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A Novel Approach to the Thermal Management of Internal Combustion Engines

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Abstract

The paper presents a novel control architecture developed with the aim to satisfy the requirements of the cooling system of an ICE, by means of an electric pump and of an ad-hoc developed control module. The developed controller is based on the Robust Model Predictive Control and is designed with the purpose to satisfy the input and output constraints and to reject the external disturbances, by adopting a lumped parameter model of the engine cooling system, which predicts the coolant temperature, the average wall temperature and the heat transfer regime including nucleate boiling. Given that the proposed methodology is valid for each condition, in the present paper the focus is on the engine operating under fully warmed conditions, with the aim to keep the wall temperature into the prescribed limits, with the lowest possible coolant flow rates. This goal is achieved by properly defining the controller parameters. Different control strategies are proposed and their effectiveness is evaluated in terms of engine wall temperature, coolant temperature, coolant flow rate and heat transfer regime in response to step-wise variations in fuel flow rate. The region of stability of the controller is also discussed. Results show that the control algorithm is robust in terms of disturbance rejections and ensures effective and safe cooling with much lower coolant flow rates if compared to the ones provided by the use of the standard crankshaft driven pump.

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Keywords: Internal Combustion Engine; Model Predictive Control; Thermal Management; Cooling System.

1. Introduction

A wide variety of innovative technologies, aimed at reducing vehicles emissions according to the requirements of regulatory agencies, are under investigation nowadays. These include new engine architecture, hybridization, transmission and others [1-3]. Among them, the cooling system plays an important role in the efficiency, emissions and reliability of ICE; therefore, it is widely investigated in numerical and experimental studies, which aim to improve its performances [4-7]. The main effort aims, in particular, at reducing the warm-up time at cold-start, where the major

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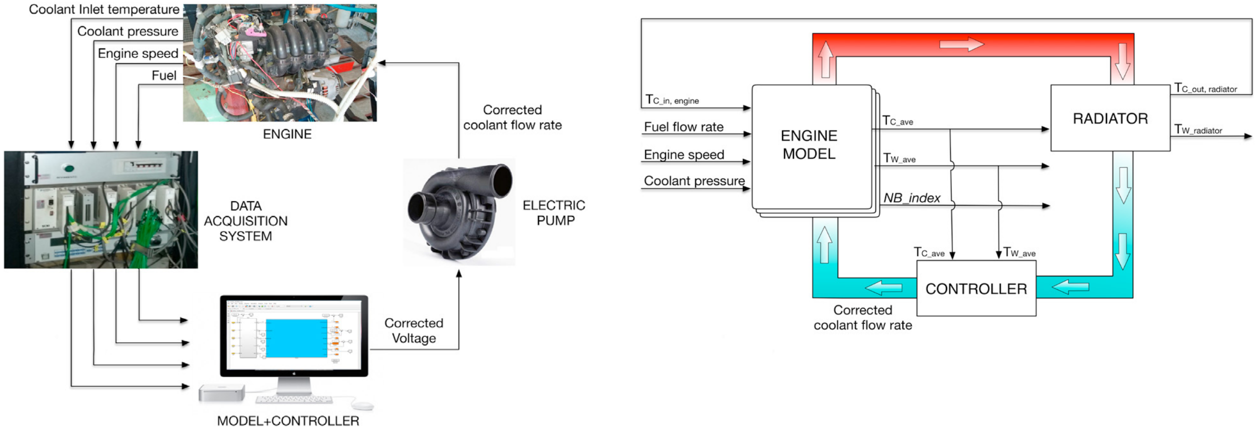

Fig. 1. Scheme of the Model Based controller.

part of pollutant emissions and engine inefficiency occur. Several solutions were proposed over the years in order to improve the regulation capabilities of the coolant flow rate for actual production engines, by substituting the standard crankshaft-driven mechanical pump with an electric one [8-11]. Other solutions could be used for controlling the coolant flow rate, like the variable-displacement vane pumps, which are currently adopted in the lubricating system of some ICE [12, 13]. The present work proposes an innovative approach to the engine thermal management, based on the use of an electric pump and on the development of a systematic control strategy of the coolant flow rate through the Robust Model Predictive Control approach [14]. The control system is developed with the aim to manage the electric pump and to define, therefore, the proper coolant flow rate, which must be supplied to the cooling system in order to satisfy the requirements of the control strategy. This methodology has a wide validity and is suitable to be applied in different situations. In [15], the control parameters were set-up to gain an engine rapid warm-up at cold start, in order to guarantee reduced frictional losses and fuel consumption. In the present work, the focus is on the engine operating under fully warmed conditions; the controller is developed to guarantee the proper cooling with the lowest possible coolant flow rates, and by keeping however the engine to operate safely.

2. Model Predictive Control

The control scheme is based on the robust Model Predictive Control (MPC) method. The engine, in fact, is a multi-input-multi-output system, and the classical PID controllers cannot be used. Furthermore, the control algorithm makes use of a model of the engine thermal exchange, which also includes the prediction of the nucleate boiling heat transfer regime. The whole system is suitable to be used both during experimental tests [15] and for simulation purposes. During the real engine operations, the integration between the controller, the engine and the electric pump is as follows: the data acquisition system (DAQ) sends the signals of the input variables (engine speed, fuel flow rate, coolant pressure and engine inlet coolant temperature) to the model, which is installed on a pc; the model, which runs in parallel with the engine, in turn, computes the actual average engine wall temperature, the coolant average temperature and the heat transfer regime (forced convection or nucleate boiling). These values are sent to the controller, which corrects the coolant flow rate in order to satisfy the control strategy requirements and enforces the proper voltage to the coolant electric pump (Fig.1-left). When the controller is used for simulation purposes, the model inputs are read from a file; in this case, the inlet coolant temperature is either read from the file or predicted from the radiator model (Fig.1 right). The engine model, the radiator model and the controller are briefly described in the following sections.

3. Engine Model

The thermal exchange between the coolant and the engine walls is modeled through a zero-dimensional approach [16], and is based on the energy conservation equations:

$$\begin{aligned} \dot{T}_W \cdot C_W &= \dot{Q}_G - \dot{Q}_C \\ \dot{T}_C \cdot C_C &= \dot{Q}_C - \dot{Q}_R \end{aligned} \tag{1}$$

Eq. (1) refer to the thermal exchange between the gases inside the cylinder and the coolant trough the engine walls and to the thermal exchange between the coolant and the atmosphere trough the radiator. C_W and C_C are the engine and coolant thermal capacities, respectively. $\dot{Q}_G$ is the thermal power released from the gases inside the engine cylinders and is computed according to the following empirical formulation, which was demonstrated to be also weakly dependent on coolant flow rate and engine speed [16]:

$$\dot{Q}_G = CN^{n_1}\dot{m}_c^{n_2}\dot{m}_f^{n} \tag{2}$$

$\dot{Q}_C$ is the thermal power from the engine walls to the coolant. It takes into account both forced convection and nucleate boiling heat transfer mechanism trough Chen's approach:

$$\dot{Q}_C = h_{mac}A(T_W - T_\infty) + h_{mic}A_{nb}(T_W - T_{SAT}) \tag{3}$$

where h_{mac} is the forced-convection heat transfer coefficient [17], h_{mic} is the nucleate boiling heat transfer coefficient [18], A is the total heat exchange area and A_{nb} is the part of the engine walls involved in the nucleate boiling phenomenon. Finally, $\dot{Q}_R$ is the amount of thermal power released from the coolant to the atmosphere through the radiator.

$$\dot{Q}_R = \dot{m}_c c_p(T_{C,out} - T_{C,in}) \tag{4}$$

If none of the two temperatures in eq. (4) is known, the engine-in coolant temperature, $T_{C,in}$, can be predicted by a radiator model as will be described in the next section. Based on the above equations, the inputs required by the model are the fuel flow rate, the engine speed, engine-in or engine-out coolant temperature and coolant pressure; by the integration of the two differential equations it is possible to compute T_W and T_C and to determine, therefore, the state of the system. Another quantity that the model computes is the distance from the onset of nucleate boiling. A metrics is defined as:

$$NB\_Index = \frac{q_W - q_{ONB}}{q_{ONB}} \tag{5}$$

where q_W is the actual heat flux through engine walls and q_{ONB} is the heat flux needed for the onset of nucleate boiling; therefore, $NB\_Index < 0$ indicates forced convection, $NB\_Index > 0$ onset of nucleate boiling and $NB\_Index > 1$ saturated boiling. Model inputs are: engine speed N, fuel flow rate $\dot{m}_f$, coolant engine-in temperature $T_{C,in}$, pressure p and flow rate $\dot{m}_c$. Model outputs are: wall and coolant average temperature T_W, T_C and NB_Index.

4. Radiator model

The radiator model is needed in order to simulate the whole cooling circuit if experimental data of engine-in nor engine-out coolant temperature is available. The radiator model equations close the set of equations (1) by computing $\dot{Q}_R$ and determine the coolant temperature at engine inlet. The model includes the thermostatic valve and the radiator fan, which acts for engine-out coolant temperatures higher than 97°C. The air velocity in such a case is set to 22 m/s. The first set of equations refers to the thermal exchange between the coolant and the radiator walls [19]:

$$\begin{aligned} \dot{Q}_R &= \dot{m}_c c_p(T_{C,in\_r} - T_{C,out\_r}) \\ (T_{C,in\_r} - T_{C,out\_r}) &= \frac{h_c(T_C - T_{W\_r})}{w_C d_e \rho_C c_C} H \end{aligned} \tag{6}$$

The thermal exchange between the radiator walls and the air is given by:

$$\dot{Q}_{air} = \dot{m}_{air} c_{air} (T_{air,in} - T_{air,out})$$
$$T_{air,out} = T_{W\_r} - (T_{W\_r} - T_{air,in})^{-(\frac{h_{air} S}{w_{air} d_e \rho_{air} c_{air}})} \tag{7}$$

Finally:

$$\dot{Q}_R - \dot{Q}_{air} = C_R \dot{T}_{W\_r} \tag{8}$$

5. Controller

The model-based control algorithm computes the actual coolant flow rate according to Eq. (9):

$$\dot{m}_C = \dot{m}_{C\_eq} + K_1 (T_W - T_{W\_eq}) + K_2 (T_C - T_{C\_eq}) \tag{9}$$

T_W and T_C are the average engine wall temperature and average coolant temperature, respectively, computed by the model according to the specific engine operating condition. T_{W_eq} and T_{C_eq} are the desired (equilibrium) engine and coolant temperatures that the system reaches with the equilibrium coolant flow rate, $\dot{m}_{C\_eq}$. Finally, K_1 and K_2, are the controller values which represent the state-feedback control law, calculated by solving a min-max (minimization of the worst case) optimization problem with constraints, following the approach presented in Kothare et al. [14].

In order to compute the controller values K_1 and K_2, a number of steps is necessary:

(a) the engine model (eq. 1) must be linearized in selected operating conditions;
(b) the constraints on inputs expected variations and on outpot allowed variations are defined;
(c) the min-max optimization problem is solved [14] and the K_1, K_2 values are obtained.

The constraints are enforced both on the state of the system, in this case the wall and coolant temperatures, and on the inputs. The constraints on the state of the system represent the maximum and minimum allowed wall and coolant temperatures that the controller has to satisfy when computing the coolant flow rate, in order to guarantee engine reliability. The inputs, which in this system are engine speed, fuel flow rate, coolant temperature and pressure, are not known in advance and, from the control point of view, they are considered as disturbances. The constraints on the inputs represent the maximum and minimum expected quantities that the controlled system must reject, keeping the state of the system in the controller stability region. Another constraint is on the maximum and minimum coolant flow rate provided by the pump. Finally, constraints on the NB_Index will guarantee that the controller operates with reduced coolant flow rates while keeping the boiling condition in the prescribed limits, avoiding, for example, that saturated boiling could occur.

The optimization problem allows a solution (K_1,K_2) only if the constraints on the output variables are reasonably wide and the ones on the input variables are reasonably narrow. For this reason, in order to reduce the range of variability of the input variables, the engine speed-torque plane was split into smaller sub-regions and the optimization problem was solved for each of them. This operation is made off-line due to the required computational effort, and during the usual engine operation or during simulations, the control parameters are selected on-line from a look-up table. This procedure guarantees the stability of the controller and a smooth transition between adjacent sub-regions. The region of stability of the controller can be represented on the state space and can be approximated as an ellipsoid. A detailed description of the controller algorithm can be found in [20].

An example of the controller response when step-wise disturbances are applied during a steady engine operating condition (2000 rpm x 2 bmep) is shown in Fig.2, where the response of the control system is reported, when the maximum allowed input variation (disturbances) are applied. In this case, the maximum allowed disturbance on fuel flow rate and on engine inlet coolant temperature are applied. The engine speed has a negligible effect and is not reported. The same holds for pressure, as long as the heat transfer regime is single-phase forced convection

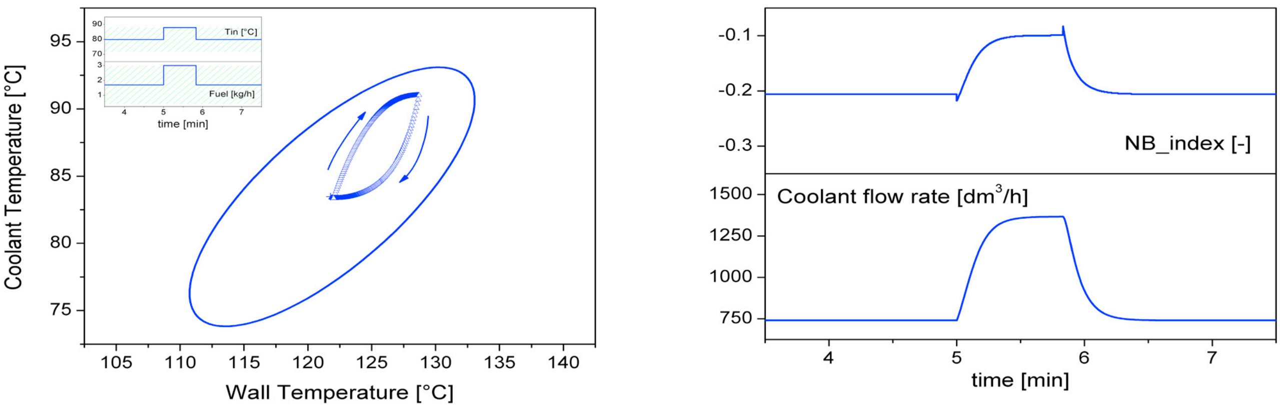

Fig. 2. Ellipsoid representing the region of stability of the controller. Operating conditions: fuel flow rate=1.7 kg/h, coolant pressure=1.8 bar, inlet coolant temperature= 80°C; Output Equilibrium values $T_W = 121.7°C$, $T_C = 83.5°C$; NB_Index=-0.2. Input disturbances within the defined constrains. Output constrains satisfied.

($NB\_Index < 0$). The figure on the left shows the stability region of the controller. The equilibrium values are: $T_{W\_eq} = 121.7°C$, $T_{C\_eq} = 83.5°C$ and $\dot{m}_{C\_eq} = 700\ l/h$. Under these conditions a negative NB_Index value is obtained ($NB\_Index = -0.2$). The figure also shows the trajectory of the system state (T_W,T_C) when disturbances are applied. The trajectory starts from the center of the ellipsoid (equilibrium point), moves (upper path) to a point distant from this center but still contained within the stability region and then returns (lower path) at the center of the ellipsoid when the disturbance is removed.

6. Results and discussion

6.1. Control strategy effectiveness

In order to show the most convenient control strategy for the engine operating under fully warmed conditions, two different cases are simulated, whose results are shown in Fig. 3. Two ellipsoids are plotted with different equilibrium conditions and by enforcing the constraints on the input and output variables. The equilibrium conditions and constraints for both ellipsoids are summarized in Table 1. Simulations are carried out by considering that the engine is operating under steady-state condition in proximity of the equilibrium of ellipsoid 1; a fuel step disturbance is then enforced. Two control strategies are possible: (i) the controller, which refers to the first ellipsoid, acts until reaching the final state (blue triangles trajectory in Fig.3 a)); (ii) the controller 1 acts until the trajectory intersects ellipsoid 2. In this second case, the control strategy switches to controller 2 until reaching the final state (red circle trajectory in Fig.3 a)). It can be observed that both trajectories lay within the ellipsoids, which indicates that the algorithm works correctly within the stability region. Figure 3 b) shows the variation in fuel and coolant flow rates for both cases. When the fuel step occurs, the controller in both cases acts in order to increase the final coolant flow rate. In fact, both the wall and coolant temperatures increase (Figure 3 c)) and the controller operates in order to keep these temperatures within the prescribed limits. The NB_Index constraints are also satisfied in both cases (Figure 3c)). It is worth to point out, however, that the control strategy, which switches from ellipsoid 1 to ellipsoid 2 gives better results in terms of coolant flow rates. In the first case, the increase in coolant flow rate is significant and reaches a value close to the one that the standard mechanical pump would produce at this engine speed ($\approx 2000\ dm^3/h$). In the second case, on the contrary, the system operates with much lower coolant flow rates while causing only a limited increase in the wall temperature ($\approx 4\ °C$) and in the coolant temperature($\approx 1\ °C$), which are however kept below the prescribed limits. The controller, therefore, guarantees the proper cooling action with more limited flow rates.

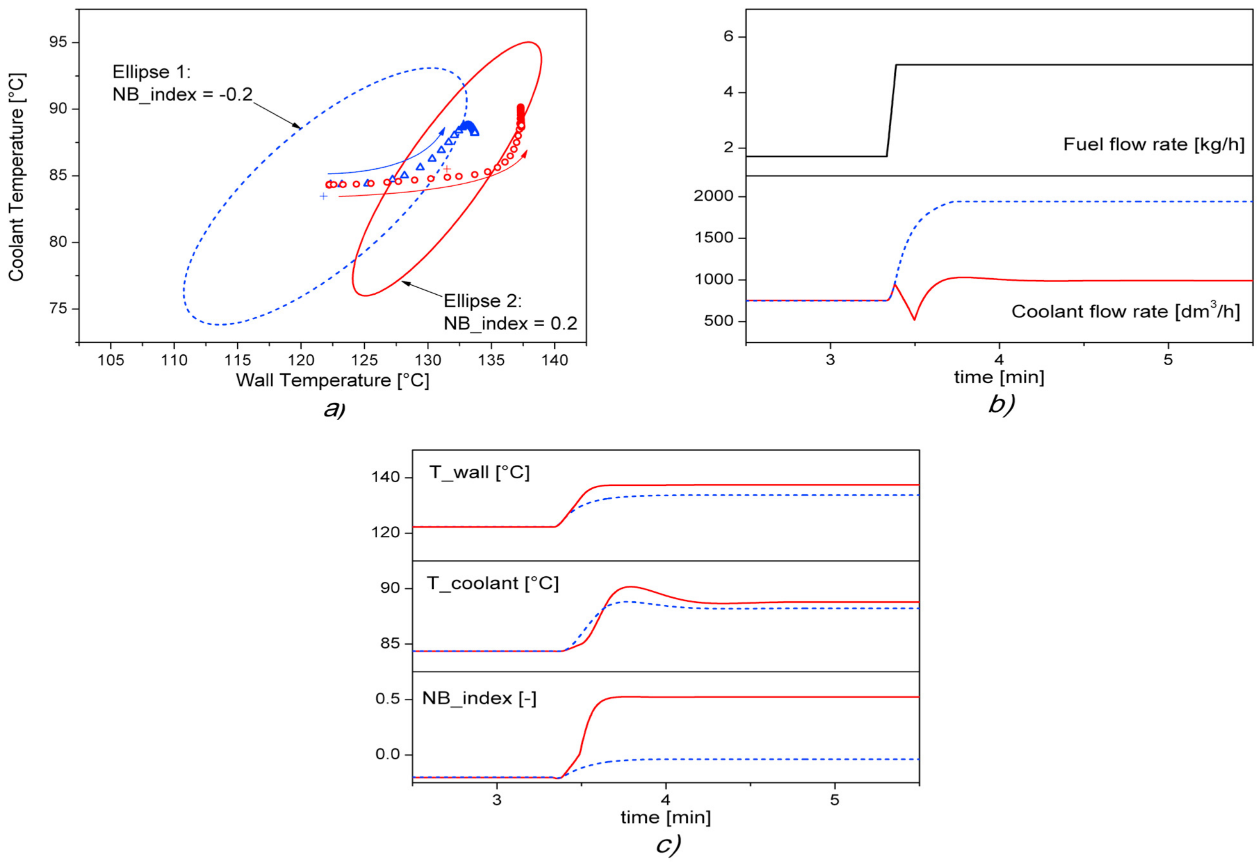

Fig. 3. Results of two different control strategies, when a fuel flow rate step variation occurs. Case one (blue triangles and dashed lines) uses one single control couple of parameters (K_1,K_2); case two (red circles and solid lines) switches from parameters of Ellipse 1 to parameters of Ellipse 2 when wall temperature exceeds the one of ellipses intersection. a) stability regions (ellipsoids) and trajectories representing the state of the system; b) time history of fuel flow rate and coolant flow rate; c) time history of wall temperature, coolant temperature and NB_Index.

Table 1. Parameters of controllers 1 and 2. Equilibrium values and constraints on the input and output variables.

	Ellipsoid 1		Ellipsoid 2	
	Equilibrium	Constraints	Equilibrium	Constraints
$T_W[°C]$	121.7	±13.7	131.5	±8.5
$T_C[°C]$	83.5	±11.5	85.5	±9.5
$\dot{m}_C$ [kg/s]	-0.2	±0.2	0.2	0 ÷ 0.6
$T_{in}[°C]$	80	±8	80	±8
$\dot{m}_f$[kg/h]	1.7	±1.3	1.7	±1.3
p_{out} [bar]	1.8	±1	1.8	±0.2
$Enginespeed$ [rpm]	2000	±1000	2000	±1000

6.2. *Fuel ramp simulations*

As Figure 3 a) shows, the ellipsoids cover only a limited region of the state space and are obtained for limited fuel flow rate ranges (Table 1). It is therefore necessary to create several ellipsoids in order to control coolant flow rates for the whole range of engine operations. Figure 4 a) shows two more ellipsoids, which were obtained by increasing the equilibrium values with respect to the previously computed ellipsoids and by considering a fuel flow rate varying

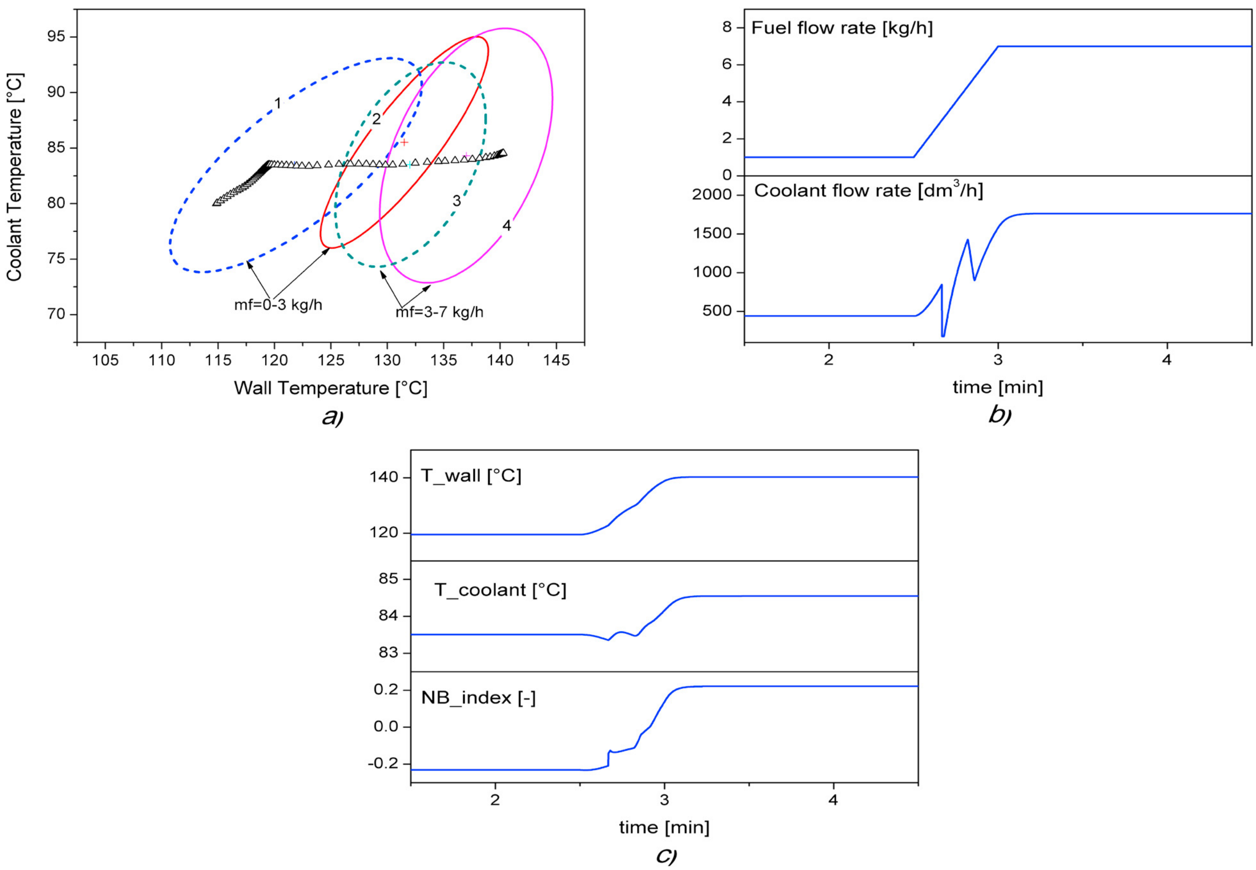

Fig. 4. Simulation results for engine operating condition varying in two different ranges of fuel flow rate. a) stability regions (ellipsoids) and trajectories representing the state of the system; b) time history of fuel flow rate and coolant flow rate; c) time history of wall temperature, coolant temperature and *NB_Index*.

between 3 and 7 kg/h. Also in this case, one ellipsoid is obtained with negative values of *NB_Index* (dotted line) and the second one with a positive *NB_Index* value (solid line), in order to cover all the possible heat transfer regimes.

Simulations are carried out by enforcing a fuel ramp varying from 1.3 to 7 kg/h. In such a way, the engine operates initially in ellipsoid 1 and then passes through the various ellipsoids before reaching ellipsoid 4. The switch criterion between ellipsoids is based on the wall and coolant temperatures corresponding to the ellipsoids intersection. As Figure 4 a) shows, the trajectory representing the state of the system during the fuel ramp, is contained within the ellipsoids. The coolant flow rate shows an increase (Figure 4 a)) and the discontinuities indicate the switch between the ellipsoids. As expected, wall temperature, coolant temperature and *NB_Index* rise (Figure 4 c)). However, these values are within the constraints, thus demonstrating that the controller works according the design specifications.

7. Summary and Conclusions

The paper proposes a novel systematic approach to the management of the cooling system of an ICE by actuating the coolant flow rate by means of an electric pump and of an ad-hoc developed regulation module. The developed controller is based on the Model Predictive Control approach, which makes use of a lumped parameter model. This proposed approach guarantees low on-board computational effort. In the presented paper the focus was on the engine operating under fully warmed conditions. Several controllers were calculated by dividing the fuel flow rate-engine speed range into sub-regions. The transition from one controller to another occurs in a smooth way. In general, For a given engine operating condition, if nucleate boiling is allowed, the controller guarantees adequate cooling with lower coolant flow rate while the increments of wall temperature are modest.

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