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Chilled Water Wall

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Abstract

A new kind of air conditioning system called the chilled water wall was developed: A surface-cooling system that uses a chilled film of water flowing down on a vertical or sloped surface. In cooling/dehumidification mode, the system runs with surface temperatures well below the dew point of the indoor air. This results in combined cooling and dehumidification of the air in contact with the chilled water. The system can also be used as an air-humidifier in an alternative operation mode. In order to use the water wall in practice, its cooling and dehumidification respectively humidification capacity was determined by following two approaches: First, measurements of the specific cooling, dehumidification and humidification performance of a prototype under defined climatic conditions were carried out. The performance test is based on the protocol for testing and rating chilled ceilings. Second, a theoretical calculation model was developed, that considers the relevant heat and moisture fluxes to and from the surface of a water wall. It was successfully validated by measurements and coupled with the hygrothermal building simulation software WUFI® Plus. This allows a dynamic simulation of the water wall's hygrothermal interaction with a room's indoor climate and its assemblies. With the dynamic model, a simulation study was executed to investigate the impact of the water wall on the indoor climate of an office building with varying room layouts and occupancy profiles. The cooling effects were examined for single and team offices. The simulations were used to determine the necessary surface area of the chilled water film.

Keywords – surface cooling; chilled water wall; WUFI® Plus; building simulation;

1. Introduction

A new kind of air conditioning system called the chilled water wall was developed: A surface-cooling system that uses a chilled film of water flowing down on a vertical or sloped surface, see Fig. 1. The water temperature is controlled by a cooling unit which is placed outside the conditioned zone. The system typically operates at temperatures below the indoor air dew point. Therefore, moisture in the air condenses onto the water film from where it is discharged into the water basin, which collects the excess water. Thereby, a combined cooling and dehumidification of the surrounding air is possible. This opens a broad field of application for the chilled water wall in comparison to other surface cooling systems, like for example chilled ceilings. The system can also be used as an air-humidifier in an alternative operation mode. Therefore, the water temperature is controlled above the indoor air dew point.

In order to use the water wall in practice, its performance must be known. Two approaches were followed to determine its cooling and dehumidification respectively humidification capacity: Measurements on a prototype under standardized climatic conditions and the development of a calculation model. Both approaches are described in this paper. The calculation model is also included in the hygrothermal building simulation software WUFI® Plus. This allows a dynamic simulation of the water wall's hygrothermal interaction with a room's indoor climate and its interior surface materials.

The dynamic building simulation model was used in a simulation study, where selected zones in an office building were designed to be conditioned with water walls. On the basis of the calculations the cooling effects are described and the necessary water film surface area is determined.

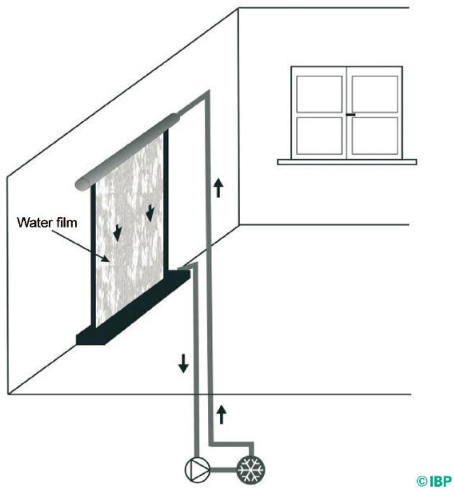

Fig. 1 Schematic diagram of a chilled water wall [6]

2. Measurements

For the measurements a prototype of a chilled water wall was used, which was supplied by a licensed manufacturer. The prototype was placed in a testing room and all relevant climate parameters indoors and outdoors as well as the operation specifics of the water wall were recorded. This includes relative humidity, air and radiation temperatures in the middle of the testing room as well as the temperatures of all indoor surfaces. At the prototype, water temperatures were measured in the basin and at the top and bottom of the water film. Together with the water flow rate, the cooling power was thus determined. Water overflow caused by air humidity condensing on the water film was directed to a recipient and its quantity was recorded. All sensors were calibrated and continuously checked during the measurements. Furthermore the testing room's temperature and humidity were controlled by radiators and air humidifiers.

The test procedure was inspired by DIN EN 14240 [4], which describes the testing and rating of chilled ceilings. To determine the cooling and dehumidification capacity, the room's air temperature was kept constant at 26 °C and the surface water temperature was varied stepwise between 2 °C and 18 °C. The tests can be divided in two main series: First, only the sensible cooling performance was determined by setting the indoor air dew point to the same temperature as the water film. This means neither condensation on, nor evaporation from, the water film can occur. In the second test series the combined cooling and dehumidification performance of the chilled water wall was measured. The same levels for air and water film temperature were used, as in the first series. In addition the relative humidity in the testing room was controlled at three set points: 40 %, 60 % and 80 %.

Performance diagrams for the specific cooling and dehumidification capacity were determined from the measurements, see Fig. 2. They can be used to design the necessary chilled water surface area as function of its operating temperature following currently used standards for the dimensioning of chilled ceilings, like DIN EN 1264 [3].

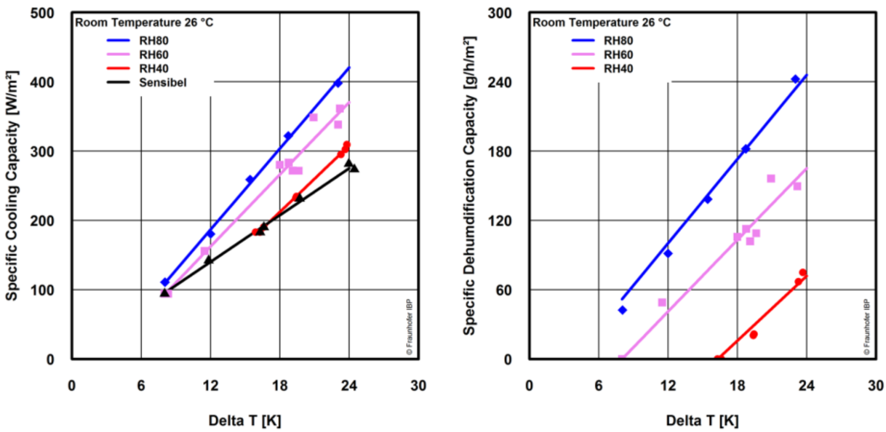

Fig. 2 Measured specific cooling (left) and dehumidification capacity (right) of the water wall prototype.

3. Model

In addition to the measurements, a model was developed that describes the combined heat and moisture exchange of the water wall with the ambient climate. Depending on the wall's geometry, its water temperature and the ambient climate conditions, the moisture flows (m_w) are calculated together with the radiant (Q_{rad}), convective (Q_{conv}) and latent (Q_{lat}) heat flows. Thus, the total heat flow (Q_{tot}) is calculated as in (1):

$$Q_{tot} = Q_{rad} + Q_{conv} + Q_{lat}. \quad (1)$$

The radiant and convective heat flows per surface area A_{CF} are calculated by multiplying the respective heat transfer coefficients with the temperature difference $\Delta\vartheta$ between the water film and the air temperature, see (2) and (3). The radiant heat transfer coefficient can be estimated with a constant value of h_r = 5.5 W/m²K for this kind of cooling system [8]. For the calculation of the convective heat transfer coefficient h_c both free and forced convection have to be considered [10]. This can be estimated by using Churchill's' correlation [2].

$$Q_{rad} = h_r \cdot \Delta\vartheta \cdot A_{CF} \quad (2)$$
$$Q_{conv} = h_c \cdot \Delta\vartheta \cdot A_{CF} \quad (3)$$

The latent heat flow is calculated by multiplying the moisture flow m_w with the enthalpy of vaporization h_v, as in (4):

$$Q_{lat} = m_w \cdot h_v. \quad (4)$$

The moisture flow is calculated from the difference Δp between saturation vapour pressure at the water surface and the room's vapour pressure, see (5). The mass transfer coefficient β can be derived from the convective heat transfer coefficient by applying the analogy of the laws of Fick and Fourier [9].

$$m_w = (\beta \cdot P_{atm} \cdot \Delta p) \; / \, (R_D \cdot \Delta T \cdot (P_{atm} - p_s(t_{CF}) \,) \cdot A_{CF}. \quad (5)$$

The measurements described in section 2 were used to validate the model output. Fig. 3 shows a comparison of the modelled and the measured specific cooling and dehumidification capacity, with a good agreement between the measured and modelled data.

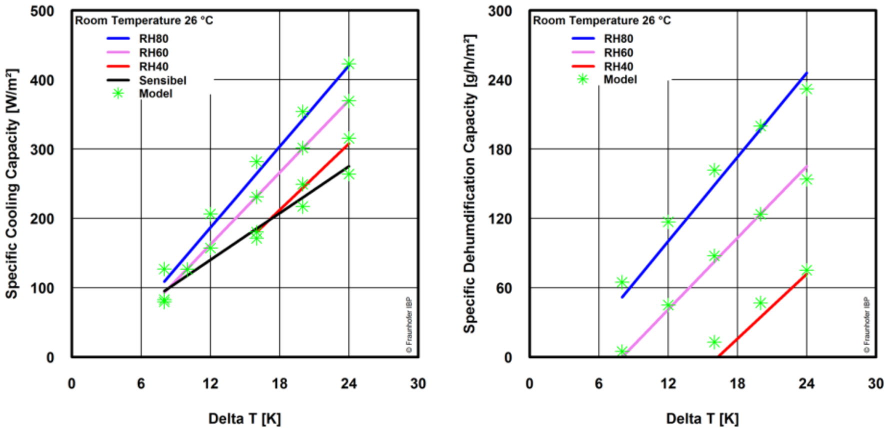

Fig. 3 Comparison of modelled (green colour, star-shaped) and measured specific cooling (left) and dehumidification capacity (right).

The validated model has been included in the hygrothermal building simulation software WUFI® Plus, where it can be selected as an additional HVAC-component. This allows a dynamic simulation of the water wall and its interaction with a room's indoor climate and its interior surface materials. Two optional extensions to the previously described model were added: The heat conduction through the construction behind the water film can be considered. Furthermore, the calculation of the radiant heat flow can be replaced by the more precise calculation of the interior longwave heat exchange. Within the software, the geometry and position of one or multiple water walls in a zone can be entered. Furthermore, the operating hours and the water surface temperatures can be defined individually for each water wall system.

4. Simulation Study

A simulation study was performed to investigate the impact of the water wall on a specific application case: For the retrofit of an office building, the cooling of selected zones should be realized solely by using chilled water walls. The dynamic model implemented in the hygrothermal building simulation software WUFI® Plus, see section 3, was used to compare different variants of chilled water surface area and to predict the resulting indoor climate. Based on the simulation results, recommendations for sizing the chilled water walls in the considered zone are given.

4.1 Building

The examined building consists of two floors. It was constructed in the early 1980s and first used as an assembly hall and depot. Later, parts of the upper floor were converted into offices. In the upcoming retrofit, these office areas will be renewed and mainly used as single and team offices and a conference room. The new installed ventilation system will be limited to keeping up the minimum required air change for hygienic conditions and contains no component for air conditioning. On behalf of the owner, only selected zones should be conditioned during the summer months by using chilled water walls: The single offices (S1 – S6) and the team offices (T1 & T2). They are highlighted in colour in the floor layout of Fig. 4. In this paper, only the results of two characteristic zones are presented: Single Office S6 and Team Office T1. The building envelope remains unchanged during the retrofit. Exterior and interior assemblies that are relevant for the simulations are summed up in Table 1.

Table 1. Assemblies

Type	Construction	U [W/m²K]
Flat Roof	Corrugated metal & insulation	0.31
Exterior Walls	Aerated concrete	0.52
Windows	Frame 30%, g = 0.6, no shading	1.30
Opaque Partition Walls	Drywall	0.36
Transparent Partition Walls	Glass	5.48
Floor	Floor on steel construction	0.72

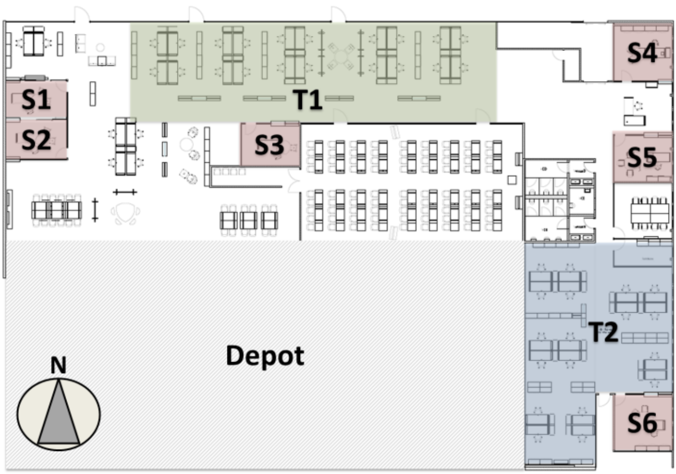

Fig. 4 Layout of the office floor. Zones with application of water walls are highlighted in color.

4.2 Boundary Conditions

As outdoor climate, the test-reference year 2004 with extreme summer of Kassel, Germany, was used. It is representative for the location of the considered building. All simulations cover a timespan of one year. The highest values for outdoor temperatures and solar radiation are in the months of June to August, therefore this period is used to predict the maximum cooling loads.

The investigated zones are used as single and team offices. Their occupancy profiles correspond to DIN V 18599-10 [5]: The building is occupied Monday to Friday, from 07:00 am to 06:00 pm. During these times internal loads from people and office equipment are scheduled as described in Table 2 [1] [7]. Outside these hours and on the weekends, no internal loads are considered.

Table 2. Internal Loads

Zone	**Occupancy**	**Heat Convective [W/h]**	**Heat Radiant [W/h]**	**Moisture [g/h]**
Single Office S6	1 Person	138	79	81
Team Office T1	20 Persons	2760	1580	1620

4.3 Single Office

A comparison of all single offices showed, that room S6 has the highest cooling demand. It has one exterior wall that consists mostly of a bank of windows and is oriented eastwards. The other walls adjoin rooms with adiabatic indoor climate. The ventilation system operates with a constant air change of 100 m³/h, which can be scaled up to 500 m³/h for increased night ventilation. This single office has a volume of 65 m³.

On behalf of the owner this zone should be conditioned by only using water walls, each with one chilled water surface of 1.20 m x 2.30 m. For the simulations, a constant water temperature of 2 °C is assumed. The operating hours of the water walls are Monday to Friday, from 06:00 am to 07:00 pm.

In the simulations three variants are compared: No cooling, application of one water wall and application of two water walls. Table 3 summarizes the main results for the indoor air temperature. The maximum air temperature in the zone can be reduced by 4.2 K to 6.8 K compared with the variant without water walls. Also the overheating degree hours, which are calculated above a set temperature of 26 °C, can be reduced significantly. DIN V 18599-10 suggests that the monthly mean temperature should be below 24 °C for office buildings during the usage hours. Both variants with water walls stay below this threshold, in contrast to the case without conditioning.

The simulations showed that this single office needs additional cooling. The variant with one water wall (1.20 m x 2.30 m) is sufficient to maintain the required temperature conditions during most times of the extreme summer climate: The set temperature of 26 °C is exceeded only during 3% of the office’s usage hours.

Table 3. Simulation results for zone “Single Office S6”

Variant	Maximum air temperature [°C]	Overheating degree hours [K*h/a]	Monthly mean temperature [°C]		
			June	July	August
No Cooling	32.4	547.2	24.0	25.9	24.9
1 Water Wall	28.2	65.8	22.2	23.5	22.6
2 Water Walls	25.6	0	21.0	21.9	21.2

4.4 Team Office

Team Office T1 is located on the northern side of the building, where its exterior surface is a glass façade. On its interior sides, this zone is bordered by a conference room and open space areas. Altogether it includes a volume of 710 m³. The ventilation system operates with a constant air flow rate of 400 m³/h. During summer, increased night ventilation with up to 1600 m³/h can be activated.

The water walls have the same geometry as in the single office described in the section before. They also operate on the same water temperature (2 °C) and time schedule (Monday to Friday, 06:00 am to 07:00 pm).

In a first draft, the building owner suggested to use six chilled water surfaces of 1.20 x 2.30 m each. In addition, variants with ten and 14 chilled water surfaces will be investigated, as well as a variant without cooling. Table 4 summarizes the main results for the indoor air temperature. For the variant without cooling, the maximum temperature is 35.7 °C. It can be reduced by the application of water walls by up to 7.2 K. The overheating degree hours can also be reduced significantly, as well as the monthly mean temperatures. The simulations indicate that six water walls are not sufficient: The overheating degree hours could be reduced by 63%, but they remain at a high level. Also the monthly mean temperatures are above 24.0 °C in the three relevant summer months. To investigate the distribution of air temperature its time above the three setpoints 26 °C, 28 °C and 30 °C was counted, see Fig. 5. The time of high temperature events can clearly be reduced by all variants with water walls, when compared with the case without cooling. With 10 water walls, the set temperature of 26 °C is exceeded during 5 % of the yearly usage time, which is an acceptable value. The variant with 14 water walls showed the best cooling performance, which can be seen in the simulation results, where 26 °C is exceeded during 2 % of the yearly usage time and all monthly mean temperatures are below 24 °C.

The simulations demonstrate that cooling is necessary for this team office. Six chilled water surfaces, as suggested by the owner, are not capable of conditioning the air temperature within acceptable limits. Therefore at least 10 water surfaces, each 1.20 m x 2.30 m, are necessary. With this variant, high temperature events can be reduced significantly. Even though the monthly mean temperature in July exceeds the recommended value of 24.0 °C by 0.5 K, this variant can still be recommended, as the other indicators are within acceptable limits. 14 water walls provide the highest cooling power and are able to keep the air temperature below the assessed indicators. The disadvantage of this variant is its high space requirement. Thus, the variant with 10 water walls was recommended for realization.

Table 4. Simulation results for zone “Team Office T1”

Variant	Maximum air temperature [°C]	Overheating degree hours [K*h/a]	Monthly mean temperature [°C]		
			June	July	August
No Cooling	35.7	1550.4	26.4	28.3	27.0
6 Water Walls	32.0	572.3	24.2	25.8	24.7
10 Water Walls	30.3	229.7	23.1	24.5	23.5
14 Water Walls	28.5	45.6	22.2	23.4	22.4

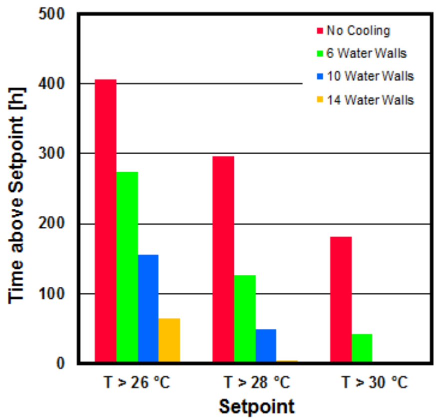

Fig. 5 Time above air temperature setpoints for zone “Temp office T1”.

5. Conclusion

Through this study, the cooling and dehumidification respectively the humidification performance of the chilled water wall could be determined both with measurements and with a calculation model. Its measured maximum specific cooling capacity of 420 W/m² is more than four times higher than common chilled ceilings. The surface temperatures of chilled ceilings have to be controlled above the dew point of the indoor air, what limits their cooling performance. As the water wall isn't bound to this restriction, the difference in cooling capacity between these two systems will even be higher in practice. It can also be used for alternative purposes, for example to create local cooled areas in an unconditioned zone or for air humidification during dry winter months.

The developed tools will support manufacturers and engineers with the design and optimization of chilled water walls in future projects. The measured performance diagrams of specific cooling, dehumidification and humidification performance can be used for a quick layout and static calculations that are applied in current standards for the design of surface cooling systems, like for example EN 1264. The validated model was implemented in the hygrothermal building simulation software WUFI® Plus. This allows a more detailed approach with a dynamic simulation of the transient heat and moisture fluxes of the water wall and the building, its usage and other HVAC components. The model's application was shown in a simulation study of an existing office building: There, the cooling performance of different sets of chilled water walls was determined and it was demonstrated how the tools that were developed for this study can be used in the design process.

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