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ON THE EFFICIENCY OF NIGHT VENTILATION TECHNIQUES FOR THERMOSTATICALLY CONTROLLED BUILDINGS

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Abstract—A new, integrated method to calculate the energy contribution of night ventilation techniques to the cooling load of a building is presented in this paper. The method is based on the principle of "Balance Point Temperature" and permits the calculation of the energy required to cool a building to acceptable comfort conditions when night ventilation techniques are used. It also permits the calculation of the energy contribution of night ventilated buildings compared to conventional air conditioned buildings. The proposed method is successfully validated with data from an extended and detailed simulation procedure using the TRNSYS simulation programme to calculate dynamically the thermal performance of buildings using night ventilation techniques. It is found that the method is of sufficient accuracy and can be used during the predesign as well as the design phase of a building to access the performance of night ventilated buildings. Copyright © 1996 Elsevier Science Ltd.

1. INTRODUCTION

Night ventilation can provide an appropriate means for passive cooling of buildings. Night ventilation techniques permit the ventilation of the building by allowing the low temperature outdoor air to enter the building and remove the stored heat, which has been trapped during the day. The air movement provides a significant increase of the heat dissipation from the building materials and the warmer air is exhausted into the low temperature atmospheric heat sink (Evans, 1957; Santamouris, 1992; Awbi, 1991).

The effectiveness of the night-time ventilation techniques is strongly related to the relative difference between indoor and outdoor air temperature values. In general terms, a reduction of the outdoor night-time temperatures represents an increase of the night ventilation system capacity (Santamouris *et al.*, 1994; Balaras, 1992).

A wide range of night ventilation passive cooling applications have been described by Santamouris (1988) and in Hoffman and Gideon (1984). Moreover, a study on the energy savings potential in office buildings in Athens, presented by Santamouris *et al.* (1994), has shown that night ventilation techniques can reduce the total cooling load of air conditioned offices by up to 30%.

Various algorithms to calculate the thermal performance of night ventilated buildings have been proposed by Koos Van der Maas and Roulet (1991) and by ASHRAE (1985). Also, several buildings simulation codes like TRNSYS, ESP, etc. can be used for the simulation of the thermal behaviour of night ventilated buildings. However, the use of simulation tools may be not suitable for the pre-design and even design phase and presents serious difficulties in obtaining manageable solutions because of their complicated structure. Therefore, there is a need for the development of integrated and accurate methods to easily calculate the contribution of the night ventilation techniques to the building's cooling load, especially during the pre-design and design phase.

The present paper aims at the development of such an integrated methodology. The presented algorithms are based on the well known principle of "Balance Point Temperature" and are validated against extensive and detailed simulations and experimental data. The method can be used to easily calculate the impact of the night ventilation techniques on the global thermal performance of a building.

2. DESCRIPTION OF THE ALGORITHMS

The instantaneous cooling load, Q_c, for an A/C building can be written as follows:

$$Q_c = [k(T_0 - T_i) + Q_s + Q_{in}]^+ \quad (1)$$

where k is the building load coefficient (W/°C), T_0 is the ambient temperature (°C), T_i is the indoor temperature (°C), Q_s is the critical part of the solar "gains" entering the building through transparent and opaque elements (W) and Q_{in}

is the critical percentage of the internal gains (W). The part of solar or internal load which contributes to the cooling load of the building is considered as critical and it is mainly a function of the building's thermal capacity, operating schedule, etc. Some methods to calculate the critical, or "useful", level of the solar and internal load have been proposed by Bida and Kreider (1987), ASHRAE (1991) and by Baker (1987). Equation (1) considers that T_i is not floating during the working period of the building.

If $Q_T = Q_s + Q_{in}$ then:

$$Q_c = [k(T_0 - T_i) + Q_T]^+. \quad (2)$$

If a balance temperature, T_b, is used, where

$$T_b = T_i - Q_T/k \quad (3)$$

the instantaneous cooling load can be calculated as a linear function of the outdoor temperature T_0:

$$Q_c = [k(T_0 - T_b)]^+ \quad (4)$$

The daily or monthly cooling load, Q_{cm}, can be calculated by integrating the eqn (4) over the time period of a day or a month. Thus:

$$Q_{cm} = 3600\ k\ \mathrm{CDD}(T_b) \quad (5)$$

where $\mathrm{CDD}(T_b)$ are the cooling degree hours on the hourly value of the balance temperature T_b for a day or a month respectively.

Based on the above well known theory, the instantaneous cooling load (Q_{cn}) for a building where night ventilation technique is used can be written as follows:

$$Q_{cn} = [K(T_0 - T_i) + Q_T - Q_{NV}]^+ \quad (6)$$

where Q_{NV} is the energy reduction due to the use of night ventilation and K is the building load coefficient of the daytime period. Also, we define that:

$$T_{bvn} = T_i - (Q_T - Q_{NV})/K \quad (7)$$

where T_{bvn} is the balance temperature for buildings using night ventilation techniques. Therefore, the cooling load is given by the following expression:

$$Q_{cn} = [K(T_0 - T_{bvn})]^+ \quad (8)$$

The daily or monthly cooling load, Q_{cnv}, can be calculated by integrating eqn (8). Therefore, we have that:

$$Q_{cnv} = 3600\ K\ \mathrm{CDD}(T_{bvn}) \quad (9)$$

where $\mathrm{CDD}(T_{bvn})$ are the daily or monthly modified cooling degree hours for buildings using night ventilation technique, calculated by the following expression:

$$\mathrm{CDD}(T_{bvn}) = \sum(T_0 - T_{bvn})S_j \quad (10)$$

$$S_j = 1 \text{ if } T_0 > T_{bvn}$$

$$S_j = 0 \text{ if } T_0 \leq T_{bvn}$$

The energy reduction due to the night ventilation, Q_{NV}, which has been introduced in eqn (6), is calculated from the following expression:

$$Q_{NV} = (mc\mathrm{NDD})/\mathrm{DAY} \quad (11)$$

where m is the mean air mass flow rate during the night period, c is the air specific heat and DAY is the daytime period in hours. NDD are the night degree days calculated on a temperature base, T_{ngh}, defined as follows:

$$\mathrm{NDD} = \sum(T_{ngh} - T_0)S_j \quad (12)$$

$$S_j = 1 \text{ if } T_0 < T_{ngh}$$

$$S_j = 0 \text{ if } T_0 \geqslant T_{ngh}$$

where T_{ngh} is the mean night-time indoor temperature of the building without night ventilation. It is proposed to be calculated from the following expression:

$$T_{ngh} = (h_{in}AT_k + m_a cT_{on})/(h_{in}A + m_a c) \quad (13)$$

where

$$T_k = f_3(T_i + T_{on}) \quad (14)$$

h_{in} is the internal heat transfer coefficient, A is the total internal surface of the building, m_a is the night air flow rate of the building when there is not use of night ventilation. Also, T_{on} is the mean night-time ambient temperature. Finally, f_3 is a coefficient defining the mean temperature of the mass, T_k, as a function of the indoor temperature and the mean night-time ambient temperature. If f_3 is not known, a value close to $f_3 = 0.5$ may be used. Equation (13) results from the energy balance of the indoor air during the night period.

In order to check if the total energy losses due to night ventilation, (3600mcNDD), are higher than the maximum possible stored energy, we defined a parameter, MCMAX, equal to:

$$\mathrm{MCMAX} = \sum(M_iC_i)(T_{ngh} - T_{on}) > 0 \quad (15)$$

where $\sum(M_iC_i)$ is the effective thermal capacitance of the building. The subscript i indicates a material of the building's structure.

In case of 3600mcNDD > MCMAX then the

cooling degree hours should be appropriately adjusted and may be taken equal to:

$$NDD = f_1 \text{ MCMAX}/(3600mc) \quad (16)$$

where f_1 is a coefficient expressing the efficiency of heat transfer from the wall to the air and the degree to which the night ventilation air is coupled to the thermal mass. This parameter is mainly a function of air flow patterns inside the building and of the possible cover of the mass. A suggested value is $f_1 = 0.8$.

A second check should compare the energy losses due to night ventilation ($3600mc$NDD) with the cooling load of the building when night ventilation techniques are not applied (Q_{cm}), where Q_{cm} is defined in eqn (5). In case of $3600mc\text{NDD} > Q_{cm}$ then:

$$NDD = f_2\, Q_{cm}/(3600mc) \quad (17)$$

where f_2 is a coefficient expressing the ability of the building to carry over the "coolth" into the occupied period on the following day. This coefficient is a function of the occupancy pattern, and the thermal mass of the building. For heavyweight buildings f_2 can vary between 0.8 and 1 as a function of the occupancy pattern and for buildings occupied at least 10 hours per day. Further information on this correction factor is given by Baker (1987).

Based on the above the contribution of night ventilation techniques to the cooling load of a building, f, can be calculated by the following

Table 1. Characteristics of night ventilated buildings, simulated to calculate the monthly cooling load

No.	Floor surface (m^2)	Characteristics	Set point temperature
1–4	400	Well insulated, 4 cm of concrete + 10 cm of insulation + 6 cm of concrete, 10 m^2 of window. Day: 1 ach, Night ventilation: 5 ach	26, 27, 28, 29°C
5–8	400	Same building. Night ventilation: 10 ach	26, 27, 28, 29°C
9–12	400	Same building. Night ventilation: 15 ach	26, 27, 28, 29°C
13–16	400	Same building. Night ventilation: 20 ach	26, 27, 28, 29°C
17–20	400	Same building. Night ventilation: 25 ach	26, 27, 28, 29°C
21–24	400	Same building. Night ventilation: 30 ach	26, 27, 28, 29°C
25–28	400	Same building. Night ventilation: 35 ach	26, 27, 28, 29°C
29–32	400	Same building. Night ventilation: 40 ach	26, 27, 28, 29°C
33–36	900	Well insulated, 8.2 cm of dense concrete + 2.3 cm of insulation + 13 cm of lightweight concrete, 10 m^2 of window. Day: 1 ach. Night ventilation: 5 ach	26, 27, 28, 29°C
37–40	900	Same building. Night ventilation: 10 ach	26, 27, 28, 29°C
41–44	900	Same building. Night ventilation: 15 ach	26, 27, 28, 29°C
45–48	900	Same building. Night ventilation: 20 ach	26, 27, 28, 29°C
49–52	900	Same building. Night ventilation: 25 ach	26, 27, 28, 29°C
53–56	900	Same building. Night ventilation: 30 ach	26, 27, 28, 29°C
57–60	2500	Well insulated. 5 cm dense concrete + 8 cm insulation + 12 cm lightweight concrete, 20 m^2 window. Day: 1 ach. Night ventilation: 5 ach	26, 27, 28, 29°C
61–64	2500	Same building. Night ventilation: 10 ach	26, 27, 28, 29°C
65–68	2500	Same building. Night ventilation: 15 ach	26, 27, 28, 29°C
69–72	2500	Same building. Night ventilation: 20 ach	26, 27, 28, 29°C
73–76	2500	Same building. Night ventilation: 25 ach	26, 27, 28, 29°C
77–80	2500	Same building. Night ventilation: 30 ach	26, 27, 28, 29°C
81–84	10000	Walls: 7.5 cm dense concrete + 2.5 cm expanded polystyrene and 15 cm lightweight concrete. Roof: 1.5 cm Asphalt + 7.5 cm lightweight concrete screed + 15 cm dense concrete. Day: 1 ach. Night ventilation: 5 ach	26, 27, 28, 29°C
85–88	10000	Same building. Night ventilation: 10 ach	26, 27, 28, 29°C
89–92	10000	Same building. Night ventilation: 15 ach	26, 27, 28, 29°C
93–96	10000	Same building. Night ventilation: 20 ach	26, 27, 28, 29°C
97–100	10000	Same building. Night ventilation: 25 ach	26, 27, 28, 29°C
101–104	10000	Same building. Night ventilation: 30 ach	26, 27, 28, 29°C
105–108	900	Roof: 1.5 cm asphalt + 7.5 cm lightweight concrete + 15 cm dense concrete. Floor and walls: 7.5 cm dense concrete + 2.5 cm polystyrene + 15.0 cm dense concrete. Day: 1 ach. Night ventilation: 5 ach	26, 27, 28, 29°C
109–112	900	Same building. Night ventilation: 10 ach	26, 27, 28, 29°C
113–116	900	Same building. Night ventilation: 15 ach	26, 27, 28, 29°C
117–120	900	Same building. Night ventilation: 20 ach	26, 27, 28, 29°C
121–124	900	Same building. Night ventilation: 25 ach	26, 27, 28, 29°C
125–128	900	Same building. Night ventilation: 30 ach	26, 27, 28, 29°C

coefficient f_3. All simulations have been carried out by considering that buildings are thermostatically controlled during the daytime and free floating during the night. Buildings were ventilated during the night period only when the outdoor temperature was lower than the indoor one. The night degree hours have been calculated automatically using either eqn (12) or eqns (16) and (17) when the total energy losses due to night ventilation were higher than the maximum possible stored energy, or the energy losses were higher than the cooling load. The method has been checked for buildings of low, medium and high thermal mass. However, the method should not be applied to buildings characterized by a very low mass, for example for buildings insulated partially with internal insulation. Also, the method is not appropriate for less than 5 air changes per hour. Finally, the method is not checked for buildings with very high thermal mass and more than 30 air changes.

Figure 1 shows the comparison of the monthly cooling load calculated from the dynamic simulation (TRNSYS, 1990) as well as from the present method. As seen from the figure, differences are between 3 and 15%. Therefore, the proposed method can be considered as sufficiently accurate and may be used to predict the contribution of the night ventilation passive cooling technique to the cooling load of a building.

The method is available in a computerized form under DOS (NORMA, 1994) and Windows (Santamouris, 1995b).

4. CONCLUDING REMARKS

A new integrated method to calculate the impact of night ventilation techniques on the global thermal performance of a building, is presented in this paper. The method is based on the principle of "Balance Point Temperature" and permits the calculation of the contribution of night ventilation techniques to the monthly cooling load of a building. An extensive validation procedure has been performed using the TRNSYS simulation programme describing the thermal performance of night ventilated buildings. From the comparison, it is found that the method is sufficiently accurate.

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REFERENCES

ASHRAE (1985) *Handbook of Fundamentals*. ASHRAE Atlanta, GA, USA.

ASHRAE (1991) *Handbook of Fundamentals*. ASHRAE Atlanta, GA, USA.

Awbi H. B. (1991) *Ventilation of buildings*, 1st Edition. Chapman and Hall.

Baker N. Y. (1987) Passive and low energy building design for tropical island climates. Prepared for the Commonwealth Science Council by the ECD Partnership, London, U.K.

Balaras C. A. (1992) The role of thermal mass on the cooling load of buildings, an overview of computational methods and proposed experimental work within PASCOOL. MDS PASCOOL meeting, Lyon, France.

Bida M. and Kreider J. F. (1987) Monthly averaged cooling load calculations—residential and small commercial buildings. *J. Solar Energy Engineering* **109**, 311–320.

Evans B. H. (1957) Natural air flow around buildings. Research report No 59, Texas Engineering Experiment Station, Texas A&M College System (1957).

Koos Van der Maas and Roulet C. A. (1991) Night-time ventilation by stack effect. ASHRAE Technical Data Bulletin Vol. 7, Number 1, Ventilation and Infiltration, pp. 32–40, ASHRAE NY.

NORMA: A passive cooling tool for Buildings. Developed by University of Athens for the European Architectural Competition "ZEPHYR" coordinated by the Energy Research Group, School of Architecture, University College Dublin. European Commission, Directorate General for Science, Research and Development (1994).

Santamouris M. (1988) Passive and hybrid cooling project in Greece. *Proc. Building 2000 Workshop*, pp. 155–193, Barcelona, Spain.

Santamouris M., Argiriou A., Dascalaki E., Balaras C. and Gaglia A. (1994) Energy characteristics and savings potential in office buildings. *Solar Energy* **52**, 59–66.

Santamouris M., Mihalakakou G., Argiriou A. and Asimakopoulos D. N. (1995) On the performance of buildings coupled with earth to air heat exchangers. *Solar Energy* **54**, 375–380.

Santamouris M., Geros V., Klitsikas N. and Argiriou A. (1995) SUMMER: A computer tool for passive cooling applications. Santamouris M. and Asimakopoulos D. (Eds), *Proc. Int. Symposium Passive Cooling of Buildings*, Athens.

Santamouris M. (1992) Natural convection heat and mass transfer through large openings. PASCOOL Report, MDS Meeting, DGXII, EEC, Lyon, France.

TRNSYS 13.1, A Transient System Simulation Program developed from Solar Energy Laboratory, University of Wisconsin-Madison, Madison, WI 53706, USA (1990).

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expression:

$$f = (Q_{cm} - Q_{cnv})/Q_{cm} \quad (18)$$

where Q_{cnv} and Q_{cm} are the cooling load of the building when night ventilation is used or not respectively.

3. VALIDATION OF THE METHOD AND RESULTS

The accuracy of the previously proposed algorithms, calculating the cooling load of night ventilated A/C buildings, has been verified using comparisons of the calculated monthly cooling load for various types of buildings and various configurations. Calculations have been performed using the previously described algorithms and an extensive version of the TRNSYS (1990) simulation programme.

Primarily, for the validation of the algorithms, calculating the cooling load of buildings when night ventilation techniques are not applied, the cooling load of buildings was calculated using the algorithms presented by eqns (1)–(5), and then TRNSYS. TRNSYS is a detailed simulation tool using transfer functions to characterize the effects of the thermal mass. The obtained results of the monthly as well as of the annual cooling load estimated by TRNSYS and the present method have been presented by Santamouris *et al.* (1994). This paper substantiated that there is a very good agreement between the two sets of data.

Furthermore, and in order to verify the accuracy of the algorithms proposed to calculate the performance of night ventilated buildings (eqns (6)–(17)), extensive comparisons have been performed using the TRNSYS (1990) simulation programme describing the thermal performance of a building using night ventilation techniques.

For this reason, 128 various cases, including different building characteristics, indoor temperatures and air changes per hour during the night-time period have been performed. The studied cases are summarized in Table 1, while climatic data taken from the National Observatory of Athens have been used.

The method prepared by Baker (1987) to calculate on a daily basis the useful solar and internal gains was used. For all simulations the correction coefficients f_1 and f_2 were equal to 0.8, while a value equal to 0.5 was used for the

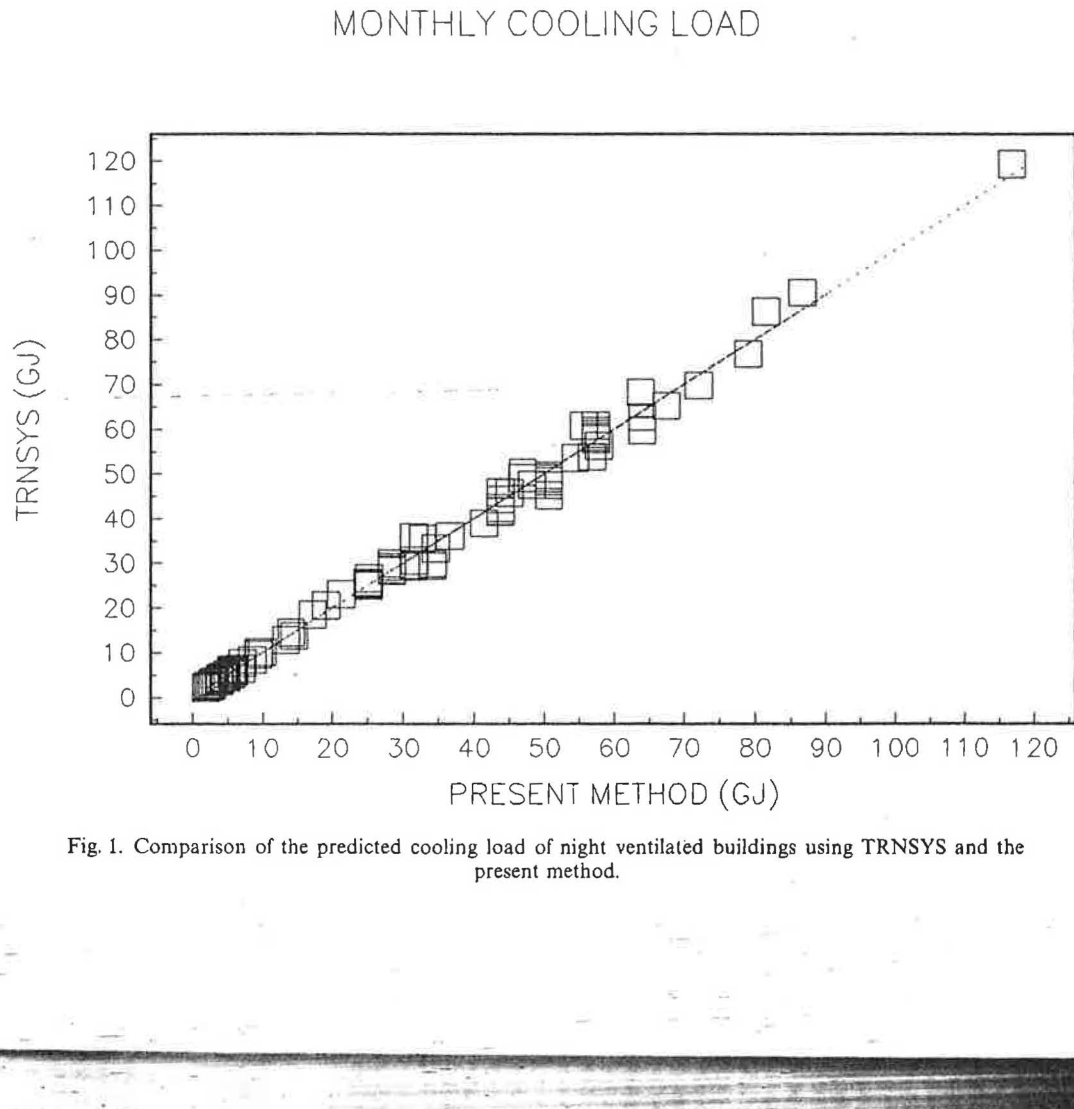

Fig. 1. Comparison of the predicted cooling load of night ventilated buildings using TRNSYS and the present method.