

# Use of a radiator for user-centric cooling – Measurement and Simulation

Matthias Winkler<sup>1</sup>, Matthias Pazold<sup>1</sup>, Andreas Zegowitz<sup>1</sup>, Sabine Giglmeier<sup>1</sup> and Florian Antretter<sup>1</sup>

<sup>1</sup>Fraunhofer Institute for Building Physics IBP, 83626 Valley, Germany

**Abstract.** With further increasing temperatures during warm summers, cooling of buildings is becoming more popular even in moderate middle or northern European climate zones. Techniques that allow fast conditioning of rooms with intermittent usage, like conference rooms or certain types of residential rooms, promise high potentials for energy savings. Combining heat pumps, that can be used both in cooling and heating modes, with floor and wall heating systems can be a suitable technology. In many cases houses have a conventional heating system with radiators and the question arise if the oil or gas based heating system can be replaced by a heat pump. Mixed systems combining e.g. gas and a heatpump are also possible. For summertime cooling, the same system that is already installed for heating can be used and the radiators allow comparatively fast reaction times in theory. However, the system comes with potential shortcomings: Cooled surfaces increase the risk of condensation and mold growth significantly while higher surface temperatures decrease cooling power of the system. Also, the system's reaction times have to be tested in realistic conditions. For a first prove of the system's applicability a study with combined measurements and hygrothermal building simulations was performed. In a test chamber measurements of a system were conducted under controlled conditions. A simulation model in the hygrothermal whole building software WUFI® Plus was developed and validated with the measurements. The research shows that the simulation model is able to represent the effects on indoor climate as well as condensation reliably.

## 1 Introduction

Due to the rising temperatures caused by climate change, the need for active cooling of rooms is already rising sharply and will continue to increase in the future, even in countries where cooling units are not yet standard equipment in new buildings. According to a forecast of the International Energy Agency (IEA), the energy required for room cooling will triple by 2050 [1].

Preliminary investigations show that with the combination of interior insulation and heating systems the heating time of rooms and the resulting associated energy requirements can be significantly reduced [2]. This enables an intermittent building operation, which further reduces the energy demand. It is assumed that a similar added value can be seen in the intermittent, user-centric and demand-oriented cooling of rooms. In well-insulated rooms, short-term cooling can be an energy-efficient alternative to permanent conditioning, for example in meeting rooms in office buildings that are only used occasionally. However, there is a risk of mould growth if the room is cooled down quickly without actively removing the moisture produced.

One possibility for active cooling of rooms is offered by systems combining heat pump and surface cooling elements. Already established systems which are

currently only used for heating could in many cases be used for cooling in reverse operation - or at least after retrofitting at manageable cost. However, this system – using heat pumps for surface cooling – requires a close examination, as it is particularly demanding in terms of building physics, like most of the systems that contain surface cooling elements: The temperature on the surface of a chilled component must be sufficiently high above the dew point of the room air to prevent mould growth or even condensation. This means that the surface humidity should remain below 80 percent relative humidity, which in turn limits the cooling power of the element. To ensure efficient and damage-free cooling, the individual conditions of the cooled room must be taken into account when controlling the system and also reaction times have to be tested to evaluate the efficiency of the system.

To test the proposed system – combining heat pumps for cooling with established heat exchangers – and its thermal performance, its reaction time and the moisture conditions in a realistic framework, a study with combined measurements and hygrothermal building simulations were performed. This first study selected a radiator as heat exchanger, which is a typical system for German households and as such represents a practical use case for applying a cooling system in a retrofit. A simplified structure of the scenario described above (intermittent operation in a typical room) was measured in

\* Corresponding author: [matthias.winkler@ibp.fraunhofer.de](mailto:matthias.winkler@ibp.fraunhofer.de)

the laboratory and various values such as the amount of condensation produced, reaction times of the system and indoor climate were measured. In addition, the setup was also implemented as a model in a hygrothermal building simulation and validated on the basis of the measurements. This validated model then offers the option to determine the application possibilities and limits of the investigated cooling system depending on different building standards, climatic conditions and user behaviour in future studies.

## 2 Laboratory tests

### 2.1 Test chamber setup

To check the hygrothermal simulation and to assess the cooling capacity and condensation risk of radiant cooling systems, laboratory tests have been carried out. A climate simulator measuring 7.0 x 6.0 x 5.8 m (L x W x H) whose temperature can be controlled in the range from minus 15 °C to plus 55 °C was utilized. The relative humidity can also be controlled in the range between 10% and 95%. A detailed description of the climate chamber is found in [2], which details research regarding performance of interior insulation under intermittent operation in heating periods. The large climate simulator was constantly conditioned to 28 °C and 68% relative humidity for all tests to be performed in this study.

Within this climate chamber, a test room was built with the dimensions 4.38 x 3.87 x 2.7 m (L x W x H). It has two 'outer walls' (AW1 and AW2) on which the 28 °C of the large climate simulator act. The surfaces on the other two walls of the test room (IW1 and IW2) can be heated separately by heating mats to represent internal walls to adjacent heated rooms. Those internal walls were also set to constant 28°C. The entrance to the test room is located in the smaller of the two inner walls (IW1). The construction of the test room's components are described in detail in chapter 3.2.

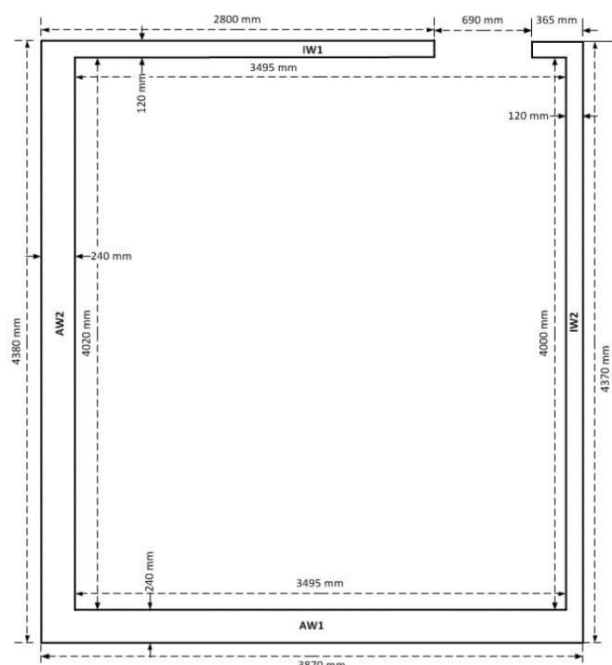
Figure 1 shows a look into the climate chamber with surface and room air measurement sensors and Figure 2 shows a look into the climate chamber towards the outside of the test room. A horizontal section through the test room including the internal and external dimensions, the wall designations and the position of the door can be seen in Fig. 3. The test room was also used to investigate interior insulations and to validate an interior long wave radiation model implanted in WUFI® Plus [2]. Therefore, temperature sensors are placed systematically on different positions in height and width on the interior and exterior surface of the walls and the floors. In total, there are 167 temperature sensors and 12 heat flow sensors.



**Fig. 1.** View into a corner in the test chamber



**Fig. 2.** Room in room system in the climate chamber. One outer wall of the test room in the climate chamber



**Fig. 3.** Cross-Section of the test room inside the climate chamber

For this study a radiator was installed inside the test room placed on the wall AW2 which was used as the cooling system. This radiation, or cooling wall surface, with a 0.72 m width and 1.00 m height has a painted metal surface. Chilled water can be pumped through attached insulated pipes from the outside through the radiator in a controlled manner.

## 2.2 Laboratory test description

The aim of this laboratory test was to measure reaction times, cooling capacity and condensation rates. As described above, the climate outside the test room was controlled to 28°C and 68% relative humidity. Regarding this, a time schedule was set with 8 different states. Four cooling phases with different cooling durations, 4, 8, 24 and 67 hours were defined. Between these phases, cooling in the room was shut off until the room reached its initial conditions (28 °C and 68% r.H.). After each cooling phase the condensation water on and below the radiator was collected and weighted. The cooling times, the set point temperature of the supply water pumped through the cooling radiator were recorded and are listed in Table 1. In addition, the impacts on the interior climate conditions inside the test room (temperature & relative humidity) and the surface temperatures at the sensor positions were recorded. The collected measurement data was used to validate the hygrothermal simulation model.

## 3 Simulation model

To scale the laboratory test to real buildings a simulation model is developed. The results of the measurement are used to validate the simulation model by reproducing the measured inner climate with the simulation with controlled and defined boundary conditions.

**Table 1.** Measurement setting.

Date/Time [h]	Time [h]	Supply-temperature [°C]
30.07.2019 09:30 to 30.07.19 13:30	4	14
31.07.2019 07:00 to 31.07.19 15:00	8	14
01.08.2019 11:00 to 02.08.19 11:00	24	14
02.08.2019 13:30 to 05.08.19 08:30	67	16

## 3.1 Hygrothermal simulation model and required extensions

For this study the hygrothermal whole building simulation model WUFI® Plus was used. This software is developed at the Fraunhofer Institute for Building Physics IBP. It couples hygrothermal component simulation [3] with a simulation of the indoor environment [4] and additional modules like dynamic and detailed HVAC-systems, dynamic simulations of 3D-objects like thermal bridges and an air flow model calculating the air exchange between zones and the environment. The simulation results of the hygrothermal building model are constantly checked and validated with both measurement data and appropriate standardized test procedures, as described in [5]. With its extension the simulation model also allows simulation of surface heating or cooling systems, like for example thermo-active building systems (TABS).

Up to now, the radiative heat exchange on surfaces was calculated by a constant radiative heat exchange coefficient from each surface to zone's air. This is a legitimate assumption, as the surface temperatures in buildings are often close to each other. If they differ more, for example with surface heating or cooling systems, a more in-depth calculation is necessary. This can be accomplished with a detailed calculation of the inner longwave heat exchange between the zone's surfaces [6] It allows a more detailed calculation of the interior radiative and surface temperatures, which also takes into account the radiation surface properties, like for example low-e coatings. Further benefits are a more comprehensive comfort assessment, like for example for asymmetric radiant temperature. Radiant temperatures can also be calculated for every position inside a zone.

In order to be able to represent component-integrated heating systems such as underfloor or wall heating, the hygrothermal component model used in the whole building model has been supplemented by a model for TABS (Thermo-Active Component Systems). Here, a certain nominal output of heating or cooling energy [kW] is transferred to a certain level of a certain component so that it can be used to heat or cool the room.

In WUFI® Plus, an opaque building component, i.e. a wall, a floor or a ceiling, is discretised into a variety of finite volumes. Individual layers of material are defined. With the coupled heat and moisture transfer, the building component model calculates, among other things, the heat transport between the individual layers or between the

individual finite volumes. The heat capacity of the material is taken into account. Enthalpy and moisture differential equations are discretised and solved at the finite volumes.

To solve this differential equation the enthalpy balance is established. The TABS model is added to the individual finite volumes (or individual areas in the cross section of the component) as heat source or sink. It inserts a pre-defined heat source or sink capacity into a finite volume or into a certain area in the one-dimensional component cross-section. Thus, this heat source has an effect on the whole component. Depending on the heat transport properties of the materials used, the heat is distributed further within the component, but is also exchanged with the interior climate and, in part, with the exterior climate via the inner and outer surfaces of the component. Due to the hygrothermal simulation, this heat source or sink does not only affect the temperature, but also the moisture distribution and enthalpy flow in the building component. Furthermore, whenever the conditions are met, condensation inside the component, but also on the component surfaces is simulated.

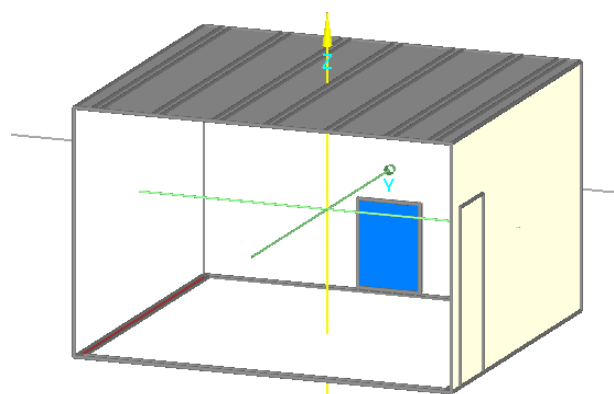
### 3.2 Climate chamber simulation model

The laboratory test room in the climate chamber, as described in chapter 2, was also built as computational simulation model in the whole building simulation software WUFI® Plus. Beside the test room dimensions, described above in Fig.3, the building components (walls, roof, floor), including their material layer assembly are modelled. Thermal and hygric material properties are chosen from available manufacturer's data and the WUFI® Material database.

The two outer walls have a thickness of 0.24 m state. They consist of three gypsum wallboards ( $\lambda = 0.316$ ) with a thickness of 0.08 m each. Attached, on the interior side there is a 0.04 m XPS interior insulation ( $\lambda = 0.034$ ) on both outer walls. This results in a U-value of 0.449 W/m<sup>2</sup>K. The interior walls consist of two gypsum wallboards. They have a thickness of 0.06 m and a U-value of 1.561 W/m<sup>2</sup>. The ceiling of the test room consists of two XPS rigid foam boards ( $\lambda = 0.032$ ), each 0.04 m thick, arranged one above the other. The lower board is continuous, the upper one is interrupted every 0.6 m by wooden beams on which a wooden board rests. This is used for safe walking on the ceiling. The average U-value of the ceiling is around 0.38 W/m<sup>2</sup>K.

The test room was used for previous studies that combined in-situ measurements with hygrothermal building simulations. Thus, a validated basic simulation model of this test room already existed [2]. The validated model was extended with the radiator that is used as the surface cooling system. Like described in chapter 2, a radiator with an surface of 0,72 m in width and 1,0 m in height is placed in the middle coherent in front of wall A2. This radiator is visualized and colored blue in Fig.4 showing the geometrical simulation model in the whole building simulation software. The component material assembly is modeled with a 0,03 mm thick metal layer, one side facing to the room itself and the other side facing

to the 'supply water': The average chilled water temperature is set on the other surface of this component as boundary condition. Concerning this, some cool down delay due to the heat capacity of the metal radiator is regarded.



**Fig. 4.** Simulation model of the test room in WUFI® Plus. The blue surface represents the radiator's cooling area

The simulation start and end time is chosen equal to the measurement. The first measured values are set as initial temperature and relative humidity of the interior air but also set for the components and their material to calculate the initial water content.

To reduce some uncertainties for this model validation some in situ measured temperatures are set directly in the simulation model. On the exterior surface of each wall, the average measured temperature for that wall during the measurement period is defined as boundary condition. However, the interior climate is simulated. The long-wave interior radiation balance is regarded for the interior surfaces.

## 4 Results and Discussion

To validate the hygrothermal whole building simulation model, the measured values from the laboratory test are compared to the values of the computational simulation. The results for the inner air temperature and relative humidity are shown in figure 5 and 6. The absolute humidity is shown in figure 7. For each course, the mean absolute error (MAE) was calculated, which is supplied with the figures.

In summary, the computational simulation can reproduce the measured values in the test room within the climate chamber in the course and in absolute values. Whenever a cooling period starts, the temperature drops quickly at the beginning, but slows down over time until the system has settled down. The course of indoor air temperature in Figure 5 shows the good agreement. After each measurement the door to the measurement room was opened, cooling was halted and the amount of condensate on the radiator and in the dripping pan was measured. These events are clearly visible in the measurement data. As a consequence, an increased air exchange between the measurement room and the climate chamber was also included in the simulation model during these times.

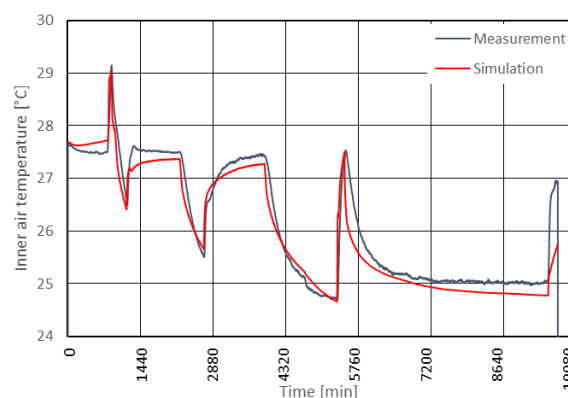


Due to the hygrothermal simulation, the humidity is also simulated including moisture storage effects of the room components. Absolute humidity in figure 7 shows good agreement between measurement and simulation. The same is for relative humidity, see figure 6. However, one effect is not considered in the simulation model so far: Whenever the chilled water flow turns on, the relative humidity of the interior rises up, because the condensation on the cooling surface hasn't started, but the air temperature falls down, resulting in that relative humidity increase. This increase is considered in the simulation in the absolute value of condensation quite well, but in the course over time, there is a longer delay in the measurement.

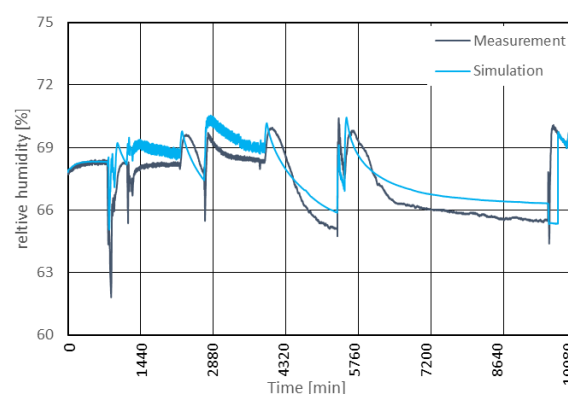
With an eye on figure 4, there is an increase in temperature to around 29 °C and a drop of humidity of more than 5% before the start of the first cooling period, which was not covered by measurement test description. It is not related to outdoor air conditions in the climate chamber, as the increase is higher than the conditions in the chamber. We assume a direct influx from outside the climate chamber as the source.

As mentioned in the laboratory test setup, at the end of each cooling period, the condensation water on and below the radiator was collected and weighted. The hygrothermal simulation also calculate the moisture flow at the radiator's surface, which is up at the end of each cooling period. Table 2 shows the result, comparing the weighted water in the laboratory test to the simulated condensation water. The four periods fit quite well comparing one simulation result assuming a completely mixed air, to a lot of measurements points inside the test room.

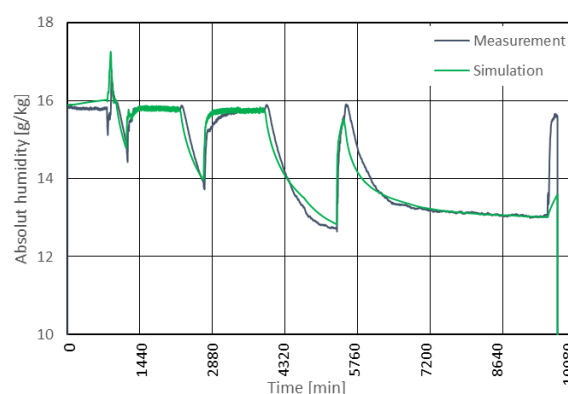
The measurements and simulation of a radiator, which is usually used for heating, show that it can also be used for cooling purposes. However, it has to be handled with care, as condensation issues can occur fast. For a practical use, the inlet water temperatures must be controlled in order to avoid condensation. Also the cooling system must be dimensioned accordingly to the room's necessary cooling loads. The tested setup featured a small radiator (0.72 m x 1.00 m) that was placed in a room with hot outdoor climate and surrounding walls with comparatively bad thermal insulation, especially the interior walls. The radiator was not able to fully cover the necessary cooling loads. Due to this, the radiator was only able to reduce the interior temperatures by around 2 K. In addition, the reaction times on the radiator itself were fast as it took about 30 minutes to reach the target temperature, see Figure 8. The effects on operative temperatures are only minimal and can be neglected in this study, which must also be attributed to the radiator's small size. However, this would be a major benefit of a fast reacting user-centric cooling system. Thus, the here described study must be seen as the beginning of a series of investigations that can now start with a validated simulation model.



**Fig. 5.** Inner air temperature: Comparison measurement and simulation (MAE: 0.23 K)



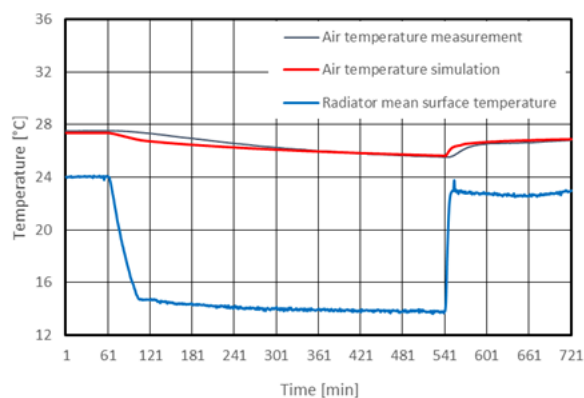
**Fig. 6.** Relative Humidity: Comparison measurement and simulation (MAE: 0.79 % r.h.)



**Fig. 7.** Absolute Humidity: Comparison measurement and simulation (MAE: 0.18 g/kg)

**Table 2.** Measured and simulated amount of condensation water on the radiator.

Time [h]	Measurement Condensation Water [g]	Simulation Condensation Water [g]
4	147,6	129
8	291	257
24	696,2	695
67	944,4	1044



**Fig. 8.** Detailed results of the 8h cooling period including measured and simulated air temperature together with radiator temperature.

## 5 Summary

Using heating systems for cooling in summer like it is possible with heat pumps in reverse mode is challenging specially if not underfloor heating systems are used for cooling but radiators. The advantage of radiators on the other hand is the fast thermal reaction. The measurement of cooled radiators in a demonstration room showed that a significant amount of condensation water has to be handled following this idea. With the hygrothermal simulation software it is shown that the effect of chilled water flowing through and cooling building components can be reproduced quite precise. The simulation is necessary whenever the cooling load in the building is high, and the chilled surfaces are small, because of the needed cold water temperatures. The risk of condensation and even the condensation water itself can be simulated accurately which allows designing buildings with a reduced risk of moisture issues.

The validated simulation model will be used to extrapolate the findings in a subsequent study. Therefore typical rooms in Germany and their construction and usage types will be represented as simulation models and the applicability of the proposed system will be tested. Then, potentials as well as limitations of the proposed

approach can be discussed on typical room and usage types with intermittent occupancy in Germany to rate the practical applicability of the proposed system. Also variations on the radiator surface areas or the cooling temperatures will be tested. This can also be used to develop automated control strategies for the proposed system in order to operate it without the risk of condensation. In addition, comparisons with existing cooling techniques must be conducted to identify benefits as well as shortcomings of the proposed reutilization of radiators for summertime cooling. This must also include the energy demand, which was not considered in this first study, yet.

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