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Control Design for a Thermal Hardware-in-the-Loop Test Bench for Automobile Thermal Management Systems ⋆

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Abstract: In this contribution the control design for a thermal hardware-in-the-loop test bench is described. The test bench was designed and constructed at the RWTH Aachen University as a means of real time testing of new hardware components for the thermal management of electrified vehicles in a realistic environment. The task of the test bench is to simulate the thermal load of the tested device which is defined by the volume flow rate and the temperature of the fluid at its inlet. For this purpose, the test bench features a flow heater, fluid pump and process cooling that are to be actuated by an appropriate control algorithm to regulate the desired thermal load. The presented control structure consists of a cascaded model-based predictive controller with underlying conventional PID-control. The controller is applied to the test bench and approved during operation. Experimental control results are presented and discussed.

Keywords: Control design, Simulation, Hardware-in-the-loop, Rapid Control Prototyping, Model-Based Predictive Control

1. INTRODUCTION

With the advent of electrified vehicles, the importance of thermal management methods as a key factor in the holistic energy efficiency analysis has increased strongly. To improve the thermal efficiency of the vehicles, new thermo-hydraulic components like heat storages or heat pumps are taken into consideration to be added to the fluidic cooling and heating circuits (see e.g. Javani et al. (2012)). Thus a thermo-hydraulic test bench has been constructed at the RWTH Aachen University to enable real time testing of these components (see also Baltzer et al. (2014); for similar applications compare to Setlur (2005) and Vermillion et al. (2009)). Furthermore, the test bench is designed such that it can be connected to the cooling circuit of a vehicle on a roller dynamometer. In that case it can be used to simulate the behavior of a thermo-hydraulic component to investigate its impact on the operation of the thermal system. In the research project 'qOpt' this test bench is used to develop a latent heat storage that is to be integrated in the heating/cooling circuit of a plug-in hybrid electric vehicle. Here the test bench serves to evaluate early stage versions of the heat storage as well as a to provide a real time testing environment for prototypes of the final device.

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The task of the test bench is to generate the thermal load of the device under test (DUT) which is defined by the volume flow rate and the temperature of the fluid at the inlet. The test bench is therefore connected with a real time platform on which the control algorithm is implemented. The desired temperature and mass flow values are also generated on this platform either by a simulation model of the environment of the DUT or by predefined trajectories. The test bench serves multiple purposes, e.g.

- measurement of the thermodynamic behavior of the thermo-hydraulic component for purposes of model evaluation/dimensioning/system identification, as well as
- real time testing of prototypes/final components with a simulated environment close to the application in the vehicle heating/cooling circuit 'in the loop'.

For any of these applications, the task of the controller presented in this contribution is to regulate the desired thermal load of the component under test as communicated by the external source. Due to the variance of applications the test bench is to be used for, different operational boundary conditions have to be taken into account: When predefined reference trajectories are to be regulated, the controller can take future set points into consideration. However, in the case of real time simulation such trajectories may not be available. In general, precise control of dynamic and static temperature trajectories for a wide spectrum of volume flow rates is desirable.

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Due to the ability to consider future set points and the slow process characteristics thus a model-based predictive control approach was chosen as the central concept.

1.1 Description of the thermo-hydraulic hardware-in-the-loop test bench

Fig. 1 shows a schematic diagram of the test bench. It consists of a circuit with several thermo-hydraulic components that are connected by pipes. A fluid pump provides a volume flow rate of the fluid that circulates in the test bench. Downstream of the fluid pump, the fluid can either be cooled by an external refrigerant system in order to reach lower temperatures down to −30 °C or in the common case via process cooling for temperatures of around 18 °C depending on the ambient temperature. Afterwards, the fluid passes a heating device (flow heater). The fluid then flows through the device under test, which can also be bypassed via parallel pipes and a proportional valve.

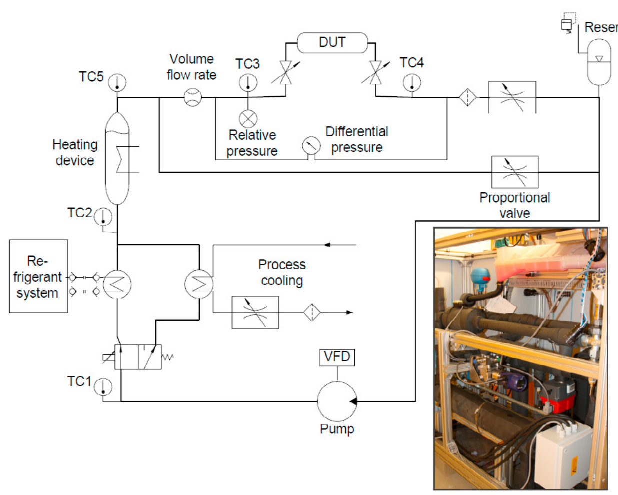

Fig. 1. Schematic overview of the thermo-hydraulic test bench

Several sensors are installed at the test bench: The temperature sensors TC1...TC5 measure the fluid temperature downstream and upstream of each component. Beside the volume flow rate into the DUT, the relative pressure at the inlet and the differential pressure between its inlet and outlet can also be measured. A water-glycol mixture similar to the fluids used in the heating/cooling circuits in automobiles is used as circulatory medium. Table 1 provides some general data of the test bench.

Table 1. Characteristics of the test bench

Data	Value
Type of fluid	water-glycol mixture (50 : 50)
Temperature range liquid phase of fluid	−40...108 °C
Amount of fluid in test bench	approx. 9 l
Max. power of flow heater	approx. 18 kW
Max. heat transfer process cooling heat exchanger	40 kW
Operating range fluid pump	1...34 l/min

2. DEFINITION OF THE CONTROL PROBLEM

The main task of the controller is to generate the desired temperature at the inlet of the DUT at a certain volume flow rate into the device. Central components from control point of view are thus the fluid pump, the flow heater and the cooling via heat exchangers, which can be done either by using the external refrigerant system or the process cooling. The test bench is to be used for different applications and therefore installed on a mobile platform. For this reason, the refrigerant system is not always available. This contribution thus focuses on cooling via process cooling which is accessible for every application.

2.1 Controlled and actuated variables

Since both the volume flow rate and temperature are measured close to the inlet of the DUT, the process variables Y_{dV} - measured by the volume flow sensor - and Y_{TC3} - measured by the temperature sensor TC3 - are used as the main controlled variables. As will be explained in the following subsection, it was chosen to control the temperature of the fluid entering the flow heater seperately, therefore the temperature Y_{TC2} - measured by temperature sensor TC2 - serves as an additional controlled variable.

The fluid is heated by the flow heater which is controlled by two power contactors to each of which a maximum voltage of 10 V can be supplied. The resulting heat flow transferred to the fluid inside the flow heater is assumed proportional to this voltage. The voltage U_H supplied to the power contactors is thus the actuated variable of the heat control.

If the measured fluid temperature at TC1 is higher than the temperature level of the process cooling (usually approx. 18 °C), the fluid can be cooled before it enters the flow heater. This is done by transferring heat from the fluid to the external process cooling circuit via a heat exchanger. Since the heat exchanger cannot be actuated directly, the heat transfer from the fluid to the secondary fluid in the process cooling circuit (water) is controlled by a valve. This valve is actuated electrically by applying electric currents from 0.004 to 0.02 A, altering the valve opening from fully closed to fully open. The valve opening degree influences the flow resistance for the secondary fluid which is driven through the valve by the line pressure. It thus determines the mass flow rate of the secondary fluid which directly influences the heat flow transferred from the (primary) fluid of the test bench to the secondary fluid. Hence the cooling of the fluid is controlled by the actuated variable U_C which represents the electric current applied to the valve of the process cooling.

The fluid pump is also actuated by an electric current with values in the range of 0.004 to 0.02 A. The value of the actuated variable U_P representing the electric current is applied to the variable frequency drive (VFD), which determines the driving power of the pump proportionally.

2.2 Control structure

The presented control concept fulfills several tasks: Actuation of the heating device, the process cooling valve and the pump in order to control the volume flow rate