Institute for Design and Control
of Mechatronical Systems

Diploma Thesis:

Predictive Thermal Management of a Combustion Engine

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Abstract

Temperature control is very important for combustion engines as temperature is a critical factor both for chemical reactions and mechanical stresses. Traditionally, temperature control is performed by feedback of a global quantity, the coolant temperature, which however is a poor indicator of specific temperatures. The use of electrical pumps opens new possibilities for thermal control, in particular in terms of efficiency, but also of pollution, especially in the cold start phase. This diploma thesis shows that predictive control and the use of electric coolant pumps allow regulating specific temperatures – here as example the cylinder head temperature.

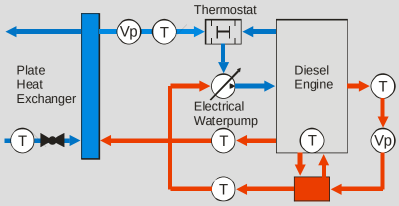
Introduction:

The principal task of the cooling system is to keep the temperatures of the engine for reasons of safety under designated boundaries. Heat transfer affects engine performance, efficiency and emissions. As a consequence, there has always been and there still is a substantial scope in achieving a temperature control of the engine. The standard solution consists of the well known by-pass solution, according to which a sufficient amount of coolant is pumped through the engine and, if the temperature of the coolant is too high, the coolant is let into an air-coolant exchanger to reduce its temperature. While this method is able to keep the temperatures inside a given region for the standard operating conditions, it is clearly not optimal, neither in terms of the time required to achieve the desired temperature nor in terms of temperature precision or power consumption. The problem of temperature control in engines is especially complicated by the fact that there is not one temperature, but a set of them. So for friction and thus for consumption, the single most relevant criteria is the oil temperature, while for raw emissions, the critical issue is the cylinder wall temperature. For turbocharged engines, it is important to minimize thermal swings of the turbocharger to prevent early failures. It is also worth noticing that the temperature affects the emissions as well. While several alternative concepts to the standard cooling configuration have been proposed, so e.g. split cooling, part cooling etc., there is some agreement that the actual cooling configuration will essentially be kept, even though with better components as the engine heat is not only a possible cause of thermal swings, but also the basis for several essential functions like wind screen de-frosting, passenger cabin heating, oil heating during start-up and last but surely not least heating of the catalyst in SI powered vehicles. So the technical challenging question is then: given the basic structure or actual configuration, how would the ideal control look like which stabilizes the temperature of a given component (or reaches it as fast as possible)? In this diploma thesis the main focus is laid on the answer to this question. The problem is solved by restating it in terms of an optimal problem, which can be easily adapted to a different configuration. Once the problem is restated as an optimal problem, two tasks remain: an on-line version is needed, and this turns out to be any receding horizon control strategy, and a way is needed to relate the measurable quantities as well the controllable quantities to the target quantity, i.e. a model. As physical models would be much too complex and difficult to derive and to parameterize in control, in this work the chosen estimator is based on simple linear identified models.

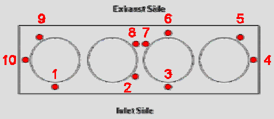
Plant

The cooling circuit installed on the test bench is shown below but the mechanical pump is coupled to an electric engine instead of the engine crankshaft.
The following study only concerns the warm engine without additional heat sinks like the passenger cabin and it shall be concerned here with two specific engine quantities, the cylinder head and the coolant temperature, which for validation of this study, have been measured with a special cylinder head gasket .

Cooling circuit:



Cylinder Head Gasket:



Temperature Control Problem

The inputs to the system are Q_{Losses} the heat produced during combustion and dissipated through the cylinder surface (engine block), and n_p the rotational speed of the coolant pump. Q_{Losses} shall be treated as a disturbance.

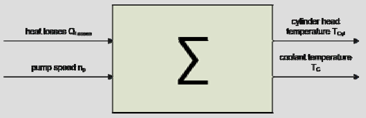
Plant Model:

$$\begin{bmatrix} T_{Cyl} \\ T_C \end{bmatrix} = \begin{bmatrix} T_{11}(z) & T_{12}(z) \\ T_{21}(z) & T_{22}(z) \end{bmatrix} \cdot \begin{bmatrix} Q_{Losses} \\ n_p \end{bmatrix}$$

Cost Function:

$$J = \min_{n_p([t,T])} \int_t^T \left(T_{Cyl} - T_{Cyl}^{*}\right)^2 dt$$

System Structure:

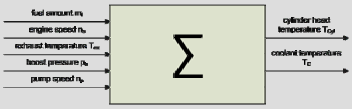


Data Based Modelling

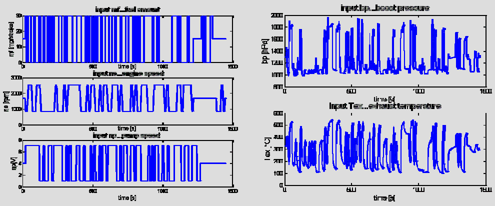
The quantities n_e, m_f, p_b and T_{ex} are actually replacements for the non measurable Q_{Losses}.

$$Q_{Losses} = f(m_f, n_e, T_{ex}, p_b)$$

System Structure for Identification:



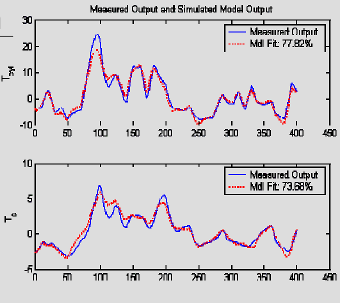
Inputs for Identification: m_f, n_e, T_{ex}, p_b, n_p



Results of Identification

Validitation of the identified models with the FIT-value of Matlab.

$$FIT = 100\,\frac{1-\|\hat{y}+y\|_2}{\|y-\bar{y}\|_2}$$

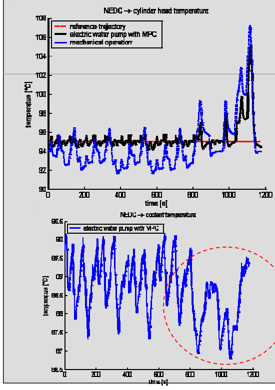


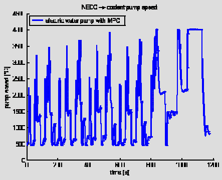
Control System Design

The identified state space model is used to design a model predictive control law keeping into account the constraints of the electrical coolant pump.

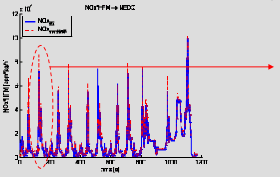
$$\begin{aligned}
&\min \sum_{k=0}^{N-1} \left[y'(t+k|t)-r'(t)\right]\cdot S\cdot\left[y(t+k|t)-r(t)\right]+\Delta u'(t+k)\cdot T\cdot\Delta u(t+k) \\
&\qquad +\rho\cdot\varepsilon^2 \\
&s.t.\; y_{\min}-\varepsilon \le y(t+k|t) \le y_{\max}+\varepsilon, k=1,\dots,N_{cy} \\
&\quad u_{\min} \le u(t+k) \le u_{\max}, k=0,\dots,N_{cu} \\
&\quad \Delta u_{\min} \le \Delta u(t+k) \le \Delta u_{\max}, k=0,\dots,N_{cu} \\
&\quad x(t+k+1|t)=A\cdot x(t+k|t)+B\cdot\left[u(t+k-1|t)+\Delta u(t+k)\right] \\
&\quad y(t+k|t)=C\cdot x(t+k|t)+D\cdot\left[u(t+k-1|t)+\Delta u(t+k)\right]
\end{aligned}$$

Results



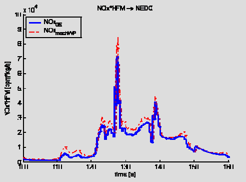


Enormous reduction of the thermal swings with the electrical coolant pump. In the last section the control problem isn‘t feasible anymore. The coolant temperature decrease and so the thermostat begin to close.



Then it isn‘t possible to remove the desired heat.

The stabilization of the cylinder head temperature has a possitive impact on emissions.



During the first part of the NEDC it is possible to reduce the NO_x emissions by 10 %. Indeed the HC emissions increase by 3 % and Opacity by 6%.

Conclusions and Outlook

- **Strong improvements in thermal oscillations of the cylinder head temperature**
- **It is possible to control the temperature of specific components**
- **It is possible to reduce the NOx spikes during NEDC**
- **Changing the mechanical coolant pump to an electrical pump is not enough**
- **It should be used a controlable thermostat, e.g. a map based thermostat**
- **A model to predict the heat losses should be investigated**
- **The MPC could be transformed into a multimodel version which uses different models depending on the operating point**