# VALIDATION OF A HYGROTHERMAL WHOLE BUILDING SIMULATION SOFTWARE

Florian Antretter[1], Fabian Sauer[1], Teresa Schöpfer[1] and Andreas Holm[1]
[1]Fraunhofer-Institut für Bauphysik, Holzkirchen, Germany

## ABSTRACT

One trend in whole building simulation is the incorporation of hygric interaction of room and enclosure. This allows besides a more detailed comfort assessment the optimization of building components to avoid moisture related damage or failure. Still, the main interest in the building design and optimization phase is the energy use combined with the occupants comfort.

Several existing standards and guidelines allow the validation of building energy simulation tools, like ASHRAE 140 (ANSI/ASHRAE 140-2007 2007) or VDI 6020 (VDI Richtline 6020 2001). A newly developed hygrothermal whole building model will be compared to the validation cases of these two standards. In addition, the validation of the hygric part of the simulation tool will be shown by comparing with an experimental set-up.

These evaluations allow on one hand a critical discussion about the usability of the standards for evaluation of building energy software. We found problems with the description of the boundary conditions, especially in VDI 6020. On the other hand, the usability of the new software for energy and comfort assessment is shown by a good agreement with both standards. Furthermore, we suggest new validation experiments to provide not only thermal, but also comfort and hygrothermal comparison cases.

## INTRODUCTION

In designing new, energy efficient buildings, whole building energy simulation is the tool of choice. Only a transient assessment of the interaction of building envelope, building equipment and use allows a comprehensive improvement of energy efficiency and thermal comfort conditions. A second state of the art technique in holistic building design is the evaluation of building components with hygrothermal assembly simulation to avoid moisture related damages.

With this background, the idea was to couple building energy simulation and hygrothermal component assessment. This allows not only faster results, but also a more detailed and comprehensive assessment of the hygric and thermal interaction of envelope and enclosed space. This paper presents a building model, WUFI®plus, combining both approaches.

Every software tool in productive use needs verification of the implemented models. Only a consistent validation allows to trust the results and to draw reliable conclusions. Different standards exist to evaluate building energy software. The evaluation process allows finding and eliminating possible problems of implemented models. The available evaluation standards do not incorporate hygrothermal test cases. Therefore, measurement calibration cases are necessary to calibrate the simulation models. Suggestions of possible enhancements to cover both, hygric and thermal model testing can be concluded.

This paper can only provide a small selection of all evaluation cases in the standards. The full evaluation of WUFI®plus with VDI 6020 (VDI Richtline 6020 2001) is documented in (Schöpfer 2010;Schöpfer et al. 2010) and with ANSI/ASHRAE Standard 140-2007 (ANSI/ASHRAE 140-2007 2007) in (Sauer 2011). First approaches for the evaluation of the hygric models were conducted in the framework of IEA ECBCS Annex 41 (Holm 2008) and with a small-scale laboratory experiment in (Antretter et al. 2010).

## BUILDING MODEL

WUFI®plus is a holistic model based on the hygrothermal envelope calculation model developed by Künzel (Künzel 1994). This model computes the coupled heat and moisture transfer in the building envelope. It takes moisture sources and sinks inside a component, capillary action, diffusion and vapour ab- and desorption as well as the well-known thermal parameters into account. Heat and mass transfer in building materials depend on each other and their coupling is a strong feature of the model.

The hygrothermal behaviour of the building envelope affects the overall performance of a building. The resulting heat and mass fluxes from the surfaces are incorporated into zonal models, taking into account inner loads and set-points of the HVAC system.

Models like WUFI®plus can help to improve energy simulations because latent heat loads and their temporal pattern can be calculated more accurately. Moisture related effects on energy use, like higher energy use because of built in moisture, can be demonstrated. The effect of moisture buffering materials on the hygrothermal conditions inside the room can be assessed, e.g. for passive climate stabilization in historic buildings. The humidity conditions inside occupied living spaces also influence the thermal comfort of the users. Only an accurate simulation of these conditions allows the holistic improvement of the thermal comfort. Last but not least, it is always important to avoid moisture related problems in building envelopes, e.g. rotting of materials, corrosion or mould growth. A combined approach of building simulation and component assessment is covering all these areas and allows a holistic building assessment and improvement even in the design phase.

As the software intends to be a tool for practitioners, for engineers and architects, a very intuitive graphical user interface is required. The options of choice of different models and possible settings are reduced to a minimum and the most meaningful default values are set. This allows to produce fast but reliable results.

The development and first calibration approaches for the WUFI®plus model by comparing its simulation results to the measured data of extensive field experiments is documented by (Lengsfeld and Holm 2007).

## BUILDING ENERGY SIMULATION EVALUATION STANDARDS

### VDI Guideline 6020

The Association of German Engineers issued a guideline in May 2001: VDI 6020 – *Requirements on methods to thermal and energy simulation of buildings and plants* (VDI Richtline 6020 2001). This guideline has been created as a tool for fundamental testing of simulation programs. For the examination of programs the guideline provides a number of test cases to test the different areas of the programs. In this paper Part 1 of the guideline for thermal and energy simulation of buildings was applied. For the calculation of the test examples a simple room type, shown in Figure 1, is defined in the guideline.

The construction of the room is, depending on the case, a lightweight or a heavy one. That allows to examine the reaction of the room on different thermal masses. The room is defined as part of a building and one wall adjoins the outer climate. There is no heat exchange over the inner walls, floor and ceiling to the adjacent rooms.

*Test cases*

The groups of test cases examine the reaction of the room on internal loading and set value changes (examples 1 to 7) and solar radiation (examples 8 to 11).

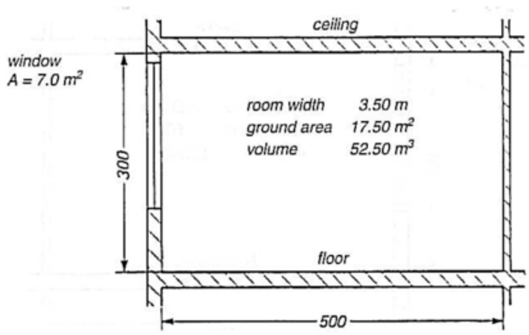


*Figure 1: Geometry of the room (VDI 6020)*

*Reaction on internal loading and set value changes*

The aim of test cases 1 to 7 is to examine the behavior of the test room with lightweight and heavy construction due to occuring inner convective and radiative loads and the reaction of the room temperature at a specific internal loading and limited plant output. For this group of test cases consistent geometry and position of the window is given. The window is defined as an opaque area oriented towards south. For all seven cases the structural-physical parameters are similar. The outer climate is with 22°C constant. In all cases the radiation is neglected.

The cases are calculated for a period of 60 days in hourly steps. Thus the transient response and the steady state can be compared with the reference values in the guideline.

*Solar radiation*

The solar radiation which was not taken into account in the first group of cases is included now (examples 8 to 11). The cases test the radiation model of the program by angular depending calculation of the solar radiation of a Test Reference Year towards components and through windows. Thus sources of error in the radiation model of the software can be easily localized. Every case is calculated in five variants which differ in orientation of the window. The calculation period is one year where a clear (August 11) and a cloudy (September 21) day are to compare with the reference values of the guideline. As outer climate the Test Reference Year 2005 of Würzburg is applied.

*Simulation*

After modelling the test rooms geometry the respective inputs regarding construction parameters, orientation and outer climate are made.

A window is to insert in the outer wall. The size of this window area is not clearly defined in the guideline and varies between 7.0 m² and 10.5 m². The given definitions for the glazing are dispensable for the first test cases as the window is specified as opaque area without storage capability. While material data for an interior door are specified, any dimension data are missing. So the door is neglected in the model. All heat transfer coefficients are specified only for convection. The given transfer coefficients for the test rooms surfaces to the adjacent rooms are ignored and replaced by an adiabatic coat. The missing or unclear input data prevent a continuous consistent application of the standard. To determine the correct input data numerous variant calculations were necessary.

For each prior described group of test cases one case is shown in this paper exemplarily.

Test case 1 examines the reaction of a heavy construction room with convective internal load of 1000 W in a operating time from 6am to 6pm. The first, the $10^{th}$ and the $60^{th}$ day are to compare with the reference values.

Test case 9 examines the radiation load without longwave radiation exchange. The construction is a heavy one as well. Calculated for each orientation the required heating/cooling load to hold 22°C in the room is to compare for a clear day in August and a cloudy day in September.

**ASHRAE Standard 140**

While developing WUFI®plus in a second step the more comprehensive validation cases in ANSI/ASHRAE Standard 140-2007 titled *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs* (ANSI/ASHRAE 140-2007 2007) were accomplished.

In this validation the building thermal envelope and fabric load tests designated as cases 195 through 960 of the ASHRAE Standard 140-2007 were performed. The results of WUFI®plus were also compared with results created by several other whole building energy analysis programs that simulated the same test cases.

*Test Cases*

The tests are divided into two main parts (i.e., the "basic" cases and the "in-depth" cases). The "basic" cases test the ability of the program to simulate such combined effects as thermal mass, window orientation, direct solar gain windows, window-shading devices, night ventilation, internally generated heat, infiltration, sunspaces, and deadband and setback thermostat control. The first set of tests (195 through 320) of the "in-depth" series prove the simulation software to create building envelope loads for a thermostat control configuration, that ensure a constant temperature, with the following variations among the cases: window orientation, no windows, opaque windows, window-shading devices, exterior/interior infrared emittance, exterior shortwave absorptance, internal gains, south solar gains, infiltration, and thermostat setpoints. The second set of tests (cases 395 through 440, 800, and 810) are similar to the cases 195 – 320. The biggest difference is the deadband thermostat control. The possible variations are nearly the same, up to cases 800 and 810. In those cases the thermal mass is changed.

To get an overview the cases are listed below with their corresponding sections in the Standard:

- Base Case (Case 600, Section 5.2.1 of Standard)
- Basic tests (Section 5.2.2 of Standard)
    - Low mass tests (Cases 610 to 650)
    - High mass tests (Cases 900 to 960)
    - Free float tests (Cases 600FF, 650FF, 900FF, 950FF)
- In-depth tests (Section 5.2.3 of Standard)
    - Cases 195 to 320
    - Cases 395 to 440
    - Cases 800 and 810

*Base Case*

Case 600 is the basic case for all other cases. That means more or less complex modifications of the base case must be made to create the other cases. However, the full-year weather data (DRY-COLD.TMY) provided with the standard are used for all tests.

Case 600 is a rectangular single zone with no interior partitions and two windows on the south surface. The dimensions of this building and its windows are shown in Figure 2.

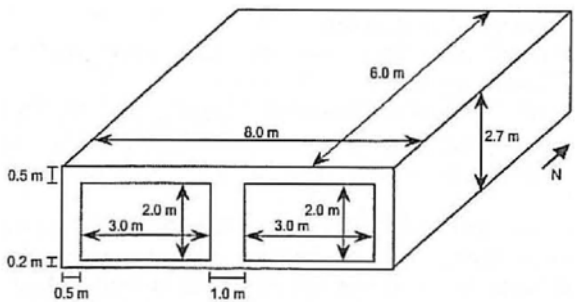


*Figure 2: Base case – isometric view (ANSI/ASHRAE Standard 140-2007)*

The building is a lightweight construction, which means that the walls and the floor have only low thermal mass. A very thick insulation effectively decouples the floor thermally from the ground in order to reduce uncertainties. The infiltration rate is 0.5 ach (air changes per hour), continuously. The internally generated heat is 200 W, 24 hours per day the full year. The internal gains are 60% radiative and 40% convective. They are also 100% sensible and 0% latent. The mechanical system consists of a 100% convective air system with equipment that is 100% efficient with no duct losses and no capacity limitations, no latent heat extraction and a non-proportional-type thermostat. The thermostat control strategy for the Base Case is:

- Heating if temperature < 20°C; otherwise off
- Cooling if temperature > 27°C; otherwise off

### *Cases 900, 600FF, 900FF*

Cases 900, 600FF and 900FF are slight modifications of Case 600 thus they can be easily explained. Although all cases were simulated and calculated only these three cases and the Base Case are presented in this paper, because it would be too unclear to explain all 39 cases and to represent and discuss their results.

Case 900 is the same as Case 600 except the material properties of the walls and the floor. They are more massive. That is why the thermal capacity is much higher than in the lightweight construction.

Case 600FF is the same as Case 600 except the mechanical system. In the free-floating cases (FF) no mechanical heating or cooling of the building is installed. Accordingly Case 900FF has also no mechanical system.

## MOISTURE BUFFER EXPERIMENT

Experiments were conducted in a A VCE 1000 climate chamber. This chamber allows conditioning the interior space from 20 °C to 130 °C with an accuracy of ± 0.1 °C and a temperature change rate of 0.3 K/min. The relative humidity can be controlled by the dew point temperature in a range between 5 °C and 60 °C supplied by an air change rate from 0 1/h to 1 1/h. The useful chamber volume is 0.916 $m^3$ resulting from dimensions 0.75 m width to 0.75 m height to 1.63 m depth.

The material, a new developed ceramic interior tile which is optimized with its pore structure to show a good performance in terms of moisture buffering, was stored inside the test chamber. The ceramic interior tiles were tested for their hygrothermal material properties at the certified laboratory of Fraunhofer IBP in Holzkirchen, with common and standardized test methods. The measured properties were used for simulation.

Air flow between the tiles in the chamber was possible and temperature and relative humidity sensors in 0.25 m and 1.00 m depth from the front opening in 0.25 m and 0.5 m height recorded the conditions inside the chamber space. The temperature was measured with inhouse calibrated ThermoSensor PT100 sensors with an accuracy of ± 0.1 °C and the relative humidity with Rotronic SC05 sensors with an accuracy of ± 2 % RH.

The boundary conditions for the test are shown in Figure 3. A constant temperature at 23 °C defines the test case. Moisture production inside the chamber is reproduced by a certain scheme of dew point temperature and air change rates. Both cases are initialized with the shown initialization conditions to reach consistent initial conditions.

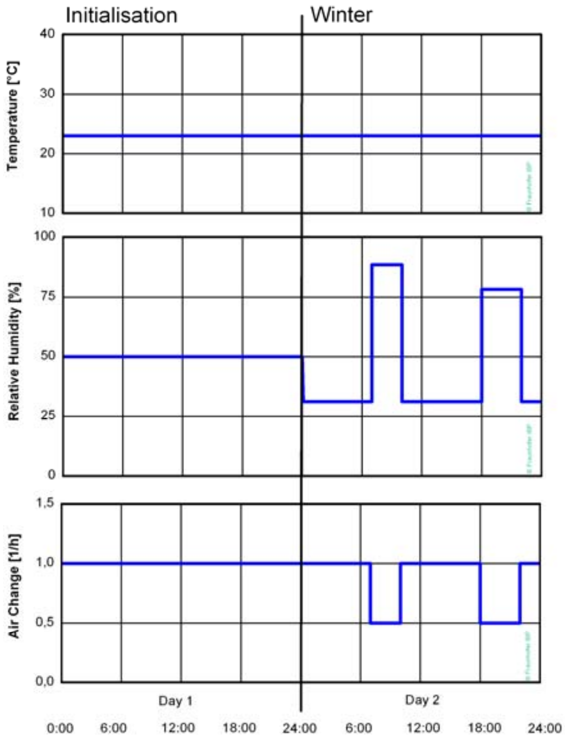


*Figure 3: Initialization and test conditions for the moisture buffer experiment*

A 3D-model of the chamber is built in WUFI®plus with all parameters recorded in the experimental setup used as input conditions. "External" temperature and relative humidity conditions as well as ventilation rates are used from the chambers target value logging. The simulation runs with a two-minute time step, to accurately model all changes in temperature and relative humidity. Outputs of the simulation are resulting temperature and relative humidity inside the chamber, which are used as validation values.

## RESULT ANALYSIS AND DISCUSSION

**VDI 6020**

After the calculation the results are to compare with the reference values in the guideline. These reference values are calculated by five simulation programs. Regrettably the guideline provides the reference values only graphically what impedes the comparison of the results. For the test cases of group 1 the reference values in VDI guideline 6007 (VDI Richtline 6007 2007) can be used. In this guideline the results of VDI guideline 6020 are provided as additional reference values. The test cases of group 2 can be compared only graphically.

Figure 4 shows the transient response of case 1 over 60 days. The results of the calculation with WUFI®plus show a more slow transient response as the reference values of the guideline. This result appears clearly in the comparison of the separate days, shown in Figure 5. The first and the $60^{th}$ days show a good fit with the reference data while on the $10^{th}$ day the reference values are slightly higher.

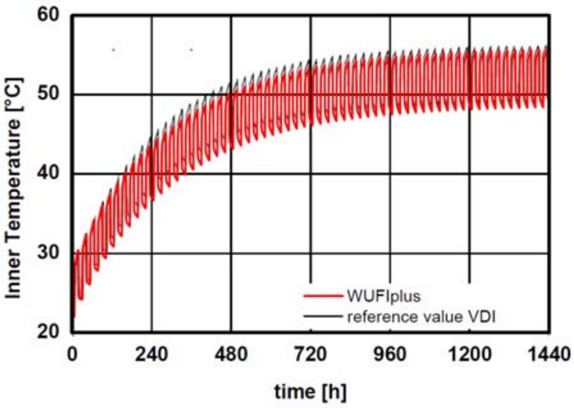


*Figure 4: Case 1 - Transient response over 60 days*

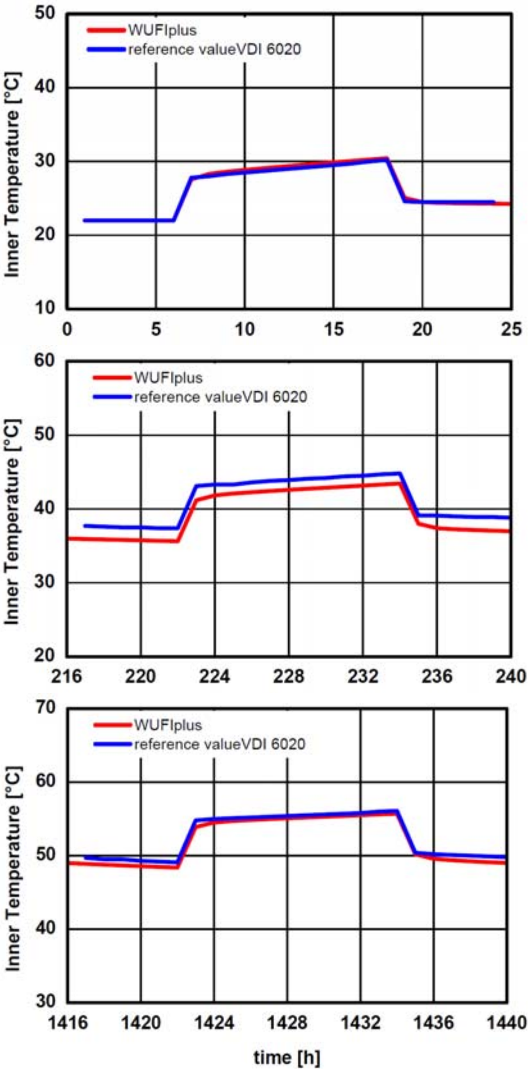


*Figure 5: Case 1 - Comparison 1st, 10th and 60th day of calculation*

The results of the calculation of the solar radiation through windows and components as required in case 9 are shown in Figure 6 and Figure 7. For both, a clear and a cloudy day, the appearing load due to solar radiation is represented comparably like the reference values in the guideline.

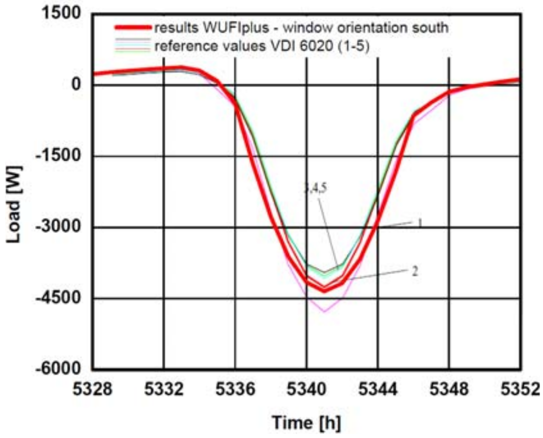


*Figure 6: Case 9 - Heating/Cooling load on a clear day - august 11$^{th}$ - window orientation south*

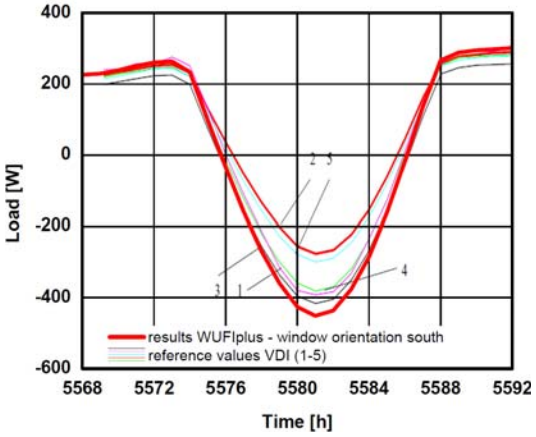


*Figure 7: Case 9 – Heating/Cooling load on a cloudy day - september 21$^{st}$ – window orientation South*

While the execution of the validation cases of the guideline VDI 6020 missing or unclear input data appeared. This prevents a continuous consistent application of the standard. To obtain more reliable results further validations were performed.

## ASHRAE 140

As already mentioned the results of WUFI®plus are compared with other whole building energy analysis programs. In Table 1 the programs that participated in the comparison are summarized. The column on the left lists the short form of the different programs and developers. They are used later again in the diagrams. In addition, the colour and the order are the same in all following charts. The results of WUFI®plus are always in red.

All results were taken from a full annual simulation. This is also valid for cases in which only daily outputs are required.

A basic prerequisite for further computations is the radiation on the differently oriented surfaces. As shown in Figure 8 WUFI®plus displays good results. The good results were expected as the program demonstrated its accuracy in other trials before.

*Table 1*
*Computer Programs of Example Results*

| CODE | PROGRAM | IMPLEMENTED BY |
|---|---|---|
| ESP-DMU | ESP-RV8 | De Montfort University, U.K. |
| BLAST-US/IT | BLAST-3.0 Level 193 v.1 | NREL[1], U.S. Politecnico Torino, Italy |
| DOE2 | DOE-2.1D 14 | NREL, U.S. |
| SRES/SUN | SERIRES/SUNCODE 5.7 | NREL, U.S. |
| SRES-BRE | SERIRES 1.2 | BRE[2], U.K. |
| S3PAS | S3PAS | University of Sevilla, Spain |
| TSYS-BEL/BRE | TRNSYS 13.1 | BRE, U.K.; Vrije Universiteit, Belgium |
| TASE | TASE | Tampere University, Finland |

[1]NREL: National Renewable Energy Laboratory
[2]BRE: Building Research Establishment

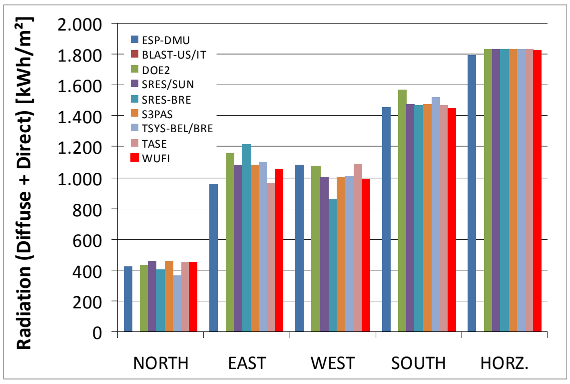


*Figure 8: Annual incident solar radiation on surfaces*

The ANSI/ASHRAE Standard 140-2007 gives also values for a cloudy day (March 5) and a clear day (July 27) for the radiation on the south and the west surfaces. These charts are presented in Figure 9. The upper graph contains the south facing the lower one the west facing. The curves are largely congruent with those of the other simulations.

In the following bar charts different type of loads are presented. Therefore some abbreviations are introduced (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

*Table 2*
*Abbreviations for bar charts*

| ABBREVIATION | MEANING |
|---|---|
| H | Annual Heating |
| C | Annual Sensible Cooling |
| PH | Peak Heating |
| PC | Peak Sensible Cooling |

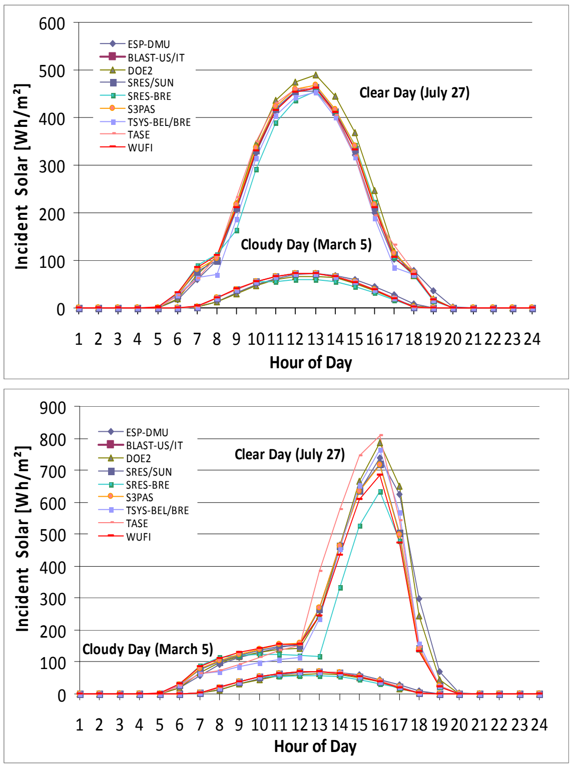


*Figure 9: Incident solar on cloudy and clear days*

The charts also include some so called "delta" results. This means that loads of one case are deducted from another case. It is simply indicated with a "-" symbol.

Figure 10 shows the heating and sensible cooling loads of one year. The results are very good especially for the heating loads. The effect of the higher thermal capacity of case 900 is clearly recognizable. The cooling loads are at the upper end compared with the other values. A reason for this could be the slightly limited window model of WUFI®plus.

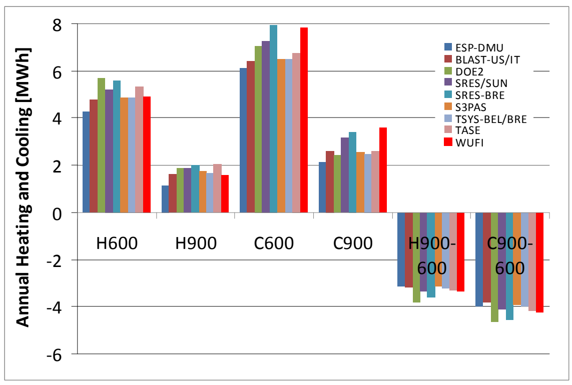


*Figure 10: Annual heating and cooling loads*

In Figure 11 the highest heating and cooling loads that occur during a year (peak loads) are shown. The same effects as in the annual consideration appear except the influence of the thermal mass for the peak heating loads is not so big. The date and the hour of the occurrence are largely the same for all participating programs. For example the peak heating is on January, 2nd at 2 a.m. for case 600 and 7 a.m. for case 900.

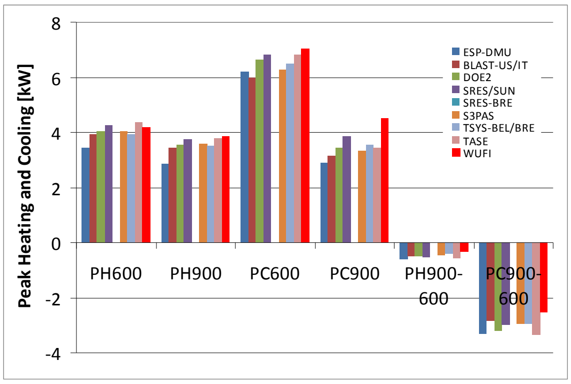


*Figure 11: Peak heating and cooling loads*

In the test cases with no mechanical equipment the ability of the program to calculate and output hourly air temperatures is tested. As already mentioned the free float cases are based on their corresponding non-ff cases. The air temperature output is for the zone air only, assuming well mixed air with no radiant effects.

Figure 12 shows the maximum (max), minimum (min) and the average temperatures (Ø) of the cases 600FF and 900FF. The calculation results of WUFI®plus show good agreement. Only the sparse higher average temperatures are conspicuous which can be also attributed to the already mentioned slightly limited window model.

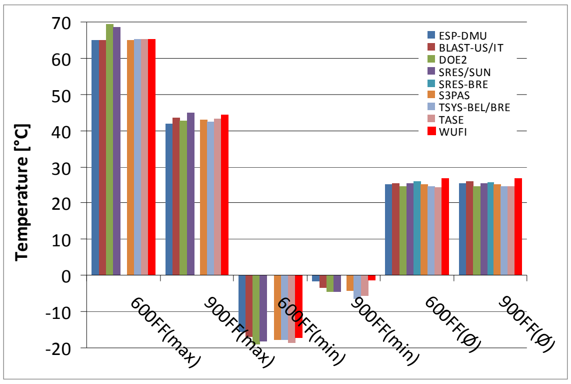


*Figure 12: Annual free float temperatures*

The temperature profile for a clear cold day (i.e. January, 4th) of case 600FF and 900FF is illustrated in Figure 13. It can be clearly seen that the higher thermal mass of case 900FF has a large effect. The flat curves point out that the internal temperature reacts much slower to the conditions outside. The difference between the curves is very small which demonstrates the accuracy of the WUFI®plus software again.

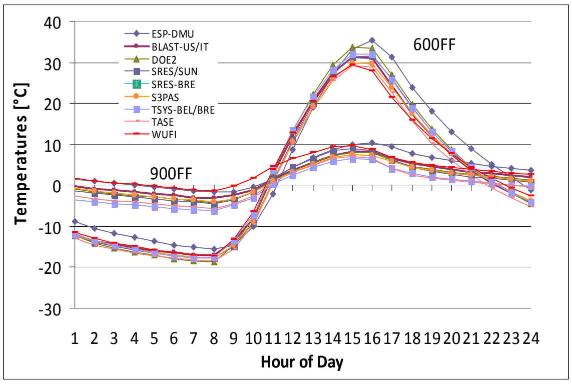


*Figure 13: Hourly free float temperatures*

**Moisture Buffer Experiment**

There is no common standard for the validation of hygrothermal whole building simulation software. The hygrothermal performance of different software was compared in the framework of IEA Annex 41 (Rode, Woloszyn 2007), where WUFI®Plus was one of the tools taking part. This comparison included a cross-comparison with other software modeling the coupled heat and moisture transport or using simple humidity buffer models. Presented in this paper, the validation of the software model WUFI®plus is performed in two steps. In a first step, the results of the measurements of the empty chamber, i.e. without moisture buffering materials in it, are compared. This validates the zone model, as moisture transport in the building enclosure is not existent. Figure 14 compares the simulation results with measurements of the relative humidity. A very good agreement between validation simulation and validation measurement is found, only the measured peak in relative humidity during the first moisture production cycle is slightly higher.

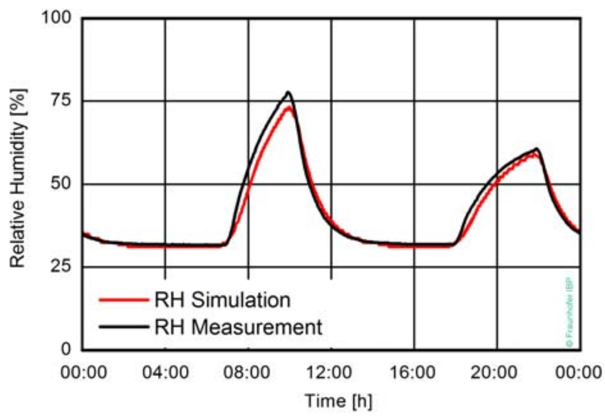


*Figure 14: Validation simulation results for empty test chamber.*

Validation measurement and validation simulation also show a very good agreement with moisture buffering tiles installed as shown in Figure 15. The dampening of the relative humidity peaks during moisture production cycles is reproduced in detail.

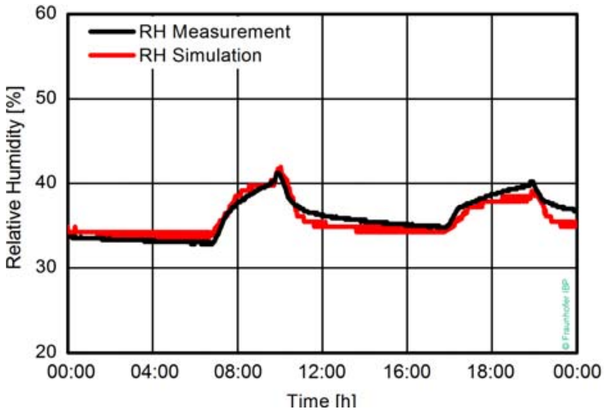


*Figure 15: Validation simulation results for test chamber with moisture buffering tiles installed.*

Modelling the experiment with the hygrothermal whole building simulation allows validating the hygric part of the tool WUFI®plus. Very good validation results can be achieved by accurately applying all necessary boundary conditions in the model. An assessment of the performance of moisture buffering materials is therefore possible.

## CONCLUSION

Validating a hygrothermal whole building simulation software requires various steps. None of the existing standards provides validation cases for all sub-models. Furthermore, some issues were found during the application of the standards/guidelines because of inconsistent and unclear definitions of the boundary conditions for the test cases. This applies especially to the guideline VDI 6020 and was already addressed in (Schöpfer, Antretter, van Treeck, Frisch, and Holm 2010).We proceeded with applying two different standards and added validation cases by measured hygric room behaviour. This is not very satisfying for consistent validation documentation. In the ideal case, one standard without discrepancies in the case definitions, covering hygric and thermal cases is available. Additionally cases for the assessment of multi-zonal energy and mass transport are required. Test cases provided in the used standards are more or less one-zonal.Further calibration/validation of the software will include cross-validation with other software and comparisons with measurements. So far, the HVAC system part of the software is not validated, as only ideal systems are available. The standards provide test cases for systems calibration, which will also be one next step.

The validation of WUFI®plus with the VDI 6020 guideline and with ASHRAE Standard 140-2007 showed good results. For all compared cases, the calculation results are comparable with the reference values. Detailed measurements of hygric conditions in a laboratory chamber allowed a very successful validation of the hygric model.

The latter pointed out the high influence of taking moisture transport and storage in the assemblies into account on calculating reasonable indoor humidity conditions. This is important for comfort assessment but even more for constructing energy efficient building envelopes that avoid moisture related problems. The introduced software is the only available tool that models not only building energy use but also hygrothermal component performance in such detail.

## ACKNOWLEDGEMENT

The German Federal Ministry of Economics and Technology funded this project.

## REFERENCES

ANSI/ASHRAE 140-2007. 2007. Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Antretter F, Mitterer C, Jung S-M, and Holm A. 2010. Use of moisture buffering tiles for indoor climate stability under different climatic requirements. Paper presented at IAQVEC 2010.

Holm A. 2008. ANNEX 41 Whole Building Heat, Air and Moisture Response (MOIST-EN).

Künzel HM. 1994. Verfahren zur ein- und zweidimensionalen Berechnung des gekoppelten Wärme- und Feuchtetransports in Bauteilen mit einfachen Kennwerten. University Stuttgart.

Lengsfeld K, and Holm A. 2007. Entwicklung und Validierung einer hygrothermischen Raumklima-Simulationssoftware WUFI®-Plus. Bauphysik 29 (3).

Rode C., Woloszyn M. 2007. Whole building hygrothermal modeling in IEA Annex 41. Thermal Performance of Exterior Envelopes of Whole Buildings X, Clearwater, USA 2007.,

Sauer F. 2011. Validierung der hygrothermischen Gebäudesimulation WUFI®plus mit ASHRAE-140. Hochschule München.

Schöpfer T. 2010. Dokumentation der Eigenschaften des hygrothermischen Gebäudesimulations-programms WUFI®plus. Fachhochschule Rosenheim.

Schöpfer T, Antretter F, van Treeck C, Frisch J, and Holm A. 2010. Validierung energetischer Gebäudesimulationsmodelle mit der VDI 6020. Paper presented at BauSIM 2010: Dritte deutsch-österreichische IBPSA Konferenz.

VDI Richtlinie 6007. 2007. Berechnung des instationären thermischen Verhaltens von Räumen und Gebäuden. Berlin: VDI-Verlag GmbH.

VDI Richtlinie 6020. 2001. Anforderung an Rechenverfahren zur Gebäude- und Anlagensimulation. Düsseldorf, Berlin: VDI-Verlag GmbH.