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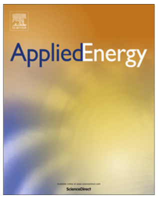

Detecting the onset of nucleate boiling in internal combustion engines

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HIGHLIGHTS

- Cooling system of an internal combustion engines equipped with an electric pump.
- Onset of nucleate boiling experimentally detected by coolant flow rate regulation.
- Different experimental techniques tested.
- Effects of coolant pressure on nucleate boiling onset investigated.

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ABSTRACT

The use of an electric pump instead of the standard crankshaft-driven one in Internal Combustion Engines, gives the possibility of controlling the coolant flow rate independently of engine speed, allowing therefore, the use of much lower coolant flow rates than usually adopted and the development of nucleate boiling flow regimes within the engine cooling system. In order to take advantage of nucleate boiling and of the associated high heat transfer coefficients, the onset of this heat transfer regime must be correctly identified. This work presents the results of an experimental campaign, which was carried out on a small displacement spark ignition engine (1.2 dm^3, 60 kW) with the aim of detecting the occurrence of nucleate boiling within the engine cooling system. The test rig was properly instrumented in order to measure coolant temperatures at engine inlet and outlet, coolant pressure at several locations in the circuit, coolant flow rate and engine metal temperatures. Operating conditions involving different coolant flow rates were selected in order to enforce both the usual single-phase heat transfer regime and nucleate boiling conditions. Several experimental quantities were analyzed with the aim of establishing the coolant flow rates ranges where the nucleate boiling occurs. The agreement in the trend of coolant temperature and pressure and engine wall temperature provides hints to identify experimentally the onset of nucleate boiling.

1. Introduction

Thermal management plays an important role for Internal Combustion Engines (ICE) performances, emissions, fuel consumption and reliability. Nowadays many works deal, in particular, with the behavior of the cooling system during the engine warm-up. As is known, in fact, high engine emissions and fuel consumption occur at low engine temperatures owing to high frictional losses and combustion inefficiency. Will et al. [1,2] estimated an increase in frictional losses amounting to 2.5 times the ones obtained under fully warmed conditions, for lubricant temperatures around 20 °C, while engine efficiency drops to about 9% after a cold start [1,3]; Samhaber et al. [4] predicted an increase of about 13.5% in fuel consumption for lubricant temperatures around 0 °C. A fast warm-up is therefore desirable and can be achieved by an optimal thermal management control strategy.

The control of the engine cooling system today is still very simple and the possibility of regulation is limited: the rotational speed of the cooling pump is imposed by the engine speed and the cooling system is designed to ensure engine reliability by providing adequate coolant flow rate under high-power conditions. Under low-load or low coolant temperature conditions, the coolant flow direction is managed by using a wax thermostatic valve, which by-passes the radiator and redirects part of the coolant to the pump, while the coolant flow rate is regulated by varying the flow resistance that is determined by the thermostatic valve. In most engine operating conditions, therefore, the coolant flow rate is higher than strictly necessary and the coolant is maintained in

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liquid phase. Brace [5], for instance, estimated that an engine is over-cooled for 95% of its operating time.

Different cooling management strategies were proposed in order to overcome the standard cooling system limitations and most of them are based on the possibility of using an electric pump, whose speed can be controlled independently of engine speed. Ap and Golm [6] proposed a reduction of the coolant flow rates by the use of a small electric water pump. Brace [5,7] proposed the use of an electric pump in cooperation with a throttle valve and developed a control strategy based on the use of empirical look-up tables; 2% improvement in bsfc was obtained. Bent [8] proposed a cooling strategy where the pump was switched on and off cyclically, in order to obtain a faster warm-up, while Gardiner [9] investigated the effects of coolant circulation rate on fuel consumption reduction during engine warm-up.

Regulation of coolant flow rates by means of electrically driven pumps, in conjunction with a proper control strategy, can be conveniently used to allow the cooling system to operate under controlled nucleate boiling flow regime [10,11], both during engine warm-up and under fully warmed conditions. The possibility of adopting new components for the cooling system of internal combustion engines and of taking advantage of the nucleate boiling regime was investigated by several researchers for decades [12–16] and is still under investigation [17]; these contribute to identify the advantages of operating under nucleate boiling: smaller coolant mass, smaller radiator, lower pump power requirements, faster warm-up time, and lower friction during the warm-up period. All these conditions allow the reduction of fuel consumption and, consequently, of CO_2 emissions [18], which is currently sought by these and other advanced internal combustion engine technologies [19,20]. In addition, a coolant pump working independently of the engine would eliminate the risk of unwanted phenomena, like after-boiling [21]. Recently, Pizzonia et al. [22] proposed and developed a control strategy which sets the coolant flow rate at much lower values than usually adopted, allowing a certain level of nucleate boiling. Under fully warmed conditions, a coolant flow rate just below that which determines nucleate boiling, ensures appropriate cooling with low coolant flow rate, still preserving engine reliability.

However, at present, the difficulty of obtaining on-board information about the heat transfer regime, which occurs under the various operating conditions, is the main obstacle to setting up a practical nucleate boiling cooling system. In order to overcome this limitation and to enable the development of such an innovative system, a deeper understanding of the behavior of a cooling system as a result of the different operating conditions is needed. At the moment, no systematic experimental analysis of Onset of Nucleate Boiling (ONB) in ICE exists.

The present work summarizes the results of an extensive experimental campaign, which was carried out at the engine test-rig, with a Spark Ignition (SI) engine properly instrumented, with the purpose to detect the occurrence of nucleate boiling and to identify the engine variables which cause nucleate boiling. Although the test rig is well instrumented, the experimental identification of nucleate boiling is not simple: the observation of vapor bubbles through transparent windows placed along the cooling circuit is not reliable, owing to the fact that in the early stages of nucleate boiling bubbles form but implode before arriving at the window; they become visible only in the fully developed stage of the phenomenon. Therefore, several experimental techniques to identify the Onset of Nucleate Boiling have been developed and are summarized in the present paper. A zero-dimensional model of the cooling system of an SI Engine, which was developed in [10] and is able to predict dynamically the occurrence and the extent of nucleate boiling flow regime, was used to help to explain better the recorded data.

2. Experimental setup

The experimental tests were carried out on a small-size four-stroke SI engine. The engine displaces about 1.2 dm^3 in four in-line cylinders with four-valve per cylinder aluminum head and about 60 kW between 5000 and 6000 rpm rated power. The standard crankshaft-driven coolant pump is substituted by a small power electric pump (127 W at 15 V, 2092 dm^3/h maximum flow rate). A schematic of the test-rig is plotted in Fig. 1.

Special attention was dedicated to the cooling circuit instrumentation (Fig. 2). A differential pressure gauge is installed at the pump ends, while the coolant pressures at engine inlet and outlet are measured with miniature piezoresistive pressure transducers, 3 kHz bandwidth. PT100-type temperature sensors are used to obtain the coolant temperatures at engine inlet and outlet. Coolant volumetric flow rate is measured at engine inlet and outlet using turbine type flowmeters, with a repeatability of ±0.05%. In addition, an optical access is also installed in the cooling circuit near the engine outlet, in order to observe the presence of bubbles in the coolant flow pattern during the experimental tests (Fig. 1). The standard radiator is immersed in a tank filled with water, which also contains the coolant expansion tank. A digital PID regulator is used to control the cool water flow rate, which is needed in the tank in order to keep engine inlet coolant temperature constant (85 °C) within a ±1 °C error band. Finally, *k*-type thermocouples are located in the cylinder block (head gasket side) and in the cylinder head at various locations, as reported in Fig. 3. The main measuring devices specifications are reported in Table 1.

All tests are performed with a 50/50 (by mass) mixture of water and commercially available ethylene glycol.

2.1. Experimental activity

Specific experimental tests were carried out to understand better the behavior of the cooling circuit. First of all, the effects of temperature on coolant pressure were investigated. The coolant pressure was measured within the sealed cooling circuit for different coolant temperatures going from 15 °C to 80 °C, while both engine and pump were switched-off. Subsequently, the pump head was recorded at switched off engine and coolant temperature of about 15 °C. During the tests, the pump voltage was fixed and the coolant flow rate in the circuit was varied through a gate valve. The circuit characteristic was also measured: in such case, the gate valve was left completely open and the coolant flow rate was varied by varying the pump speed. Finally, in order to identify the onset of nucleate boiling several experimental campaigns were carried out, with different couples of engine speed–bmep values, both under steady state and transient conditions. Here, a specific test is reported, where the engine was operated under stable conditions at fixed engine speed (2000 rpm) and bmep (2 bar), while the coolant flow rate was varied from a maximum value of 2000 dm^3/h down to 500 dm^3/h as a sequence of steady state conditions. The coolant temperature at the engine inlet was kept constant at 85 ± 1 °C. Tests were replicated on different days to assess the day-by-day repeatability [10]. The experimental tests are summarized in Table 2.

3. Results

The analysis of the experimental data was focused on three main physical quantities: coolant pressure, coolant temperature and metal temperature. Other quantities like the coolant pressure pulsations or the engine-in/engine-out volumetric flow rate comparison, which proved useful for detecting the onset of the nucleate boiling in [11], where an atmospheric expansion tank