MODELLING THE ENERGY PERFORMANCE OF NIGHT-TIME VENTILATION USING THE QUASI-STEADY STATE CALCULATION METHOD

Jérôme Le Dréau[1], Per Heiselberg[1], Rasmus L. Jensen[1] and Ayser D. Selman[1]
[1]Department of Civil Engineering, Aalborg University, Aalborg, Denmark

ABSTRACT

Many European countries assess the heating and cooling needs of buildings using the quasi-steady state calculation method described in EN ISO 13790. The energy need is calculated by establishing the monthly balance of heat losses and heat gains, and the dynamic effects are taken into consideration by introducing correlation factors. The difficulty of evaluating night-time ventilation with such a method comes from the strong influence of the dynamic effects. In this paper, two different calculation methods for modelling night-time ventilation have been developed and tested: one is based on correcting the convective heat transfer by ventilation using the factor C_{ve} (method proposed in the standard), and the other one introduces an adjustment factor C_{γ} on the relative heat gains.

288 simulations of a typical Danish office building have been performed using different boundary conditions: level of thermal mass, level of insulation, orientation, internal heat loads, duration and air change rate of night-time ventilation. For both methods, the derived correction factors are highly dependent on the thermal mass of the building. An influence of the period of activation of night-time ventilation has also been observed. Correlations have been developed and an improvement of the accuracy has been observed: the uncertainty on the annual energy consumption obtained with adjustment factor has been decreased from around 10 % down to 5%.

INTRODUCTION

In order to satisfy the requirements of the EPBD (Energy Performance of Buildings Directive), simplified calculation methods have been developed to assess the heating and cooling needs of buildings. The European Standard EN ISO 13790 “Calculation of energy use for space heating and cooling” (2008) proposes three different calculation methods to evaluate the performance of buildings: a quasi-steady state, an hourly and a fully dynamic calculation method. The quasi-steady state method is based on a monthly balance of heat losses and heat gains. The dynamic effects are taken into consideration by introducing correlation factors. It is the successor of the standard EN 832 (1998), which aimed at evaluating the heating consumption of residential buildings. Many European countries have adopted this calculation method for its transparency, robustness and reproducibility (Van Dijk et al., 2005).

The purpose of this paper is to improve the ability of the quasi-steady state calculation method to model night-time ventilation (NTV). In many non-residential buildings, night-time ventilation is used instead of air conditioning to achieve thermal comfort during the summer season. The building structure is cooled down overnight with relatively cold outdoor air, in order to provide a heat sink during the occupied period of the next day by making use of the exposed thermal mass (Goethals et al., 2011). Therefore, the night temperature profile inside the building is modified compared to a traditional cooling system (Breesch et al., 2011).

The difficulty of modelling night-time ventilation in the quasi-steady state calculation method arises from the large influence of the dynamic effects. It has been observed that the accuracy of the monthly calculation method is highly dependent on the right definition of the dynamic parameters; they should be carefully determined and tailored to the building stock and the climate (Corrado et al., 2007). The precision is greatly affected by calculation assumptions, boundary conditions and input values (Jokisalo et al., 2007).

The objective of this paper is to define a parameter that could take into consideration the dynamic effects in play when using night-time ventilation. First the calculation method proposed in EN ISO 13790 will be detailled. Then two different calculation methods will be developed by performing dynamic simulations of a typical Danish office building under different boundary conditions. Finally the improvement achieved by using the calculation methods will be assessed by comparing the errors on the total energy consumption.

MONTHLY CALCULATION METHOD

Calculation of the cooling consumption

The calculation of the cooling need in the quasi-steady state method is based on a monthly balance of heat losses and heat gains. The dynamic effects are taken into consideration by introducing a loss utilisation factor $\eta_{C,ls}$. Only part of the transmission and ventilation heat transfer is utilized to decrease the energy need for cooling, the rest leading to an undesired decrease of the internal temperature below the set-point (during night for example):

$$Q_{C,nd} = Q_{C,gn} - \eta_{C,ls}\, Q_{C,ht} \quad (1)$$

where $Q_{C,nd}$ energy need for cooling (MJ)
$Q_{C,ht}$ heat losses (MJ)
$Q_{C,gn}$ heat gains (MJ)

The total monthly heat losses of the building $Q_{C,ht}$ are equal to the sum of the heat transfer by transmission and by ventilation:

$$Q_{C,ht} = (H_{tr} + H_{vent})\,(\theta_{int,SP} - \theta_{ext})\; t \quad (2)$$

where H_{tr} transmission heat transfer coef. (W/K)
H_{vent} ventilation heat transfer coef. (W/K)
$\theta_{int,SP}$ set-point temperature, i.e. 26°C
θ_{ext} external temperature (°C)
t period of time (Ms)

The total monthly heat gains of the building $Q_{C,gn}$ are equal to the sum of the internal (Q_{int}) and solar heat gains (Q_{sol}):

$$Q_{C,gn} = Q_{int} + Q_{sol} \quad (3)$$

The loss utilisation factor is defined as follows:

$$\eta_{C,ls} = \frac{1 - \gamma_C^{\,-a_C}}{1 - \gamma_C^{\,-(a_C+1)}} \quad (4)$$

where γ_C relative heat gains for cooling (-)

$$\gamma_C = \frac{Q_{C,gn}}{Q_{C,ht}} \quad (5)$$

a_C numerical parameter for cooling (-), function of the building time constant τ (h)

$$a_C = a_{C,0} + \frac{\tau}{\tau_{C,0}} \quad (6)$$

The numerical parameter $a_{C,0}$ and the time constant $\tau_{C,0}$ are reference parameters that are defined at national levels. The values proposed in EN ISO 13790 (2008) and in the Danish Building regulation (SBi, 2010) are presented in the Table 1. The values used in Denmark have been obtained from experiments on the PASLINK test facility (Vandaele et al., 1994). The values used in this paper have been derived from 576 dynamic simulations performed on the same typical building as the one presented in this paper; details can be found in the report from Le Dréau et al. (2013).

Table 1: Reference parameters for cooling

	τ_0 (h)	a_0 (-)
EN ISO 13790	15	1
DENMARK	83	1.83
THIS PAPER	35	2.12

The time constant of the building τ characterizes the internal thermal inertia of the conditioned zone. It is a function of the thermal mass of the building and of the heat losses:

$$\tau = \frac{C_m \,/\, 3600}{H_{tr} + H_{vent}} \quad (7)$$

where C_m internal heat capacity (J/K)

Calculation of the ventilation heat losses

In the standard EN ISO 13790, night-time ventilation is evaluated as an extra ventilative flow:

$$H_{vent,extra} = \rho C_p b_{ve}\, C_{ve}\, f_{ve,t,extra}\, q_{ve,extra} \quad (8)$$

where ρC_p heat capacity of air (J/m^3·K)
b_{ve} temperature adjustment factor (-)
C_{ve} adjustment factor (-)
$f_{ve,t,extra}$ time fraction of operation (-)
$q_{ve,extra}$ additional airflow rate (m^3/s)

The dynamic effects and the effectiveness of night-time ventilation are defined by the adjustment factor C_{ve}. No calculation method is given in the standard, only the default value is specified (equal to 1). The temperature adjustment factor b_{ve} corrects the mean monthly temperature if the supply temperature is different from the external environment. In this paper, the value of this parameter has been set to 1 according to Breesch et al. (2011).
In addition to increasing the ventilation losses, night-time ventilation will decrease the building time constant due to larger heat transfer coefficient by ventilation (Equation 7). It will also lead to a decrease of the utilisation factor (Equation 4).

Methods tested for evaluating night-time ventilation

The difficulty of evaluating night-time ventilation in a monthly calculation method comes from the strong influence of the dynamic effects. The efficiency of night-time ventilation depends on the amount of heat that can be stored during the day, but also on the amount of heat that can be released during the night. This interdependence between day and night is the challenge of the calculation method.

In a previous study, Breesch et al. (2011) developed a method to assess the performance of mechanical night cooling. They defined a correlation between the time fraction of operation $f_{ve,t,extra}$ and the ratio $1/\gamma_C$. The adjustment factor C_{ve} was kept constant, equal to 0.7. Nevertheless, when comparing the new calculation method to the results of dynamic simulations, it showed “a non-linear and uncertain correspondence”.

In this study, the time fraction of operation $f_{ve,t,extra}$ will be assumed constant and calculated using the maximum operation time of night-time ventilation.

This parameter will be chosen in a range, which corresponds to the normal use of night-time ventilation for the building and climate studied. The effect of the thermal mass, the air change rate and the level of internal heat gains will be then observed. Two different methods will be tested: one is based on the proposal from EN ISO 13790, and the other one introduces an adjustment factor directly on the ratio of gains to losses γ_C. The adjustment factors will then be derived for different cases and the relations with parameters, such as the level of thermal mass, will be studied.

- *Method 1:* C_{ve}

In this first method tested, the amount of ventilation losses is corrected with an adjustment factor C_{ve} (cf. Equation 8), larger than zero. $C_{ve} = 1$ indicates that all the excess heat can be stored and then discharged totally by the ventilation system. It has to be noticed that this parameter can be higher than one: referring to Equation 8, it could indicate that the ventilation system and the thermal storage are more efficient than physically possible; but it is not true, as the building time constant and also $\eta_{C,ls}$ are decreasing with values of C_{ve} larger than one (Equation 7).

- *Method 2:* C_γ

In the second method tested, the adjustment factor will be applied directly on the ratio of gains to losses. The justification for testing this method is the correlation between the effectiveness of night-time ventilation and the ratio of gains to losses. In fact the efficiency of night-time ventilation does not depend only on the ability of the ventilation system to remove heat, but also on the ability of the building to store heat during the day. The ventilation losses are calculated assuming $C_{ve} = 1$ and the relative heat gains are defined as follows:

$$\gamma_C = C_\gamma \frac{Q_{C,gn}}{Q_{C,ht}} \tag{7}$$

This adjustment factor should be higher than zero, indicating than only part of the gains can be stored in the thermal mass during day-time, or only part of the heat can be discharged from the thermal mass during night-time.

CASE STUDY

Building structure

A typical office room located in Denmark has been studied. The internal dimensions of the room are 5×3.50×2.55 m (length × width × height), resulting in a floor area of 17.5 m². Only one wall is in contact with the outdoor environment, the other surfaces are defined as adiabatic. The external wall has an area of 8.9 m² and 55% of this surface is glazed (dimension 2×2.5 m). The g-value of the window is equal to 0.59.

In order to cover a wide range of building types, the orientation, the thermal mass and the level of insulation of the room have been modified. The different levels of thermal mass have been calculated according to the matrix method of EN ISO 13786 (2008) and represent light to extra-heavy buildings (SBi, 2010). The structure of light buildings (60 Wh/m².K) typically consists of sandwich walls (plasterboards and insulation) and thin concrete decks, whereas internal surfaces of heavy buildings (160 Wh/m².K) are usually made of concrete or plaster. Two levels of insulation have been modelled, corresponding to the Danish building regulations 2010 and the Danish Low Energy Class 1 for 2015. For each type of building presented in Table 2, the four orientations have been simulated (North, East, South and West) in order to cover a large range of relative gains γ_C. In total, 24 types of buildings have been simulated.

Table 2: Definition of the building types

	C_m (Wh/K.m²$_{internal}$)	U_{wall} (W/m².K)	U_{window} (W/m².K)
Room 1	80	0.18	1.3
Room 2	116		
Room 3	161		
Room 4	59	0.15	0.9
Room 5	96		
Room 6	140		

Parameters of the simulations

The outdoor conditions have been selected from the weather data of the Design Reference Year (DRY) in Copenhagen. Denmark is characterised by relatively low temperature during night, even during the warmer months. In Copenhagen, only 7 nights during the year have a climatic cooling potential (CCP) below 80 K.h (Artmann et al., 2007). The potential for night-time ventilation is therefore very high.

The cooling set-point is set to 26°C and an operative temperature down to 20°C is allowed during night-time. The level and schedule for the internal heat loads and the ventilation system (during daytime) are described in Table 3. The schedule corresponds to typical office hours. The air change rate of the ventilation system has been chosen according to EN ISO 15251 (2007), for a low polluting building and a ratio of occupancy of 0.1 person/m².

Table 3: Daytime parameters for internal heat loads and ventilation

	Schedule	Level
Internal heat loads	Working days (8am – 5pm)	10.3 W/m²$_{internal}$ or 20.6 W/m²$_{internal}$
Ventilation	Working days (8am – 5pm)	≈ 1,85 ACH (23 L/s)

During nights of working days, the ventilation system is activated for a maximum period of 8 hours up to 15 hours depending on the simulations (Table 4). When the temperature in the building drops below the heating set-point (20°C), the night ventilation stops. There is no preheating of the outdoor air and the air change rate varies from 4 up to 7.5 ACH. In total, 288 different cases have been simulated.

Table 4: Night-time parameters for ventilation

	Time start	Latest stopping time
8 hours	9pm	5am
12 hours	6pm	6am
15 hours	5pm	8am

The simulations have been performed using the software BSim (SBi, 2011). The convective heat transfer coefficients are calculated dynamically using the correlations from ASHRAE (2009).

Effect of night-time ventilation on the cooling consumption

The cooling need for the South facing rooms is presented in Figure 1. The cooling need is greatly reduced by using night-time ventilation. It can also be observed that the higher the thermal mass, the more efficient night-time ventilation.

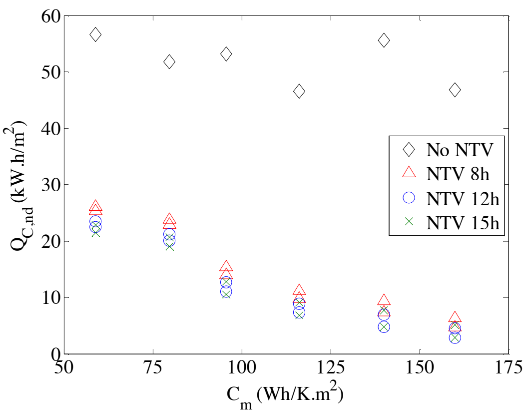

Figure 1: Yearly cooling need in the rooms facing South (heat loads = 10.3 W/m²)

METHOD OF ANALYSIS

Calculation of the adjustment factors

The technique chosen for determining the adjustment coefficients is based on the method proposed by Corrado et al. (2007). They detailed a calculation method to derive the reference parameters $a_{C,0}$ and $\tau_{C,0}$ from dynamic simulations.

From each simulation case, the parameters $Q_{C,ht}$, $Q_{C,gn}$, $\eta_{C,ls}$ and γ_C can be extracted for the 12 months by performing three dynamic simulations:

- a first simulation with no gains (solar and internal) and a fixed set-point of 26°C is executed to obtain $Q_{C,ht}$
- $Q_{C,gn}$ is derived from a second simulation with a fixed set-point of 26°C
- $\eta_{C,ls}$ is finally obtained from the third simulation, with the operative temperature kept within the range of 20 to 26°C

From these results, the adjustment factor C_{ve} can be calculated for each simulation case through an iterative process. The parameters $Q_{C,nd}$ and $Q_{C,gn}$ are obtained from the dynamic simulations. $\eta_{C,ls}$ and $Q_{C,ht}$ are derived theoretically for different values of C_{ve}. Finally the correct value of C_{ve} is selected by minimising the error between the annual calculated cooling consumption and the value obtained through the dynamic simulation (third simulation).

A similar iterative process is performed to obtain the value of C_γ. In this case, all the parameters except a_C are derived from the dynamic simulations.

Validation of the calculation method

The validity of the method of analysis has been tested by using the same conditions as the one described in EN ISO 13790. The ventilation system is running all day long, and the internal heat gains are constant. The weather data corresponds to Trappes (France). In order to validate the method of analysis, the values of a_C obtained through the dynamic simulations should be similar to the one described in the standard.

First, the results of the four orientations with similar boundary conditions are grouped. It is possible to perform such a combination because the rooms have the same time constant, i.e. thermal mass and losses heat transfer coefficients identical (Equation 7). In this way, a wider range of γ_C is available for deriving the adjustment coefficients, resulting in a better accuracy on the final result. In total, 48 data points compose the graph $\eta_{C,ls} = f(\gamma_C)$ (Figure 2) and the value a_C can be derived for one specific time constant (Equation 4).

Finally the different values of a_C obtained by simulations (red crosses in Figure 3) can be compared to the values calculated with the default parameters proposed in EN ISO 13790 (continuous line in Figure 3). A good agreement is observed.

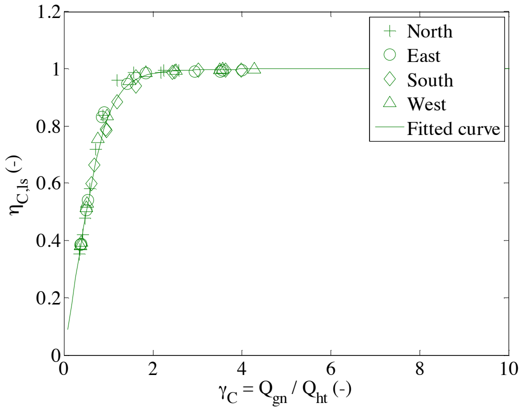

Figure 2: Loss utilisation factor as a function of the relative heat gains for the 4 orientations (τ = 83.4h)

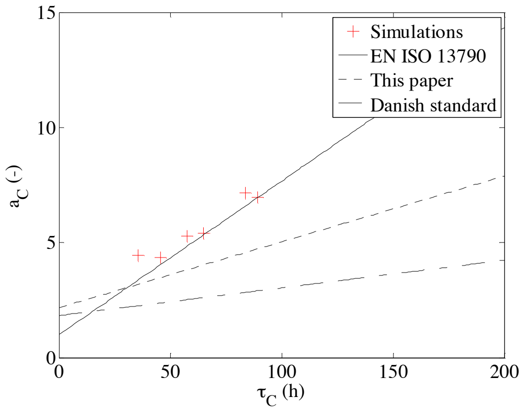

Figure 3: a_C as a function of the building time constant using the test case of EN ISO 13790

RESULTS ANALYSIS

Results with Method 1 (C_{ve})

From the 288 simulations performed, the adjustment coefficients C_{ve} have been derived. The values obtained have been correlated to different parameters, such as the thermal mass, the air change rate, the number of operating hours of night-time ventilation, the level of internal heat load, and the daily asymmetry in the heat gains-losses. From all these parameters, it has been observed that the thermal mass of the room has the largest influence on the value of C_{ve}. Therefore, all the results will be presented as a function of the thermal mass.

From Figure 4, it can be observed that there is a strong correlation between the adjustment coefficients C_{ve} and the thermal mass. The higher the thermal mass, the higher the value of C_{ve}. This can be explained by a better use of the thermal mass to store heat during the day, and release it during the night. For very light buildings (lower than 80 Wh/K.m²), the value of C_{ve} is not decreasing anymore, suggesting a threshold. Different colours and markers have been set according to the maximum time of operation and the air change rate of night-time ventilation. A correlation can be observed with the duration of night-time ventilation: the longer the period of operation, the higher the value of C_{ve}. In fact, operating night-time ventilation for a longer period allows a deeper activation of the thermal mass of the building (except if the thermal mass has already been fully discharged).

Figure 4 and Figure 5 present the results for two levels of internal heat loads. The adjustment coefficient is not influenced by the amount of heat accumulated in the room.

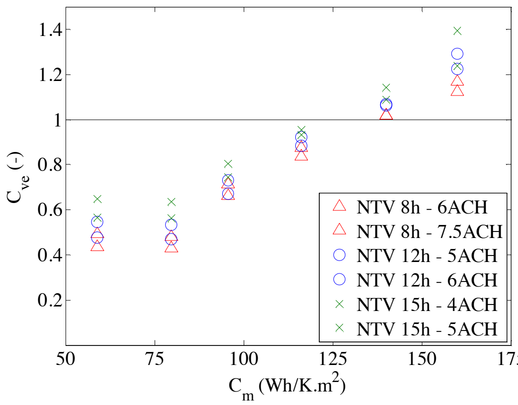

Figure 4: Adjustment coefficient C_{ve} as a function of the room thermal mass (heat loads = 10.3 W/m²)

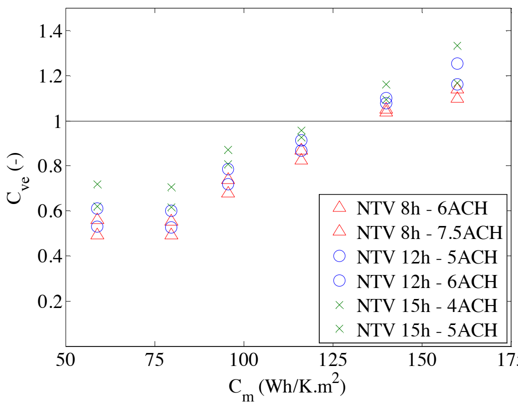

Figure 5: Adjustment coefficient C_{ve} as a function of the room thermal mass (heat loads = 20.6 W/m²)

From the previous observations, it can be concluded that the adjustment coefficient C_{ve} depends mainly on the thermal mass of the room, but also on the maximum operating time of night-time ventilation. Therefore a correlation has been developed based on these parameters:

$$C_{ve} = max\left(\frac{-0.251 + 0.008\,C_m + 0.016\,max\,hrs_{NTV}}{0.55}\right) \quad (10)$$

A minimum threshold value has been set in order to avoid too large errors for buildings with low thermal mass. Comparing the derived values of C_{ve} to the one obtained with Equation 10, a mean deviation of 6.1 % on C_{ve} has been observed.

In order to evaluate the improvement achieved with the use of customized values of C_{ve}, the annual cooling consumption obtained with $C_{ve} = 1$ and with Equation 10 have been compared to the values obtained from dynamic simulations (Figure 6). The error is expressed a percentage of the total energy consumption, as performed in EN ISO 13790. In this standard, deviations up to 10 % have been observed.

As expected, the default value $C_{ve} = 1$ underestimates the cooling consumption due to an overestimation of the efficiency of the storage and the night cooling. The use of a customised value of C_{ve} improves the accuracy of the calculation method: the uncertainty is lowered down to 4.5%. The largest error is observed in the case of buildings with low thermal mass.

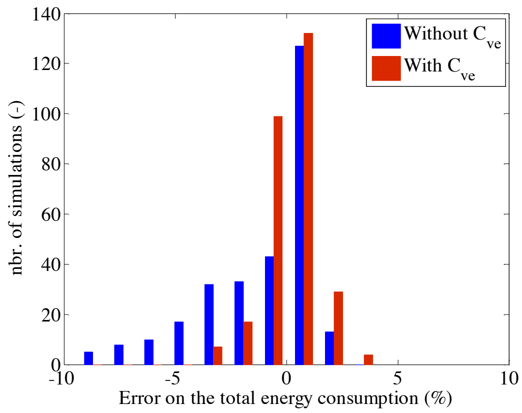

Figure 6: Comparison of the error on the total energy consumption with and without C_{ve}

Results with Method 2 (C_γ)

The method used for analysing the results with the correction factor C_γ is similar to the one described in the previous section. In this case, a strong correlation between thermal mass and adjustment factor has also been observed (Figure 7). But the threshold, which has been observed in the case of C_{ve}, is not so distinct in this case. Similarly to method 1, there is also a dependence between the maximum operating time of night-time ventilation and the value of C_γ.

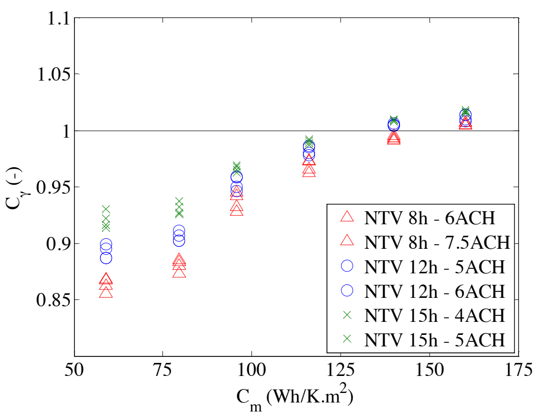

Figure 7: Adjustment coefficient C_γ as a function of the room thermal mass (all simulations)

Therefore, another correlation has been developed between C_γ and these parameters:

$$C_\gamma = 0.7666 + 0.0013\, C_m + 0.0044\, max\ hrs_{NTV} \quad (11)$$

Comparing the derived values of C_γ to the one obtained with Equation 11, a mean deviation of 1.2 % on C_γ has been observed. This value is lower than the one obained for C_{ve}, but it does not mean that the method is more accurate, as the variation range of C_γ is smaller.

Figure 8 compares the accuracy of the original calculation method, to the one using the parameter C_γ. Even though the new calculation method slightly underestimates the performance of night-time ventilation, a large improvement of the accuracy can be observed.

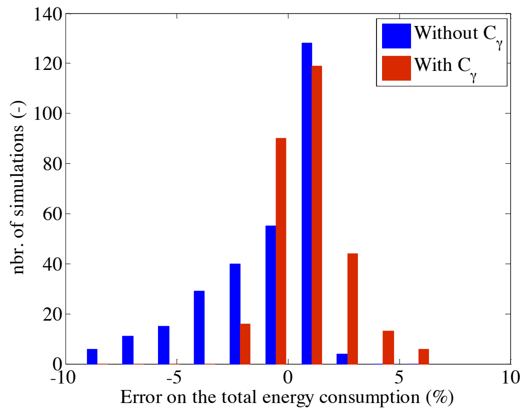

Figure 8: Comparison of the error on the total energy consumption with and without C_γ

CONCLUSION

The possibility of modelling night-time ventilation in the quasi-steady state method (also named monthly calculation method) has been studied by mean of dynamic simulations. The case of a typical office room located in Denmark has been simulated under different conditions. The thermal mass, the level of insulation, the orientation, the internal heat loads and also the duration and the air change rate of night-time ventilation have been varied resulting in a total of 288 simulations.

The dynamic effects have a strong influence on the efficiency of night-time ventilation. The decrease of the cooling consumption depends on the ability of the building to store heat during the day, but also on the efficiency of the ventilation system to remove this heat during night. This interdependence day/night is the main issue when defining a calculation method.

Two different calculation methods have been tested: one corrects the convective heat transfer by ventilation using the factor C_{ve}, and the other one introduces an adjustment factor C_γ on the relative heat gains. For both methods, the derived correction factors are highly dependent on the thermal mass of the building. An influence of the maximum period of activation of night-time ventilation has also been observed. Correlations have been developed for C_{ve} and C_{γ} (Equation 10 and 11) for buildings having a thermal mass between 50 up to 175 Wh/K.m^2. The increase of accuracy has been assessed by comparing the annual cooling and heating consumption obtained with and without adjustment factor. The use of such coefficients improves the accuracy of the calculation method, lowering the uncertainty from around 10 % down to 5%. The first method proposed (C_{ve}) showed a slightly better accuracy, but is quite dependant on the threshold set. The second method has a better accuracy for low thermal mass buildings, and is easier to apply.

In order to further validate the methods and assess the most suitable model, simulations on a whole building with different shapes and windows sizes should be performed. It has to be noticed that these adjustment factors are probably climate-dependant, i.e. not applicable to climate with a different Climatic Cooling Potential (CCP). The use of a pre-heating system or a different minimum temperature (20°C in this case) might also influence the correlations.

ACKNOWLEDGEMENTS

This paper summarizes the scientific results achieved during the EUDP-funded project "Multifunktionelle betonkonstruktioner til renovering og nybyg".

REFERENCES

Artmann, N., Manz, H., Heiselberg, P. 2007. Climatic potential for passive cooling of buildings by night-time ventilation in Europe. Applied Energy 84, 187–201.

ASHRAE. 2009. ASHRAE Handbook - Fundamentals - Chapter 4: Heat transfer, American Society of Heating, refrigeration and Air-Conditioning Engineers, Inc., Atlanta, GA.

Breesch, H., Goethals, K., Janssens, A. 2011. Development of a quasi-steady-state assessment method of night cooling. Tampere : 9th Nordic Symposium on Building Physics.

Corrado V., Fabrizio E. 2007. Assessment of building cooling energy need through a quasi-steady state model: Simplified correlation for gain-loss mismatch. Energy and Buildings, Vol. 39. 569-579.

European committee for standardization. 1998. EN 832 Thermal performance of buildings - Calculation of energy use for heating - Residential buildings.

European committee for standardization. 2007. EN ISO 15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

European Committee for standardization. 2008. EN ISO 13786 - Thermal performance of building components - Dynamics thermal characteristics - Calculation method.

European committee for standardization. 2008. EN ISO 13790 - Energy performance of buildings - Calculation of energy use for space heating and cooling.

Goethals K., Breesch H., Janssens A. 2011. Sensitivity analysis of predicted night cooling performance to internal convective heat transfer modelling, Energy and Buildings. 43, 2429-2441.

Jokisalo J., Kurnitski J. 2007. Performance of EN ISO 13790 utilisation factor heat demand calculation method in a cold climate.

Le Dréau J., Selman A. D., Heiselberg P., Jensen R.L.. 2013. Thermal Mass & Dynamic effects Danish Building Regulation. Aalborg University.

SBi, Danish building research institute. 2010. Be10 - Danish buildings energy calculation program.

SBi, Danish building research institute. 2011. BSim. version 6,11,1,14.

Vandaele, L., P. Wouters. 1994. The PASSYS summary report, European Commission Publication, EUR 15113 EN.

Van Dijk, D., Spiekman, M., de Wilde, P. 2005. A monthly method for calculating energy performance in the context of European building regulations. 9th International IPBSA conference, Montréal.