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A Robust Model Predictive Control for efficient thermal management of internal combustion engines

Francesco Pizzonia [a], Teresa Castiglione [a], Sergio Bova [a,*]

[a] DIMEG, Department of Mechanical, Energy and Management Engineering, Università della Calabria, Via P. Bucci, Cubo 44C, 87036 Rende, Italy

HIGHLIGHTS

- A Robust Model Predictive Control for ICE thermal management was developed.
- The proposed control is effective in decreasing the warm-up time.
- The control system reduces coolant flow rate under fully warmed conditions.
- The control strategy operates the cooling system around onset of nucleate boiling.
- Little on-line computational effort is required.

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ABSTRACT

Optimal thermal management of modern internal combustion engines (ICE) is one of the key factors for reducing fuel consumption and CO_2 emissions. These are measured by using standardized driving cycles, like the New European Driving Cycle (NEDC), during which the engine does not reach thermal steady state; engine efficiency and emissions are therefore penalized. Several techniques for improving ICE thermal efficiency were proposed, which range from the use of empirical look-up tables to pulsed pump operation. A systematic approach to the problem is however still missing and this paper aims to bridge this gap.

The paper proposes a Robust Model Predictive Control of the coolant flow rate, which makes use of a zero-dimensional model of the cooling system of an ICE. The control methodology incorporates explicitly the model uncertainties and achieves the synthesis of a state-feedback control law that minimizes the "worst case" objective function while taking into account the system constraints, as proposed by Kothare et al. (1996). The proposed control strategy is to adjust the coolant flow rate by means of an electric pump, in order to bring the cooling system to operate around the onset of nucleate boiling: across it during warm-up and above it (nucleate or saturated boiling) under fully warmed conditions. The computationally heavy optimization is carried out off-line, while during the operation of the engine the control parameters are simply picked-up on-line from look-up tables. Owing to the little computational effort required, the resulting control strategy is suitable for implementation in the ECU of a modern engine.

The control strategy was validated by means of experimental tests under several operating conditions, involving both warm-up and fully warmed engine thermal states. The tests were carried out with a small displacement Spark-Ignition Engine which was equipped with an electric coolant pump, directly driven by the control algorithm.

Results show that the controller is robust in terms of disturbance rejections, it respects the defined system constraints and is also very fast in terms of response to the perturbations. The experimental tests proved that the proposed control is effective in decreasing the warm-up time and in reducing the coolant flow rate under fully warmed conditions as compared to a standard configuration with pump speed proportional to engine speed. The adoption of these cooling control strategies will, therefore, result in lower fuel consumption and reduced CO_2 emissions.

* Corresponding author. Tel.: +39 0984 494828.
E-mail address: sergio.bova@unical.it (S. Bova).

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Nomenclature

A	engine surface area (m^2)
A_{nb}	part of engine surface involved in nucleate boiling (m^2)
bmep	engine brake mean effective pressure (bar)
c	constant value in Eq. (3)
c_p	coolant specific heat (J/kg K)
C_c	coolant thermal capacity (kJ/K)
C_w	engine thermal capacity (kJ/K)
h_{mac}	macro-convection heat transfer coefficient (W/m^2 K)
h_{mic}	micro-convection heat transfer coefficient (W/m^2 K)
K_1, K_2	values of the controller
$\dot{m}_c$	coolant flow rate (kg/s)
$\dot{m}_f$	fuel flow rate (kg/s)
N	engine speed in Eq. (3) (rpm)
n	exponent in Eq. (3)
n_1	exponent in Eq. (3)
n_2	exponent in Eq. (3)
p	coolant pressure (bar)
q_{ONB}	nucleate boiling heat flux (W/m^2)
q_w	combustion chamber thermal flux (W/m^2)
$\dot{Q}_c$	thermal power removed by the coolant from the combustion chamber walls (W)
$\dot{Q}_g$	thermal power supplied by the fuel to the combustion chamber walls (W)
$\dot{Q}_r$	thermal power supplied by the coolant to the radiator (W)
T_c	coolant temperature (K)
T_{c_eq}	equilibrium coolant temperature (K)
T_{in}	coolant temperature at engine inlet (K)
T_{ONB}	wall temperature for onset of nucleate boiling (K)
T_{out}	coolant temperature at engine outlet (K)
T_{sat}	saturation temperature (K)
T_w	engine wall temperature (K)
T_{w_eq}	equilibrium engine wall temperature (K)
T_∞	bulk flow temperature (K)

1. Introduction

A wide variety of innovative technologies are under development for meeting the requirements of regulatory agencies on vehicle emissions [1,2]. Most of them point toward an increase in engine efficiency and fuel saving and many are already on the market. An optimal engine thermal management constitutes one of the most promising solutions and can be achieved at very limited costs, with respect to the various technological options. Cipollone and Di Battista [3] show that the cooling system management offers interesting possibility for efficiency increase at the very limited cost of about 200 €/km/l of saved fuel. A comprehensive review of influences of thermal management on internal combustion engines efficiency was also reported by Roberts et al. [4]. The main effort aims to speed up the warm-up time during a standard homologation cycle, where the major part of pollutant emissions and engine inefficiency happens after the cold start. Engine efficiency and emissions are, in fact, heavily influenced by the thermal conditions; although typical part-load efficiency is about 20–25% for a Spark Ignition Engine and about 30% for a diesel engine [5], this efficiency drops to about 9% after a cold start [6,7].

Low engine temperatures determine poor engine efficiency and emissions due to increased friction losses and to combustion inefficiency. The main factor responsible for this is the cylinder liner mid-stroke temperature; this temperature, in fact, influences the lubricant temperature and, therefore, the friction losses, especially during warm-up. Under low lubricant temperature conditions (around 20 °C) Will et al. [6,8] estimated that frictional losses can be up 2.5 times higher than the ones in fully warmed conditions and Samhaber et al. [9] predicted an increase of about 13.5% in fuel consumption if the temperature is even lower, around 0 °C. In addition, the cylinder liner temperature influences directly the temperature of the unburned gases within the crevices volumes inside the combustion chamber, which are the main source of unburned hydrocarbon emissions in Spark Ignition Engines [10].

Mid-stroke cylinder liner temperature can be controlled by means of the coolant flow rate. During warm-up, when the radiator is by-passed and the coolant temperature at engine-inlet is almost equal to the coolant engine-out one, by diminishing the coolant flow rate, a decrease of coolant temperature and an increase of liner temperature can be achieved [11]. On the other hand, under steady state conditions, by keeping the engine-in coolant temperature constant, both the engine-out coolant temperature and the head and cylinder block temperature increase as coolant flow rate diminishes [12]. As the cooling pump is driven by the crankshaft today, its speed is proportional to that of the engine, so that the coolant flow rate can only be reduced by using the thermostatic valve. According to Brace [13], as a result of this poor regulation capability, engines are over-cooled for about 95% of their operating time.

Several different techniques were proposed for controlling the coolant flow rate independently of engine speed, all of them focusing on using electrically driven pumps. Ap and Golm [14] first addressed the issue of cost reduction of engine cooling components and proposed the use of a small electric water pump with reduced coolant flow rates. Brace [13] proposed the use of an electric pump in a control strategy, which was based on the use of empirical look-up tables. More recently the same author [15], again using electrically driven pumps, found that a 2% improvement in bsfc was obtained by reducing the coolant flow rate by means of a throttle valve. Bent [16] adopted a pulsed coolant flow strategy with an electric pump switched ON and OFF in order to circulate the coolant only when it was required. Other types of pump could be used for controlling the coolant flow rate, like variable-displacement vane pumps [3,17], which are currently adopted in the lubricating system of some ICE. Electric pumps are usually preferred in laboratory tests owing to their ease of use.

A more systematic approach to coolant flow rate control can however be adopted, which can make use of the recent developments of the control and optimization techniques. As most of the energy plants are MIMO (Multi Input Multi Output) systems, it is not possible to adopt straightforward classical control approaches with them, such as the PID control. A widely used approach for MIMO slow-dynamical systems is the Model Predictive Control (MPC), where a model of the plant is used to evaluate the system evolution [18,19]. Several researchers used the MPC technique in different fields for increasing energy efficiency. For example, Van Staden et al. [20] employed this procedure to optimize the shifting of electricity demand from peak demand periods to off-peak ones; Parisio et al. [21] used the same approach to minimize the operating cost of a micro-grid while satisfying the required energy demand; Kwak et al. [22] adopted this method for analyzing the