A methodology for evaluating the ventilative cooling potential in early-stage building design

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ABSTRACT

As a result of the new initiatives and regulations towards nearly zero energy buildings, designers are more frequently exploiting the cooling potential of the climate to reduce overheating and improve indoor well-being of people. At early stage of design, climate analysis is particularly useful for determining the most cost-effective passive cooling methods, such as ventilative cooling. However, besides the external climate conditions, building energy uses are characterized by occupancy pattern and needs, envelope characteristics and internal loads. Therefore, the climate analysis cannot be abstracted from building characteristics and use.

Within the IEA Annex 62 project, national experts worked on the development of a ventilative cooling potential tool, which aimed at assessing the potential of ventilative cooling by considering building envelope thermo-physical properties, internal gains and ventilation needs. The calculation methodology has been further developed within CEN/TC 156/WG21 TG on "Ventilative cooling systems - Design". The main development regards the application of thermal balance calculation method from EN ISO 52016-1:2017 to calculate free-floating temperature, heating and cooling loads with and without ventilative cooling contribution, which considers also lumped thermal capacity.

The analysis is based on a single-zone thermal model applied to user-input climatic data on hourly basis. The tool predicts the percentage of hours when direct ventilation with minimum airflow rate required for indoor air quality or increased airflow rates can potentially ensure indoor thermal comfort.

Moreover, such methodology could provide building designers useful information about the level of ventilation rates needed to maintain acceptable indoor thermal comfort conditions.

The paper aims at presenting the new calculation methodology and at validating the calculation results on a reference room according to the guidelines reported in the ASHRAE Standard 140-2020.

In particular, the influence of using dynamic loads, adaptive thermal comfort model, building thermal mass and ventilation needs in the thermal balance calculation of the building are analysed. Despite the methodology is simplified, the overall goal is to provide engineers a tool for predicting in preliminary design phase and with a limited degree of uncertainty whether the building can exploit ventilative cooling to maintain indoor comfort conditions.

KEYWORDS

Ventilative cooling, early-stage design, overheating, design airflow rate, natural ventilation

1 INTRODUCTION

Climate change, economic growth, affordability of air conditioners and other increasing demographic factors (population growth, ageing and urbanization) are the main causes for the space cooling to grow faster than any other energy use in buildings (International Energy Agency, 2018). Furthermore, high energy performance standards to reduce heating demand led to high insulated and airtight buildings which can encounter overheating issues especially in heating dominated climatic regions, where there is no tradition of using external solar shadings and no cultural knowledge on how to operate them (Taylor et al., 2023). The growth of space

cooling need is not only causing an overall increase of energy demand but also of peak power, putting the electricity grid under pressure (International Energy Agency, 2018).
Ventilative cooling, meant as the use of natural or mechanical ventilation to cool indoor spaces, is considered an effective solution to reduce space cooling need in buildings and might be even a key solution to reach zero emission targets. Since it depends on the availability of suitable outdoor air conditions, climate analysis is particularly useful to support early-stage decision making on building design. However, besides the external climate conditions, space cooling uses are also characterized by solar gains control, occupancy patterns and comfort expectations, as well as by envelope characteristics and internal loads. Therefore, the climate analysis cannot be abstracted from building characteristics and use.
To this purpose, national experts worked on the development of a ventilative cooling evaluation tool within the IEA Annex 62 project (Belleri et al., 2018).
The calculation methodology has been further improved within CEN/TC 156/WG21 TG on "Ventilative cooling systems - Design". The main improvement regards the application of thermal balance calculation method from EN ISO 52016-1:2017 to calculate free-floating temperature, heating and cooling loads with and without ventilative cooling contribution and which considers also lumped thermal capacity.
The aim of this paper is to outline the new calculation method to assess ventilative cooling potential in a preliminary design phase and its validation process.

2 METHODOLOGY FOR EVALUATING VENTILATIVE COOLING POTENTIAL (VC)

The calculation method to evaluate ventilative cooling potential is based on a single-zone thermal model applied to user-input climatic data on an hourly basis. The thermal balance calculation method from EN ISO 52016-1:2017 is applied to calculate free-floating temperature and heating and cooling loads (with and without ventilative cooling contribution) of a reference thermal zone of the building.
EN ISO 52016-1:2017 has been developed to assess the energy performance of a detailed building design or building in use. For early design phase applications, the detailed hourly thermal balance equations have been reduced to the essential (lumped) parameters, including also lumped thermal capacity. Figure 1 shows the simple 1RC model selected as the most suited model for such early design phase.

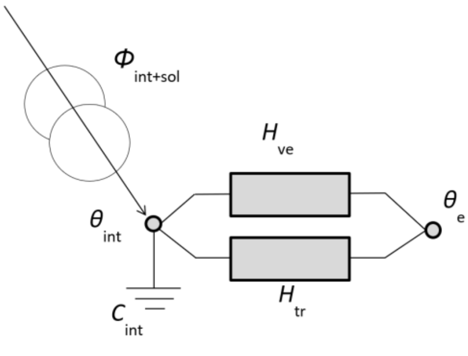

Figure 1: Simple 1RC lumped parameter model suited for the early design stage.

The previous ventilative cooling potential tool was presented by Belleri et al. (Belleri et al., 2018) and referred to the method proposed by NIST (Axley et al., 2002; Emmerich et al., 2011). Direct ventilation was considered useful to maintain indoor conditions when outdoor dry bulb temperature exceeded the heating balance point temperature. The latter parameter refers to the outdoor air temperature below which heating must be provided to maintain comfort condition within the thermal zone. However, thermal capacity of the building was not taken into account in this previous tool.

2.1 Input

The calculation requires basic information about a typical room of the building and an annual record of climatic data on hourly time resolution. The climatic data shall include outdoor dry bulb temperature, relative humidity and solar radiation.

The input data related to the building are needed to calculate the solar and internal gains, the thermal capacity of the building structure, the ventilation and transmission losses. These are calculated based on the geometry data of the reference room and window area/orientation, building use, comfort requirements and thermal properties of the envelope, as well as the presence of external shading elements.

Internal gains can be pre-calculated according to standard load profiles of occupancy, lighting and electric equipment (EN 16798-1:2019), or defined based on design needs. Furthermore, the occupant presence within the thermal zone can be indicated through the time control section.

Comfort temperatures are calculated according to the adaptive comfort model (EN 16798-1:2019). The overall heat transfer coefficient by transmission through the opaque and transparent envelope and the internal heat capacity of the zone are calculated according to EN ISO 52016-1:2017. The internal thermal capacity of the entire thermal zone corresponds to the sum of the thermal masses due to building envelope, internal partitions, air and furniture.

2.2 Thermal balance calculations

The following variables are used, with symbols and subscripts, where applicable, partially adopted from EN ISO 52016-1:2017 or specifically added to work out the methodology:

H_{tr}	= overall heat transfer coefficient by transmission (W/K);
$q_{V;t}$	= airflow rate at time interval *t* (m^3/s);
$\rho_a \cdot c_a$	= heat capacity of air per volume (J/(m^3K) = 1.204 x 1 006);
$H_{ve;t}$	= overall heat exchange coefficient by ventilation at time interval *t* (W/K);
$\theta_{int;t}$	= internal air or operative temperature at time interval *t* (°C); NOTE: For the 1RC model there is no distinction between air and operative temperature.
$\theta_{int;0;t}$	= internal air or operative temperature in free float at time interval *t* (°C);
$\theta_{int;t-1}$	= internal air or operative temperature at previous time interval (t-Δt) (°C);
$\theta_{int;set;H;t}$	= internal operative temperature setpoint for heating at time interval *t* (°C); NOTE: Setpoint can vary in time, e.g. if the adaptive comfort model is applicable.
$\theta_{int;set;C;t}$	= internal operative temperature setpoint for cooling at time interval *t* (°C); NOTE: Setpoint can vary in time, e.g. if the adaptive comfort model is applicable.
$\theta_{e;a;t}$	= external air temperature at time interval *t* (°C);
$\Phi_{int;t}$	= total internal heat gain at time interval *t* (W);
$\Phi_{sol;t}$	= total solar heat gain at time interval *t* (W); NOTE: In EN ISO 52016-1:2017 the solar gains are split into direct (into the zone, through the windows) and indirect (absorbed in external constructions); for the VCP tool it is just the total. The effect of movable solar shading provisions can be taken into account on an hourly basis.
$\Phi_{HC;t}$	= heating load (if positive) or cooling load (if negative) at time interval *t* (W);
C_{int}	= (lumped) internal thermal capacity (J/K); NOTE: For VCP tool this is the simplified lumped capacity, covering internal capacity in the building and weighted capacity of the constructions.
Δt	= length of the time interval *t* (s, in casu: 3600 s);
$q_{V;min}$	= required airflow rate for hygienic ventilation (m^3/s);
$q_{m;t}$	= air mass flow rate (kg/s);

ACH_t	= volumetric air change per hour (1/h);
$q_{V;VCS;req;t}$	= required airflow rate for ventilative cooling (m^3/s);
$\Delta\theta_{crit}$	= minimum temperature difference between indoor and outdoor temperature in order to drive natural airflow and/or to have a more than negligible cooling potential (K, i.e. 3K);
$\Phi_{HU;e;a;t}$	= relative humidity of outdoor air (%); NOTE: EN ISO 52016-1:2017 uses absolute humidity as input variable.
$\Phi_{HU;max}$	= maximum relative humidity of outdoor air for ventilative cooling (%) (e.g. 85%);
$\theta_{int;comfort;t}$	= indoor comfort temperature according to adaptive comfort model of EN 16798-1:2019 (°C).

At each timestep (*in casu* 1 hour) the heat balance of the thermal zone according to the 1RC model can be formulated as follows:

$$\left[\frac{C_{int}}{\Delta t} + H_{ve} + H_{tr}\right]\theta_{int;t} = \frac{C_{int}}{\Delta t}\cdot\theta_{int;t-1} + [H_{ve} + H_{tr}]\cdot\theta_{e;a;t} + \Phi_{int;t} + \Phi_{sol;t} + \Phi_{HC;t} \quad (1)$$

Since the unknown terms are either the node air temperature or the heating/cooling loads, the equation can be rewritten as follows, with A and B known at each time interval t.

$$A_t\,\theta_{int;t} = B_t + \Phi_{HC;t} \quad (2)$$

Starting from the heat balance, the potential of ventilative cooling is assessed carrying out the following steps for each time interval. The time series are first calculated in free float temperature and without the effect of ventilative cooling to have a basic case that can serve for validation purposes. The same time series are then computed considering the influence of heating and cooling needs. Ventilative cooling potential is still not evaluated. In the early design stage, the goal is just to estimate the amount of heating and cooling loads that needs to be satisfied at each hour, therefore there is no upper limit to the heating or cooling capacity. Consequently, this implies that the indoor temperature will never drop below the lower setpoint or exceed above the higher setpoint for a given interval value. In case of intermittent heating, the temperature is allowed to drop to a lower limit during intermittency. The third and last step involves the calculation of time series with heating/cooling loads and ventilative cooling potential. The goal is to reveal the ventilative cooling potential making a comparison with the second step. A one-month initialization period to avoid the influence of assumed indoor temperature at the start of the calculation has been adopted from EN ISO 52016-1:2017.

2.3 Evaluation criteria

For each hour of annual climatic record of the given location, the energy balance is calculated according to the model described previously and an algorithm splits the total number of hours when the building is occupied in the following groups:

1. **VC-mode [0]**: ventilative cooling is not required when the indoor temperature is below the lower comfort zone limit (heating is needed);

   If $\theta_{int;0;t} < \theta_{int;set;H;t}$
   then $q_{V;t} = q_{V;min}$ (with heat recovery)

   In this mode $q_{V;t}$ is not counted as part of the ventilative cooling potential.

2. **VC-mode [1]**: direct ventilative cooling with airflow rate maintained at the minimum required for IAQ can potentially ensure comfort when the outdoor temperature is within comfort ranges;

If $\theta_{int;set;H;t} \leq \theta_{int;0;t} \leq \theta_{int;set;C;t}$
then $q_{V;t} = q_{V;min}$ (no heat recovery needed)

Unlike the previous case, $q_{V;t}$ is counted as part of the ventilative cooling potential.

3. **VC-mode [2]**: direct ventilative cooling with increased airflow rate can potentially ensure thermal comfort and indoor air quality in the air node;

   If $\theta_{int;0;t} > \theta_{int;set;C;t}$, $\theta_{e;a;t} \leq (\theta_{int;set;C;t} - \Delta\theta_{crit})$ and $\Phi_{HU;e;a;t} < \Phi_{HU;max}$
   then $q_{V;t} = q_{V;VCS}$

   Obviously, in this case, $q_{V;t}$ is counted as part of ventilative cooling potential.

4. **VC-mode [3]**: residual discomfort hours in which ventilative cooling cannot provide benefits.

   $q_{V;t} = q_{V;min}$

2.4 Ventilation rate assessment

The required extra ventilation rate needed to supply ventilative cooling can be assessed assuming that all cooling power is provided by extra ventilation. Then cooling loads are assumed to be null.
At each time interval, if VC mode = [2]:

$$\left(A_t + \Delta H_{ve;VCS;req;t}\right)\theta_{int;t} = B_t + \Delta H_{ve;VCS;req;t} \cdot \theta_{e;a;t} \qquad (3)$$

As a consequence,

$$\Delta H_{ve;VCS;req;t} = \frac{B_t - A_t\,\theta_{int;t}}{\theta_{int;t} - \theta_{e;a;t}} \qquad (4)$$

The internal temperature $\theta_{int;t}$ of the previous equation corresponds to the cooling setpoint. Then, the required extra ventilation for ventilative cooling is equal to:

$$\Delta q_{V;VCS;req;t} = \frac{B_t - A_t\,\theta_{int;set;C;t}}{\rho_a\, c_a(\theta_{int;set;C;t} - \theta_{e;a;t})} \qquad (5)$$

with $\theta_{int;t} = \theta_{int;set;C;t}$

The ventilation rate needed to provide ventilative cooling is given by the sum of the minimum required ventilation rates and the extra ventilation required.

$$q_{V;VCS;t} = q_{V;min} + \Delta q_{V;VCS;req;t} \qquad (6)$$

Once the actual ventilation rate has been calculated according to VC-mode, heating or cooling loads and the internal temperature are calculated again, before moving to the next time step.

2.5 Output

The performance indicators calculated through the ventilative cooling potential methodology described in the previous sections are outlined below.

1. Percentage of time within each month when:
   - Ventilative cooling is not required (VC-mode [0]) according to the evaluation criteria described in section 2.3;
   - Direct ventilative cooling with airflow rate maintained at the minimum required (VC-mode [1]) according to the evaluation criteria described in section 2.3;
   - Direct ventilative cooling with increased airflow rate required (VC-mode [2]) according to the evaluation criteria described in section 2.3;

- Direct ventilative cooling is not useful (VC-mode [3]) according to the evaluation criteria described in section 2.3;
2. Required ventilation rates to cool down the building when direct ventilative cooling with increased airflow rate is required (VC mode [2]);
3. Monthly and annual sensible energy needs of heating and cooling with and without ventilative cooling;
4. Ventilative cooling capacity.

The just mentioned outputs are useful to compare the ventilative cooling potential in different climatic conditions for different building typologies and thermal masses. From design point of view, those output provide a rough estimation in early-stage design of the airflow rates needed to cool down passively the building in relation to the input provided initially, such as internal gains, comfort requirements and envelope characteristics. Statistics about extra ventilation rates needed are useful to define design ventilation rates for ventilative cooling.

3 VALIDATION

The calculation methodology has been validated according to the guidelines provided by ASHRAE Standard 140-2020 and reported in EN ISO 52016-1:2017. Two test cases (BESTEST) referring to a geometry consisting of a single thermal zone with two different types of envelopes (heavyweight and lightweight) were analyzed in the climate of Denver, USA. The test room is 8 x 6 x 2.7 m with two windows (3 x 2 m each) on South façade. All the characteristics of the reference room, such as thermophysical properties of the opaque and transparent envelope, specific heat capacity of air and furniture, boundary conditions, internal gains, ventilation and thermostat control strategies are given in detail in EN ISO 52016-1:2017. BESTEST 940 and 640 are the case identifiers present in EN ISO 52016-1:2017 to describe the heavyweight and lightweight cases respectively combined with intermittent setpoint.
All the input provided to the model are summarized in the Annex (Table 2).
The proposed methodology is validated if the calculated outputs are consistent with the BESTESTs' results reported in EN ISO 52016-1:2017. The outputs considered for validation are:

- Monthly and annual sensible energy needs for heating $\Phi_{H;nd}$ and cooling $\Phi_{C;nd}$;
- Monthly average values of the operative temperature $\theta_{op;av}$.

Regarding the BESTEST 940 and 640 reference cases, the ASHRAE Standard 140-2020 does not provide the maximum error beyond which results should not be considered reliable. On the contrary, the standard only indicates that data trends and orders of magnitude should be respected. Regardless of this, to have an accurate idea about the tool uncertainty with respect to the BESTESTs' results, taking as reference the ASHRAE Guideline 14 (ASHRAE, 2014), the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) was calculated for each output. According to ASHRAE Guideline 14, the maximum monthly acceptable calibration tolerance is equal to 15%. Generally, this error is used to calibrate and validate dynamic simulation software: since the tested methodology refers to early-stage design phase, it is plausible that the abovementioned threshold is not always respected.

3.1 Results

This section illustrates the results of the validation. The graphs in Figure 2 **Error! Reference source not found.**show the monthly sensible energy needs for heating and cooling and the monthly operative temperatures registered analysing both reference cases. The results of ISO 52016-1:2017 are directly compared with the ventilative cooling potential methodology outputs (VCT). The effect of ventilative cooling is not taken into account during the validation process. The comparison of results allows to validate the methodology output as well as to analyse the effect of thermal mass on output results. The methodology tends to overestimate the results during the winter months, in which the need of ventilative cooling potential is less crucial. On the contrary, a good prediction of monthly cooling loads occurs during the summer period. The comparison of the results can be also seen in the Annex (Table 3 and Table 4).

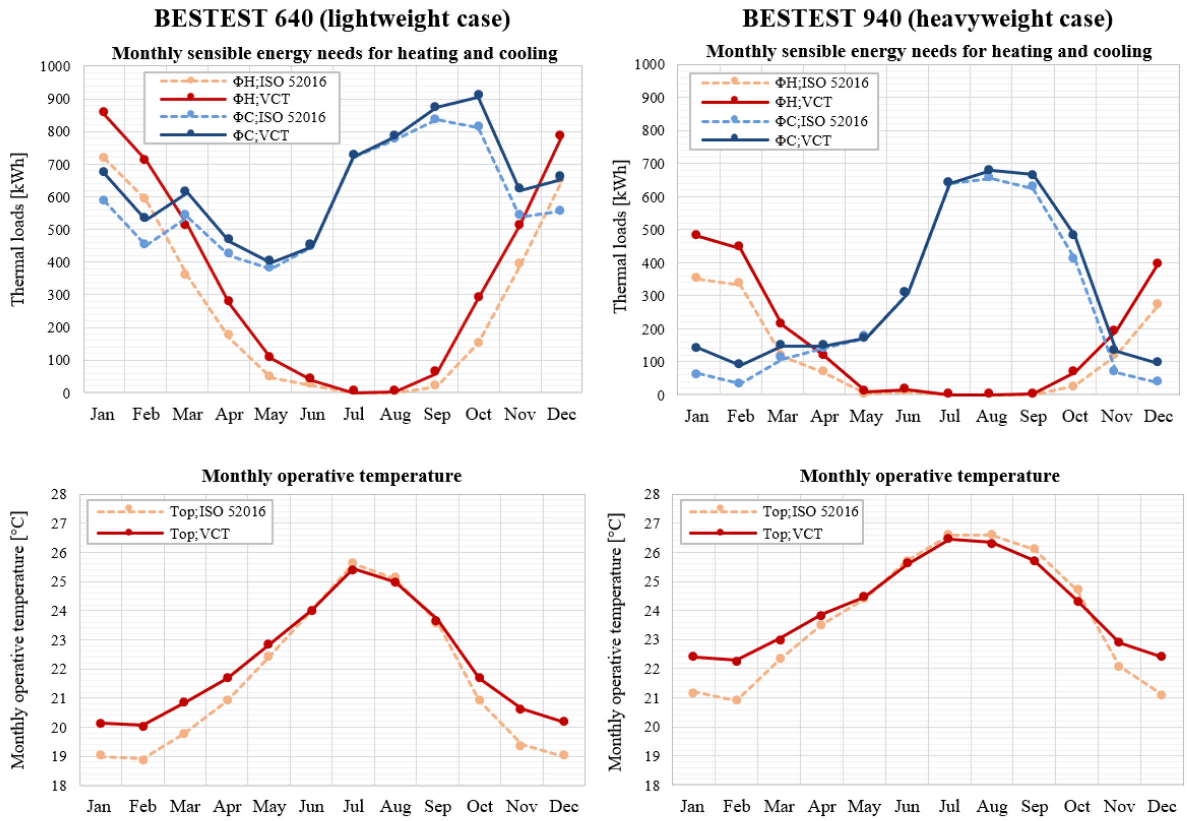

Figure 2: Validation results of BESTEST 640 and BESTEST 940. Dashed lines represent the reference results reported in EN ISO 52016-1:2017, while continuous lines represent the simple 1 RC lumped parameter model output used in the ventilative cooling potential tool (VCT).

The effect of thermal capacity is visible comparing BESTESTs monthly thermal loads. In the heavyweight reference case, characterized by a concrete-based construction system, the heating needs are lower due to the opaque envelope's ability to store heat during the winter season so that it can be released with beneficial inward effects. On the other hand, during warm period, the high thermal capacity of envelope retards the heat flow passing through it, reducing cooling loads.

Table 1**Error! Reference source not found.** reports the statistical error CV(RMSE) calculated and verified for all the output. According to the monthly criteria values provided by ASHRAE Guideline 14, CV(RMSE) index is respected for all the selected outputs except for the monthly sensible energy needs for heating. Overall, the errors calculated for the BESTEST 640 (lightweight case) are lower compared to the heavyweight case. The higher uncertainty in the second reference case is probably caused by the influence of higher thermal mass in the 1 RC lumped parameter model. Although the statistical error is not always respected, the methodology can still be considered validated: it is important to remember that this method is simplified compared to a building energy model (BEM) software.

Table 1: CV(RMSE) calculation and verification for all the selected output to assess model validation.

	BESTEST 640 (lightweight case)			**BESTEST 940 (heavyweight case)**		
Output	$\boldsymbol{\Phi}_{H;vct}$	$\boldsymbol{\Phi}_{C;vct}$	$\boldsymbol{\theta}_{op;vct}$	$\boldsymbol{\Phi}_{H;vct}$	$\boldsymbol{\Phi}_{C;vct}$	$\boldsymbol{\theta}_{op;vct}$
CV(RMSE)	29.71%	9.86%	3.66%	44.83%	15.03%	3.09%
	✗	✓	✓	✗	✓	✓

Charts reported in

Figure 3 show the comparison of monthly cooling needs taking into account the contribution of ventilative cooling in the two selected BESTEST cases (lightweight and heavyweight). Light blue bars represent cooling needs without the effect of ventilative cooling into the thermal zone, while blue bars represent cooling needs considering the contribution of ventilative cooling. Both graphs highlight that the implementation of ventilative cooling strategies allows to lower cooling needs consistently (reduction by 69% for lightweight case and by 60% for heavyweight case over the year), for the given climate, building and building use.

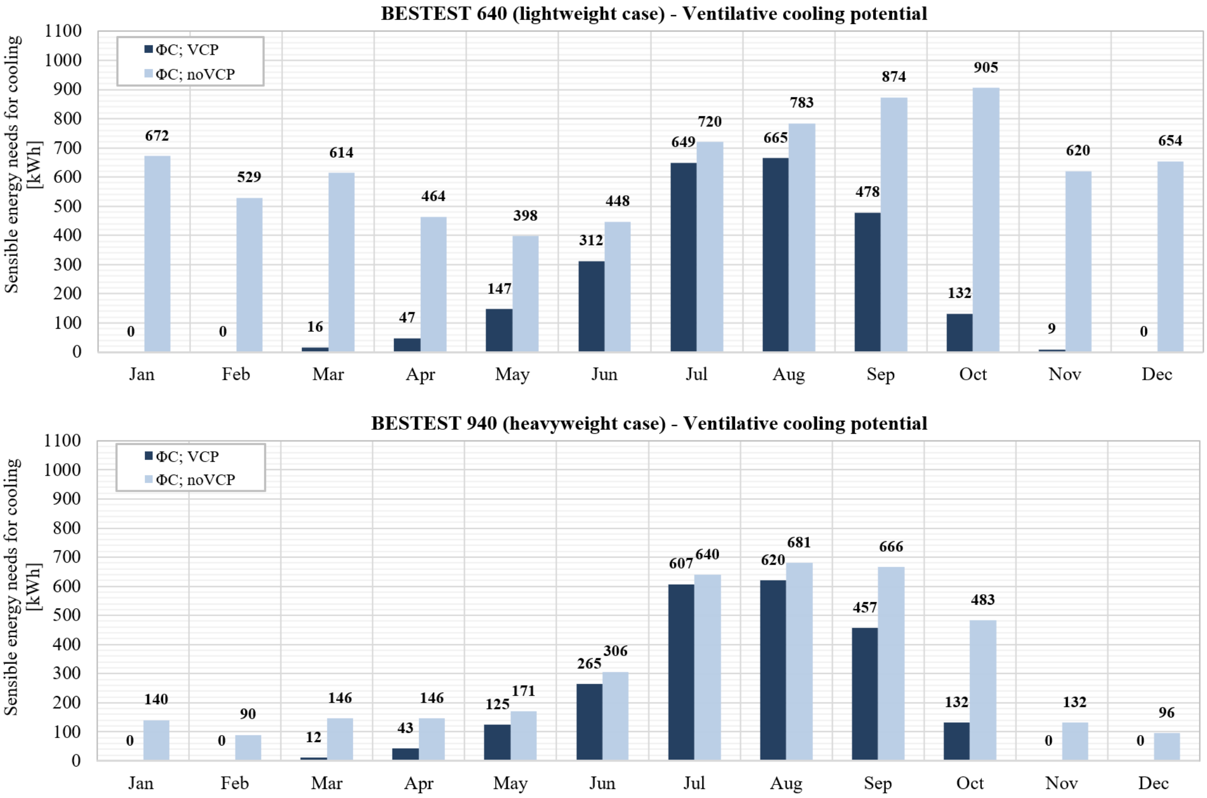

Figure 3: Comparison of sensible energy needs for cooling with and without the contribution of ventilative cooling on the heavyweight (940) and lightweight (640) reference cases.

4 DISCUSSION

A 1RC lumped parameter model was selected as the most suited model for predicting energy needs and indoor temperatures at the early design phase. The addition of more complexity to the model (as in the 3RC model outlined in EN ISO 13790:2008) may not lead to higher accuracy because most of the input data, such as details of the constructions, are unknown during early design stage. In case such input data are known, the detailed model of EN ISO 52016-1:2017 shall be applied. Although the calculation method presented and validated returns satisfactory results, some limitations are present. A limitation of the 1RC model is that indoor air temperature and indoor operative temperature are not distinguished. This limitation is acceptable in cases where air velocity is small (<0.2 m/s) or where the difference between mean radiant temperature and air temperature is small (<4 °C) (EN ISO 7730:2006). These conditions typically occur in highly insulated buildings with mechanical ventilation. Since ventilative cooling implies the use of high airflow rates to cool the environment, the assumption of air velocity smaller than 0.2 m/s might not be true. Therefore, it is important to underline that the evaluation needs to be repeated at later design stages with more detailed calculation methods, i.e. dynamic simulations.

The analysis is carried out only on one thermal zone and assumes the air is well-mixed within the zone volume. The use of these results for the evaluation of ventilative cooling potential at building level depends on the building architecture and features and in general on how representative is the selected thermal zone for the entire building. The results obtained for the reference room can be considered valid for other building rooms with similar internal (occupancy, lighting and electric equipment density and patterns) and solar gains (same exposure, window to wall ratio and shading system). Otherwise, it is recommended to repeat the calculation for each building room.

Draft risk and localized discomfort cannot be predicted using 1RC models. In case ventilative cooling occurs to be useful during middle seasons and at low outdoor temperatures, more detailed evaluation through i.e. computational fluid dynamic models shall be carried out at later design stages.

The calculation considers only direct ventilative cooling. However, the potential of supplementary cooling solutions shall be considered within the building design to target low energy buildings. Passive night cooling, evaporative cooling, ground cooling, cooling recovery or use of smart air movement can be effective and complementary measures to ventilative cooling.

Ventilative cooling strategies shall be also future-proof and therefore it is recommended to evaluate the potential of ventilative cooling under future weather scenario to check its resiliency.

5 CONCLUSIONS

The paper presents the calculation methodology developed first within IEA Annex 62 and then within CEN/TC 156/WG21 TG on "Ventilative cooling systems - Design" to evaluate the ventilative cooling potential at early design stages. The methodology is based on a 1RC lumped parameter model that simplifies the energy balance of a reference building room. The 1 RC lumped parameter model was selected as the most suited model for predicting energy needs and indoor temperatures at the early design phase, when few information about the building features are available.

The calculation methodology has been validated according to the guidelines provided by ASHRAE Standard 140-2020 by comparing the 1RC model calculation results with the BESTEST reported in EN ISO 52016-1:2017 for two different types of envelopes (heavyweight and lightweight), in the climate of Denver, USA. The coefficient of the variation of the predicted cooling needs by the 1RC model relative to the BESTEST cooling needs reported in the EN 52016 standard is 9% in the lightweight case and 15% in the heavyweight case. The validation results are considered very promising since the level of detail of input data required for the 1RC model is very low.

Therefore, the ventilative cooling potential evaluation method is useful to compare the ventilative cooling capacity in different climates for different building typologies and thermal capacities. The outputs of the calculation can support the decision making about the application of ventilative cooling strategies and by providing an estimation of the ventilative cooling capacity and statistics about the ventilation 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.

6 ACKNOWLEDGEMENTS

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8 ANNEX

Table 2: Model input provided for validation purpose.

Weather data	Denver, USA
Building geometry	Test room indicated in EN ISO 52016-1:2017
Thermal capacity (C)	$C_{env;940}$ = 15 479 952 J/K $C_{env;640}$ = 2 732 538 \J/K $k_{m;int}$ = 10 000 J/m^2 K (specific heat capacity of air and furniture)
Thermal transmittance (U)	$U_{o;940}$ = 0.3158 W/m^2 K (U-value of the opaque envelope) $U_{o;640}$ = 0.3167 W/m^2 K (U-value of the opaque envelope) U_w = 2.984 W/m^2 K (U-value of the fenestration)
g-value	0.71
Shading control setpoint (Shd)	120 W/m^2
Shading factor (Y)	0
Internal gains (Φ_{int})	4.16 W/m^2 (constant all year long)
Time control	From 0 to 24 (reference room is always occupied)
Intermittent setpoint	From 7 to 23 (daytime): $\theta_{int;set;H;t}$ = 20 °C and $\theta_{int;set;C;t}$ = 27 °C From 23 to 7 (night-time): $\theta_{int;set;H;t}$ = 10 °C and $\theta_{int;set;C;t}$ = 27 °C
Heating/cooling capacity	$\Phi_{H;avail}$ = $\Phi_{C;avail}$ = 1000 kW (1 000 000 W)

Table 3: Comparison of lightweight case results obtained with the methodology and ISO 52016-1:2017.

BESTEST 640						
Time	$\boldsymbol{\Phi_{H;vct}}$ **[kWh]**	$\boldsymbol{\Phi_{H;ISO\ 52016}}$ **[kWh]**	$\boldsymbol{\Phi_{C;vct}}$ **[kWh]**	$\boldsymbol{\Phi_{C;ISO\ 52016}}$ **[kWh]**	$\boldsymbol{\theta_{op;vct}}$ **[°C]**	$\boldsymbol{\theta_{op;ISO\ 52016}}$ **[°C]**
Jan	853	718	672	586	20.1	19.0
Feb	711	591	529	451	20.0	18.9
Mar	513	358	614	537	20.8	19.8
Apr	273	169	464	421	21.7	20.9
May	105	47	398	380	22.8	22.4
Jun	38	22	448	446	23.9	24.0
Jul	1	0	720	720	25.4	25.6
Aug	1	0	783	775	25.0	25.1
Sep	60	19	874	835	23.7	23.6
Oct	290	151	905	812	21.6	20.0
Nov	512	389	620	538	20.6	19.4
Dec	784	646	654	557	20.1	19.0
Year	4141	3110	7680	7058	-	-

Table 4: Comparison of heavyweight case results obtained with the methodology and ISO 52016-1:2017.

BESTEST 940						
Time	$\boldsymbol{\Phi_{H;vct}}$ **[kWh]**	$\boldsymbol{\Phi_{H;ISO\ 52016}}$ **[kWh]**	$\boldsymbol{\Phi_{C;vct}}$ **[kWh]**	$\boldsymbol{\Phi_{C;ISO\ 52016}}$ **[kWh]**	$\boldsymbol{\theta_{op;vct}}$ **[°C]**	$\boldsymbol{\theta_{op;ISO\ 52016}}$ **[°C]**

Jan	480	350	140	63	22.4	21.2
Feb	444	333	90	34	22.3	20.9
Mar	212	118	146	108	23.0	22.3
Apr	119	69	146	141	23.8	23.5
May	11	4	171	173	24.4	24.4
Jun	16	8	306	306	25.6	25.7
Jul	0	0	640	638	26.5	26.6
Aug	0	0	681	656	26.3	26.6
Sep	3	0	666	625	25.7	26.1
Oct	66	27	483	412	24.3	24.7
Nov	193	120	132	68	22.8	22.1
Dec	396	272	96	36	22.4	21.1
Year	1941	1301	3699	3260	-	-