Moisture-Buffering Effect—Experimental Investigations and Validation

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ABSTRACT

Well-balanced conditions of thermal, moisture, and air quality are very important in buildings because an imbalance of these factors could have significant influences on the construction and the inhabitants. The focus is the influence of different materials on the fluctuation of relative humidity, specifically humidity peaks. In lieu of complicated and expensive laboratory testing, several different software tools have been developed to estimate the indoor environmental conditions of buildings. In the context of the IEA Annex 41 project, a common exercise was carried out. For the common exercise at the free field investigation area in Holzkirchen (Germany), two identical rooms were used to measure the moisture buffering capacity of several interior finish systems. To address the questions of buffering capacity, the Fraunhofer-Institute of Building Physics developed a hygrothermal simulation tool, WUFI®-Plus (Holm et al. 2006). Using the measurement data from the common exercise, calculations were carried out with several software tools for its validation. In this paper, the results of the laboratory tests and simulation results are described.

INTRODUCTION

Appropriate indoor climatic conditions are important for human beings as well as for avoiding the growth of mold. Humidity plays an important part in both cases. The thermal comfort and the temperature conditions in rooms are frequently discussed, but to achieve thermal comfort in interiors it is also important to take relative humidity into consideration. Due to increasingly higher requirements for energy efficiency, airtightness of buildings (DIN 2003), and shifting of habits of the residents, there has been an increase in mold growth in interiors. An essential cause is the reduced air change rate due to the integration of airtight windows or a change in ventilation habits, caused by a higher absence rate of the residents. In this context, there are discussions on the influence of high moisture levels, which may cause mold growth and can have a negative influence on health (Hartmann et al. 2004). Yet, if humidity is too low, this can also have health risks, for example, causing dry mucosa or dry eyes.

To provide ways to reduce the risk of damage in buildings caused by humidity, a common exercise (CE) was carried out in context of the IEA Annex 41 project with the aim of developing and validating hygrothermal simulation tools for cost-effective methods to estimate the climatic conditions in buildings. For this CE, experimental investigations were made focusing on the moisture buffering effect of different materials under real conditions in two identical test rooms. There are variations in the buffering behavior according to the respective materials. The buffering effect is dependent on the interaction of sorption capacity and diffusion openness of the materials, whereby the characteristic of hysteresis between adsorption and desorption has an important influence. The measurement results of the different variations of the experiments provide a basis for the validation of the developed simulation tools. The main focus of this paper is on the calculated results with the hygrothermal software developed at the Fraunhofer-Institute of Building Physics. In the following sections, first the experimental investigations are described and then the results of the simulations of all the software tools participating in the CE are presented.

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EXPERIMENTAL INVESTIGATIONS

Test and Experimental Setup

The two test rooms are identical and situated in a test building that was erected in the 1980s, with west-east direction, whereby the two rooms are located at the south side of the building. The ground plan of both rooms is shown in Figure 1.

The external walls of the rooms are constructed of 24 cm bricks and 10 cm Polystyrene external insulation, and the U-factor of the walls is 0.32 W/m·K. On the south side, one window for each room is integrated in the wall with a U-factor of 1.1 W/m·K and a total solar energy transmittance of 0.6. The internal walls to the adjacent rooms are thermal decoupled. For this reason, the test rooms are not influenced by the boundary conditions of the environment in the building (Kuenzel et al. 2004).

In the following paragraphs, the left room is defined as the reference room, which has a traditional internal painted gypsum plaster wall and ceiling surface. The test room is identical to the reference room with regard to geometry and dimensions. The difference in comparison to the reference room is that the wall and ceiling surfaces are covered with aluminium foil to prevent the sorption of the surfaces. The floor in both rooms is covered with a vapor-tight floor covering, which is supposed inert from the hygrothermal point of view. The volume of each room is approximately 50 m and the total surface of the room (without floor, window, and door) is approximately 67 m.

The indoor air temperature of the test rooms was held at 20°C. One essential parameter influencing the indoor conditions is the air change due to infiltration via joints or other leakage. The natural air change rate was reduced in both rooms by masking surface defects. The air change rate was determined in both rooms by the Blower Door measurement method (DIN 2001). The air change rates are related to pressure differences of 4 Pa; the result for the reference room is $n = 0.04\ h^{-1}$ and for the test room is $n = 0.03\ h^{-1}$. A ventilation system is installed in both rooms, providing a constant air change. (According to DIN [2003], the minimum air change must be $n = 0.5\ h^{-1}$ in case of mechanical ventilation of the rooms). The air change rates during operation of the ventilation system were determined by tracer gas measurements. The air change rate for the reference room is $n = 0.63\ h^{-1}$ and for the test room is $n = 0.66\ h^{-1}$.

To achieve a realistic assessment of the course of relative humidity with regard to the moisture buffering effect, 2.4 kg of water vapor is introduced into each room per day, which simulates the equivalent amount for a household of three persons (Hartmann et al. 2001). To differentiate short- and long-term moisture buffering of surrounding surfaces, a practically orientated daily repeated moisture production cycle was chosen whose peaks show a short but high intensity in the morning and a larger but moderate intensity in the evening. Thus, the moisture profile (Ellinger 2004) (Figure 2) shows two peaks, one in the morning from 6:00 a.m. to 8:00 a.m. and one in the afternoon from 4:00 p.m. until 10:00 p.m. These peaks simulate taking showers, washing, cooking, and the presence of human beings. The moisture is generated according to the profile shown in Figure 2 by using ultrasonic evaporators controlled by a clock timer.

To record room climatic conditions, temperature and humidity sensors are installed in the test rooms. The temperature of the wall surfaces, temperature layering in the middle of the rooms, as well as relative humidity in the rooms are determined. The energy consumption of the heating system is measured by a power meter. The temperature and humidity in the center of the room is considered for the evaluation of the following tests. Measured data are constantly recorded by means of a data acquisition system, are stored in a database, and then are evaluated.

Variations

Before being integrated in the test room, the material to be tested is preconditioned to assure a defined initial state for the tests. The gypsum boards were stored at 20°C and 50% relative humidity over a period of several weeks.

The sequence of the experiments carried out is listed in Table 1. The first measurement sequence in an empty test room, i.e., the room with aluminium foil on the walls and ceiling, serves as a reference. The untreated gypsum boards are then first installed on the walls and later on the walls and the ceiling. In addition, tests are carried out with painted gypsum boards on the walls. In a final step, the indoor climatic condi-

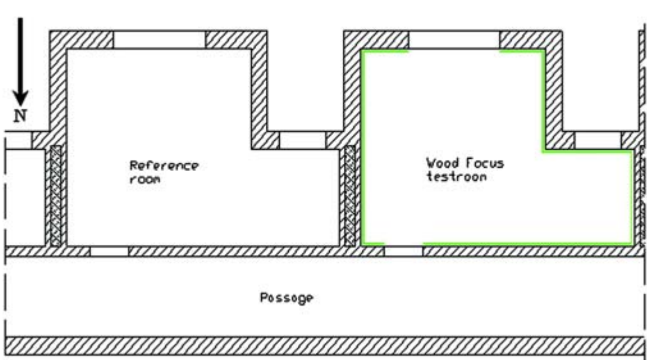

Figure 1 *Ground plan of the two test rooms (Kuenzel et al. 2004).*

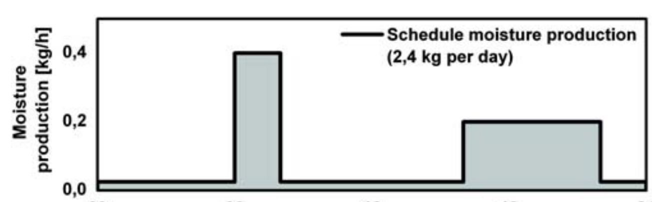

Figure 2 *Course of the daily humidity generation in the two test rooms (Ellinger 2004).*

Table 1. List of the Individual Steps of Testing

Variation	Material in the Test Room	Projected Area, m^2
Step1	Aluminium foil (walls and ceiling)	67
Step 2	Gypsum boards (walls)	45
Step3	Gypsum boards (walls and ceiling)	67
Step 4	Painted gypsum boards (walls)	45
Reference room	Painted internal (gypsum) plaster (walls and ceiling)	67

tions in the reference room were measured and used for the validation of the software tools.

Comparison of the Individual Investigation Results

The reduction of the humidity-generated changes of indoor air humidity in the test room in relation to the situation in the reference room with gypsum plaster is a measure for the moisture buffering effect of the materials installed in the test room. The measurements of several materials and coatings should point out the influence of products with different sorption properties and water vapor resistance factors regarding the moisture buffering effects. The results of the experimental steps are shown in Figure 3. As the uncovered test room does almost have no hygroscopic moisture buffering capacity, the humidity amplitudes are higher there than in the gypsum-plastered reference room. All investigated coverings have in common that they have a higher moisture buffering capacity than the painted internal plaster, even if the installed test surface is smaller than in the reference room. The influence of the area of a sorptive surface is made obvious by the humidity amplitudes of the two variations with unpainted gypsum boards. An interesting effect occurs when comparing the results of the painted gypsum boards with those of the unpainted boards. As was to be expected, the moisture buffering effect is clearly reduced by the diffusion resistance of the coating. This is, however, more significant in the case of a short-term and high moisture load than in the case of a long-term and low moisture load. As concerns the painted gypsum boards, a higher reduction of the amplitude (right bar of Figure 3) can be observed with the moisture load in the afternoon in comparison to the reference room than with the moisture load in the morning (left bar of Figure 3) and vice versa concerning the untreated gypsum boards. The additional water vapor resistance factor of the paint reduces the speed of the absorption and desorption of the underlying material. The influence of the additional diffusion resistance of the paint is higher in the morning during the higher moisture generation

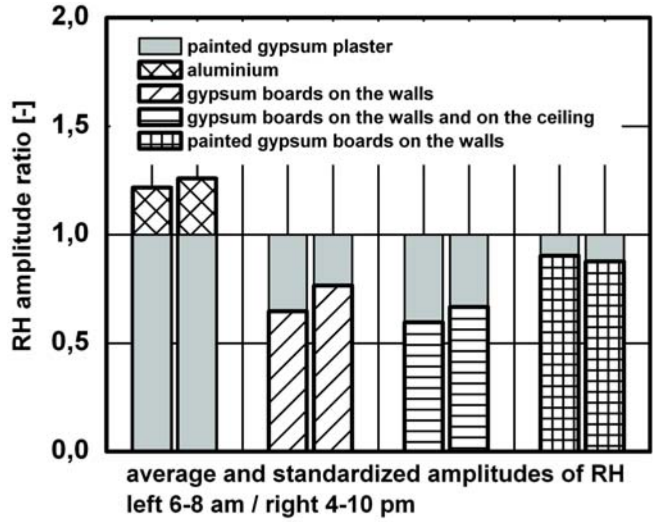

Figure 3 *Comparison of the averaged and standardized humidity amplitudes of the different test variations in relation to the conditions in the reference room.*

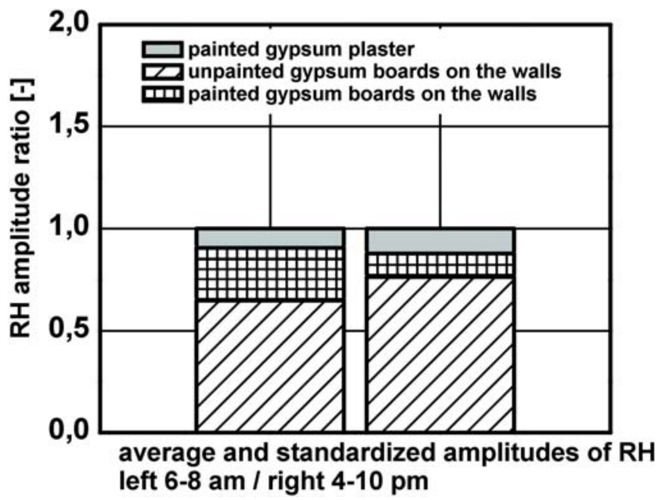

Figure 4 *Comparison of the averaged and standardized humidity amplitudes of the different test variations with and without painted gypsum boards in relation to the conditions in the reference room.*

than it is in the afternoon. This is representative in the difference, which is shown in Figure 4, between the height of the amplitudes compared to the uncoated gypsum boards in the morning and the difference in the afternoon. The explanation for this effect is that during a longer and continuous moisture generation, the sorption isotherm is the main factor that influences the moisture buffering effect and by a short moisture production the diffusion resistance is the main factor.

The moisture buffering effect of the painted gypsum board, with acrylic paint with a higher s_d value than the paint of the gypsum plaster in the reference room, is higher than in the reference room with more sorptive surface and a lower s_d value.

VALIDATION

For successful validation of the developed simulation tools, an accurate description of the construction and boundary conditions of the test facilities is necessary. The material data and construction of the adjacent components are known, and through continuous measurements of the climatic boundary conditions around the rooms, the essential data are available. The collected data for the test facilities, boundary conditions, and equipment were provided to all participants in the CE. Before the simulation studies began, all data for the construction, air change rate, moisture production, and climatic conditions needed to be determined for input into the various software. The main focus of these simulation studies was the calculation of the indoor relative humidity of the test rooms; therefore, in the following only the results of the relative humidity of the different experimental steps are shown. The indoor relative humidity was taken at the midpoint of the room. The temperature in the room was controlled at 20°C constantly, and all simulation results show very good agreement with the measured temperature. Therefore, the results of the calculated relative humidities are considered in the following.

The simulation studies in the context of the IEA Annex 41 CE were the first three variations of the investigation schedule. Step 4, with painted gypsum boards on the walls, was not included in the CE, but the measurement results were used for further validation of the software developed at the Fraunhofer-Institute.

Results of the Validation

During the first testing phase, the walls and the ceiling were covered with aluminium foil, and through this no absorption and desorption of the surfaces was possible. The aim of step 1 was to calculate the indoor climate without sorptive surface and only with the air change rate. The results of the measurement and the calculations of 12 different simulation tools are shown in Figure 5 for two exemplary days. The main influence to the indoor climate in this step is the air change rate. The measured air change rate is 0.66 h^{-1} in the test room. Comparing the calculated relative humidity to the measured, the spreading of the results is in the tolerance range. Comparing the results of the simulation studies to the experimental data, the simulation results are within an acceptable range of tolerance. The results of all of the simulation tools in this step show good agreement with the measurement results.

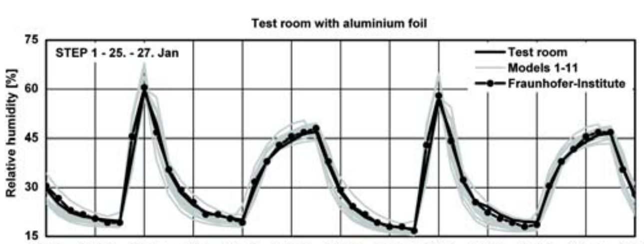

Figure 5 *Courses of the relative humidity in the test room where all surfaces are completely covered with aluminium foil.*

The second step was with gypsum boards on the walls in the test room. The area of the sorptive surface is approximately 45 m. In this step, the moisture buffering effect of the uncoated gypsum boards is evident. The courses of the measured and calculated indoor relative humidity are shown in Figure 6.

The spreading of the results in this case was high. The variation in the relative humidity during the moisture peak in the morning was between –5% and approximately +30% from the measured data. Many of the simulation tools have difficulty modeling the moisture buffering effect of the uncoated gypsum boards in this step. The calculation of the indoor relative humidity with the tool developed at the Fraunhofer-Institute was able to model the moisture buffering effect reasonably well.

Step 3 was almost the same as step 2, but for this experiment gypsum boards were installed on the walls and the ceiling. The sorptive surface in the test room was approximately 67 m. The results of step 3 are shown in Figure 7 for two exemplary days.

The results of step 3 show almost the same spreading as in step 2. It was not easy to model the moisture buffering effect with the simulation tools used. Even the results of the Fraunhofer-Institute tool, while in general agreement with the experimental data, showed some divergence during the periods with low moisture generation.

Normally gypsum boards are not installed on the surfaces of room walls and ceilings without a coating. Therefore, an

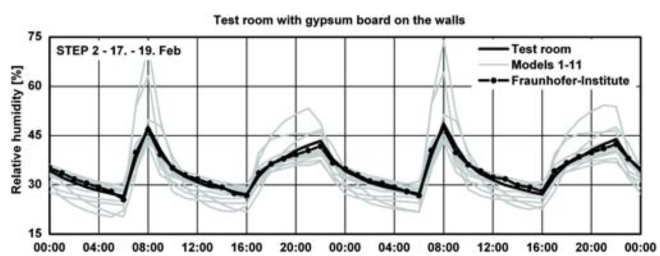

Figure 6 *Courses of the relative humidity in the test room with gypsum boards on the walls.*

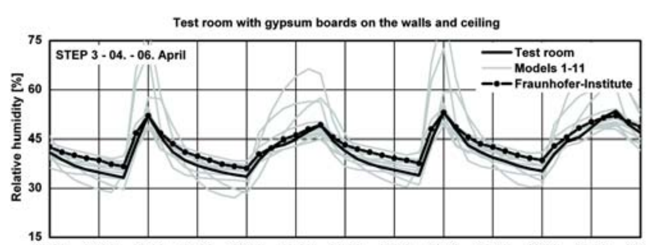

Figure 7 *Courses of the relative humidity in the test room with gypsum boards on the walls and the ceiling.*

additional experiment was carried out. In the test room, painted gypsum boards were installed on the walls. The surface was painted with an acrylic paint with a water vapor resistance factor (s_d value) of 0.34 m. Step 4 was not part of the CE of the IEA Annex 41 project and the validation was only made with the model developed at the Fraunhofer-Institute. The results of this investigation and simulation are shown in Figure 8.

The experiment with additional painting on the surface of the gypsum boards demonstrates the influence of a thin layer of paint on the moisture buffering effect. The results of the simulation show good agreement with the measurement results.

In the context of the CE, the last step was to simulate the indoor climatic conditions in the reference room. The walls and the ceiling were covered with a commonly used painted gypsum plaster. The water vapor resistance factor (s_d) of the paint is 0.15 m. The results of the measurement and simulations are shown in Figure 9.

From Figure 9 it is clear that most of the simulation tools have no difficulty predicting the indoor relative humidity correctly if the surface of the walls and the ceiling are covered with paint. With an additional layer of paint on the surface, the good sorptive properties of the gypsum plaster are reduced. In this step, the spreading of the results are only between –5% and +5% of the measured relative humidity.

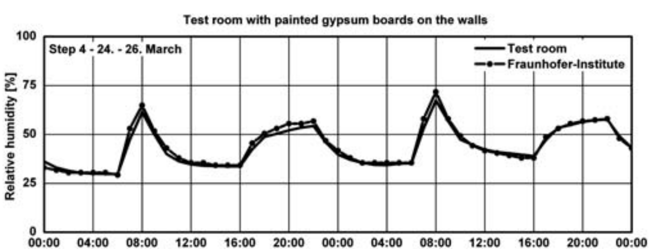

Figure 8 *Courses of the relative humidity in the test room with painted gypsum boards on the walls.*

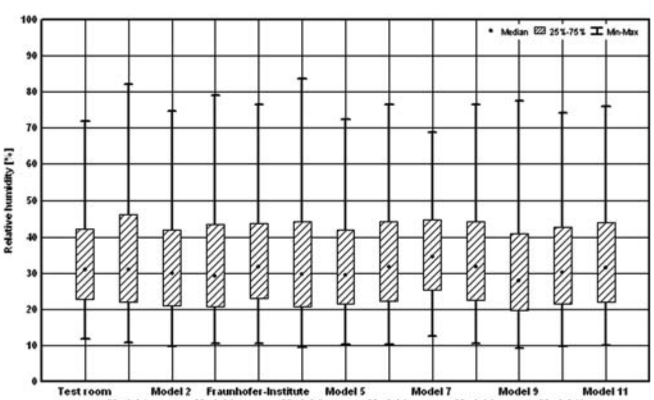

Figure 10 *Results of the descriptive statistical analysis of the results of step 1 with the test room with only aluminium foil.*

Statistical Analysis of the Validation Results

The simulation results were analyzed statistically, and the regression lines and the coefficients of correlation were calculated. For all analyses, the whole periods of the different measurements are considered.

Figures 10 and 11 show the results of the statistical analyses of step 1 in the test room with aluminium foil. The period of this step ran 16 days. For the calculation of the median, 25th and 75th percentiles, and the maximum and minimum values, all data of the period were used. For the first step with only aluminium foil on the walls and the ceiling, the variations of the medians and percentiles of step 1 show good agreement with the measurement, which is the first plot in the diagram in Figure 10.

In Figure 11, the regression lines of the calculated relative humidity versus the measured relative humidity in the test room are shown. In addition to the regression lines, the coefficients of correlation are listed in Table 2. On the basis of the coefficients of correlation, it is reflected that the results of the

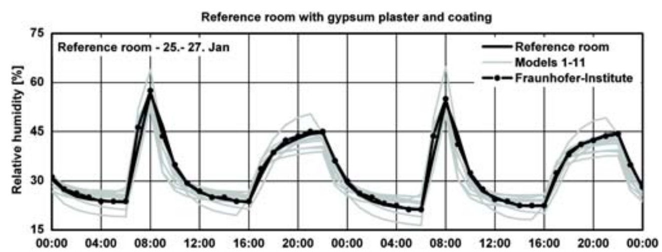

Figure 9 *Courses of the relative humidity in the reference room with painted gypsum plaster on the walls and the ceiling.*

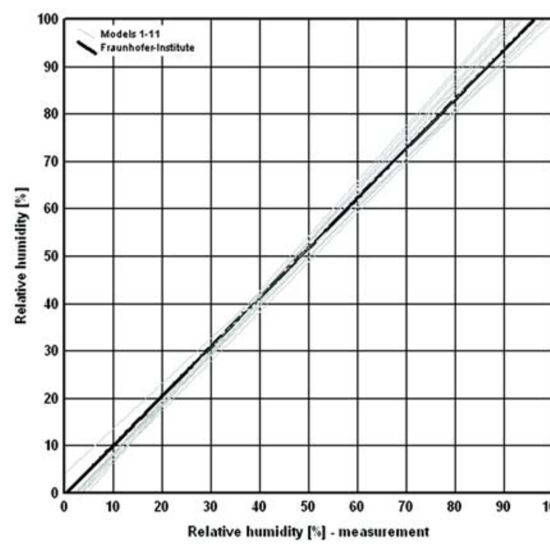

Figure 11 *Statistical analysis with regression lines of the results of step 1 with the test room with only aluminium foil.*

Table 2. List of the Coefficient of Correlation for Step 1 with Aluminium Foil

Simulation Tool	Coefficient of Correlation
Model 1	0.97
Model 2	0.99
Model 3	0.97
Fraunhofer-Institute	0.99
Model 4	0.97
Model 5	1.00
Model 6	0.98
Model 7	0.99
Model 8	1.00
Model 9	0.97
Model 10	0.99
Model 11	0.99

Table 3. List of the Coefficient of Correlation for Step 2 with Gypsum Boards on the Walls

Simulation Tool	Coefficient of Correlation
Model 1	0.87
Model 2	0.97
Model 3	0.95
Fraunhofer-Institute	0.97
Model 4	0.86
Model 5	0.94
Model 6	0.97
Model 7	0.97
Model 8	0.98
Model 9	0.95
Model 10	0.94
Model 11	0.97

simulations offer a maximum deviation of only 3% from the measurement results.

The same statistical analyses were done for step 2, the test room with gypsum boards on the walls. Figure 12 shows the medians, 25th and 75th percentiles, and minimum and maximum values over a period of 34 days. The results of the measurements are the first plot in the diagram. In this case, the variation between the simulations and the measurement are slightly higher. The differences between the results are visible by the regression lines, which are shown in Figure 13. The coefficients of correlation in Table 3 point out deviations between 2% and 12% in comparison to the measurement results.

The results for step 3 with gypsum boards on the walls and the ceiling are shown in Figures 14 and 15. The analyses comprised the results over a period of 26 days. The results of the descriptive statistic show similar results as for step 2. Three

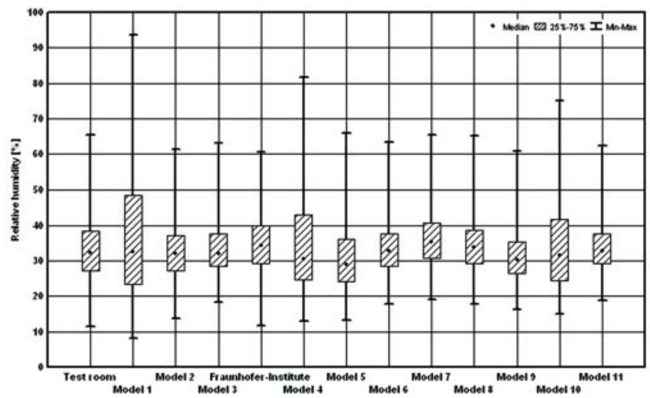

Figure 12 *Results of the descriptive statistical analysis of the results of step 2 with the test room and gypsum boards on the walls.*

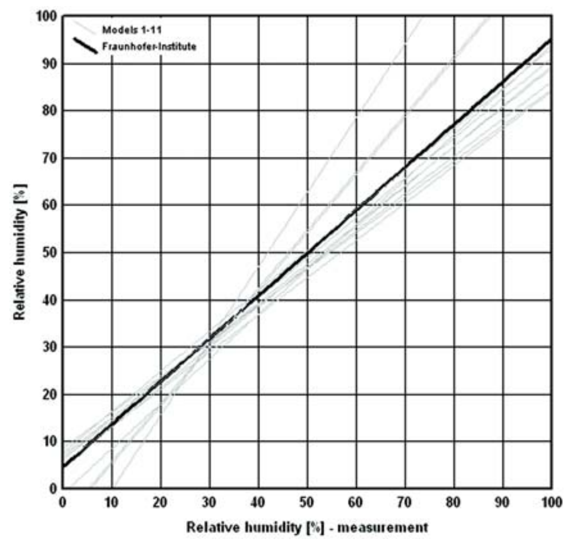

Figure 13 *Statistical analysis with regression lines of the results of step 2 with the test room and gypsum boards on the walls.*

models point out a higher deviation than the other models and the measurements. The varieties between the results are visible with the regression lines, which are shown in Figure 15 and Table 4, and the coefficients of correlation have a spreading of 10%–22% in comparison to the measurements.

The last statistical analyses were done for the results of the measurements and calculations in the reference room with painted gypsum plaster on the walls and the ceiling. Figure 16 shows the results of the descriptive analyses. The results of model 1 are those with the highest deviation to the measurements again.

In Figure 17, the regression lines of the results of the reference room with painted gypsum plaster are shown. The coefficients of correlation are shown in Table 5. Most of the lines are located in the same area; only one curve from model 1 is

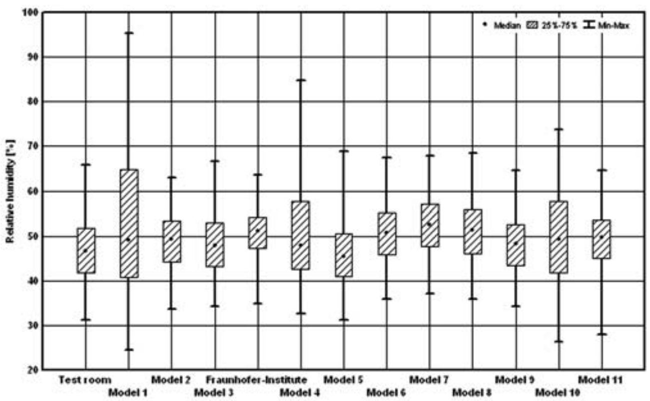

Figure 14 *Results of the descriptive statistical analysis of the results of step 3 with the test room and gypsum boards on the walls and the ceiling.*

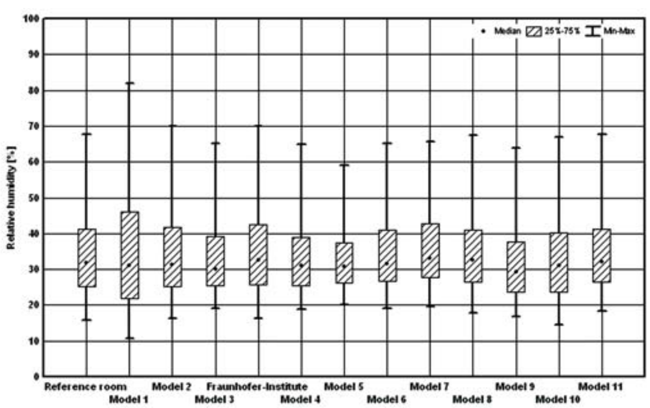

Figure 16 *Results of the descriptive statistical analysis of the results of the reference room with painted gypsum plaster on the walls and the ceiling.*

different. The results of the coefficients of correlation show a maximum variance from the measurements of 8%.

CONCLUSIONS

To properly assess hygrothermal indoor climatic conditions in interiors comprising several materials, complex experiments are needed. It is possible, however, to estimate the climatic conditions in buildings using simulation tools especially developed for this purpose. In context of the IEA Annex 41 project, experimental investigations and a common exercise for the validation of the software tools was carried out.

Experimental investigations were carried out at the outdoor test site of the Fraunhofer-Institute of Building Physics in Holzkirchen in order to determine the moisture buffering effect of interior wall coverings. Gypsum boards with and without coating were compared to a commercial painted interior plaster. The influences of materials with regard to the buffering behavior were assessed by investigations in two identical test rooms under defined boundary conditions. The indoor

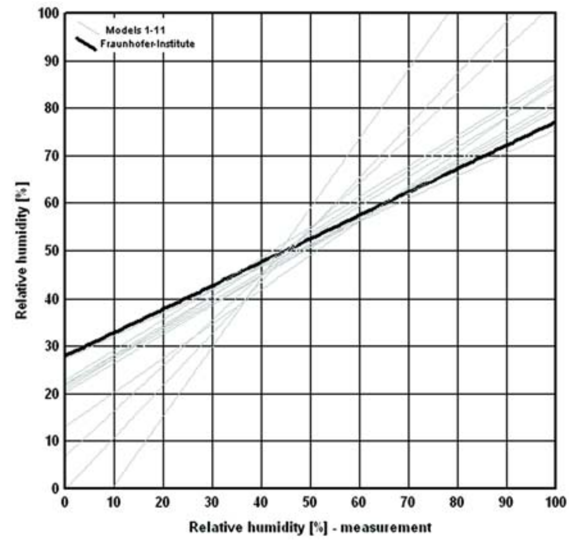

Figure 15 *Statistical analysis with regression lines of the results of step 3 with the test room and gypsum boards on the walls and the ceiling.*

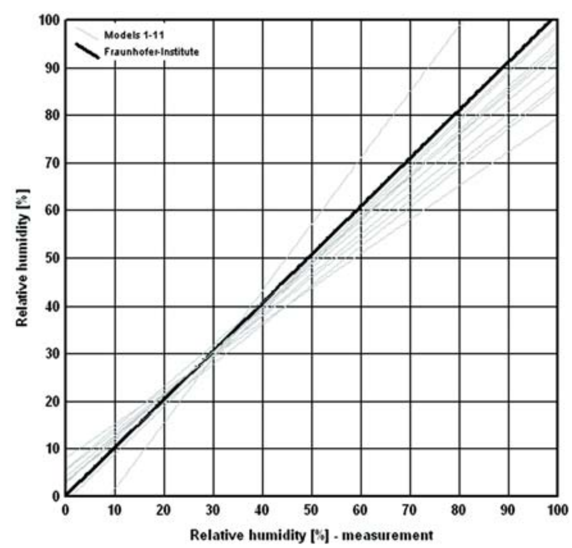

Figure 17 *Statistical analysis with regression lines of the results of the reference room with painted gypsum plaster on the walls and the ceiling.*

climate in both test rooms was constantly measured. The investigations showed that all variations with gypsum boards had a better moisture buffering effect than the traditional painted interior gypsum plaster. Whereas the untreated gypsum boards on the walls or on the walls and ceiling reduced humidity peaks by 40%, painted gypsum boards, which are installed on the walls, reduced humidity peaks by only 10% to 15% in comparison to the moisture buffering of an interior gypsum plaster. The reason was that applying a coating system with a s_d value of 0.34 m changed the sorptive properties of the gypsum boards below.

Table 4. List of the Coefficient of Correlation for Step 3 with Gypsum Boards on the Walls and the Ceiling

Simulation Tool	Coefficient of Correlation
Model 1	0.83
Model 2	0.86
Model 3	0.85
Fraunhofer-Institute	0.85
Model 4	0.79
Model 5	0.88
Model 6	0.87
Model 7	0.88
Model 8	0.88
Model 9	0.87
Model 10	0.90
Model 11	0.78

Table 5. List of the Coefficient of Correlation for the Reference Room with Painted Gypsum Plaster on the Walls and the Ceiling

Simulation Tool	Coefficient of Correlation
Model 1	0.97
Model 2	1.00
Model 3	0.94
Fraunhofer-Institute	0.99
Model 4	0.92
Model 5	0.97
Model 6	0.99
Model 7	0,97
Model 8	0,99
Model 9	0,94
Model 10	0,99
Model 11	0,99

All results of the experimental investigations were used for the validation of newly developed simulation tools developed within context of the IEA Annex 41 project. The validation was made by twelve participants with different simulation tools. For all results, statistical analyses were made to point out how good the simulation tools are and where the problems for the calculation of the indoor climate are. All of the models could calculate the indoor relative humidity within a minimum correlation of 97% inside the test room with no sorpive surfaces inside. But with gypsum boards, which have good moisture buffering behaviors, most of the models had difficulty modeling the indoor relative humidity correctly. The results show a correlation between the measurement and the simulation of approximately 80%. But if the buffering behavior is not so distinctive, the agreement with the measured results are better and the correlation increases to a minimum of 92%. The comparison of the measurements and the calculations with WUFI®-Plus shows in all cases a good agreement.

Through the application of these newly developed simulation tools, it is possible to simulate the indoor climatic conditions with different boundary conditions and materials in an accurate and cost-effective manner.

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