# Control-oriented test bed for mobile air conditioning systems

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ABSTRACT: Model-based control schemes demand experimental investigations to derive a suitable model for control, tune the controller settings, and evaluate the controller performance. Especially with the increased usage of secondary loop refrigeration units, which allow for much more flexible control of the cooling operation, the urge to test sophisticated control schemes on hardware has risen drastically. Since experimental investigations of mobile refrigeration units during development are costly and sometimes not feasible due to incomplete hardware, this work presents a test bed for mobile refrigeration systems, particularly for evaluating controllers. The test bed stands out due to its simple, low-cost construction and the absence of environmentally harmful coolants. The test bed comprises multiple cooling units and a cooling chamber, enabling low-cost experiments for high-level temperature controllers. With a electric heater and a door spanning one side of the cooling chamber, it is possible to investigate the influence of door openings and other disturbance heat flows on the controller performance.

## 1 INTRODUCTION

The environmental damage caused by HFC refrigerants has led to increased research into more environmentally friendly refrigerants for mobile air conditioning systems. Propane (R290) as a coolant promises to be a viable alternative for this purpose and is already being used successfully in the industry (PBX 2023). However, due to the flammability of propane and the resulting safety hazards, additional measures are necessary to use this coolant for mobile refrigeration systems. One way to overcome this issue is to separate the coolant from the inside of the cooling chamber by a secondary cooling loop (Wang et al. 2009). Furthermore, such architectures offer the possibility of using the additional loop as a thermal energy storage. Due to the additional flexibility provided by the thermal storage in the operation strategy of the refrigeration unit, sophisticated model-based control schemes promise significantly lower energy consumption compared with conventional controllers (Shafiei & Alleyne 2015; Lösch 2022). Nevertheless, the implementation of such controllers in the industry is restrained by limited time, availability, and the high cost of experimental investigations on actual vehicles. However, numerous experiments are required to derive suitable models for control, tune the controller settings, and evaluate controller performance during the development of model-based controllers. Therefore, this work presents a test bed for supporting the development of high-level control schemes for mobile air conditioning systems.

In the following, the layout of the test bed and its analogy to a cooling system with a secondary loop is described in detail. Next, experimental measurements of the test rig are shown and discussed. Finally, the paper concludes with a summary and an outlook on the possible use cases of the test bench.

## 2 TEST BENCH DESCRIPTION

Fig. 1 shows a refrigerated vehicle equipped with a secondary loop cooling unit.

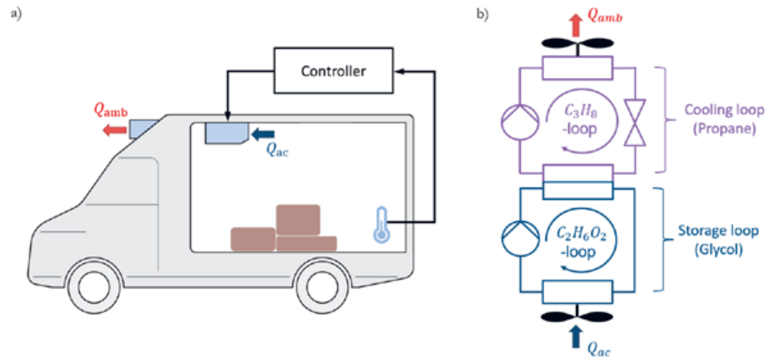


*Fig. 1: Scheme of (a) a refrigerated vehicle with (b) a secondary loop refrigeration unit*

The cooling unit under consideration has a cooling loop using propane as refrigerant and a storage loop filled with a water-glycol mixture. The cooling loop is a conventional vapor compression refrigeration cycle with a condenser, evaporator, compressor, and expansion valve. A pump moves the glycol through the storage loop, and the two loops exchange a heat flow via a heat exchanger on the evaporator side of the cooling loop. Fans attached to the condenser of the cooling loop and a heat exchanger connected to the storage loop increase the heat exchange with the environment $Q_{\text{amb}}$ and the cooling chamber $Q_{\text{ac}}$, respectively.

The temperature of the cooling chamber is controlled by a high-level controller, calculating the required heat flow of the cooling unit $Q_{\text{ac}}$. Note that the scope of this work and the test bench presented do not consider the low-level controllers of the individual components of the secondary loop cooling unit, such as control of the evaporator superheat.

The presented test bench is intended to replicate the dynamics of this configuration, referred to below as the original configuration, to experimentally test high-level temperature controllers for such vehicles and refrigeration units. For pictures of the test bed, see Fig. 2.

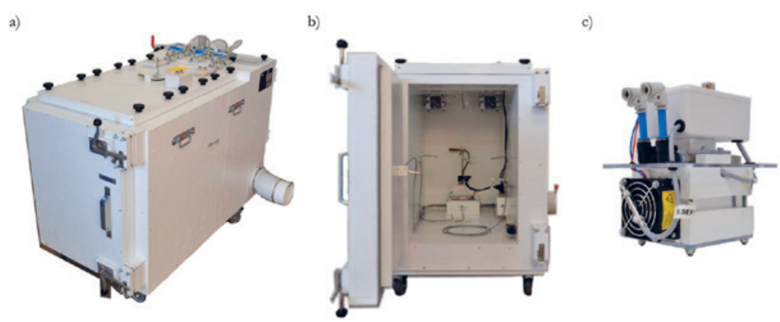


*Fig. 2: Test bed in (a) outside and (b) inside view, and detailed view of (c) a cooling unit*

### 2.1 COOLING UNIT

The cooling units used in this test bed are thermoelectric coolers. These are based on the Peltier effect and have the advantage of having no liquids or moving parts compared to the cooling unit of the original configuration, which both saves costs and extends the lifetime of the test bed. Since only higherlevel temperature controllers are to be tested and lower-level controls of the individual cooling components are irrelevant for the test bench, this simplification is justifiable. The test bed can be equipped with up to three cooling units. An illustration of an individual cooling unit with important measurement and control variables is given in Fig. 3.

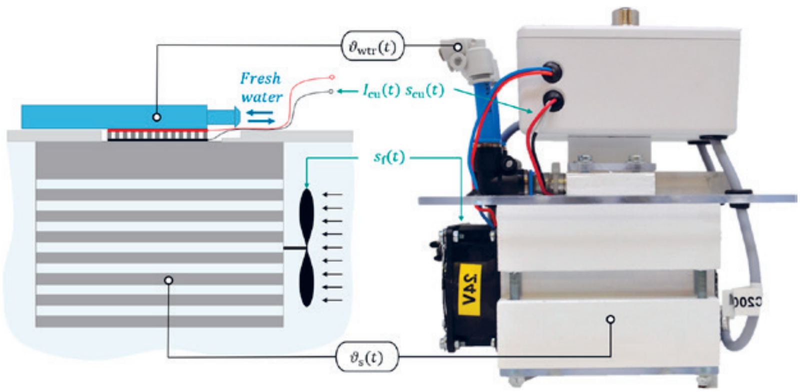


*Fig. 3: Illustration of one of the test bed's cooling units*

A heat sink is mounted on each side of the thermoelectric cooler. On the side of the cooler where the excess heat is dissipated, a water cooling block is installed, which is fed with fresh water with temperature $\vartheta_{wtr}$. On the other side of the cooler, a large air-cooled heat sink is installed with the temperature $\vartheta_s$. This heat sink emulates the storage loop of the original configuration, as it can also store thermal energy before it is transported to the inside of the cooling chamber. A fan mounted to this heat sink can evoke a heat flow by natural or forced convection to the air inside the cooling chamber. The status (on/off) of the fan $s_f$ can be freely selected for temperature control. Another variable for control is the current through the thermoelectric cooler $I_{cu}$, corresponding to the heat flow $Q_{ac}$ of the original configuration. Further, the control schemes to be tested can turn the cooling unit on or off by the variable $s_{cu}$.

### 2.2 COOLING CHAMBER

The cooling units are mounted to the roof of the cooling chamber, see Fig. 4.

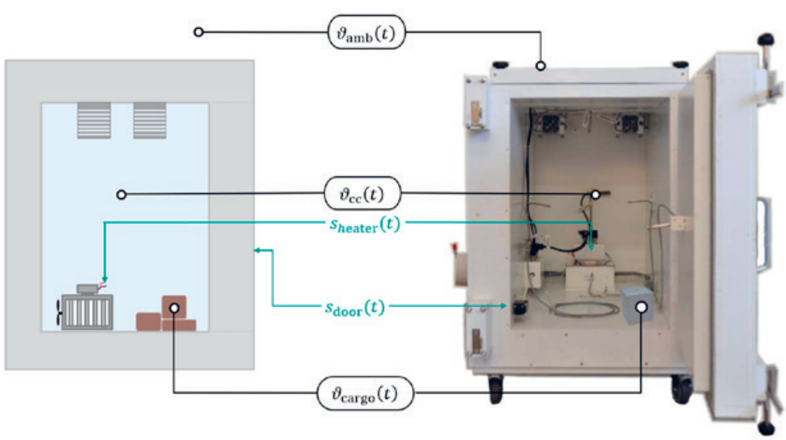


*Fig. 4: Illustration of the test bed's cooling chamber*

Insulated walls surround the cooling chamber, and one side of the chamber can be opened by a door. Door openings are detected by a sensor and indicated by the variable $s_{door}$. A heater is installed in the cooling chamber, which generates a disturbance heat flow when active, $s_{heater}$. This disturbance heat flow can later be used to test control schemes for disturbance rejection. Several sensors are installed within the chamber to measure the air temperature $\vartheta_{cc}$ of the cooling chamber. Optionally, cargo can be placed in the chamber. Its temperature can be measured, indicated by the variable $\vartheta_{cargo}$. These measurements make it possible to develop control schemes that regulate not only the temperature of the air inside the chamber but also the temperature of the cargo directly.

## 3 EXPERIMENTAL INVESTIGATION

This chapter describes experimental open-loop tests in which the controlled variables are set manually. In Fig. 5, a short experiment with a duration of 40 min is shown.

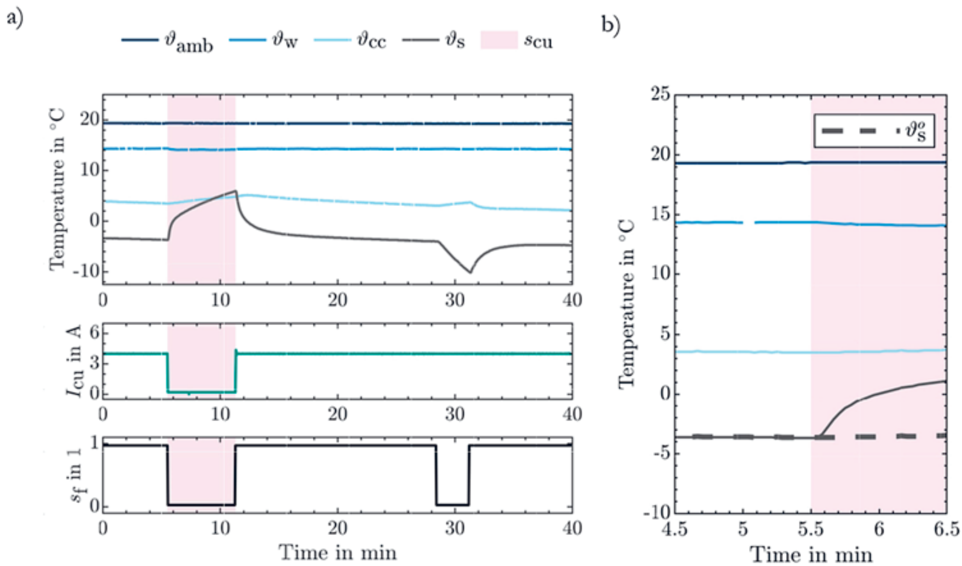


*Fig. 5: Experimental results and comparison to dynamics of the original configuration. The complete experiment is shown in (a), and a detailed view of the deviations from the test bed to the original configuration is given in (b).*

During the entire experiment, the door is closed, and the heater is switched off. In the interval highlighted in red, when the cooling unit is switched off, the temperature of the heat sink $\vartheta_s$ rises very quickly. These dynamics are due to the thin dimensions of the thermoelectric cooler. Therefore, there are high heat losses through the cooler to the water block by thermal conduction. When the cooling unit is active, these losses can be interpreted as operating losses, but when the cooling unit is off, these losses are undesirable and do not correspond to those of the original configuration. The heat conduction losses of the original system, when the cooling unit is switched off, are significantly lower, meaning that it can store thermal energy for much longer periods compared to the test bed. To obtain the same storage capabilities as the original configuration, an impedance controller compensates for conductive heat losses when the test bed's cooling units are switched off by inducing a current through the thermoelectric cooler, $I_{imp}$. This subordinate controller automatically becomes active when the cooling unit is switched off ($s_{cu}$=0), thus emulating the behavior of the original cooling unit with a secondary loop. The details of this impedance controller are described elaborately by Fallmann et al. (2023).

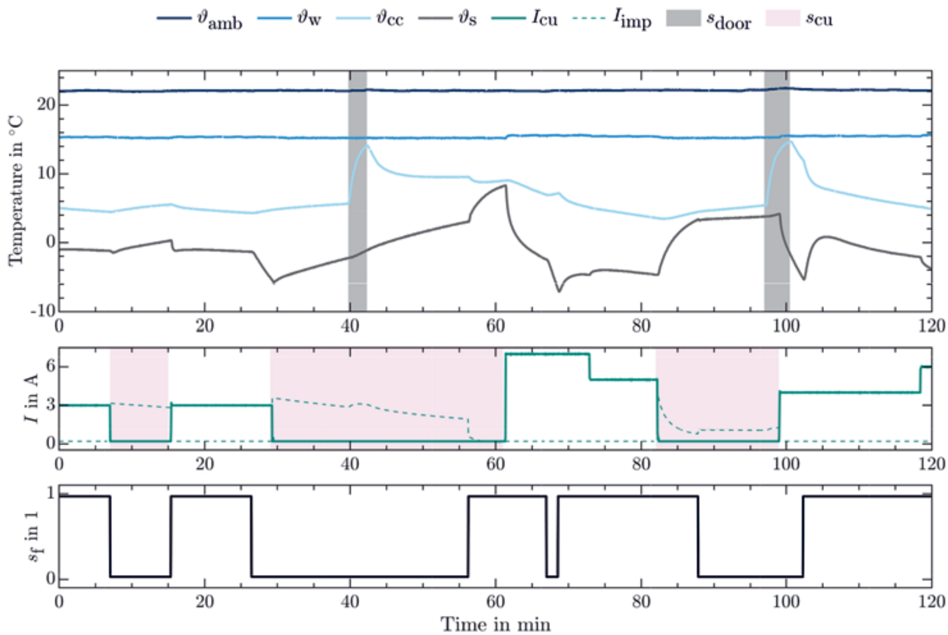


*Fig. 6: Experimental result of test bed with active impedance controller*

Fig. 6 shows experimental results with the impedance controller in action. When the cooling unit is turned off, the impedance controller becomes active and compensates for the conductive heat losses through the thermoelectric cooler. During this experiment, the door of the cooling chamber is opened two times (highlighted by gray background shading), resulting in a rapid increase of the cooling chamber temperature. In this experiment, the control variables of the current through the cooling unit $I_{cu}$, cooling unit status $s_{cu}$ and the fan status $s_f$ are prescribed manually. In the future, to evaluate high-level temperature controllers, the control schemes can set these variables to test their performance regarding, for example, setpoint tracking or disturbance rejection.

## 4 SUMMARY AND OUTLOOK

This work presents a test bed for evaluating high-level temperature controllers of mobile air conditioning systems. The test bench enables a comprehensive evaluation and comparison of controllers, which significantly supports the development of sophisticated control schemes. Especially for model-based optimal control schemes, such a test bed is essential to develop them cost-efficiently. Such controllers allow for flexible adjustment of the control targets, such as minimum energy consumption or strictly obeying temperature requirements. Therefore, this test bed can reduce the refrigeration industry's environmental burden by simplifying the development of new control schemes, which are currently hampered by unavailable or costly test equipment.

This test bed is also suitable for the development and testing of decentralized control schemes, as up to three cooling units can be installed inside the cooling chamber. Decentralized control has the advantage over centralized controllers that they generally require less computing power and can be used on less powerful computing units. Further, they are also operational if one cooling or computing unit fails.

Model-based control techniques also offer the possibility of incorporating predictions of future disturbance into the control law, which can significantly improve the performance of the control schemes. A control scheme that includes forecasts of future door openings in calculating the control variables has already been tested (Lösch 2023). These tests have shown that significant energy savings are possible by incorporating predictions of future disturbances into the control law compared with conventional controllers. Further research on similar control schemes will be investigated on this test bench.

Conventional controllers of mobile air conditioning systems typically regulate the air temperature of the cooling chamber, but direct control of the cargo temperature would be more reasonable. Due to the possibility of placing cargo inside the cooling chamber and measuring its temperature, such controllers can also be developed with this test bed.

Further, it can be utilized to develop high-level temperature controllers for other cooling applications, such as air conditioning systems for buildings or household refrigerators.

## LITERATURE

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