Validation of Dynamic Model BSim to Predict the Performance of Ventilative Cooling in a Single Sided Ventilated Room

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ABSTRACT

Ventilative cooling (VC) is an application (distribution in time and space) of air flow rates to reduce cooling loads in spaces using outside air driven by natural, mechanical or hybrid ventilation strategies. VC reduces overheating in both existing and new buildings - being both a sustainable and energy efficient solution to improve indoor thermal comfort. VC is promising low energy cooling technology that has potential to substantially reduce the use of mechanical cooling in airtight and highly insulated buildings. However, architects and engineers are skeptic to apply natural VC in their building design due to the uncertainty in the prediction of energy performance and thermal comfort.

Firstly, BSim software, that is a whole building simulation tool, is validated according to procedure proposed in EN 15255 standard (Thermal performance of buildings – Sensible room cooling load calculation – General criteria and validation procedures). The aim of validation according to standard is to control if BSim modules provide reliable results and would not cause the discrepancy between measured and simulated operative temperature.

Secondly, simulated operative temperatures for five different ventilation system configurations are compared to on-site building measurements of a single sided ventilated office room.

Paper shows that simulation model is capable of estimating the operative temperature during a summer period reasonably accurate. The maximum obtained deviation of the simulated operative temperature for five different system configurations, is within -19% and 5.1%.

Moreover, out of 13 selected validation cases proposed in EN 15255, 11 have passed and 2 have not pass the validation procedure. The paper provides explanation for the 2 cases that did not pass the validation procedure and share the conclusions drawn from validation procedure.

KEYWORDS

Ventilative cooling, natural ventilation, dynamic simulation, validation.

1 INTRODUCTION

Study presented in this paper is a part of subtask A: “Methods and Tools” of the on-going research of Annex 62 “Ventilative Cooling” that operates under International Energy Agency (IEA).

Ventilative Cooling (VC) can be described as effective use of outside air by means of natural, mechanical, or hybrid ventilation strategy to reduce or eliminate the need for compressed cooling.

VC is not a product and should be rather regarded as an integrated part of the design strategy. Case studies demonstrated that the use of VC, in many situations, can result in considerable energy savings as well for new constructed buildings (Tranholm, 2012) as for renovation or retrofit situations (Flourentzou, 2012).

In spite of the considerable energy saving potential of VC, architects and engineers are sceptical to apply VC in their building design. One of the major reasons is the uncertainties regarding the estimation of energy performance and thermal comfort in buildings in which VC is applied. A possible key incentive to increase the opportunities for VC, and lower the uncertainties for building designers, are regulatory measures. In the article of (Kapsalaki, 2015), the current building regulations of 8 European countries are investigated regarding if these regulations assess the potential of VC. The study showed that regulations usually consider VC rather simplified and do not address its complexity. Another important finding is that the majority of the countries estimate the cooling demand based on monthly models (Kapsalaki, 2015). However, it is uncertain whether monthly models can evaluate the complexity and cooling potential of VC. Kolokotroni (Kolokotroni, 2015) state that further research should be conducted to study if VC potential can be estimated using monthly time steps. Monthly average models could under estimate the cooling potential of VC and therefore, reduce the application for building designers. On the other hand, it seems relevant to start considering incorporation of dynamic, hourly-based models in the building regulations. These models increase the possibilities to evaluate and optimize VC and thereby increase its application potential. However, due to the complexity of VC the hourly based models also impose adequate control strategies and appropriate input parameters. An important input parameter to assess the VC performance is the outdoor wind velocity and temperature. The ventilation rate and cooling power of VC is induced by thermal buoyancy and outdoor wind pressure difference. The latter one is highly turbulent and variable over time. The most of dynamic hourly-based building performance simulation tools applies hourly-based meteorological weather data as input for the determination of the local solar radiation, temperature and wind velocity. It is however questionable whether an hourly input is sufficient enough to take the turbulent behaviour into consideration and estimate correctly the VC potential.

In the present study the simulation results of dynamic model with an hourly based meteorological input data are compared to measurements of an existing building to assess the accuracy and the deficiencies of this kind of models.

The comparison is made based on a single-sided ventilated room consisting of a side hung window for both night and continuous ventilation strategies. The software used for the simulation is BSim developed by the Danish Building Institute, (Wittchen, 2005). In this study the following main research question is answered:

- What is the estimated operative temperature accuracy of a dynamic model with hourly based meteorological input data for a single sided natural ventilated room?

To answer the main research question, the following sub research question is answered:

- What is the accuracy of the BSim simulation program regarding the sensible cooling load in comparison with the EN-15255 standard?

Firstly, methodology is presented. Thereafter the measurement protocol is described. Subsequently the applied equations in BSim and the sensibility of different parameters are discussed. Weekly comparisons between measured and simulated operative temperature are presented. Paper closes with discussion and conclusions.

2 METHODOLOGY

2.1 Validation with EN 15255

Firstly, BSim software is validated according to procedure proposed in EN 15255 standard (CEN, 2006). The aim of validation according to standard is to control if other BSim models provide reliable results and will not be the reason for discrepancy between measured and simulated operative temperature.

The standard EN 15255 validation procedure consists of 15 tests cases of which 13 were considered relevant for this study, see Table 1. The validation consists of a comparison between the simulated cooling load, and average cooling load with reference values specified in the standard.

Table 1: 13 chosen validation tests

Test	**Column Title**
1	Reference case
2	Test 1 + modification of the thermal inertia
3	Test 1 + modification of the internal gains
4	Test 1 + modification of the glazing system
5	Test 1 + modification of the system control
6	Test 1 + intermittent operation of the system
7	Test 6 + modification of the thermal inertia
8	Test 6 + modification of the internal gains
9	Test 6 + modification of the shading
10	Test 6 + modification of the ventilation
11	Test 6 + modification of the max. cooling power
12	Test 6 + modification of system control
13	Test 6 + modification of the shading control

Validation procedure has indicated some limitation concerning the standard. The standard does not take into account: dynamic solar path tracking, self-shading, and dynamic material properties. BSim is an advanced simulation software and had to be simplified in order to mimic requirements stipulated in EN 15255.

To comply with the standard the maximum cooling load and average cooling load must not deviate 5% from the reference values provided in the standard for each 15 cases. In Fig.1 are presented mismatch percentages of the average cooling and maximum cooling load obtained by BSim. Of the 13 cases conducted 11comply with the accuracy requirements. The maximum cooling power in test 2 and 4 from Table 1 is estimated slightly higher in comparison with the reference values stated in the standard.

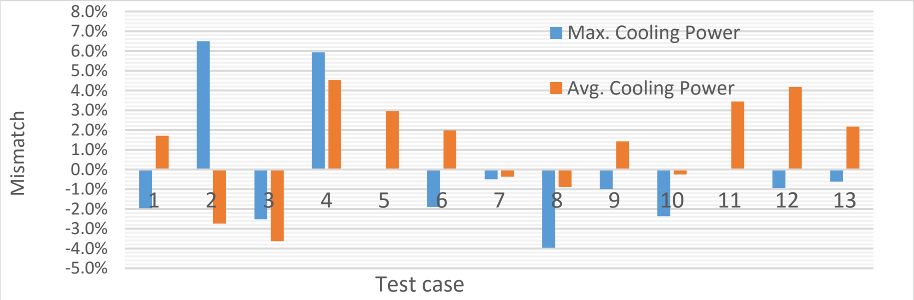


Figure 1: Mismatch of the maximum and average cooling load in relation to the reference results

The overestimation of the maximum cooling power in test 4 can be possibly ascribed to the not fully equalized operative temperature with the air temperature (EN 15255 requires air temperature whereas BSim is controlled according to operative temperature). For the validation purpose operative temperature in BSim is weighted with factor 0.9 for air component and only 0.1 for radiant component. This small but still difference becomes especially important for cases with high solar gains. Test 4 consists of a glazing system without shading device. The high solar radiation increases the wall temperature resulting in a larger difference between the mean radiant and air temperature. Due to this effect the air temperature is 1.5 K lower compared to the operative temperature at the hour with the highest solar radiation. Probably if both the operative and air temperature were fully equalized case 4 would fall within the accuracy requirements. A clear explanation cannot be given for the overestimation of the maximum cooling power with 1.5 % point in test 2. One clarification could be that the adjustments and assumptions made for the simplification of the program, result in a slightly higher accuracy mismatch. These assumptions and simplifications are well substantiated. Nevertheless, the assumptions to equalize the operative temperature with the air temperature and the increase of the transmittance of the solar shading have a considerable influence on the cooling load. The combined inaccuracy of the made simplifications could result in a small overestimation of the maximum cooling power for specific cases. In authors opinion BSim passed validation procedure and mismatch between standard reference values and simulated values is mostly not due to incorrect calculation method in software but rather due to mismatch in input parameters defining reference cases.

2.2 Reference building description and measuring campaign

In this section the building and the measurement protocol are described. Building selection and measuring campaign on the building was conducted by the consulting/research company ESTIA from Switzerland. Measurements were conducted in the primary school building located in St-Germain, Switzerland in west oriented room highlighted in yellow in Fig. 2.

Figure 2: West façade view of the measured building, the monitored room is highlighted in yellow.

The chosen room has a rectangular shape (5,3 x 7,6 x 3,3m), heavy weight construction, mechanical ventilated HVAC system, and a glazing composition consisting of an openable glass area of 1m^2 and fixed glass area of 7m^2 plus an exterior shading device which covers both the side hung window and the fixed window glass area. The primary school is located in an open area. Obstructions around building were taken into account in the simulation model. Due to the asphalt surrounding the building a ground reflectance of 0.1 is assumed as appropriate value.

Temperatures were measured inside, outside and in the adjacent rooms of the investigated room. The measurements were conducted for 6 weeks from 1-7-2015 till 13-8-2015. The data was logged over this period with an interval of 10 minutes. A concise function description of the most important sensors is given below in this chapter. The air temperature in the monitored room was measured at floor and ceiling height. Additionally, in the middle of the room was measured operative temperature. In order to appropriately address the heat transfer between monitored room and the adjacent rooms, temperature sensors were placed also in all adjacent rooms and in the corridor. To acquire insights of the wall surface temperature, a sensor was placed against one of the inner walls. Based on the measured local weather conditions a weather data file was prepared and uploaded to BSim. The solar radiation on site was not measured and therefore, it was collected from an official weather station located 2-4 km in the vicinity of the monitored building.

Section view Plan view

Figure 3: Overview of temperature sensor locations in and around the monitored room.

Measurements are performed under 6 test conditions in order to investigate if software is able to provide reliable results under different VC strategies. The different 6 test cases are presented in Table 2. It has to be indicated that during the measuring campaign monitored building was not occupied.

Table 2: Overview of 6 test cases.

Case	Blinds position	Mech. ventilation	Window position	Intern. gains [W]
1	Standard	On	Closed	300
2	Standard	Off	35% open (nigh)	300
3	Standard	Off	35% open (permanent)	300
4	Standard	Off	62% open (permanent)	300
5	Standard	Off	Closed	300
6	Open	Off	Closed	300

Specification of the control settings of each system:

- Standard blind position refers to following daily repeated position in standard time:
  - Blind is completely open at 06:00
  - Blind is closed at 13:00 at pitch angle of 45°
  - Blind is completely closed at 17:00
  - Blind is completely closed during the weekend
- The internal gains resemble people load (building is not occupied during measuring campaign) and follow a daily profile. Heat gains are activated from 07:00 till 11:00 and 12:00 till 16:00.

The inlet air temperature from the mechanical ventilation is measured at 26°C at a daily repeated ventilation rate of 150m^3/h between 07:00 till 16:00 and 62 m^3/h between 17:00 till 23:00. For the rest of the hours the ventilation system is not in operation. The open area of the window is calculated as summation of the open areas at the side of the side hung window and bottom triangular. The top triangular in this case is not taken into account because of the lintel.

2.3 Natural ventilation in BSim

This chapter shortly present calculation method for natural ventilation that is applied in BSim. BSim general expression to calculate the total airflow q_v, that takes into account an air flow induced by wind and thermal buoyancy.

$$q_v = |q_w^2 + q_{vT}^2|^{\frac{1}{2}} = \left| \frac{C_v}{|C_v|} (C_v V_{10})^2 + \frac{\Delta T}{|\Delta T|} \left(C_T |\Delta T|^{\frac{1}{2}} \right)^2 \right|^{\frac{1}{2}} \tag{1}$$

in which C_V is a constant determined by building and wind conditions and C_T is constant determined by building and temperature conditions, V_{10} is wind velocity at the height of 10 m, ΔT is air temperature difference between inside and outside . This expression is used for both single side and cross natural ventilation. The distinction between these two is made by the application of different constants.

To apply general expression in Eq. 1 for a situation of one single opening with combined wind and thermal buoyancy, BSim first numerically calculates the height of the neutral plane by the mass balance Eq. (2). With the known neutral plane height, the C_T coefficient is calculated by Eq. 3. This derivation is proposed by Andersen (Andersen, 2003) based on fundamental flow equations.

$$\sum_{j=1}^{n} C_{d,j} A_j \left|H_0 - H_j\right|^{1/2} \frac{H_0 - H_j}{\left|H_0 - H_j\right|} = 0 \qquad (2)$$

$$C_T = \sum_{j=1}^{n} C_{d,j} A_j \left(\frac{2(H_0 - H_j)g}{T_i}\right)^{1/2} \qquad (3)$$

Where H_0 is neutral plane height, H_j is height difference between ground level and middle of jth opening, *Cd* is opening's discharge coefficient, *A* is opening geometrical area.

The C_v coefficient is based on the empirical equation derived by Warren and Parkins 1985 and is calculated by Eq. (4).

$$C_v = 0.03A \qquad (4)$$

Both constants substituted in Eq. 1 results in Eq. 5 for calculation of total air volume flow.

$$q_v = \left|(0.03AV_{10})^2 + \sum_{j=1}^{n} C_{d,j} A_j \left(\frac{2(H_0 - H_j)g}{T_i}\right)^{1/2}\right|^{\frac{1}{2}} \qquad (5)$$

The used C_v coefficient is based on theoretical considerations, wind tunnel experiments, and two scale measurements. This expression represents a minimum estimate of the ventilation rate for wind induced natural ventilation and does not take into consideration the incidence angle of the wind and disregards the C_d value of the window. Although Eq. 4 is simplistic, it is quite accurate, also in relation to a window system including a shading device. Koffi (Koffi, 2015) showed by means of site measurements that the average derivation of Eq. 4 is 14.7% for a window including a horizontal sliding shutter. The shading device applied in this study is different, namely a venetian blind. Nevertheless, this study provides a proper indication of the expected accuracy. Important to note is that the wind direction during the measurement conducted in this study was mostly windward. No reference is found to verify the accuracy of Eq. 3. The same applies for the combination of both equations in Eq.5. Therefore, the judgement about the overall accuracy of the calculation method cannot be given.

2.4 Important assumptions to models input parameters

In the model several important parameters had to be carefully estimated. These are: solar radiation, Cd coefficient of the window and vertical temperature gradient in the room. In this section are presented investigations behind the assumptions.

Solar radiation

Only the global radiance in W/m^2 was available for this study. To divide the global radiation into a direct and diffuse horizontal radiation, the model of Perez (Perez, 1992) was applied.

Discharge coefficient

During the measurements the venetian blinds changes position and angle. This influences the discharge coefficient *(Cd)* of the window, since friction and turbulences in the window opening are affected. BSim does not allow applying different Cd values for the same simulation. Therefore, a simplified average value has to be used. To evaluate the effects of the shading position on the flow rate through the opening, measurements in the room were conducted. Indoor and outdoor temperature and CO_2 level were measured. The CO_2 was used as tracer gas. By means of the decay method the air flow through the window was estimated, see Eq. 6.

$$Q = -\frac{1}{6} ln\left(\frac{C_0}{C_i(t)}\right) \tag{6}$$

At which the C_0 is the initial CO_2 concentration and $C_i(t)$ the concentration at time x. With the obtained air flow through the window, the Cd coefficient is estimated by Eq. 7. derived by (Flourentzou, 1997).

$$C_d = \frac{Q}{\frac{1}{3}A\sqrt{\frac{(T_i - T_e)gH}{\bar{T}}}} \tag{7}$$

Table 3: Measured/calculated Cd coefficient for different shading position

Blind position	**Opened**	**45°**	**Closed**
Cd	0.60	0.44	0.43

To investigate sensitivity of the model to Cd coefficient, a comparison between the operative temperature of models with a Cd value of 0.6, 0.5, and 0.44 was performed. The outcomes showed an insignificant difference between the simulated operative temperature of the different models and finally it was decided to use Cd of 0.6 for all test cases.

Vertical temperature distribution

Dynamic building simulation programs often assume that air in the room is fully mixed. This simplification in some cases is far from reality. For example, for displacement ventilation or natural ventilation with a substantial temperature difference between exterior and interior this might be the case. The experimental study of (Heiselberg, 2001) showed that especially for single sided ventilation the airflow through the window is downwards and at large opening angles reaches the floor and turns into the room as a stratified airflow. The stratified flow result in a vertical temperature distribution at which the assumption of the fully mixed zone no longer holds. Important to note is that the experiments were conducted with a temperature difference between the outside and inside at 20 K. The temperature difference in this study varies between 10 and 0 K. The vertical temperature gradient in BSim can be adjusted by activation of “Kappa Coefficient”. The Kappa value is a coefficient which is related to a linear simplification of the actual temperature vertical profile. To assess the sensibility of models to this coefficient several simulations with Kappa values 1, 0.9 and, 0.7 were conducted. Results are presented for period of 3 days and the open area of the side hung window is for these hours 62%. Kappa value equal 1 represents fully mixed air and the lower the number become the higher the stratification becomes. The results for the three chosen days are visualized in Fig. 4. From Fig.4 can be observed that simulated operative temperature strongly depends on Kappa value. Kappa value of 0.7 overestimates the temperature gradient. While a fully mixed assumption, Kappa 1, under estimate the temperature gradient. Kappa value of 0.9 appears to be a good estimate and indicate that air temperature has tendency to stratify. For detailed explanation of Kappa model please refer to (Brohus, 2013).

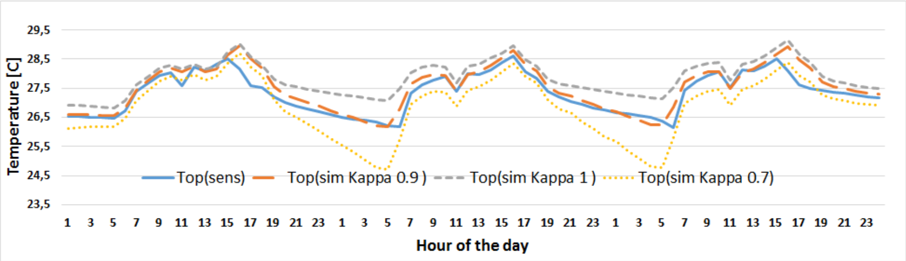


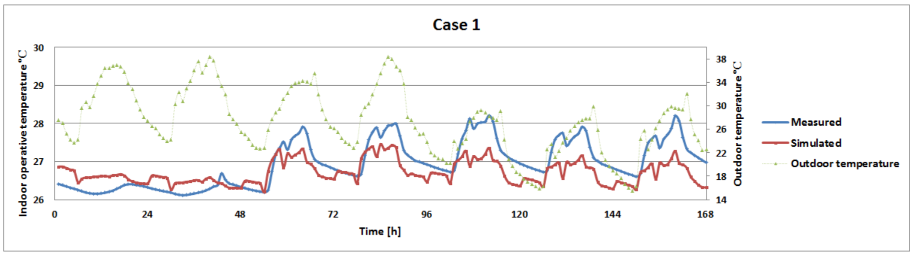
Figure 4: Simulated operative temperature for different Kappa values compared to the measured temperature Top (sens).

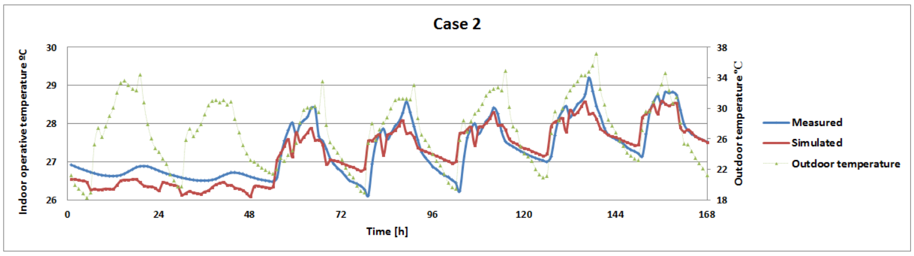
3 RESULTS

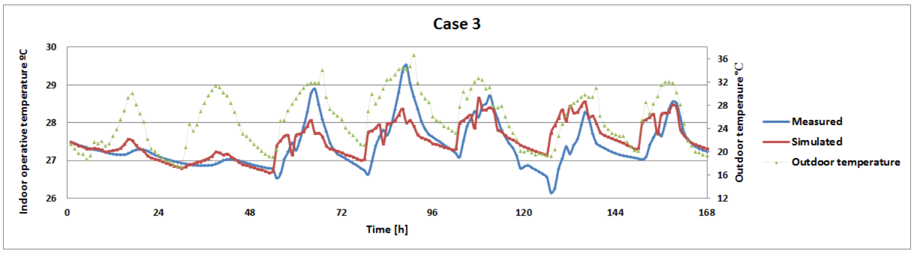
In this chapter are presented plots depicting simulated and measured operative temperature for the 6 investigated VC strategies, see Fig. 5. Case 6 is only the last day in case 5 when solar shading was not activated therefore it is depicted on one figure together with results for case 5. Summary of the obtained results is presented in Table 4. In Table 4 can be found mean, min and max deviation between measured and simulated operative temperature. Next to percentage deviation can be found absolute mean, min and max temperature difference between measured and simulated operative temperature.

Table 4: Summary of all cases - comparison between simulated and measured operative temperature.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Deviation mean	0.8%	0.3%	-0.5%	5.2%	-4.3%
Deviation min.	-1.9%	-5.8%	-6.4%	19.0%	-9.5%
Deviation max.	4.4%	3.3%	5.1%	0.4%	0.5%
Temp. diff.mean	0.23	0.1	-0.1	-1.3	-1.1
Temp. diff. min.	-0.49	-1.5	-1.7	-4.3	-2.4
Temp.diff. max.	1.23	1.0	1.5	0.1	0.1







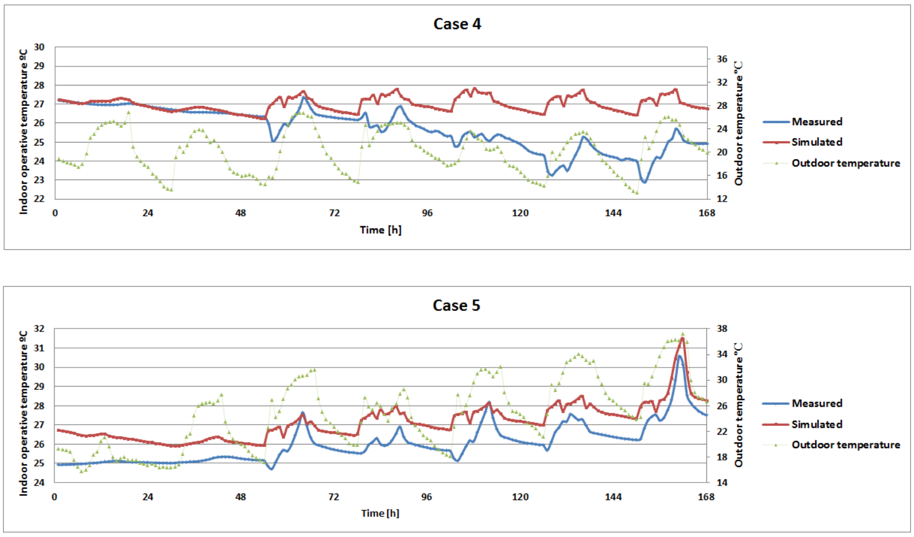


Figure 5: Comparison of operative temperature measured and simulated for 6 investigated operation scenarios.

4 DISCUSSION

Figure 5 (Case 1) presents results for the first week of the measuring campaign. This week starts with weekend, which means no internal gains were present during these two days. Case 1 is the only case with mechanical ventilation operating. Even though air flow to the room is kept under control there can be observed temperature difference between measurements and simulations. The highest discrepancy of approximately 1 ºC is observed for day hours. Difference in results could be due to applied method to convert global solar radiation to direct and diffuse component.

For case 2 and 3 temperature agreement between simulated and measured operative temperature is very satisfactory. This applies both to weekend days and week days.

The discrepancy becomes significant first after the weekend in case 4 (62% opened window). Measured and simulated operative temperature begins to depart from each other. At the end of the week, measured temperature becomes almost 2 degrees lower than the simulated one. Analysis indicates that measured temperature is significantly lower than simulated temperature. In the case 4 window is kept opened and outdoor air temperature during that week is significantly lower than, for example, previous week. It could be expected that inlet cold air would decay towards floor, spread along the floor and rise up at heat gains. Such air distribution resample displacement ventilation and could result in higher air temperature gradient and thus lower operative temperature in the middle height of the room.

This could explain difference in observed and simulated operative temperature in that case. The solution could be to apply lower Kappa value that would represent displacement air distribution. On the other hand, since each simulation in BSim can be assigned only one Kappa value this would influence results in the previous weeks and that would not lead to correct solution. This case indicate that temperature stratification and air flow in the room is an important issue that should be addressed carefully and that even in dynamic detailed models such as BSim there is still place for improvement.

In case 5, measured and simulated temperature has the same profile but with 1 ºC shift. It is likely that the 5th case is influenced by the big difference from the 4th case as the thermal inertia in the building is causing some of the deviations due to discrepancy in the previous week. The last day in week 5 represent case 6 when no solar shading was active. The effect of lack of shading is immediately noticeable both in simulation and in measured data.

5 CONCLUSION

In general agreement between simulated and measured operative temperature is satisfactory.

With regards to discrepancy between simulation and measurements, there could be several reasons for the mismatch between simulated and measured temperature. The largest impact on the operative temperature during day time has solar radiation. As indicated in the paper, in this study global solar radiation was collected from local weather station and then it was converted by the model of (Perez, 1992) to a direct and diffuse component. This model has a mean bias error of 14%. The error might contribute to the discrepancy between measurements and simulations.

From the presented study, it can be concluded that natural ventilation can be considered as mixing ventilation but for some cases it would behave like displacement ventilation. Many of the whole building simulation tools, including BSim, has it difficult to take into account both ventilation principles, namely mixing and displacement, in one simulation model. Moreover, as a recommendation for the software developers can be stated that closer attention should be paid to tools supporting definition of vertical temperature stratification in the rooms.

Presented study indicates that even in hourly dynamic and detailed models results can differ with up to 1- 2 ºC from measurements due to complexity of VC performance. That imposes question, weather monthly tolls should be considered at all for modelling of VC and weather regulatory measures should focus their recommendation on advanced dynamic tools.

6 ACKNOWLEDGEMENT

PRESENTED WORK IS CARRIED OUT AS PART OF IEA EBC ANNEX 62 VENTILATIVE COOLING:
http://venticool.eu/annex-62-home/

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