The Role of Ventilation
15th AIVC Conference, Buxton, Great Britain
27-30 September 1994

Standardised Measurements of the Cooling Performance of Chilled Ceilings

F Steimle, B Mengede, K Schiefelbein

Universität Essen, Angewandte Thermodynamik und Klimatechnik, Universitätstr.15, 45141 Essen, Germany

Synopsis

One important aim for the development of new air conditioning systems is the reduction of the total energy consumption. This can be reached by separation of cooling and ventilation in air conditioning systems, because it is more effective to transport energy by using water systems instead of air to deliver cooling energy to the consumers. This strategie was the base for the development of several chilled ceilling systems during the last years, so that at present there are many different systems on the market.

One problem during the design period is to calculate the cooling performance of these systems depending on different operating conditions. So it is necessary for the companies to find characteristic data to describe the heat transfer of these elements. But an objective comparison of different systems and an accurate planning is only possible, if these data were investigated under comparable boundary conditions. Parallel to the Germany standard organisation (DIN) the working group "Heating and cooling surfaces" of the German FGK e.V., in which the leading manufacturing, planning and installation companies of chilled ceiling systems are represented, had outlined a guidline to guarantee standardized measurements under clearly defined boundary conditions. It is planed to discuss the main aspects of this guideline and the conditions for measurements of the cooling performance of open convective chilled ceiling systems.

List of symbols

A_a	[m^2]	active surface of the investigated chilled ceiling
C		regression coefficient
ε	[-]	emission coefficient
k_0	[W/m^2]	heat transfer coefficient from heat carrier to the surface
$\dot{M}$	[kg/s]	massflow of distribution medium
n		regression coefficient
$\dot{q}$	[W/m^{2}K]	heat-flux density
$\dot{q}_a$	[W/m^{2}K]	heat-flux density with structured surfaces
$\dot{q}_b$	[W/m^{2}K]	heat-flux density with closed surfaces
$\dot{Q}_H$	[W]	simulated cooling load
t_a	[°C]	ambient temperature
t_i	[°C]	initial temperature of the heat distribution medium
t_r	[°C]	return temperature of the heat distribution medium

t_A	[°C]	air temperature inside the testing chamber
t_R	[°C]	room temperature inside the testing chamber
t_0	[°C]	surface temperature at the chilled ceiling modul
$t_{0,m}$	[°C]	mean temperature at the surface of the chilled ceiling
Δt_0	[K]	logarithmic temperature gradient between surface and heat carrier
Δt_R	[K]	logarithmic temperature gradient between room and heat carrier

1. Introduction

During the last years the reduction of energy consumption in building became one of the most important aim for the development of new technologies. A significant share of energy consumption in non-residential buildings bases on the requirement of cooling and air conditioning. Due to energy saving issues its nessecary to develop new air conditioning and cooling strategies, which lead to an continious reduction of energy consumption.

One possible starting point for the development of these systems is the separation of cooling and ventilation in air conditioning systems, because it is more effective to transport energy by using water systems than to use only air to deliver the cooling energy to the rooms. This strategie was the basic for the development of hybrid systems. By using these systems, it is possible to reduce the ventilation rates to the minimum, which ensures dehumidification and guarantees an satisfying air exchange due to hygenic aspekts. The part of sensible cooling can be delivered to the room by induction-coil, heat exchangers with free convection or chilled structural elements in the room like chilled ceilings.

During the last few years many chilled ceiling systems were developed and in Germany they are nowadays often installed in combination with ventilation systems, which guarantees the necessary ventilation rate. The chilled ceilings can be installed as well in new as in retrofit comercial buildings. At the begining of this period, there was no guidline or technical standard available, which regulates or standardizes the measurement of cooling performance of chilled ceilings. So sometimes the given characteristic date for the design of these systems were related to different operating parameters like room temperature or mean temperature of the cold water, which is mainly used as transport medium to distribute the cooling energy within the building. Also it was possilble, that given data of cooling performance varied within a wide range for systems with nearly the same structure and design.

An accurade planning of these chilled ceiling systems during the design period and an objective comparison of different systems is only possible, if the characteristic data for the description of heat transfer and cooling performance were investigated under comparable and clearly defined boundary conditions. The demand of such a guidline, which guarantees an ojektive comparision of the cooling performance of different chilled ceiling systems, was recognized by the German FGK e. V., in which the leading manufacturing, planning and installation companies are reperesented. The workinggroup, which handels with "heating and cooling surfaces", had outlined a guidline, which guarantees the measurements of cooling performance of chilled ceilings at clearly defined boundary conditions.

2. Testing chamber and conditions for measurements

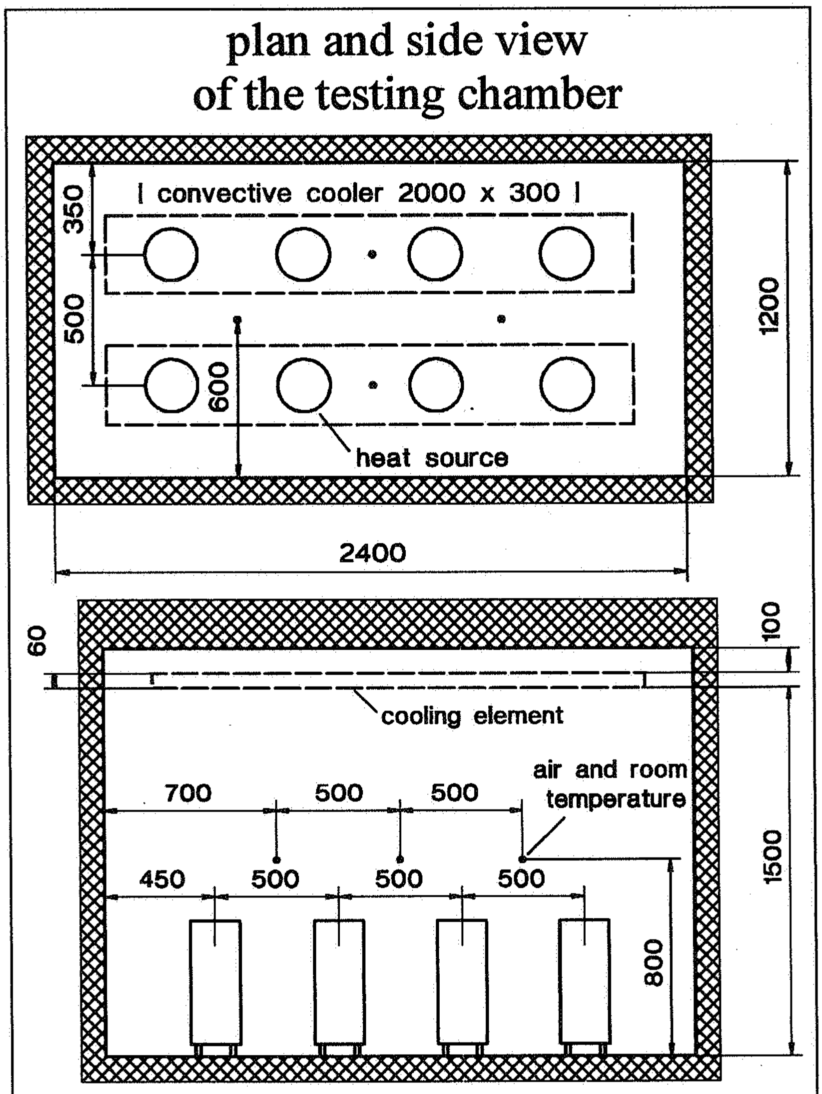

fig. 1

Chilled ceilings are installed in spaces with dimensions in a wide range. In practice chilled ceiling elements with fixed dimensions are combined to large surfaces. So a uniformed measurement is only possible at this ceiling elements, which are normaly available for only a few dimensions and applications as prefabricated moduls. The testing facility, that are explained in the guidline of the FGK e. V., bases on thermal measurements at these chilled ceiling elements with closed or open surfaces in a testing chamber as shown with plan and side view in fig. 1.

This chamber has to be built with a inside length of 2.4 m and the inside width has to be 1.2 m. The chilled ceiling elements must be installed with a vertical clearance of 1.5 m. All elements of this testing chamber have to be well insulated. The thickness of insulation with a thermal conductivity less than 0.04 W/mK must be more than 0.1 m for walls and floor, for the ceiling the thickness has to be more than 0.2 m. The emission coefficient ε of the inside surfaces of the chamber must be higher than 0.9. Also it must be possible, that air circulates around the chamber while the temperature diffenence between the ambient air and air inside the testing chamber has to be less than 1 K. The reference temperature inside the chamber is the so called room temperature, which will be measured by a temperature sensor inside a black ball (diameter of 35 mm). For the investigation of cooling performance the share of active cooling moduls with closed surfaces has to be more than 70% of the total ceiling of the testing chamber. The rest of the surface has to be closed with a insulation material. The shown installation in Fig. 1 with two convective coolers (2000 x 300 mm) is not provided in this guidline. The cooling load will be simulated by 8 clearly defined cylindrical heat sources with a black surface ($\varepsilon > 0.9$).

In this testing chamber a lot of sensors have to be installed to get knowledge about the operating conditions of the chilled ceiling modules and the temperature distribution inside the testing chamber. The following list shows the variables and the allowed uncertainty of measurements.

measurement variable	unit	symbol	uncertainty of measurement
room temperature inside the testing chamber	[°C]	t_R	± 0.1 K
air temperature inside the testing chamber	[°C]	t_A	± 0.1 K
surface temperature at the chilled ceiling modul	[°C]	t_0	± 0.1 K
initial temperature of the heat distribution medium	[°C]	t_i	± 0.1 K
return temperature of the heat distribution medium	[°C]	t_r	± 0.1 K
ambient temperature	[°C]	t_a	± 0.1 K
massflow of distribution medium	[kg/s]	$\dot{M}$	± 0.1 kg/s
simulated cooling load	[W]	$\dot{Q}_H$	± 5 W
active surface of the investigated chilled ceiling	[m²]	A_a	± 0.02 m²

The room and air temperature inside the testing chamber have to be measured at at least 4 positions as marked in Fig. 1. Additional temperature sensors have to be installed at the center of wall and bottom surfaces. The selection of 8 measurment points at the surface of the chilled ceiling must guarantee the measuring of a repersentive temperature distribution.

Each water temperature has to be measured by two seperate temperature sensors, while a difference of less than 0.05 K between these sensors is allowed. Otherwise they have to be exchanged.

The investigation of the characteristic of a chilled ceiling element includes at least 3 series of measurments with different initial temperatures of heat carrier medium. The rated temperature are 12, 14 and 16°C with a tolerance of ± 0.5 K, while the room temperature inside the chamber has to be 26°C ± 0.2 K. The cooling load simulated by the heat sources has to be regulated continiously from 0 to 100 % of their capacity, while the 4 heat sources in the centre can be switched symmetricaly.

parameter	standard deviation
t_i	0.1 K
t_r	0.1 K
$\Delta t_{i,r}$	0.05 K
t_a	0.2 K

During a period of at least one hour with stationary operating conditions 10 measurement points have to be determined to describe the cooling performance of the chilled ceiling elements. During this period the standard deviations of some parameters are limited as shown in the list. If the registrated data do not fulfil these requirements, the measurements have to be repeated. If the absolute difference between simulated absolute cooling load and cooling performance of the chilled ceiling is higher than 12 W, it is not allowed to use the data to describe the cooling performace. So the measurements have to be repeated.

3. Uniformed description of cooling performance

The guidline "thermal measurements at chilled ceilings" includes two different posibilities to descripe the cooling performance in a uniformed and comparable way.

The cooling performance of chilled ceilings with a smooth and plan surface can be descriped by a so-called "characteristic curve of the chilled ceiling", because the room itself has only a small effect on the cooling performance.

$$\dot{q} = k_0 \cdot \Delta t_0 \qquad \Delta t_0 = \frac{t_i - t_r}{\ln \dfrac{t_{0,m} - t_r}{t_{0,m} - t_i}}$$

The value k_0 can be explaind as a heat transfer coefficient from heat carrier to the surface and the Δt_0 is the logarithmic mean temperature gradient between heat carrier und mean representive temperature $t_{0,m}$ at the surface of the cilled ceiling. So the characteristic of such a chilled ceiling can be descriped clear by k_0.

In practice the surfaces of sutch chilled ceilings are not smooth, they are often structered with holes or breaks (not closed) and they are perfabricated with structered surfaces (not smooth). Chilled ceilings, which are not closed, can be investigated in the testing chamber too. In a first measurement series, the cooling performance $\dot{q}_a$ will be determined with openings in the ceiling. In a second measurment series the openings must be closed and the cooling performance $\dot{q}_b$ has to be determind once more. For these kind of chilled ceiling the value $\dot{q}_b$ is given as the cooling performance and the relation $\dot{q}_a/\dot{q}_b$ describes the increase of cooling performance because of the structured surface or opening within the ceiling. In the case of slight structered surfaces, the cilled ceiling can be handelt as a smooth one. But this is only allowed, if the relation between real active surface to the basal surface is less than 1.2.

Parallel to the "characteristic curve of the chilled ceiling" it is possible to describe the cooling performence of open and strong profiled cilled ceilings by using the so-called "room characteristic". In this case, the cooling performance depends on the ambient conditions in the room, in which the chilled ceiling has to be installed. The results of the measurements of cooling performance in the testing chamber can be described by

$$\dot{q} = C \cdot \Delta t_R^n \qquad \Delta t_R = \frac{t_i - t_r}{\ln \dfrac{t_R - t_r}{t_R - t_i}}$$

The parameters C and n have to be determined by a regression basing on the measured parameters and Δt_R, the logarithmic mean temperature gradient between heat carrier and room temperature as measured with the "black balls". This room characteristic can be used as well for open and structured ceillings as for closed ceilings with a smooth surface. So cooling performance of these different types of ceilings can be described by this equation and parameters C and n. A comparison of the cooling performance of different types of chilled ceiling can be done by the value of $\dot{q}$ for $\Delta t_R = 8$ K.

The evaluation of cooling performance of chilled ceilings by the shown room characteristic was primary developed for typs of ceilings, where heat transfer bases mainly on radiation and where convective shares are very low. The investigation of ceilings, where the heat transfer bases mainly on convection, by using the testing chamber and the evaluation of cooling performance by the room characteristic is possible, if aditional parameters will be met. If active and non-active elements are combined to a ceiling, the share of active surface has to be more than 1 m^2. If cooling elements will be installed above a intermediate ceiling, they have to be investigated with the same type of intermediate ceiling in the testing chamber and the temperature distribution at the surface has to be measured too.

Investigations at free convective coolers, which are installed in the testing chamber as shown in Fig. 1, where carried out, to characterise the cooling performance and the effects on operating conditions and distibution of heat sources. During the first measurement series the effect of the heat carrier mass-flow on cooling performance was investigated. Five different flow rates of cold water (280 l/h, 330 l/h, 380 l/h, 430 l/h and 480 l/h) were adjusted at each of the two separate connected and measured coolers. The analysis of cooling performance includes the determination of two different "room charcteristics". The first one bases on the equiations as discribed in the guidline, where the cooling performance has to be related to the basal surface of the chilled ceiling (Fig. 2). The second "room charcteristic" bases on the cooling performance per length of cooler, so that the coefficient C varies. This value is often given by manufacturers of convective coolers to describe the cooling performance of their products.

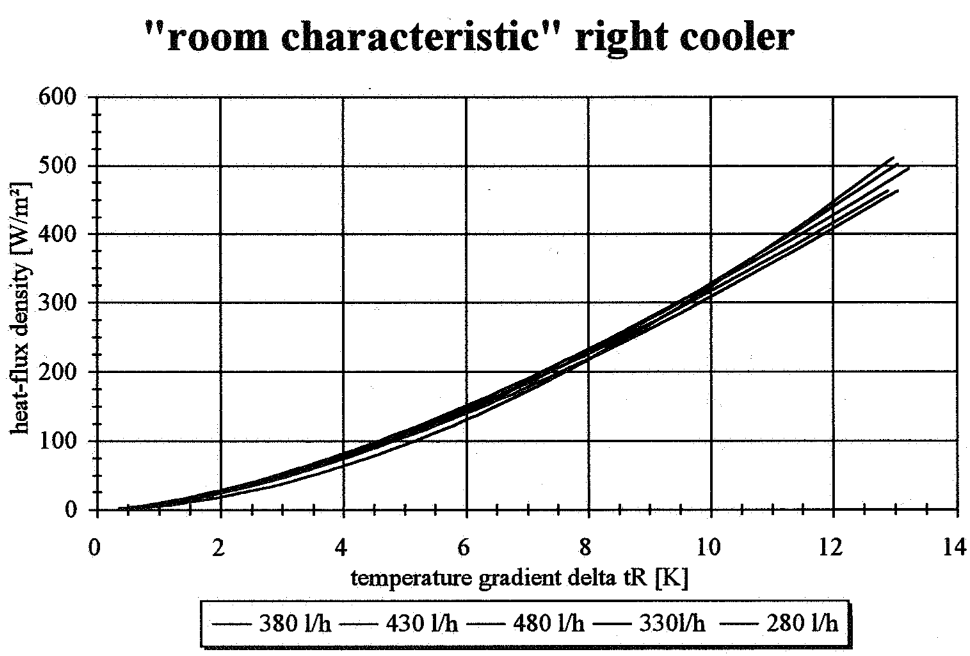

fig.2

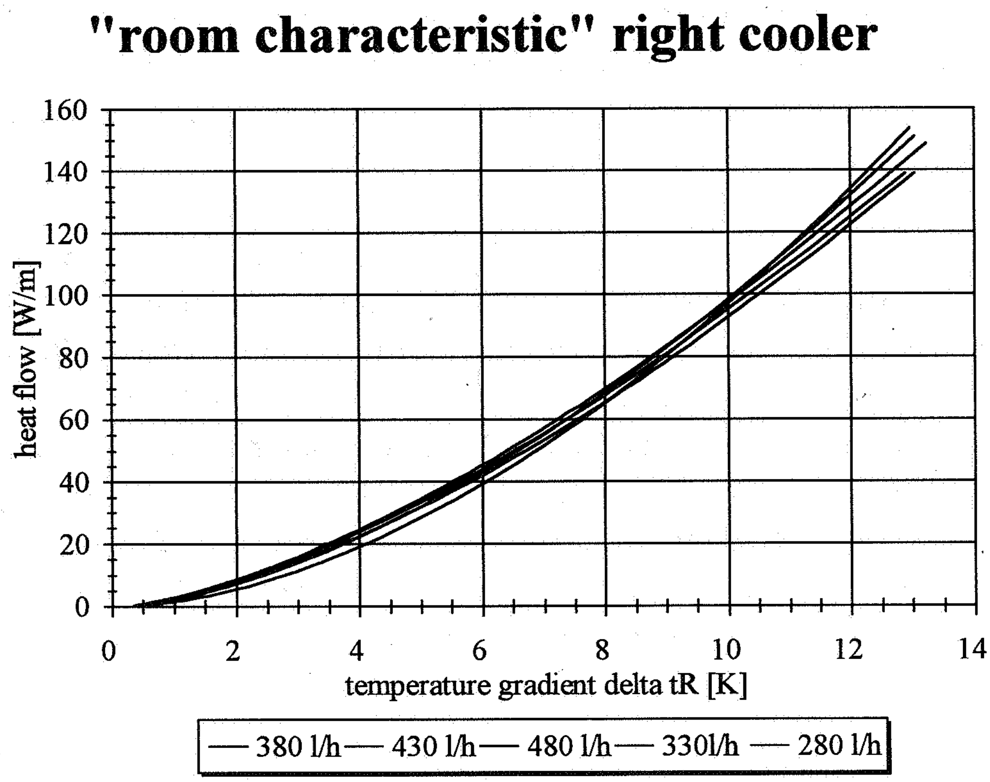

fig. 3 (flow-rates for both coolers)

The analysis of the measured series with different flow-rates shows, that the cooling performance varies only a little in the chosen range of flow-rates. The reason for this characteristic is the low gradient between cold water and room temperature because of the adjusted flow-rates and the low cooling performance. It can be estimated, that cooling performance increases at same logarithmic temperature gradients with the mass-flow of heat carrier. The deviation between estimated and investigated characteristic in the range of low temperature gradient can be related to the uncertainty of measurements and the regression.

Nevertheless the determined cooling performance of the convective coolers installed inside the testing chamber is much lower than the values, which can be reached in practise at the operating conditions. One reason for these lower cooling capacities during the measurements are the bad heat transfer conditions at the coolers in comparison to real operating conditions. Because the testing chamber is well insulated, the cooling load has to meet the cooling performance of the coolers. Because the basal surface of coolers and heat sources are nearly equal, the heat-flux densities in both layers are nearly equal too. Due to the arrangement of heat sources and convective coolers, natural convection of air at the coolers is reduced by the natural convection of the heat sources. The part of cooling performance by convection drops.

In practice coolers will not be installed above heat sources with nearly the same heat-flux density as the cooler. In practice the installation position of the free convective coolers inside the room depends on the given distribution of internal heat sources and solar gain. So the caused air flow pattern may have a positive effect on cooling performance, because the natural convection at the convective coolers can be forced.

The investigated "room characteristcs" of the right cooler by a heat-carrier flow rate of 165 l/h per cooler are shown in Fig. 4. During these mearsurements the effect of the distribution of the heat sources on cooling performance was investigateted while only one of the two installed coolers was active. The comparison of the "room characteristics" with heat sources below the active or inactive cooler shows, that the distribution of the heat sources has an effect on the cooling performance. The characteristic shows a slightly lower cooling performance of the right cooler with heat sources below the cooler than the characteristic with both coolers and heat sources. This effect can be related to the heat transfer conditions by radiation, because the share of surfaces with high temperatures was higher, when both coolers and all heat sources were active.

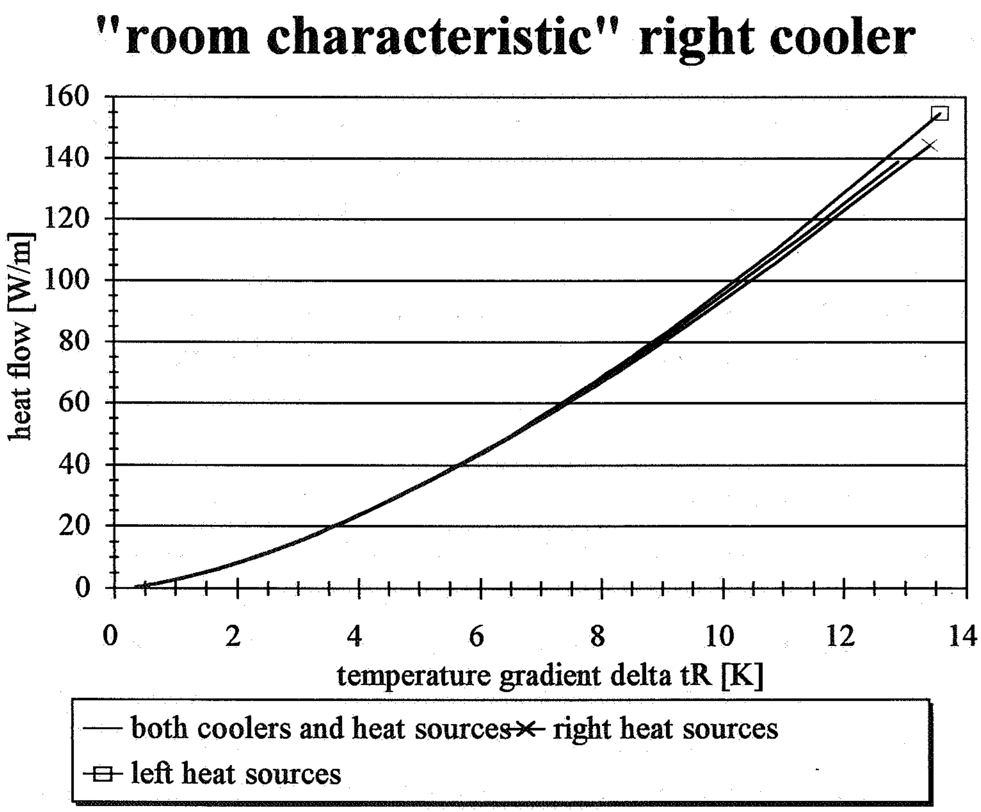

fig. 4

The investigation of the convective coolers with symmetric and different unsymmetric distributions of the heat sources has shown the estimated effects of the varied parameters on cooling performance. But in practice the cooling performance varies in a range, which is larger than determined on the base of the measurements in the testing chamber. Distribution of heat sources in relation to the cooler position, air flow pattern and type of intermediate ceiling have a significant effect on cooling performance, so that the investigation of these convective coolers in larger testing rooms with real headroom of 2.6 - 3 m may lead to smaller differences between investigations in a test room and installations in buildings.

5. Summary

The described guidline "thermal measurement at chilled ceilings" guarantees a uniformed measurement of cooling performance of chilled ceiling elements under clearly defined boundary conditions. Since these guidline was outlined, the range of cooling performance of systems, where the heat transfer bases mainly on radiation, investigated by several companies and institutes decreases. An objective comparison of different systems and a accurate planning is possible by using the characteristic data described in the guidline. But the certainty of the characteristic data basing on measurements in the testing chamber decreases, if the share of heat transfer by convection increases. The determination of cooling performance of free convective coolers should be investigated in larger testing chambers with realistic distributions of heat sources and positions of coolers.

6. Acknowledgement

The measurements were part of a research project, which was supported by the Bundesministerium für Forschung und Technologie under the contract number 0329399A.