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Evaluation tool of climate potential for ventilative cooling

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ABSTRACT
The ventilative cooling potential tool (VC tool) aims at assessing the potential effectiveness of ventilative cooling strategies by taking into account also building envelope thermal properties, occupancy patterns, internal gains and ventilation needs. The analysis is based on a single-zone thermal model applied to user-input climatic data on hourly basis. For each hour of the annual climatic record of the given location, an algorithm identifies over the occupied time the number of hours when ventilative cooling is useful and estimates the airflow rates needed to prevent building overheating. As validation of results, the ventilative cooling potential tool outputs are compared with the predictions of a building energy simulation model of a reference room in two different climates. The VC tool is particularly suitable for early design phases, providing building designers with useful information about the level of ventilation rates needed to offset given rates of internal heat gains.

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Ventilative cooling potential; natural ventilation; climate analysis; early design stages; overheating; airflow rates

Introduction

The new initiatives and regulation towards low energy buildings forces designers to exploit the cooling potential of the climate to reduce the overheating occurrence and to improve thermal comfort indoors. Climate analysis is particularly useful at early design stages to support decision-making towards cost-effective ventilative cooling solutions. The first step to design ventilative cooling is to analyse the climate potential; in other words, the natural forces that drive natural ventilation (outdoor temperature and wind velocities and direction).

As buildings with different use patterns, envelope characteristics and internal loads level react differently to the external climate condition, the climate analysis cannot abstract from building characteristics and use.

The existing methods (Artmann, Manz, & Heiselberg, 2007; Ghiaus, 2003) for climatic cooling potential (CCP) evaluation are based on degree-hours approaches. Degree-hours approaches rely on indoor and outdoor temperature gradients on hourly basis.

Statistically significant outdoor temperatures can be derived from series of historical data gained from weather stations at standard conditions, typically located in airports.

Several attempts have been made to assess indoor temperatures without relying on detailed building data which would be hard to define at early design stages. Artmann et al. (2007) assumes the building temperature to oscillate harmonically according to a predefined function to simulate the dynamic effect of heat storage in the structure materials. Emmerich, Polidoro, and Axley (2011) suggest to use the balance point temperature defined as the outdoor air temperature at which the

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total heat gains equal the total loss. Similarly, Ghiaus (2003) used the indoor temperature of the free-running building, defined as the indoor temperature of the building in thermal balance with the outdoor environment when neither heating nor cooling is used.

Lately, Ghiaus, Allard, Santamouris, Georgakis, and Nicol (2006) assessed the natural ventilation potential to reduce cooling need using probability distribution of temperature and wind velocities and directions. It is here assumed that wind and stack have no opposite effect.

Yang, Zhang, Li, and Chen (2005) proposed a method to estimate natural ventilation potential based on pressure difference Pascal hours due to stack and wind forces and compare them with the required pressure difference for acceptable indoor air quality (IAQ) and thermal comfort. Emmerich et al. (2011) also developed a method based on a single-zone model of natural ventilation heat transfer in commercial buildings to characterise the natural direct ventilation rates needed to offset given internal heat gains rates to achieve thermal comfort during overheated period; and the potential internal heat gain that may be offset by night-time cooling for those days when direct ventilation is insufficient.

In the night-time cooling case, the building is considered very massive so that all the daytime heat gains are expected to be stored in the building structure. In this way, the maximum heat transfer rate at which energy may be removed from thermal mass can be calculated. Based on this method, Emmerich (2001) developed a web-based tool which estimates the required ventilation rates when direct ventilation is effective and the internal gains that can be offset on the subsequent day for a nominal unit night-time air change rate when night cooling is effective. The internal temperature is assumed to be constant, as well as the internal heat gains which do not take into account about the solar gain variability over throughout the day and over the whole year. Therefore, the tool outputs the percentage of occupied time over a year when the direct cooling is effective, if not, whether it is due to too hot or too cold temperatures or because of humidity.

Within International Energy Agency (IEA) Annex 62 project (IEA EBC Annex 62 - Ventilative cooling, 2014–2017), experts from 13 countries developed the ventilative cooling potential tool (VC tool), which aims at assessing the potential effectiveness of ventilative cooling strategies by taking into account also building envelope thermal properties, occupancy patterns, internal gains and ventilation needs. It has to be considered only as a preliminary analysis on the assumption that thermal capacity of the building mass is sufficiently high and therefore does not limit the heat storage process. The paper presents the VC tool and its features. The tool is then validated by comparing the tool results with building dynamic simulations outputs.

The ventilative cooling potential tool

The VC tool is an excel-based tool intended to be used during early design stages for estimating the potential of ventilative cooling, for different types of building use and climate.

Theory

The VC tool refers to the method proposed by Emmerich (2001) further developed within the IEA Annex 62 activities.

This method assumes that the heating balance point temperature ($T_{o-\mathrm{hbp}}$) establishes the outdoor air temperature below which heating must be provided to maintain indoor air temperatures at a defined internal heating set point temperature ($T_{i-\mathrm{hsp}}$).

Therefore, when outdoor dry bulb temperature ($T_{o-\mathrm{db}}$) exceeds the heating balance point temperature, direct ventilation is considered useful to maintain indoor conditions within the comfort zone. At or below the heating balance point temperature, ventilative cooling is no longer useful but heat recovery ventilation should be used to meet minimum air change rates for IAQ control and reduce heat losses.

The heating balance point temperature ($T_{o-\mathrm{hbp}}$) can be calculated as follows:

$$T_{o-\mathrm{hbp}} = T_{i-\mathrm{hsp}} - \frac{q_i^{''}}{\dot{m}_{\min} c_p + \sum hA} \tag{1}$$

where $T_{o-\mathrm{hbp}}$ is the heating balance point temperature [°C], $T_{i-\mathrm{hsp}}$ is the heating set point temperature [°C], $q_i^{''}$ is the total internal gains [W/m^2], c_p is the air capacity [J/kg K], $\dot{m}_{\min}$ is the minimum required mass flow rate [kg/s], $\sum hA$ is the envelope heat exchange [W/K], h is the average heat transfer coefficient of the envelope [W/m^{2}K] and A is the envelope area [m^2].

The minimum required ventilation rate refers to IAQ standards, i.e. EN 15251:2007.

The equation derives from the energy balance of a well-mixed single-zone delimited by heat transfer surfaces and relies on the assumption that the accumulation term of the energy balance can be negligible. It is a reasonable assumption if either the thermal mass of the zone is negligibly small or the indoor temperature is regulated to be relatively constant. Under these conditions, the energy balance of the zone is steady state and can provide an approximate mean to characterise the ventilative cooling potential of a climate. This assumption will be further discussed and validated in the next paper sections.

The comfort zone is determined according to the adaptive thermal comfort model proposed in the EN 15251:2007 standard. The upper and lower temperature limits of the comfort zone are calculated as follows:

$$T_{i-\max} = 0.33 \cdot T_{\mathrm{rm}} + 18.8 + K \tag{2}$$

$$T_{i-\min} = 0.33 \cdot T_{\mathrm{rm}} + 18.8 - K \tag{3}$$

where $T_{i-\max}$ is the upper operative temperature limit of the comfort zone [°C], $T_{i-\min}$ is the lower operative temperature limit of the comfort zone [°C], T_{rm} is the outdoor running mean temperature [°C] and K is the constant depending on required comfort category: $K = 2$ if comfort cat. I, $K = 3$ if comfort cat. II, $K = 4$ if comfort cat. III.

Below an outdoor running mean temperature of 10 °C, the upper temperature limit is set as the upper temperature limit for heating recommended by EN 15251:2007. Below an outdoor running mean temperature of 15 °C, the lower temperature limit is set as the lower temperature limit for heating recommended by EN 15251:2007.

Input

The tool requires basic information about a typical room of the building, the building use and the climate. Figure 1 reports the tool GUI with input and outputs visualisation.

Within the building data section, the user is required to input basic internal geometry data of the reference room as well as the type of the building and the comfort category.

Comfort requirements refer to the comfort categories defined by the EN 15251:2007 standard. Recommended input values given for each of the different comfort categories are included in the tool and automatically selected.

Various thermal and technical properties specifications about the envelope features are required to determine the transmission losses and the solar gains. Minimum required air change rates (l/s-m^2) calculated according to EN 15251:2007 determine the ventilation losses within the energy balance of the reference room.

The tool includes a database of standard load profiles of occupancy, lighting and electric equipment for different building typologies, which are included in the new standard on energy performance of buildings (PrEN 16798-1, 2016-02-07 under approval). According to the selected building type, the tool sets automatically the typical corresponding occupied time and load profiles on hourly basis due to occupancy, lighting and electric equipment.

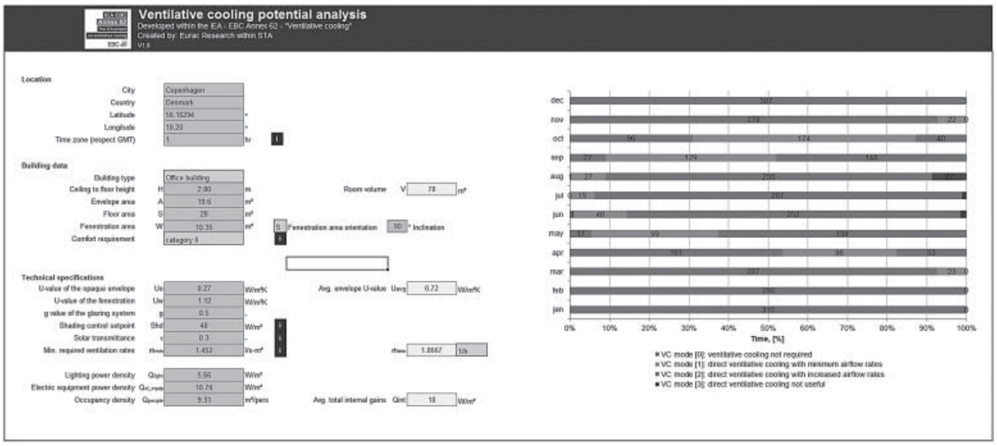

Figure 1. The ventilative cooling potential tool.

Internal gains are calculated according to the lighting and electric equipment power density and the occupancy density input by the user in terms of average number of people per square meters (person/m^2).

Annual record of climatic data is user-input on hourly time steps. The climatic data used on this tool are the dry bulb temperature, the extra-terrestrial horizontal radiation and the global horizontal solar radiation. The weather data should be representative of the typical meteorological year for the given location.

The tool calculates the global radiation incident on the specified tilted surface using the isotropic model (Liu & Jordan, 1960).

Evaluation criteria

The analysis is based on a single-zone thermal model applied to user-input climatic data on hourly basis. For each hour of the annual climatic record of the given location, an algorithm splits the total number of hours when the building is occupied into the following groups:

(1) *Ventilative Cooling mode* [0]: When the outdoor temperature is below the heating balance point temperature, no ventilative cooling is required since heating is needed;

$$\text{If } T_{o-\text{db}} < T_{o-\text{hbp}} \text{ then } \dot{m} = 0$$

(2) *Ventilative Cooling mode* [1]: Direct ventilation with airflow rate maintained at the minimum required for IAQ when the outdoor temperature exceeds the balance point temperature, yet it falls below the lower temperature limit of the comfort zone;

$$\text{If } T_{o-\text{hbp}} \leq T_{o-\text{db}} < T_{o-\text{hbp}} + (T_{i-\max} - T_{i-\min}) \text{ then } \dot{m} = \dot{m}_{\min}$$

(3) *Ventilative Cooling mode* [2]: Direct ventilative cooling with increased airflow rate when the outdoor temperature is within the range of comfort zone temperatures.

$$\text{If } T_{o-\text{hbp}} + (T_{i-\max} - T_{i-\min}) \leq T_{o-\text{db}} \leq T_{i-\max} - \Delta T_{\text{crit}} \text{ then } \dot{m} = \dot{m}_{\text{cool}}$$

The airflow rate required to maintain the indoor air temperature within the comfort zone temperature ranges is computed as in Equation 4. Direct ventilative cooling is not considered useful if the temperature difference between indoor and outdoor is below a ΔT_{crit} of 3 K;

$$\dot{m}_{\text{cool}} = \frac{q_i}{c_p(T_{i-\max} - T_{o-\text{db}})} \tag{4}$$

(4) *Ventilative Cooling mode* [3]: Direct ventilative cooling is not useful when the outdoor temperature exceeds the upper temperature limit of the comfort zone;

$$\text{If } T_{o-\text{db}} > T_{i-\max} - \Delta T_{\text{crit}} \text{ then } \dot{m} = 0$$

If direct ventilative cooling is not useful for more than an hour during the occupied time, the night-time CCP over the following night is evaluated using the method described in Artmann et al. (2007). Night-time ventilation is calculated by assuming that the thermal capacity of the building mass is sufficiently high and therefore all the exceeding internal gains can be stored in the building mass.

Compared to the method proposed by Emmerich (2001), the ventilative cooling potential analysis tool presented in this research includes two main new features:

- Dynamic load profiles and heating balance point temperature calculation;
- Adaptive thermal comfort based control.

Validation

In order to validate the VC tool outputs, we modelled a reference office room in EnergyPlus simulation software (EnergyPlus v.8.4.0, 2015) and compared the simulation results with the tool outputs.

The reference office is 4 m width x 7 m large x 2.8 m height (volume 78 m^3) and is occupied by three persons. The room has only one external wall (facing south) with 53% glass to wall ratio. Lighting and electric equipment power density amounts at 5.7 W/m^2 and 10.7 W/m^2, respectively.

We tested the tool assumptions validity on two different climates: Rome (Mediterranean) and Copenhagen (Northern continental-temperate). The building features are set according to the typical construction of these two climates: the reference office in Copenhagen is assumed to have a light-frame construction (~4 kg/m^2 of wall surface) insulated with glass wool; the reference office in Rome is assumed to have a massive construction (~260 kg/m^2 of wall surface) made of bricks with 5 cm extruded polystyrene insulation (XPS). Table 1 reports the heat transfer coefficient of envelope components, as well as wall density and *g*-value of the glazing system.

Solar gains are assumed to be reduced by 70% when the global incident solar radiation on the window exceeds 40 W/m^2 thanks to solar shadings control.

We considered that thermal comfort and IAQ conditions are acceptable if within the category II (new or renovated buildings) limits defined by EN 15251:2007. According to the IAQ requirements

Table 1. Wall construction used for the reference office in Rome and Copenhagen.

	Copenhagen	Rome
U-value of the wall (W/m^{2}K)	0.3	0.3
Wall density (kg/m^2)	4	260
U-value of the fenestration (W/m^{2}K)	1.1	2.9
g-value of the glazed surfaces (–)	0.5	0.5

defined by the standard EN 15251: 2007 for category II, the minimum required air change rates are 1.452 l/s-m^2 (1.9 h^{-1}).

The weather file used for Copenhagen derives from the International Weather for Energy Calculations database (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2001). The weather file used for Rome was generated by Meteonorm (2015).

The internal gains schedules of the EnergyPlus model are defined in order to perfectly match the load profiles used by the tool. The design flow rates are input as hourly values in a schedule file that reports the required airflow rates, both minimum and increased, calculated by the VC tool. The simulation is run in free-floating mode.

The predicted indoor operative temperatures on hourly frequency were compared with the comfort ranges set in the tool according to the following assumptions:

- If the predicted indoor operative temperature is lower than the lower temperature limit of the comfort zone and the airflow rates are set at the minimum, then direct ventilative cooling is not useful (VC mode [0]);
- If the predicted indoor operative temperature is within the comfort zone and the airflow rates are set at the minimum, then direct ventilative cooling is useful if airflow rates are maintained at the minimum required (VC mode [1]). Also, time-steps when the predicted indoor temperature is lower than the lower temperature limit of the comfort zone and the airflow rates are set at an increased value, are classified as VC mode [1];
- If the predicted indoor operative temperature is within the comfort zone and the airflow rates are set at an increased value, then direct ventilative cooling is considered useful (VC mode [2]);
- Finally, if the predicted indoor operative temperature is higher than the higher temperature limit of the comfort zone and the airflow rates are set at an increased value, then direct ventilative cooling is not enough to cool down the reference zone (VC mode [3]).

Furthermore, we analysed the effect of the new features introduced in the VC tool compared to the original method developed by Emmerich (2001), namely:

(1) Adaptive thermal comfort-based control instead of standard comfort zone;
(2) Constant loads and heating balance point temperature.

The graphs in Figures 2 and 3 show the analysis results for the reference office in Copenhagen and Rome over the whole year for the following cases:

- BES: building energy simulation model results;
- VC tool (a): output of the VC tool;
- VC tool (b): output of the VC tool considering the standard comfort zone, with lower temperature limit of 20 °C and upper temperature limit of 24 °C;
- VC tool (c): output of the VC tool considering constant internal gains (18 W/m^2) and heating balance point temperature (12 °C).

For the reference office in Copenhagen, the number of hours when direct ventilation is useful (VC mode [2]), calculated by the VC tool, are 1309 h compared to the 1173 h predicted by BESs. For the reference office in Rome, the number of hours when direct ventilation is useful (VC mode [2]), calculated by the VC tool, are 1969 h compared to the 1798 h predicted by BESs. Both analysis result in a 10% uncertainty compared to the BES model predictions. The use of a standard comfort zone within the evaluation criteria of the VC tool causes an unacceptable overestimation (over 80% in both reference cases) of the number of hours when direct ventilative cooling is not useful compared to the case with adaptive thermal comfort based control. That is due to the fact that the upper temperature limit does not vary according to the outdoor temperatures.

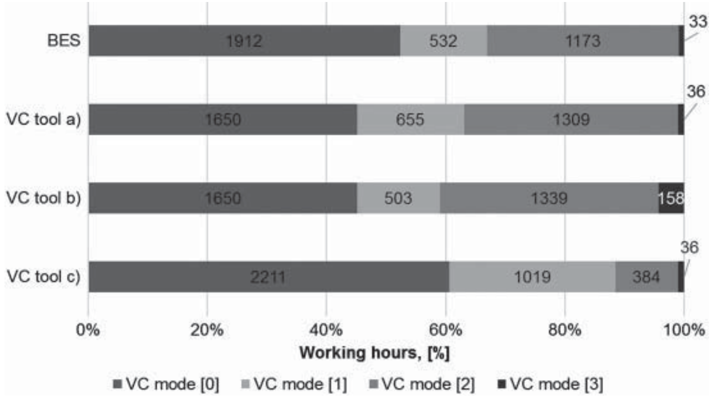

Figure 2. Building energy simulation (BES) and ventilative cooling (VC) tool output for the reference office in Copenhagen according to different evaluation criteria.

The ventilative cooling potential (VC mode [2]) predicted by the VC tool over the year is approximately 10% more than the one predicted by the building simulation model for both the reference office in Rome and the reference office in Copenhagen.

The following paragraphs report and discuss the results at monthly level for the reference office in Copenhagen and Rome.

Ventilative cooling potential for the reference office in Copenhagen

The graph in Figure 4 reports the ventilative cooling mode distribution in terms of the percentage of time when the building is occupied, considering category II requirements. Direct ventilative cooling is useful for more than 54% of the occupied time during the whole year. The tool also outputs the required ventilation rates, average and standard deviation (see Table 2), to cool the building during occupied hours (VC mode [2]). For example, according to the results for Copenhagen, an average airflow rate of $4.8 \pm 2.6\ h^{-1}$ is expected to ensure that indoor temperatures are within the comfort zone during July for more than 90% of the time. Furthermore, by decreasing the solar and internal

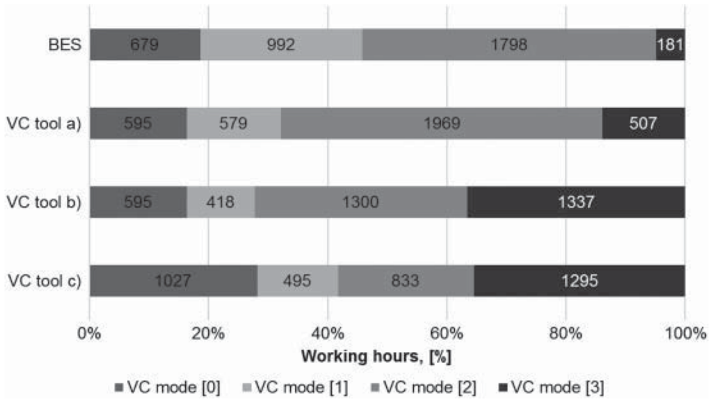

Figure 3. Building energy simulation (BES) and ventilative cooling (VC) tool output for the reference office in Rome according to different evaluation criteria.

Table 2. Ventilative cooling tool output for the reference office in Copenhagen: required ventilation rates in VC mode [2].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average airflow rate	2.7	2.6	3.0	3.7	4.3	4.7	4.8	5.5	3.6	3.3	2.9	0
Standard deviation	0	0.2	0.4	1.2	1.6	2.7	2.6	4.0	1.0	0.6	0.4	0
No. of hours when VC mode [2] is on	1	18	56	86	172	227	269	252	147	99	8	0

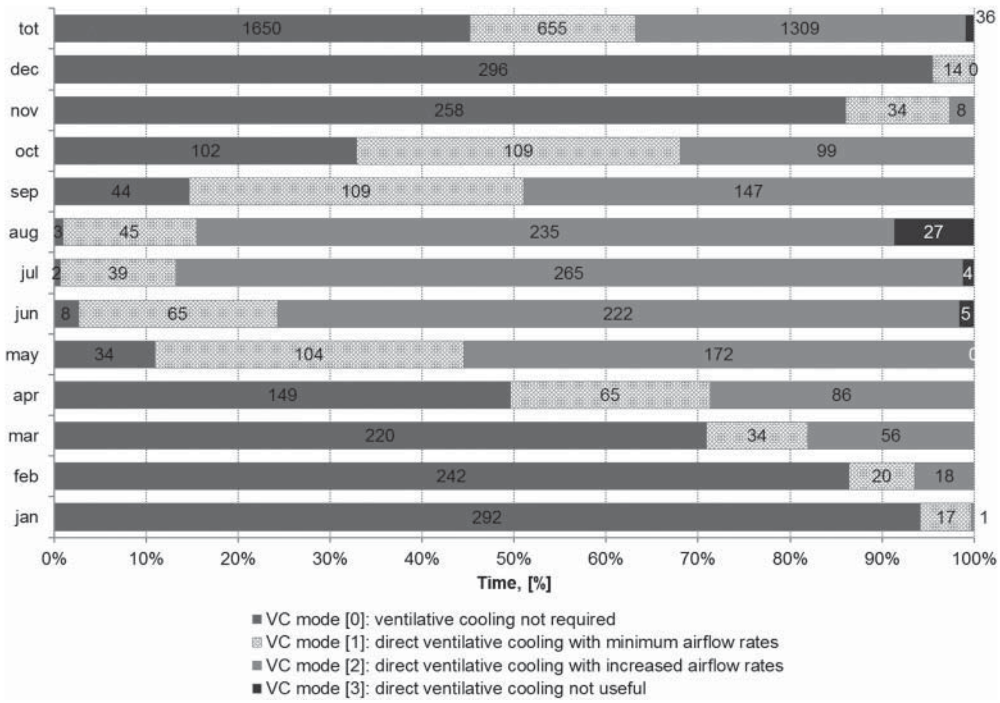

Figure 4. Ventilative cooling tool output for the reference office in Copenhagen: percentage of working hours when ventilative cooling is not required, direct ventilative cooling is useful or not useful.

loads level, the airflow rate required to provide ventilative cooling would decrease as well and therefore the passive cooling of the building might be possible or more effective using commonly available ventilation strategies.

During wintertime, outdoor temperatures are too cold and direct ventilation would cause higher heating demand and/or draught problems due to too low indoor temperatures.

Direct ventilative cooling is not useful due to too high outdoor temperature for only 3% of the time in August. In these cases, the night-time CCP is around 8 $W/m^2 \cdot h^{-1}$, which means that an airflow of 1 h^{-1} can offset 8 W/m^2 of internal gains produced during the previous day. The average monthly diurnal temperature swing is around 2.9 K during summer.

The graph in Figure 5 shows the percentage of working hours when ventilative cooling is not required, direct ventilative cooling is useful or not useful based on the analyses of BES model predictions.

Table 3 reports the differences in terms of number of days between the BES model predictions and the VC tool outputs, which generally do not exceed 7 days per month.

Highest differences occur during shoulder seasons for the time when ventilative cooling is not useful (VC mode [0]) and during hot periods for the time when ventilative cooling is not useful (VC mode [3]). Generally, the VC tool overestimates the number of hours when ventilative cooling is not

Table 3. Number of days (considering 10 h/day) difference between BES model predictions and ventilative cooling potential tool outputs.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
VC mode [0]	−1.7	−2	−3.4	−6.1	−1.9	0.8	0.2	0.3	−0.3	−7.3	−3.4	−1.4	−26.2
VC mode [1]	1.6	2	−2.2	−1.2	−3.8	−0.9	0.1	0.6	−1.5	0.2	2.6	1.4	−2.9
VC mode [2]	1	1.8	5.6	7.3	5.7	−2.4	−5	−6.2	1.8	7.1	0.8	0	16.6
VC mode [3]	0	0	0	0	0	2.5	4.7	5.3	0	0	0	0	12.5

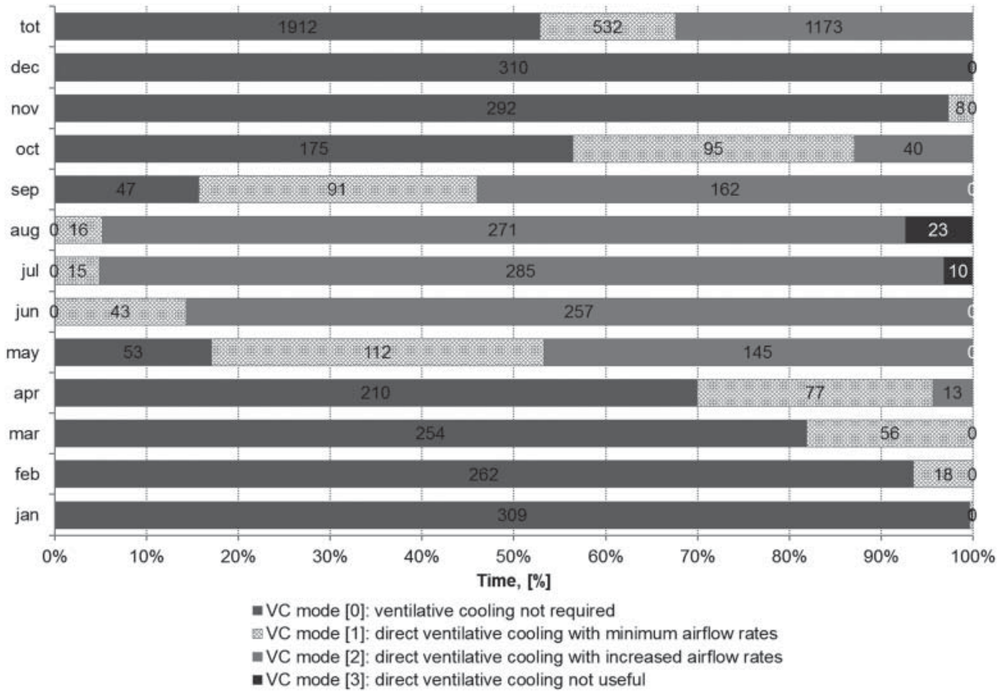

Figure 5. BES output for the reference office in Copenhagen: percentage of working hours when ventilative cooling is not required, direct ventilative cooling is useful or not useful.

useful (July, August) and underestimates the number of hours when ventilative cooling with increased airflow rates is useful (VC mode [2]).

The differences are mainly related to the evaluation criteria and the simplifications in the heating balance point temperature calculation. According to the indoor temperature prediction of the BES model, the average heating balance point temperature is around 15 °C. The VC tool calculates an average heating balance point temperature of 12 °C.

Ventilative cooling potential for the reference office in Rome

The graph in Figure 6 reports the ventilative cooling mode distribution in terms of the percentage of time when the building is occupied. In Rome climate, direct ventilative cooling is useful for almost 70% of the occupied time during the whole year. The required ventilation rates to cool the building during occupied hours (VC mode [2]), according to the results for Rome, are on average airflow rate of $6 \pm 3\ h^{-1}$(Table 4).

Direct ventilative cooling is not needed for 15% of the time (wintertime) due to the lower outdoor temperatures. Direct ventilative cooling is not useful due to too high outdoor temperature for more than 50% of the time in July and August. In these cases, the night-time cooling

Table 4. Ventilative cooling tool output for the reference office in Rome: required ventilation rates in VC mode [2].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average airflow rate	4.9	5.0	5.0	5.5	6.3	6.1	6.5	7.0	6.9	7.0	6.2	4.8
Standard deviation	1.5	1.8	1.5	2.3	2.8	2.8	3.2	3.8	3.7	3.8	3.1	1.7
No. of hours when VC mode [2] is on	118	109	169	174	225	179	151	143	228	228	134	111

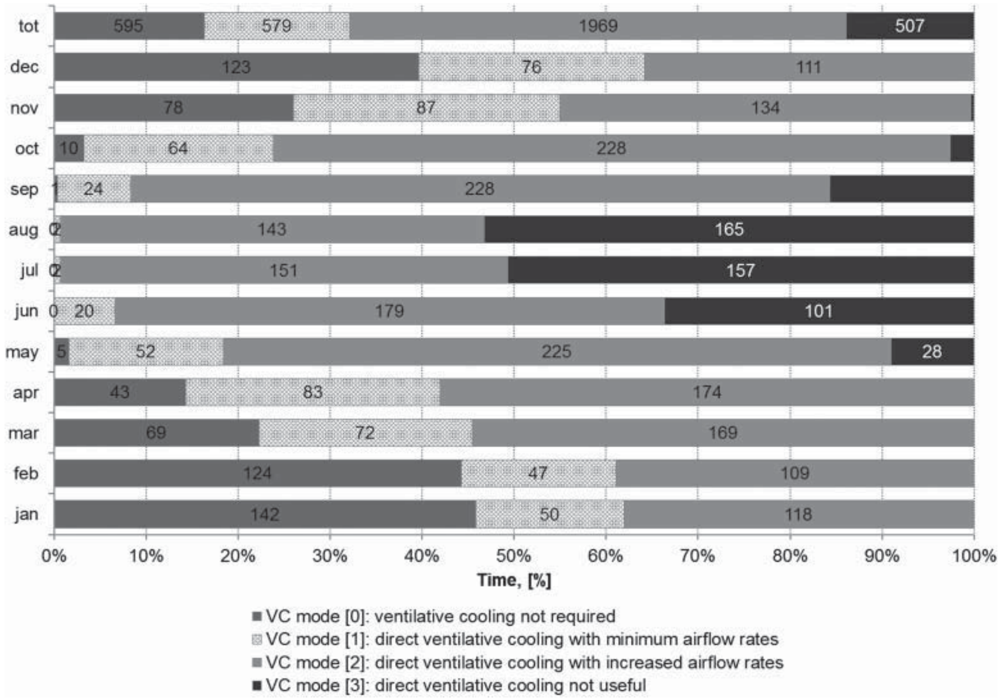

Figure 6. Ventilative cooling tool output for the reference office in Rome: percentage of working hours when ventilative cooling is not required, direct ventilative cooling is useful or not useful.

potential is around 7 $W/m^2 \cdot h^{-1}$, which means that an airflow of 1 h^{-1} can offset 7 W/m^2 of internal gains produced during the previous day. The average monthly diurnal temperature swing is around 3 K during summer.

The graph in Figure 7 shows the percentage of working hours when ventilative cooling is not required, direct ventilative cooling is useful or not useful based on the analyses of BES model predictions.

Table 5 reports the differences in terms of number of days between the BES predictions and the VC tool outputs.

Compared to the Copenhagen climate, higher differences occur between BES predictions and VC tool outputs but in any case, they do not exceed 13 days per month. Highest differences occur during middle seasons for the time when ventilative cooling is useful (VC mode [1], VC mode [2]) and the time when ventilative cooling with increased airflow rates is useful (VC mode [2]) and not useful (VC mode [3]) during summer time. Generally, the VC tool underestimates the number of hours when ventilative cooling is useful and overestimates the number of hours when ventilative cooling with increased airflow rates is not useful.

The differences are mainly related to the evaluation criteria and the simplifications in the indoor temperature calculation, which does not take into account thermal mass effects.

Table 5. Number of days (considering 10 h/day) difference between BES model predictions and ventilative cooling potential tool outputs for the reference office in Rome.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
VC mode [0]	−4.4	−4	−2	1.7	0.5	0	0	0	0.1	1	3.9	−5.2	−8.4
VC mode [1]	−7.3	−6.9	−7.9	−2.4	−1.7	−2	−1.5	0	−0.4	−0.5	−5.5	−5.2	−41.3
VC mode [2]	11.7	10.9	9.9	0.7	−1.6	−7.8	−10.9	−6.2	−0.2	−1.3	1.5	10.4	17.1
VC mode [3]	0	0	0	0	2.8	9.8	12.4	6.2	0.5	0.8	0.1	0	32.6

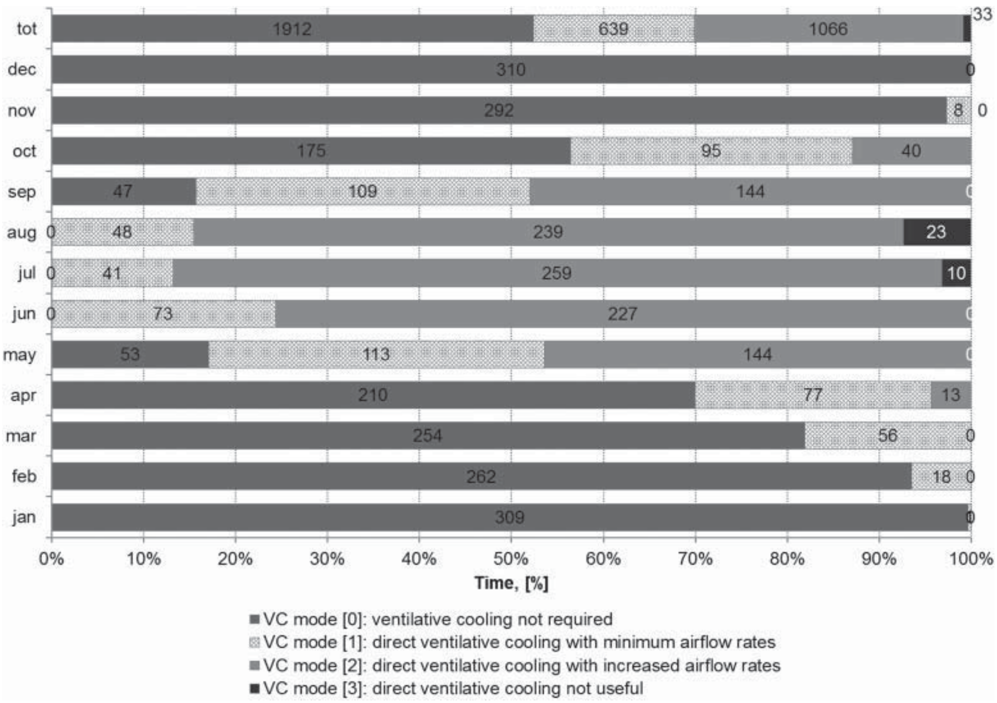

Figure 7. BES output for the reference office in Rome: percentage of working hours when ventilative cooling is not required, direct ventilative cooling is useful or not useful.

Discussion

On yearly basis, the VC tool is able to predict with 10% error the number of hours when direct ventilative cooling is potentially useful to cool down the building compared to the results of a more detailed BES model. Highest differences occur in hot climate (Rome) on monthly basis: up to 40% error might occur as thermal mass effects are neglected. The error is mainly related to the evaluation criteria and the simplifications used for the heating balance point temperature calculation which does not take into account thermal mass effects.

Nevertheless, the tool is capable to catch the natural drivers of ventilative cooling and to identify climate suitability for the application of ventilative cooling strategies.

The new features introduced (dynamic internal gains and heating balance point temperature) improve significantly the VC tool predictions. The ventilative cooling potential is circa 70% less than the one predicted by the BES model when internal gains and heating balance point temperature are considered constant over the whole time.

Furthermore, the tool provides statistics on required air change rates to cool the building which can be useful as design guidance for preliminary considerations about the ventilation system and the control strategy.

Conclusions

The paper presents the VC tool which is under development within the IEA Annex 62 project. The tool analyses the potential of ventilative cooling by taking into account not only climate conditions, but also building envelope thermal properties, internal gains and ventilation needs.

The analysis is based on a single-zone thermal model applied to user-input climatic (hourly) basis and thermal data. For each hour of the annual climatic record of the given location, an algorithm identifies over the occupied time the number of hours when ventilative cooling is useful and estimates the airflow rates needed to prevent building overheating.

The tool is particularly suitable for early design phases, as it requires only basic information about a typical room of the building, the building use and an annual climatic record of outdoor air temperatures and solar radiation. Furthermore, the tool provides building designers with useful information about the level of ventilation rates needed to offset given rates of internal heat gains.

As validation of results, the VC tool outputs are compared with the predictions of a BES model of the reference room in two different climates (Rome and Copenhagen), highlighting the following aspects:

- The outputs are useful to compare the ventilative cooling potential in different climates for different building typologies;
- The outputs also support the decision-making by selecting the most efficient ventilative cooling strategy and by providing rough estimation of the airflow rates needed to cool down the building in relation to internal gains, comfort requirements and envelope characteristics;
- The tool enables also to analyse the effect of other energy efficiency measures, like internal gains reduction, solar gains control and envelope performance, on ventilative cooling effectiveness.

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