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Mobile climate chamber for thermal stabilization of machine tools and production environments based on energy-efficient and biological climate control elements

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Abstract
The demand for higher accuracy combined with an increase in productivity and energy efficiency requires the use of new and improved technologies in production, which is not limited to the area of a single machine. In addition to the necessary consideration of the entire value chain, above all the production environment is an essential component. The requirement for controlled climatic ambient boundary conditions can be justified with two examples. In the first example, changing ambient temperatures lead to greater thermally induced errors on the machine, which can be many times greater than those caused by internal heat sources (e.g. waste heat of motors, bearing friction). Secondly, a stable environment enables reliable quality control sample measurements and safe calibration of measuring equipment. According to the current state of the technology, stable room temperatures can be achieved on the one hand by expensive shop floor air conditioning, or on the other hand with the help of stationary climate chambers. Both methods require high investment costs and energy consumption for the necessary air conditioning technology. They are also location-bounded and dependent on the supply infrastructure. A mobile solution is an attractive way to make a decisive contribution to sustainability. The main challenge is to ensure functionality and reliable operation in connection with the mobile design (low weight, fast installation/dismantling, modularity). The other main focus would be sustainability and low energy consumption, therefore avoiding conventional air conditioning technology as much as possible. In this article, approach of utilizing a mobile climate chamber to overcome those limitations will be introduced and first measuring results will be discussed.

Cooling, Environmental, Measuring instrument, Thermal error

1. Introduction

In addition to the machine characteristics, the room climate (ambient temperature and humidity) is an important operating parameter in a production environment [1]. Normally, it is subject to the periodic fluctuations of a day-night cycle. Ambient temperatures of 10 °C to 40 °C are possible, depending on the geographical location. In summer, day-night fluctuations of 6 K - 10 K are common. For this reason, modern shop floors are elaborately air-conditioned [2]. Due to the large volume, large air mass flows are necessary, which must be provided by powerful air conditioning units with high energy consumption [3]. The corresponding energy (electricity, heating) is usually provided with the help of fossil fuels. An alternative to this is a mobile climate chamber in modular design, whose output can be scaled according to the volume requirements of the immediate production environment. This ensures that only the relevant area is air-conditioned. Due to the concept of a closed and tempered water circuit as heat transfer medium and the easily possible connection to a renewable energy source (e.g. photovoltaics, solar thermal modules, heat pump), the mobile climate chamber can be operated self-sufficiently at any time and even under rough environmental conditions. In order to meet the last mentioned challenges, the technology of passive air conditioning is to be used with the help of special EcoSyst®climate control elements [3]. There is no continuous exchange of air in the inner volume, but the heat is released very efficiently via thermal radiation on the rough surface of the climate control elements. The high heat capacity of tempered

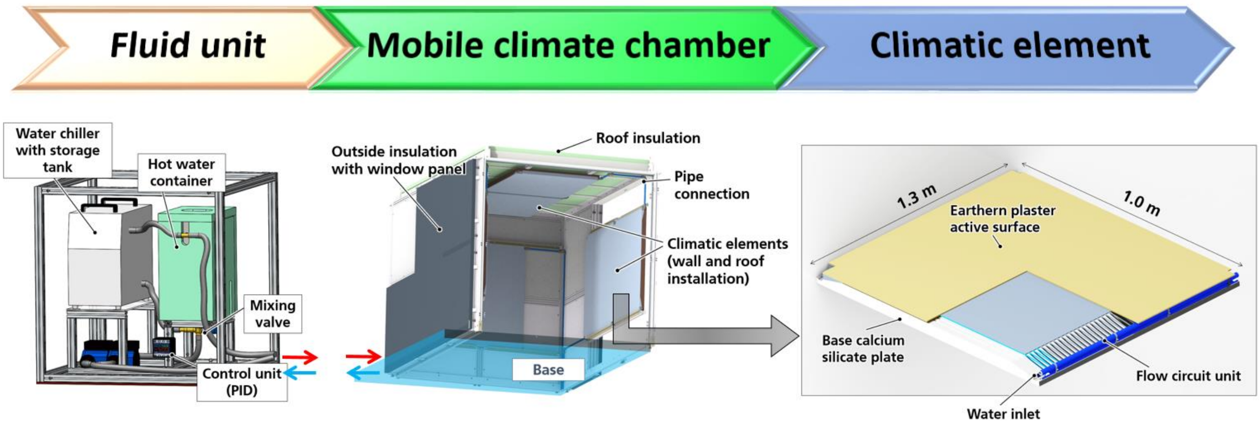

Figure 1. General overview of the main assemblies of the mobile climate chamber with EcoSyst®-climate control elements [3]

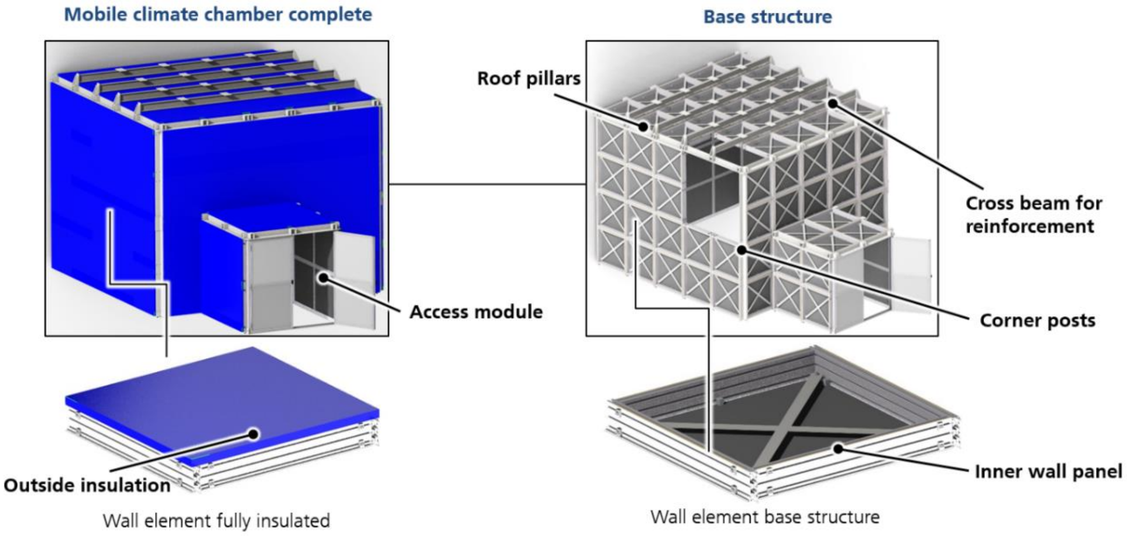

Figure 2. Base mechanical structure and external insulation

water, which flows through the climate control elements in a closed circuit, is used to transport the energy.

2. Design and operation of the mobile climate chamber

The mobile climate chamber has as its primary function the stabilization of a defined air temperature at a fixed value compared to the conventional ambient temperature fluctuations. This air temperature can be freely defined by the user, which is set by the climate chamber controller based on closed-loop control. Real-time monitoring is carried out by means of temperature and flow sensors close to the process, which provide the corresponding signals to the control module and the air-conditioning unit. A conceptual diagram of the main components of the mobile climate chamber is shown in Fig. 1. The greatest advantage of the entire system, apart from its modular design, is the division of the system into the climate chamber and the climate unit. Both systems are both scalable and linkable together as required. For example, several fluid modules can be connected in parallel to increase cooling or heating performance.

2.1. Modular design of the base structure

The base structure limits the space to be conditioned and isolates it from the global environment. The net volume is the product of the internal dimensions of width, height and length. Mechanical stability is ensured by the basic structure with corner pillars and reinforcing bars in the roof area. In each wall and in the roof area, wall elements with the unit size of 1 x 1 meters are placed and clamped. Each wall element acts as an insulating element and is provided with external insulation. The interior of the mobile climate chamber can be entered via a double-door lock. This can be placed anywhere outside the wall. If necessary, window elements can be placed anywhere, which are equipped with transparent panels on both sides. The mechanical structure of the chamber is shown in Fig. 2.

2.2. Room air conditioning technology

The room temperature is adjusted via passive air conditioning by heat absorption/ or emission from the surface of the climate control elements. The heat transfer takes place mainly by thermal radiation (approx. 80 %) and the other part by natural convection (20 %). The efficiency of the climate control elements could be proven by several experimental investigations (among others according to DIN EN 14037-5). A single air-conditioning element can dissipate or absorb a heat flow of up to 90 Watts with an effective temperature difference of 10 K. This performance is already achieved with a low volume flow of circulating water of 2.2 m^3/hr. There are no disturbing air streams (as in conventional air conditioning, where there is a continuous exchange of air) in the inner room [5]. Thus, expensive and energy-consuming air-conditioning devices such as fans, refrigeration unit and air filters are no longer necessary. For this reason, the room air conditioning is particularly

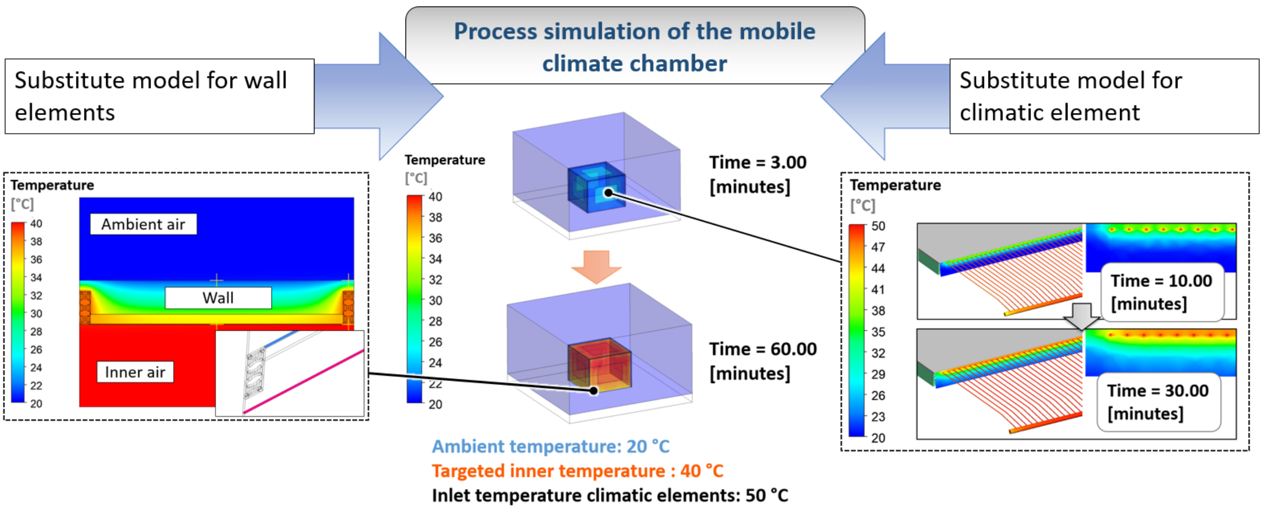

Figure 3. Representation of the thermal simulation models (wall, process model, climate control element)

environmentally friendly, since only minimal energy input is required and no emissions are produced. The air-conditioning elements are connected to a closed water circuit that provides the appropriate supply temperature. The water circuit is circulated with the use of an energy-saving pump. A coupled heating and cooling module ensures a stable water temperature. The required flow temperature is provided by a mixing valve and a sensor-controlled adjustment unit. A climate element has dimensions of 1.0 x 1.3 meters and has a earthern plaster layer on its surface, through which excess air humidity can be absorbed and subsequently stored in the hygroscopic calcium silicate base plate. Thus, the climate element additionally serves to stabilize the air humidity. The ability of passive air tempering coupled with sorption/desorption of water not only enables cooling below the dew point, but also stabilizes room humidity in a highly effective manner.

3. Simulation-based optimization in the development

The development and product optimization of the climate chamber and the climate control elements was substantially supported with the help of thermal flow simulations (CFD) and mechanical simulations (FEM) [4]. High-resolution simulations for thermal optimization (max. heat dissipation at the surface of the climatic element with acceptable pressure drop) were calculated, as well as complete process simulations of the entire climate chamber for thermal operating behavior. The mechanical stability was investigated and verified using structural mechanics (FEM), both with static self-loading and with possible wind load.

3.1. Thermal flow simulation (CFD)

The purpose for the thermal simulation is to study the operating behavior over time at different rates of temperature change. For this project, modeling was done in three sections, the latter being the overall process model of the entire mobile climate cell with ground and environment. Simplified surrogate models for the climate control elements and the wall structure were introduced in this model. The corresponding parameters for the surrogate models were obtained from the high-resolution partial models. The first partial model represents the complete climatic element. In this model, all flow channels of the tube sheet are mapped and meshed according to 3D volumes. The results of this partial model are the temporally mapped heat flows at the active surface. At the same time, this model is used for the design optimization of the climate control elements. Optimization calculations were able to show that the heat dissipation rate at the surface can be increased by up to 37 %. In parallel to the simulations, measurements were carried out on real climate control elements. The measurements were mainly used to validate the simulation model for the climate control elements.

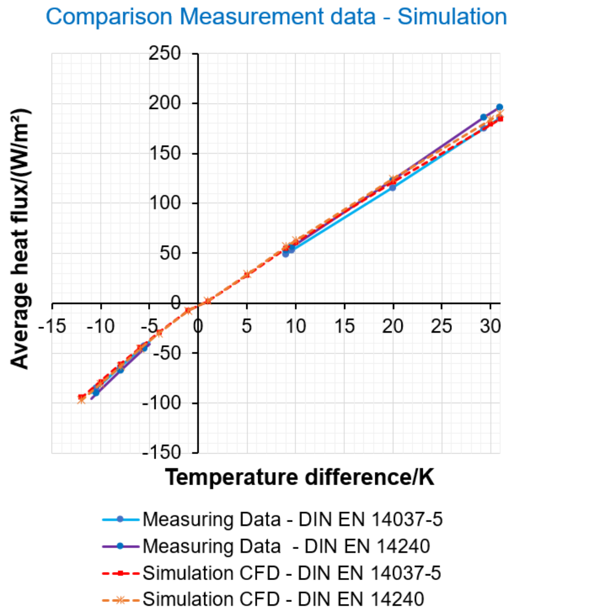

Figure 4. Comparison of simulation data with measured data for the climatic element

A comparison between the heat flows at the plate surface determined by measured data and the simulated average heat flows can be seen in Fig. 4. Both cooling tests (plate temperature < ambient temperature) and heating tests were performed and simulated. The second model is to simulate the heat transfer through the wall modules. In addition to obtaining substitute values for a simple wall substitute model (density, spec. heat capacity, thermal conductivity coefficient), the main objective is to evaluate the heat loss of the insulation (k-value). The two submodels wall and climate element, as well as the entire process model are presented in Fig. 3.

3.2. Experimental studies on the climatic element

In addition to the simulative investigations, real experiments were performed on the climate control elements in a stationary climate chamber. On the one hand, temperature measurements were carried out to determine the cooling behavior of the climate control elements, and on the other hand, sorption tests has been taken in the case of condensation. For this purpose, the climatic element was connected to a closed water circuit and flowed with water at constant temperature (6 °C). A cooling aggregate was installed for this purpose. The ambient temperature was stable at 20 °C and 30 °C. During the condensation tests, a precision weighing device was also used to measure the water stored and released during condensation as a change in mass over the time (see Fig. 5). During these tests, warm, humid air with up to 80 % humidity was present in the

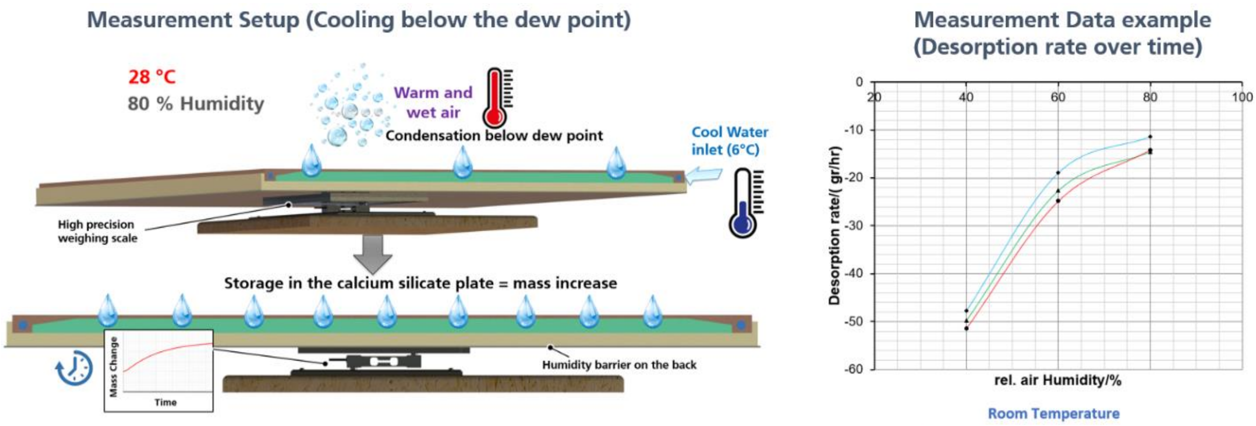

Figure 5. Measurement Setup for climatic elements for temperature and sorption experiments

measuring chamber. A supply temperature of 6 °C was set in the cooling circuit to ensure that the temperature fell below the dew point and condensation occurred. The measurement results show on the one hand a delayed cooling/heating behavior of the climate control element, which must be taken into account in the subsequent controllability (see Fig. 6). This is due to the mass and heat capacity of the climatic element (solid material). On the other hand, the high sorption/desorption rate of condensed water in this element is evident. The desorption rate is much more dependent on the humidity than on the ambient temperature (Fig. 5). The climate control elements ensure a passive stabilization of the air humidity. In addition, the climate element can store more than twice its own weight of condensed water.

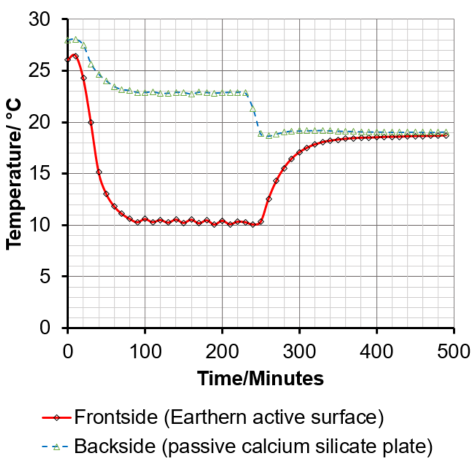

Figure 6. Heating/Cooling behavior of the climatic element

4. Possible applications of the mobile climate chamber

The mobile climate chamber is primarily used to create defined climate conditions for a variety of possible applications in the test field and in industrial production. The following application scenarios could be implemented with this product:

- Thermal testing and characterization of machines (e.g. mobile machines and machining centers)
- Creation of a test environment for measurement of components and workpieces (quality assurance)
- Temperature environment for calibration of measuring equipment, sensors or tools
- Continuous temperature tests for material testing
- Demonstration of a thermal measurement of a mobile machine at trade fairs
- Creation of defined climatic conditions in rough environments
- Use in the context of a robot-machine collaboration and subsequent quality testing (mobile climate cell with airlock as test room)

Ultimately, all areas in science and industry are possible fields of application where controlled ambient temperatures are required. An example of a possible application is shown in Fig. 7, in which a machine demonstrator is tested at different ambient temperatures as part of a scientific study [6].

5. Conclusion and Outlook

This paper describes the development and operation of a innovative mobile climate chamber, which is to be used and further developed within the framework of research projects. The first priority in the development and use is both sustainability and energy efficiency. For the development, high-quality components were selected, which are characterized by a high power density and reliability. State-of-the-art simulation tools were applied for the technological development. The effectiveness of the approaches and the planned assumptions could be confirmed both simulatively and by real measurements. On the real demonstrator, it could be shown that the climate control elements are suitable for room temperature regulation in the intended manner. The next steps would be mainly an improvement and optimization of the structure as well as a modern adapted control unit with a lot of functions. For the mass application, especially the further development regarding the cost reduction and the simplicity during the assembly is to be considered further.

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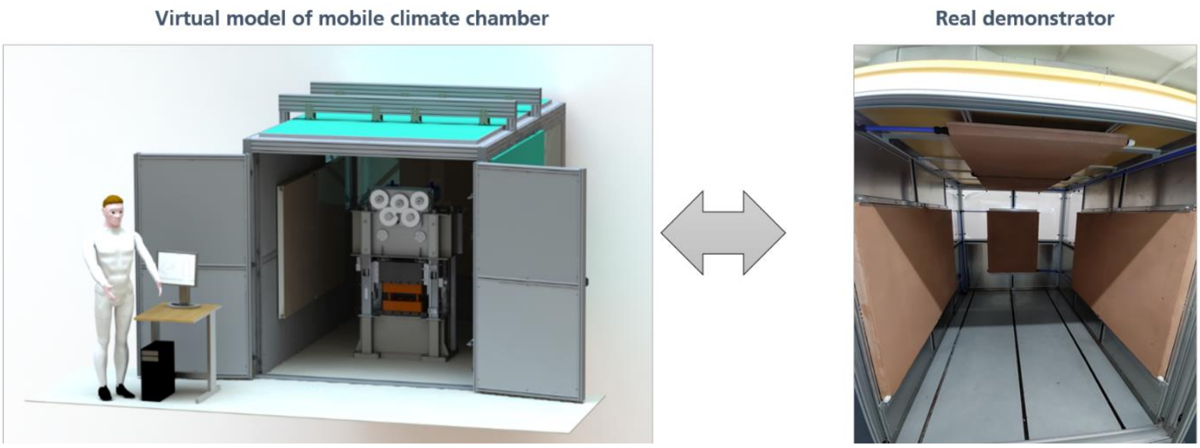

Figure 7. Demonstrator of mobile climate chamber with machine