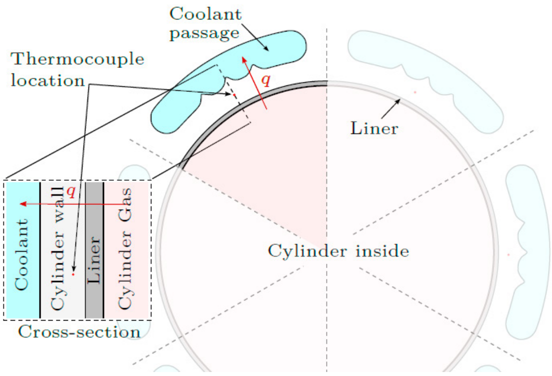

Fig. 3. Top view of the cylinder block (Bauer, 2014)

In order to develop and simplify the static model, the following assumptions were made.

(i) Since the walls are very thin, the heat transfer area between cylinder inside and cylinder wall is assumed to be the same as the area between the cylinder wall and the coolant passage.

(ii) The gas temperature and the convective heat transfer coefficient of the gas are assumed constant. They are time-averaged values over the engine cycle.

(iii) The radiation heat transfer is assumed negligible.

(iv) The effect of the environment temperature is omitted. This assumption is reasonable since the cooled part of the cylinder wall is not in contact with the surrounding air, and there is negligible direct conduction area between these two regions in this system.

(v) At the point where the wall temperature is measured the fluid has the measured flow rate and temperature. This means the local heat transfer coefficient at that point is assumed to be the same as the heat transfer coefficient before the fluid enters the cooling passage.

(vi) Circumferential heat transfer will have negligible effect on the coolant system design.

Assumption (v) was necessary because only the coolant's temperature before the passage is measured. Therefore, it is not possible to determine the actual fluid temperature at the point where the thermocouple is installed. However, with the new HTS2 (see chapter 3 of Bauer, 2014) we can compute