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Experimental evaluation of night ventilation phenomena

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Abstract

The present paper aims to investigate, in a systematic way, and by using both experimental and theoretical tools, the potential of night ventilation techniques when applied to full scale buildings, under different structure, design, ventilation, and climatic characteristics. Also, to investigate the impact and the limitations of night ventilation techniques regarding the thermal behavior of various types of buildings. Real scale measurements in three buildings operating under free-floating and air conditioning conditions have been performed. The cooling potential of night ventilation techniques applied to buildings operating under different conditions and with variable air flow rates, has been experimentally and theoretically studied. Additionally, sensitivity analysis on the impact of the major parameters determining the phenomena has also been carried out. Practical considerations on the impact of main parameters are given. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Night ventilation; Cooling techniques; Air conditioning

1. Introduction

Passive cooling techniques present a very important alternative to conventional air conditioning of buildings. The increase of family income, especially in Europe, has made the use of A/C systems highly popular. Sales of air conditioning equipment in Southern European countries have been considerably increased and have reached values close to ECU1.7 billion per year, [1]. Thus, the development of efficient passive cooling techniques is a first priority for building scientists.

Recent research has shown that night ventilation techniques, when applied to massive buildings, can significantly reduce the cooling load of air conditioning buildings and increase the thermal comfort levels of non air conditioning buildings [2].

Night ventilation techniques are based on the use of the cool ambient air as a heat sink, to decrease the indoor air temperature as well as the temperature of the building's structure. The cooling efficiency of these techniques is mainly based on the air flow rate as well as on the thermal capacity of the building and the efficient coupling of air flow and thermal mass. Based on the flow regime, three main operational concepts can be mentioned, as follows.

- Ventilation by natural means, i.e., through the building's openings. In this case the air flow is variable and random and depends on the temperature and wind driven pressure differences between the indoor and outdoor environment. Thus, the efficiency of this technique is affected by the interdependence of the environmental parameters.
- Ventilation by mechanical means, i.e., by using supply and exhaust fans. The supply fans maintain a constant flow of the ambient air circulated to the building. Additionally, exhaust fans should be used in order to avoid the over-pressurization of the building, that causes a decrease in the efficiency of the fans. Thermostatic controllers can be installed to drive the fans and to shut them down when the outdoor temperature is higher than the indoor one.
- Ventilation using both mechanical and natural means, i.e., by using fans and the openings of the building. In this case only supply or exhaust fans can be used while openings assist the outflow or the inflow of the air, respectively. In order to increase the efficiency of the technique, thermostatic controllers can be installed to turn on and off the fans as a function of the indoor and ambient temperature.

Recent research on the efficiency of night ventilation techniques is more concentrated on specific experiments as well as on the development of evaluation methodologies.

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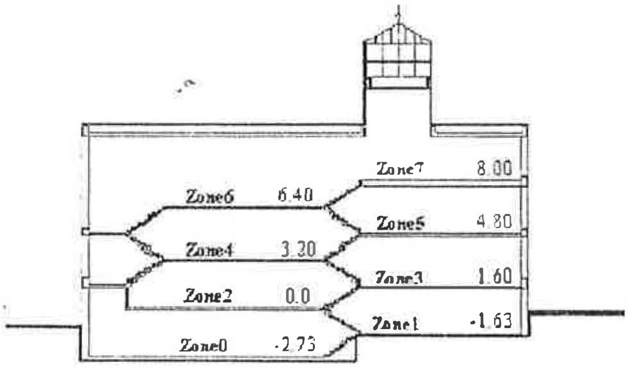

Fig. 1. Section of the 'Meletitiki' building showing the different zones and levels.

Extended experiments using night ventilation [3], have resulted in the development of an empirical formula to predict the indoor maximum temperature as well as the cold storage and the diurnal cooling capacity of the building. Other experiments carried out in an existing building [4], have permitted to develop indices to characterize the energy gain due to night ventilation as well as the possible comfort improvements.

A detailed methodology to calculate the performance of air conditioned as well as of free-floating night ventilated buildings is presented in Refs. [2,5]. The method is based on the principle of Modified Cooling Degree Days and is extensively evaluated against theoretical and experimental data. Another model to calculate the cooling potential of the night ventilation by stack effect is presented in Refs. [6,7]. Furthermore, a tool calculating the impact of night ventilation in office buildings has been developed and presented in Ref. [8].

The aim of the present paper is to investigate, in a systematic way, and by using both experimental and theoretical means, the potential of night ventilation techniques when applied to full scale buildings, under different structure, design, ventilation, and climatic characteristics. Also, to investigate the impact and the limitations of night ventilation techniques regarding the thermal behavior of various types of buildings. Real scale measurements in three buildings operating under free-floating and air conditioning conditions have been performed. The cooling potential of night ventilation techniques applied to buildings operating under different conditions and with variable air flow rates, has been experimentally and theoretically studied. Additionally, sensitivity analysis on the impact of the major parameters determining the phenomena has also been carried out.

2. Description of the experimental procedure

In order to investigate the cooling potential of night ventilation techniques, extended measurements have been carried out, during the summer of 1995 and 1996, in three real scale buildings, presenting different characteristics. In particular, the following buildings have been monitored.

- A multizone air conditioned office building located in the suburban area of Athens, named Meletitiki hereafter. Measurements have been performed during the summers of 1995 and 1996. The building is mainly composed by seven zones (Fig. 1), and has no internal partitions as it is designed as a unique volume. It has a heavy structure and it is heavily ventilated during the night by mechanical and natural means. The design air flow rate during night is approximately 30 air changes per hour (ACH). It is also thermostatically controlled and air conditioned using nine air to air heat pumps. During the experiments, night ventilation was achieved using two exhaust fans located on the roof of zones 6 and 7 over the two staircases. During the night period windows of zones 2, 3, 5 and 7 remained opened. The capacity of each fan is close to 25,000 m^3/h.

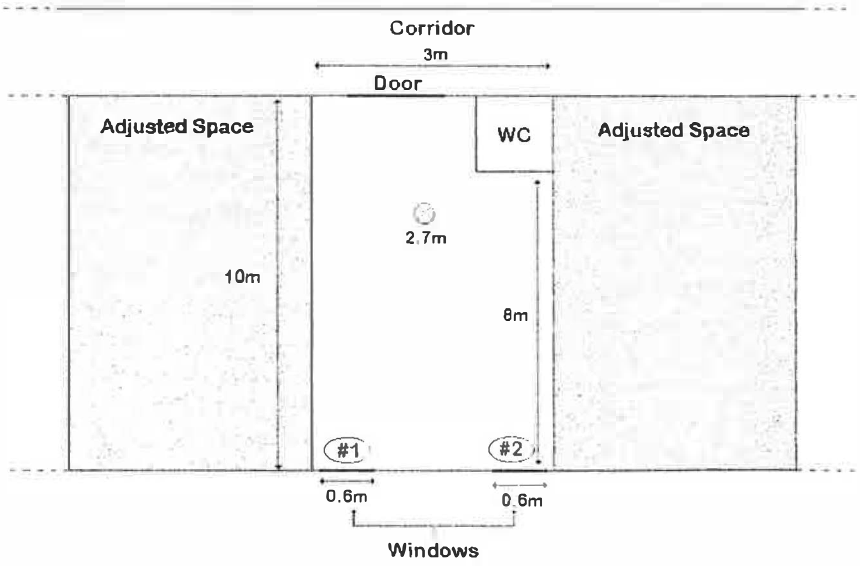

Fig. 2. Plan of the zone where experiments have been carried out in the 'University' building.

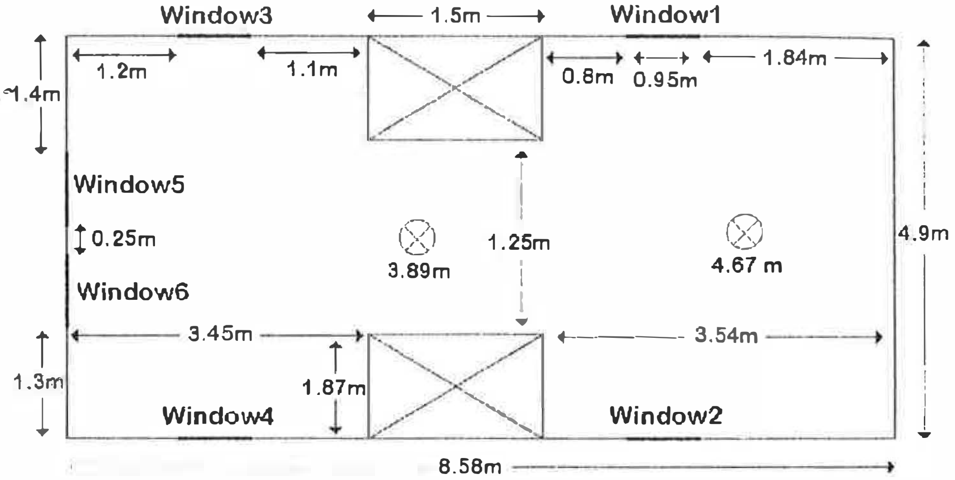

Fig. 3. Plan of the zone where experiments have been carried out in the NOA building.

- An air conditioned office building located in the central area of Athens, named University hereafter. Measurements were performed during the summer of 1996. The experiments have been performed in a specific zone (Fig. 2), located on the third floor of a six-storey building. The building has a light structure while the internal gains are very high. During the experiments night ventilation was achieved by natural means and in particular through two open windows located in one facade of the zone (single sided ventilation).
- A free-floating office building, located in a low density built area in central Athens, named 'National Observatory of Athens' or NOA hereafter. Experiments have been carried out during the summer of 1996. The experiments have been performed in one zone, of this single storey building (Fig. 3). The building has a very heavy structure and medium internal gains. During the experiments night ventilation was achieved by natural means, and through the openings of the zone (Fig. 3).

In all buildings, continuous measurements of the indoor temperature distribution as well as of the air flow rates, when night ventilation is applied, have been performed. Constant injection tracer gas techniques have been used. In both air conditioned buildings, the following two operational schedules have been studied:

- Free-floating conditions during day and night, with and without night ventilation.
- Thermostatically controlled conditions during the day period (operation of the air conditioning system), with and without night ventilation.

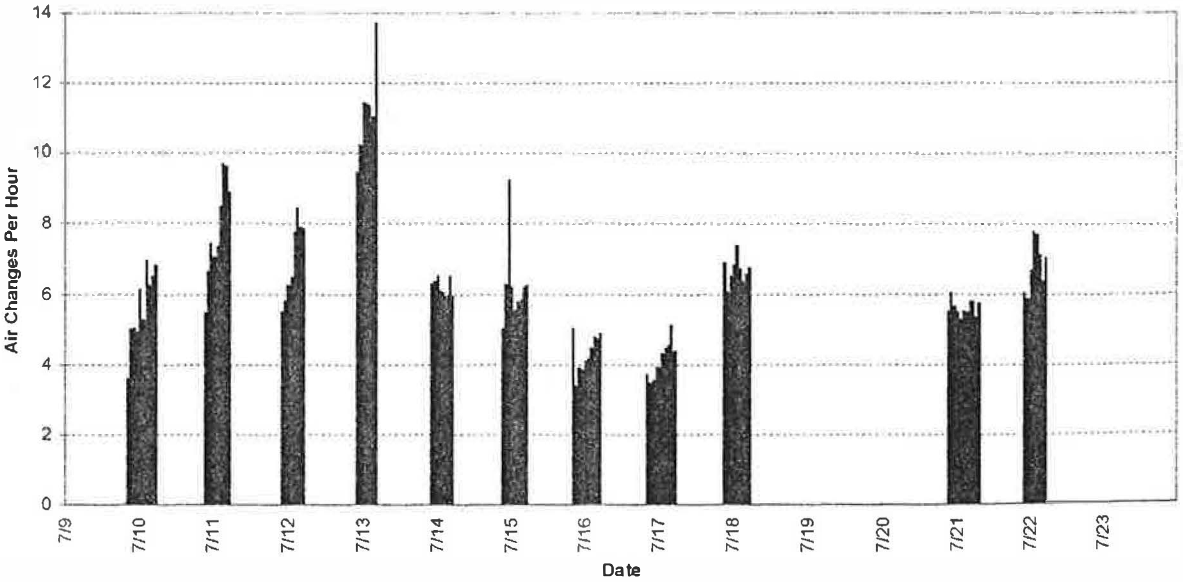

Fig. 4. Measured air changes per hour (ACH) when night ventilation is applied in the 'University' building.

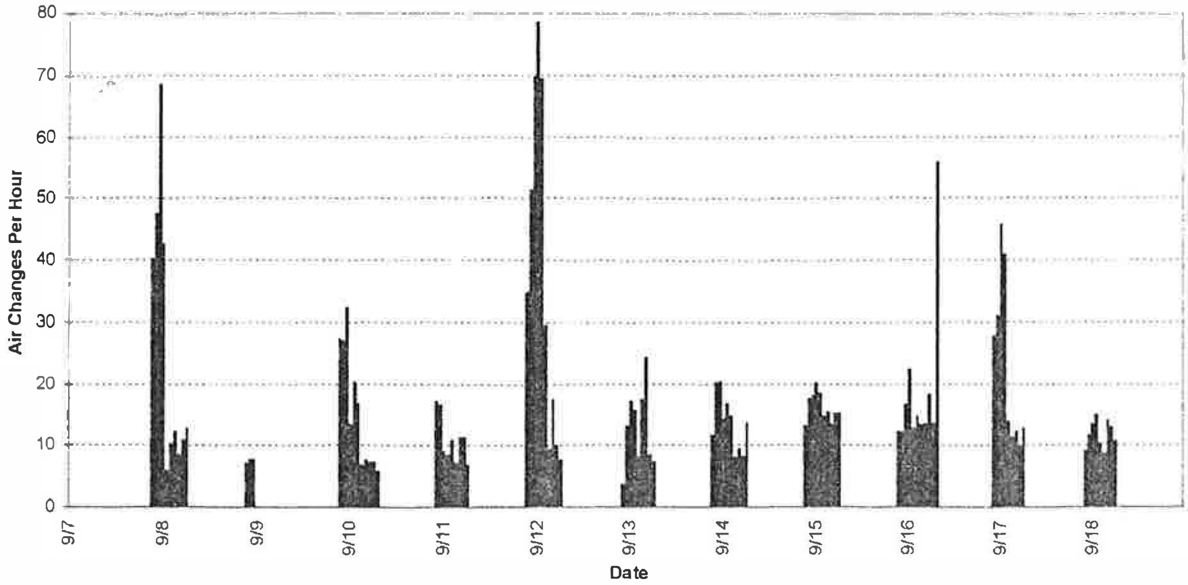

Fig. 5. Measured air changes per hour when night ventilation is applied in the 'NOA' building.

In the Meletitiki building and during the 1995 summer experimental period, measurements have been carried out between July 26 and August 11, when the building was empty from the occupants, while during the summer of 1996 experiments have been performed between May 24 and July 8, during the normal operation of the building. Indoor air temperature was measured in the main zones of the building and in particular in zones 2, 4, 6 and 7 and in eight different points. Night ventilation was applied between 2200 and 0600 h.

In the University building, experiments were performed between July 9 and July 23. The achieved air flow rate, as measured using constant injection tracer gas, is given in Fig. 4. As shown, night ventilation was applied during 11 nights of the above period.

Experiments in the NOA building were carried out between September 7 and September 18. Fig. 5 gives the measured air flow rate during the experiment. As shown, night ventilation was applied during the 11 nights of the above period.

3. Thermal performance of night ventilation techniques in the 'Meletitiki' building—free-floating conditions

In order to study the performance of night ventilation techniques when applied to the Meletitiki building and

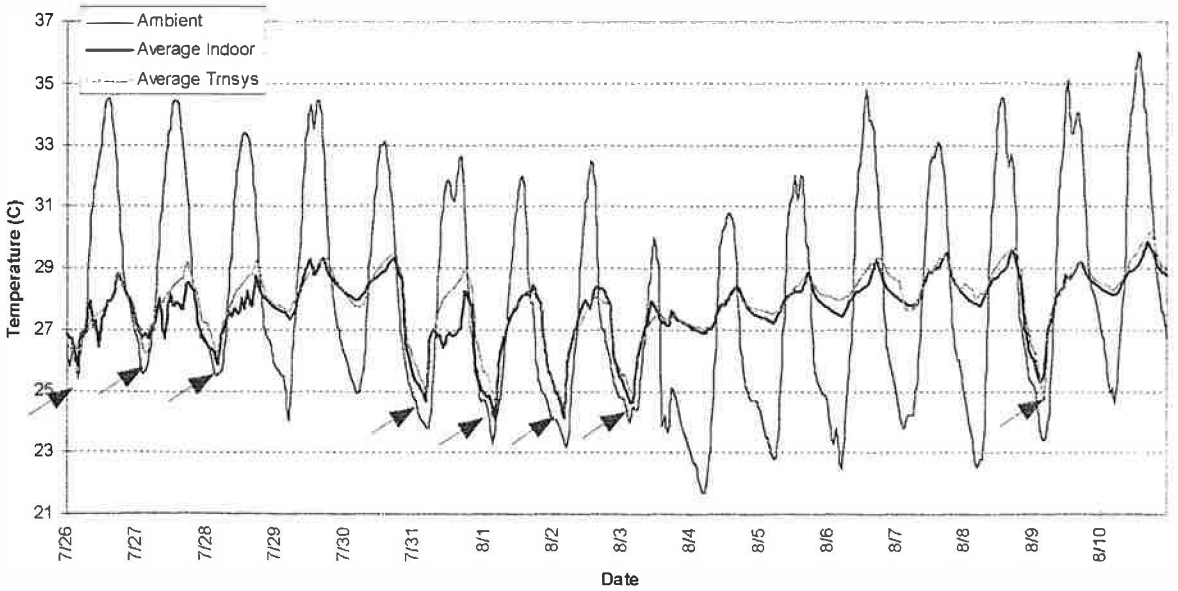

Fig. 6. Mean measured and simulated indoor temperatures for the entire building ('Meletitiki'—Summer 1995).

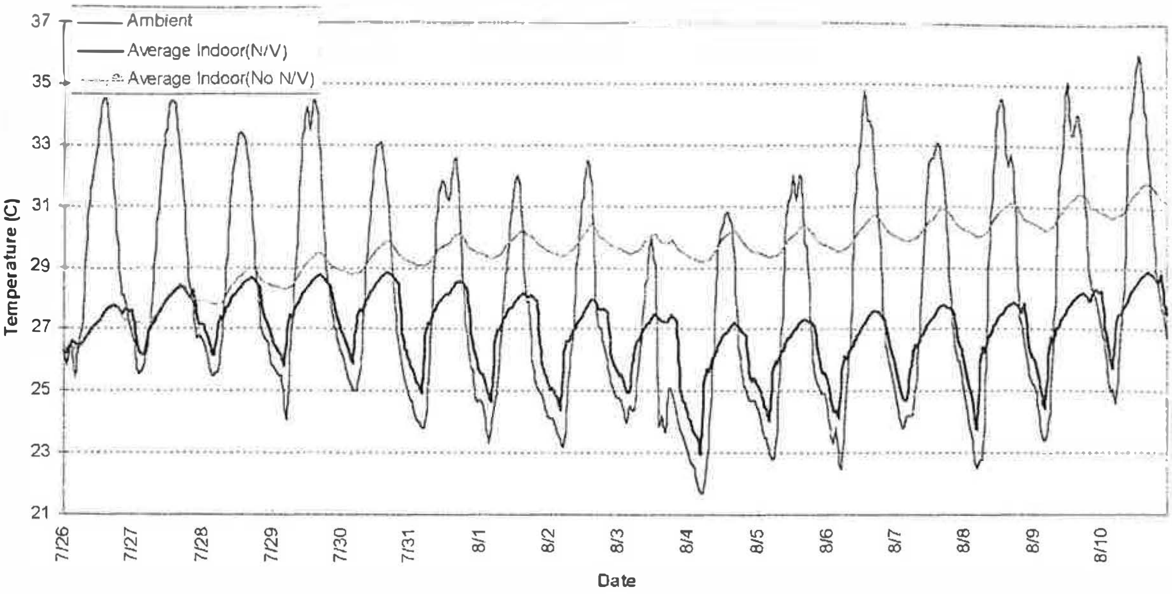

Fig. 7. Mean indoor temperatures with and without night ventilation ('Meletitiki'—Summer 1995).

analyze in detail the obtained experimental data, a series of simulations have been performed using the TRNSYS [9] simulation tool. To simulate the specific air flow processes when night ventilation is applied, an additional air flow routine based on the network approach has been coupled to TRNSYS. The model can simulate the air flow through internal and external openings under natural and forced conditions. The basics of the model as well as its validation are described in Ref. [10]. For further validation of the air flow model, comparisons of the tracer gas measurements and the theoretical predictions for the Meletitiki building were carried out [11] and a satisfactory agreement has been found.

During the first stage of the analysis the developed model has been calibrated against the collected experimental data. Simulation results concerning the first experimental period (summer of 1995), when the building operated under free-floating conditions and with low internal gains, were compared with the corresponding measurements. The results of the comparison are given in Fig. 6. Arrows in the figure, indicate the periods when night ventilation was applied. As shown, the agreement between simulated and measured values is satisfactory. The mean difference between measured and simulated temperatures is found close to 0.3°C, while the corresponding r^2 value between the two sets of data was higher than 0.90. Thus, the developed

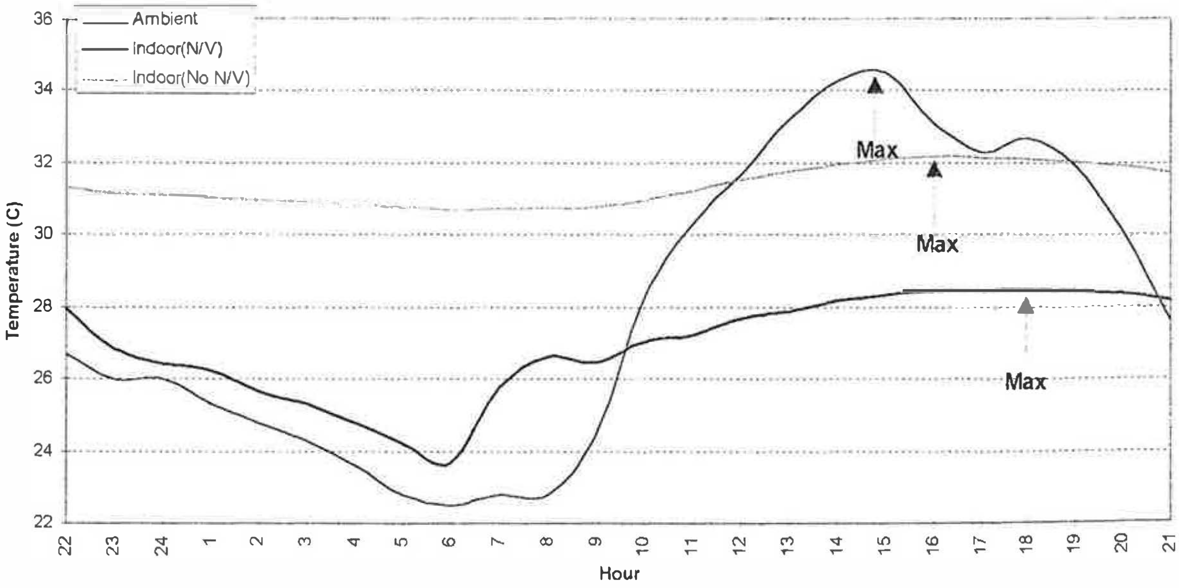

Fig. 8. Time delay of the maximum indoor temperature due to night ventilation. (August 8—zone 7; 'Meletitiki'—Summer 1995).

Table 1
Mean reduction of the indoor air temperature when 10, 20 and 30 ACH are considered during night ('Meletitiki'—Summer 1995)

Air flow supply (ACH)	Zone 2	Zone 4	Zone 6	Zone 7	Average
10	1.59	2.41	2.61	2.42	2.26
20	1.87	2.77	3.02	2.85	2.62
30	1.99	2.90	3.18	3.02	2.77

theoretical model of the building is considered to describe the specific thermal behavior of the building with satisfactory accuracy.

In a second step and in order to evaluate the specific contribution of night ventilation to decrease the indoor temperature of the building under free-floating conditions, the theoretical model has been used to simulate the thermal behavior of the building both under night ventilation and standard conditions. In both cases simulations were carried out for the whole experimental period. During the simulations the fan system was considered as thermostatically controlled and outdoor air was circulated into the building when its temperature was lower than the indoor one. Comparison of the obtained results is given in Fig. 7, where the calculated mean indoor air temperatures for both scenarios are given. As shown, under free-floating conditions, use of high rate night ventilation contributes to a decrease of the peak indoor temperature of the building, during the next day, up to 3°C. Additionally, the hourly decrease of the indoor building's temperature due to night ventilation, for the whole period, the average reduction of the temperature in the various zones varies between 1.8 and 3°C, while the mean reduction for the entire building is close to 2.6°C, presenting a maximum reduction close to 6.2°C.

When applied to massive buildings, night ventilation causes a delay in the peak indoor temperature during the day period. Time delay is a function of the building's thermal mass, the ambient temperature amplitude as well as the applied air flow rate during the night period. To illustrate time delay effects, Fig. 8 presents the temperature distribution in a zone of the building with and without night ventilation as well as the distribution of the ambient temperature for a specific day (August 8). As shown, night ventilation decreases the indoor temperature, in the beginning of daytime period, to about 2°C compared to the case where no night ventilation techniques are applied. The initial decrease of the indoor temperature combined with the thermal capacitance of the building causes a delay of the peak indoor temperature to about 3 h later than the peak ambient temperature, while the corresponding peak when no night ventilation is applied, is close to 1 h.

To study the impact of various air flow rates during the night period on the building's thermal behavior, simulations considering 10, 20 and 30 ACH have been carried out. The maximum reduction of the indoor air temperature achieved due to night ventilation is close to 7.3°C, while its average decrease varies between 2.3 and 2.8°C when the air supply during night varies from 10 to 30 ACH, (Table 1). Generally speaking, an increase of the air changes per hour from 10 to 30 results in an average decrease of the peak indoor temperature of the building from 1.8 to 2.2°C, respectively.

An index to characterize the contribution of night ventilation techniques to the indoor thermal comfort conditions, the number of overheating hours during the whole summer period, may be used. Three base temperatures, 25, 27 and 29°C, to calculate the overheating hours have been considered. For each base temperature three air changes during the night period have been considered, 10, 20 and 30 ACH. The obtained results are given in Table 2 and are compared with the corresponding data when no ventilation is considered. As shown, for the base temperature of 25°C, the achieved reduction of the overheating hours due to night ventilation varies between 39% and 51% for air flow rates between 10 and 30 ACH, respectively. For 27°C, the corresponding decrease varies between 69% and 79%, while for 29°C, the reduction is between 92% and 96%.

4. Thermal performance of night ventilation techniques in the 'Meletitiki'—air conditioned building

During the second experimental period (summer of 1996), the building was air conditioned and operated under

Table 2
Average number and reduction of overheating hours when the base temperature varies between 25 and 29°C and the air flow rate during night varies from 10 to 30 ACH ('Meletitiki'—Summer 1995)

Air flow supply (ACH)	Base temperature 25°C		Base temperature 27°C		Base temperature 29°C	
	ANOH[a]	ROH[b]	ANOH[a]	ROH[b]	ANOH[a]	ROH[b]
0	1253	–	1044	–	713	–
10	761	39.3%	324	69.0%	60	91.6%
20	657	47.5%	249	76.2%	36	95.0%
30	615	51.0%	221	78.8%	31	95.7%

[a] ANOH: Average number of overheating hours.
[b] ROH: Reduction of overheating hours.

thermostatic control. Also, compared to the previous experimental period, the building was occupied and internal loads were important. To understand the performance of night ventilation techniques when applied to air conditioned buildings, a series of theoretical investigations have been performed.

In a first step, the model developed in TRNSYS was calibrated against the collected experimental data for conditions of thermostatic control. The obtained simulation results were compared with the corresponding measurements of the indoor temperature. Fig. 9 illustrates the simulated and the measured temperatures for the entire building. The arrows indicate the nights when night ventilation was applied by mechanical means. For all the other days, night ventilation was achieved through natural means. As shown, the achieved agreement between simulated and measured indoor temperatures is satisfactory. The mean difference between measured and simulated temperatures was close to 0.3°C and the corresponding r^2 value between the two sets of data was close to 0.94.

To evaluate the cooling potential of night ventilation techniques applied to A/C buildings, a series of comparative simulations has been performed. Real climatic data collected during the experiments have been used. In the first series the building was considered as a conventional one while in the second series the building is treated as a night ventilated one. Night ventilation techniques were considered for every night of the studied period and between 2300 and 0700 h of the next day. The fan used to circulate the air during the night was also thermostatically controlled. The cooling capacity of the air conditioning system was supposed to be high enough to meet the building's cooling requirements. The A/C system was scheduled to operate from 0800 to 1700 h. Three different set point temperatures were considered: 25, 27 and 29°C, to investigate the impact of night ventilation with various indoor temperature profiles. The obtained distribution of the mean indoor temperature, when night ventilation is considered, shows that the average difference in the early morning hours when 25 and 27°C are used as set point temperatures, is close to 0.7°C, while the corresponding average difference for set point temperatures 27 and 29°C is close to 0.3°C. The comparison of the indoor temperature distribution with and without night ventilation, is given in Fig. 10, for 2 representative days, (June 15–16). As shown, the smaller the set point temperature, the smaller the initial indoor temperature when night ventilation starts and consequently the smaller the indoor air temperature during night ventilation.

Furthermore, the lower the set point temperature, the lower the increasing rate of the indoor temperature after the end of night ventilation. The high thermal mass of 'Meletitiki' reduces the increasing rate of the indoor temperature.

The average indoor temperature reduction, during night ventilation, has been calculated in order to evaluate the influence of night ventilation on the indoor temperature profiles. For set point temperatures 25, 27 and 29°C, the average indoor temperature reduction are 1, 1.8 and 2.8°C, respectively.

Energy gains due to night ventilation are mainly a function of the potential reduction of the indoor air temperature, compared to the case of a non night ventilated building, during the early morning hours and before the

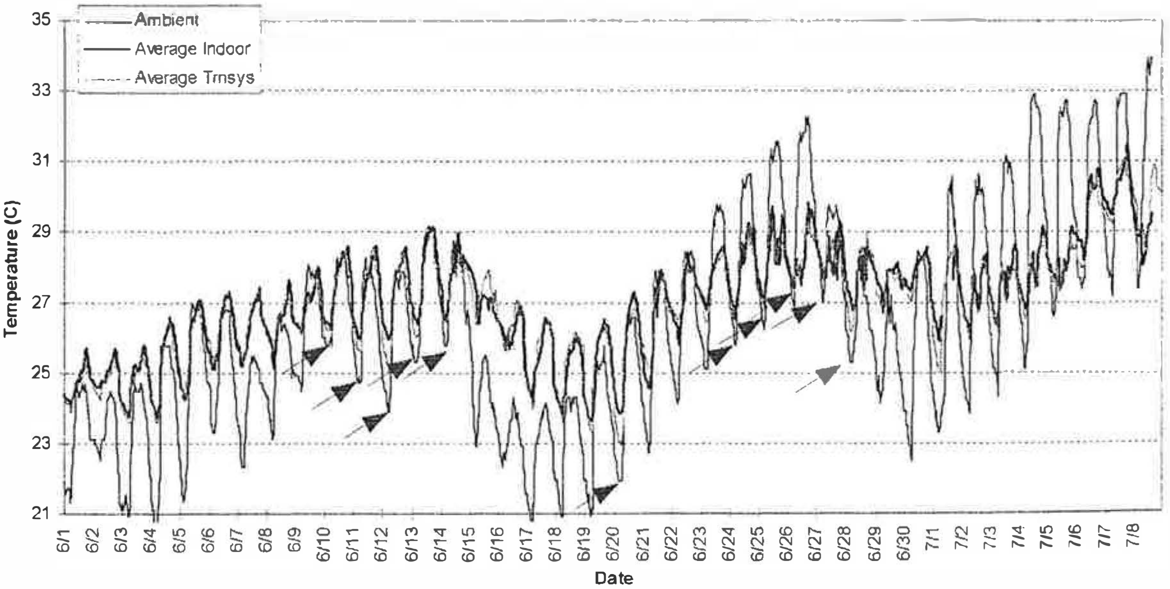

Fig. 9. Mean measured and simulated indoor temperatures ('Meletitiki'—Summer 1996).

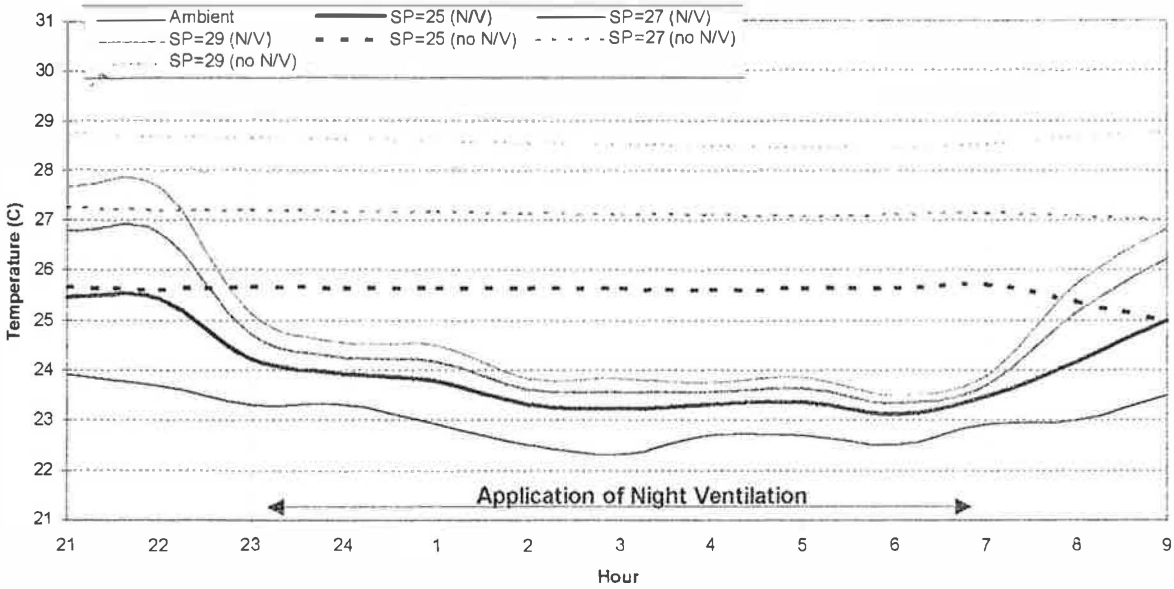

Fig. 10. Mean indoor temperatures with and without night ventilation for three set point temperatures: 25, 27 and 29°C, on June 15–16 ('Meletitiki'—Summer 1996).

A/C system is switched on. While the temperature reduction is high, the peak cooling demand is delayed and decreased, and thus the total cooling load of the building is lower. The overall analysis has shown that the set point temperature affects seriously the temperature reduction in the early morning hours. In particular for set point temperatures equal to 25, 27 and 29°C the average early morning indoor temperature reduction is close to 0.8, 1.5 and 2.5°C, respectively.

To investigate the impact of various air flow rates of night ventilation on the building's thermal performance, simulations considering 10, 20 and 30 ACH have been carried out for three set point temperatures and in particular 25, 27 and 29°C. A summary of the obtained results is given in Table 3. As shown, the mean reduction of the indoor air temperature during the night period, varies between 0.85 and 2.43°C, for 10 ACH, and set point temperatures between 25 and 29°C, respectively. Moreover, for 20 ACH the corresponding reduction varies between 1.01 and 2.8°C. Finally, for 30 ACH the mean reduction of the indoor temperature during the night varies between 1.08 and 2.93°C. Also, the early morning indoor temperature reduction varies between 0.71 and 2.50°C for air flow rates during night between 10 to 30 ACH and set point temperatures between 25 and 29°C. Fig. 11 illustrates the mean indoor temperature of the building, during the night between June 15 and 16, for 10, 20 and 30 ACH and a set point temperature equal to 27°C.

To determine the potential for energy conservation due to night ventilation, a series of simulations have been performed to calculate the corresponding cooling load of the building. Calculations have been performed for three set point temperatures and in particular for 25, 27 and 29°C, and for 10, 20 and 30 ACH during the night period. Table 4 gives the calculated cooling load and the corresponding energy conservation during the whole cooling season (May–September), for the various set point temperatures and air flow rates. As shown, when the set point temperature is 25°C, the energy conservation due to night ventilation varies from 48% to 56% for 10 to 30 ACH, respectively. Also, for a set point of 27°C, the reduction of the cooling load varies between from 72% to 80% for 10 to 30 ACH, respectively. Finally, for a set point temperature equal to 29°C, the energy conservation varies between 90% and 94% according to the selected air flow rate. Thus, as expected it is found that, the higher the air flow rate, the

Table 3
Mean reduction of the nighttime indoor air temperature when 10, 20 and 30 ACH are considered during the night period ('Meletitiki'—Summer 1996)

Air flow supply (ACH)	Set point temperature 25°C		Set point Temperature 27°C		Set point temperature 29°C	
	AITR1[a]	AITR2[b]	AITR1[a]	AITR2[b]	AITR1[a]	AITR2[b]
10	0.85	0.71	1.57	1.31	2.43	2.13
20	1.01	0.82	1.84	1.51	2.80	2.41
30	1.08	0.87	1.96	1.61	2.93	2.50

[a] AITR1: Average indoor temperature reduction during the night period.

[b] AITR2: Average indoor temperature reduction at the early morning hours and prior to the operation of the air conditioning system.

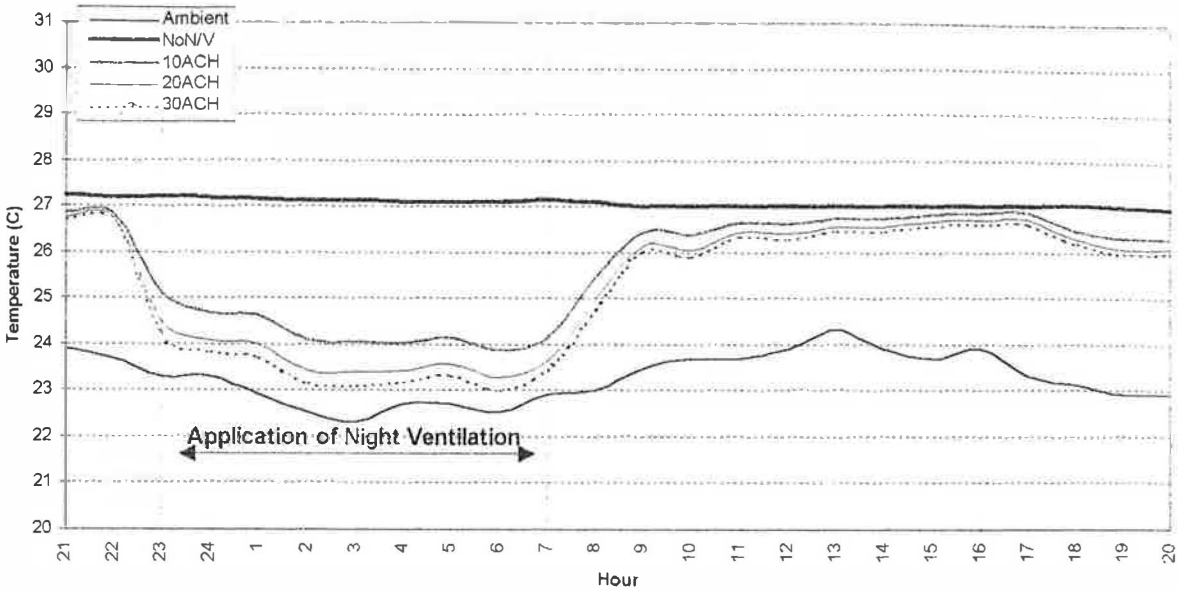

Fig. 11. Mean indoor temperatures for various ACH during the night period, for a set point temperature of 27°C. (June 15–16; 'Meletitiki'—Summer 1996).

higher the energy conservation, however, the relative gains for higher air flows are not considerable. Also, the higher the set point temperature, the higher the energy conservation, as the difference between the operational temperature of the building and the night ambient temperature is higher and thus the cooling potential increases.

Comparison of the night ventilation efficiency during the two experimental periods shows that this technique was much more efficient during the 1995 period. This is due to various reasons. First, during the second experimental period convective and radiative internal gains were important and thus the thermal balance of the walls was more positive, decreasing thus the cooling potential of convection phenomena during the night period. Second, during 1996, the building operated under air conditioned conditions and at lower temperatures than during the first experimental period where the building operated under free-floating conditions. As previously shown, higher indoor operational temperatures improve the performance and the contribution of night ventilation techniques. Finally, during the second year the amplitude of the ambient temperature was much lower. The daily amplitude of the ambient temperature defines, to a high degree, the cooling potential of night ventilation. As shown in Fig. 12 the average amplitude of the ambient temperature during 1995 was close to 9.53°C, while during 1996 it was close to 4.62°C.

5. Thermal performance of night ventilation techniques in the 'University' building

In order to evaluate the efficiency of night ventilation techniques when applied in low to medium thermal mass buildings like the 'University', a series of simulations have been carried out using TRNSYS. The zone where experiments were carried out was simulated using as inputs the measured air flow rate (Fig. 4). At a first step, the model has been calibrated against the collected experimental data. Fig. 13 gives the simulated as well as the measured temperature distribution of the selected zone. The mean difference between the two sets of data was close to 0.3°C, while the corresponding r^2 value was close to 0.88. Thus,

Table 4
Cooling load and corresponding energy conservation during the summer period for various air flow rates during night and set point temperatures of 25, 27 and 29°C, ('Meletitiki'—Summer 1996)

Air flow supply (ACH)	Set point temperature 25°C		Set point temperature 27°C		Set point temperature 29°C	
	CL[a] (kW h/m^2)	RCL[b]	CL[a] (kW h/m^2)	RCL[b]	CL[a] (kW h/m^2)	RCL[b]
0	21.32	–	14.09	–	8.27	–
10	10.99	48.5%	3.99	71.7%	0.85	89.8%
20	9.80	54.0%	3.22	77.1%	0.60	92.8%
30	9.35	56.2%	2.94	79.1%	0.52	93.7%

[a] CL: Cooling load.
[b] RCL: Cooling load reduction.

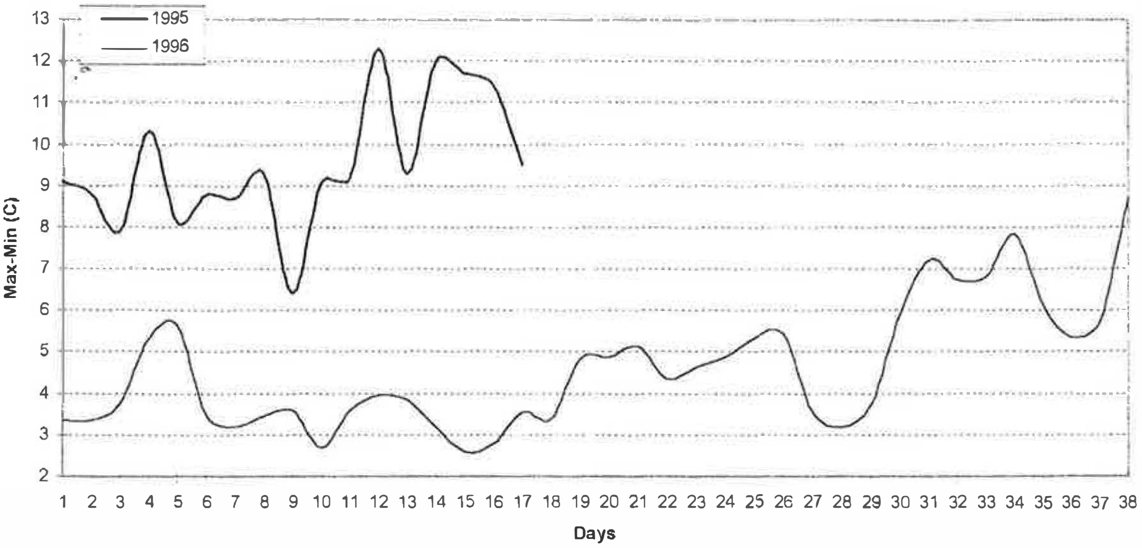

Fig. 12. Ambient temperature amplitude during the experimental periods of 1995 and 1996 ('Meletitiki').

it can be accepted that the achieved agreement between simulated and measured values is acceptable.

The building is studied under both free-floating and air conditioning operational conditions. Extended simulations considering various set point and comfort temperatures as well as air flow rates during the night period were performed. In the following, the obtained results for the free-floating as well as the air conditioning operation are discussed.

The evaluate the impact of night ventilation techniques, when applied in free-floating buildings of low to medium thermal capacity, a series of comparative simulations were performed with and without considering ventilation during the night period. The flow patterns and rates measured during the experimental period have been applied as inputs to the simulation. The obtained results are given in Fig. 14. As shown, the impact of night ventilation is not important and the calculated decrease of the next day peak indoor temperature is close to 0.2°C, while the average temperature decrease during the whole day and night was close to 0.4 and the maximum one close to 2.4°C.

The impact of the night air flow rate on the performance of the building has also been investigated. Simulations were carried out for 5, 10, 20 and 30 ACH. The

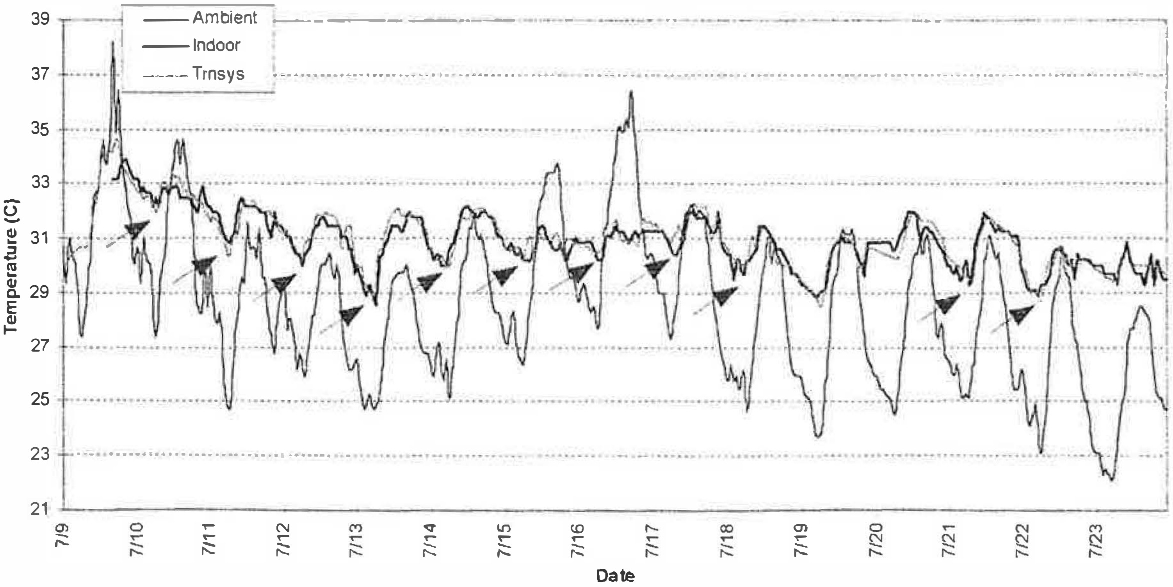

Fig. 13. Measured and simulated indoor temperatures ('University'—Summer 1996).

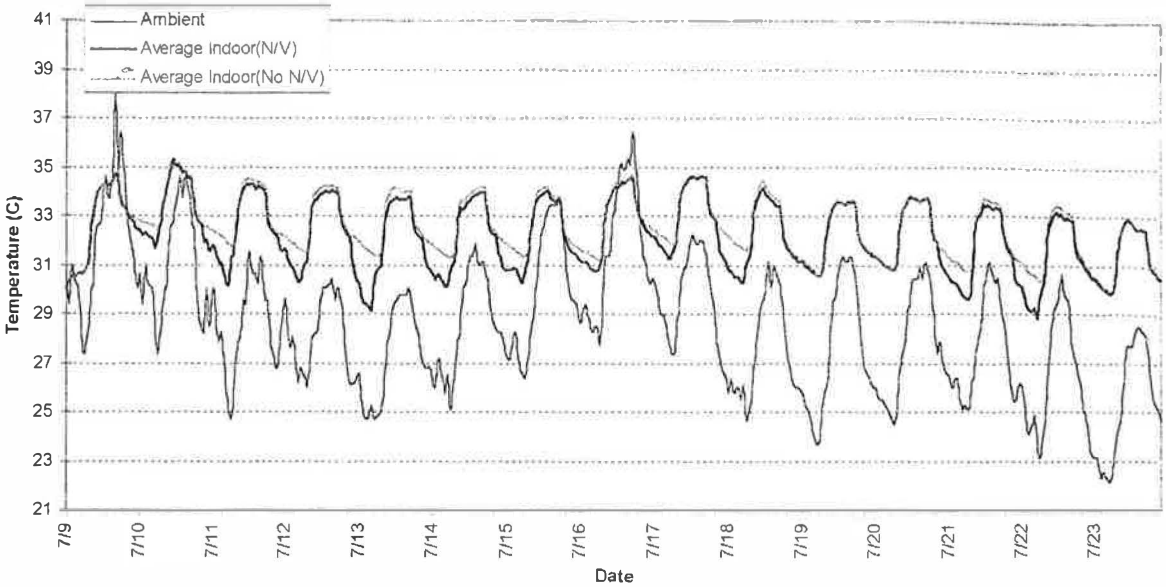

Fig. 14. Mean indoor temperature with and without night ventilation ('University'—Summer 1996).

obtained results show that the maximum reduction of the indoor air temperature due to night ventilation varies between 1.5 and 5°C, while its average decrease varies between 0.4 and 1.6°C, and the reduction of the next day peak indoor temperature is between 0.19 and 0.6°C, for air flows between 5 and 30 ACH, respectively. No delay in the maximum daily peak temperature has been observed for 5 ACH, while for 10, 20 and 30 ACH the peak indoor temperature is delayed to about 2 h (Fig. 15). At the same time, the use of night ventilation was found to decrease the early morning indoor temperature between 1 and 2.5°C as a function of the flow rate.

The possible energy conservation due to the application of night ventilation was also evaluated considering that the building is thermostatically controlled. Three set point temperatures, 25, 27 and 29°C as well as four air flow rates, 5, 10, 20 and 30, have been considered. The obtained results are given in Table 5. As shown, for 25°C, the calculated energy conservation varies from 14% to 36% for 5 to 30 ACH, respectively. The corresponding energy

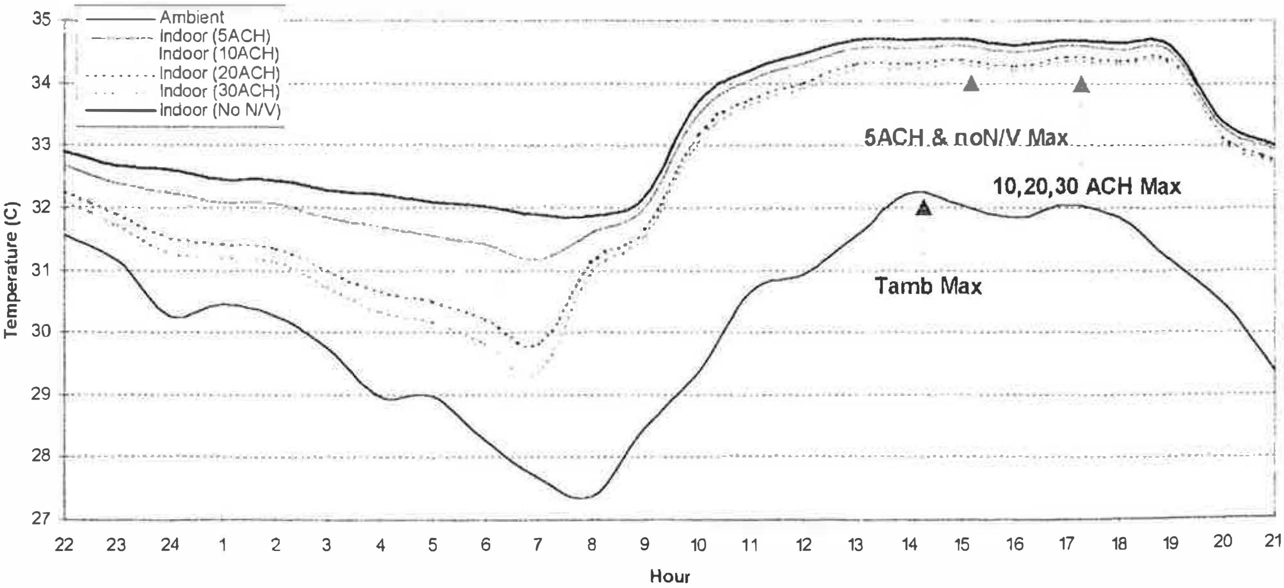

Fig. 15. Time delay of the maximum indoor temperature due to night ventilation. (July 17; 'University'—Summer 1996).

Table 5
Cooling load and corresponding energy conservation for the University building during the whole cooling season for set point temperatures of 25, 27 and 29°C ('University'—Summer 1996)

Air flow supply (ACH)	Set point temperature 25°C		Set point temperature 27°C		Set point temperature 29°C	
	CL[a] (kW h/m^2)	RCL[b]	CL[a] (kW h/m^2)	RCL[b]	RCL[a] (kW h/m^2)	RCL[b]
0	105.62	–	98.64	–	91.66	–
5	91.00	13.8%	77.36	21.6%	63.50	30.7%
10	82.02	22.3%	64.58	34.5%	47.28	48.4%
20	72.31	31.5%	51.68	47.6%	32.77	64.3%
30	67.41	36.2%	45.70	53.7%	26.86	70.7%

[a] CL: Cooling load.
[b] RCL: Cooling load reduction.

conservation for 27°C set point, varies between 22% and 54% while for 29°C, the energy conservation varies between 31% and 71%.

6. Thermal performance and ventilation effectiveness of night ventilation techniques in 'NOA' building

The NOA building is a very heavy, massive and free-floating building where night ventilation was applied by natural cross-ventilation. Experiments were carried out using and not night ventilation. As for the previous buildings, a thermal model using TRNSYS has been developed. The results given by the theoretical model has been compared with the corresponding experimental data and a good agreement has been achieved when ventilation techniques are not used. However, when the measured air flow rate was used as an input to calculate the thermal performance of the building when night ventilation is applied, the impact of night ventilation on the thermal performance of the building is overestimated, (Fig. 16). In this case the mean difference between measured and simulated temperatures is close to 0.7°C, while the corresponding r^2 value during the whole experimental period is close to 0.83.

This is mainly attributed to the non efficient coupling of the air flowing through the building with the thermal mass of the building. In fact, during the experimental procedure problems related to short circuit air flow through the windows were observed. This type of phenomena are very common in cross-ventilation configurations. Thus, only a part of the flow has really contributed to decrease the temperature of the buildings thermal mass.

To evaluate the impact of the above phenomenon, simulations were carried out in order to estimate the 'effective' air flow rate, i.e., the rate that when used as input gives the measured temperature profile. The simulation results are given in Fig. 16. The curve named Trnsys (Measured ACH), represents the calculated indoor air temperature when the measured values of the air flow rates have been considered, while the curve named Trnsys (Fixed ACH), gives the temperature distribution calculated by trying to calibrate the air flow rate to the measured temper-

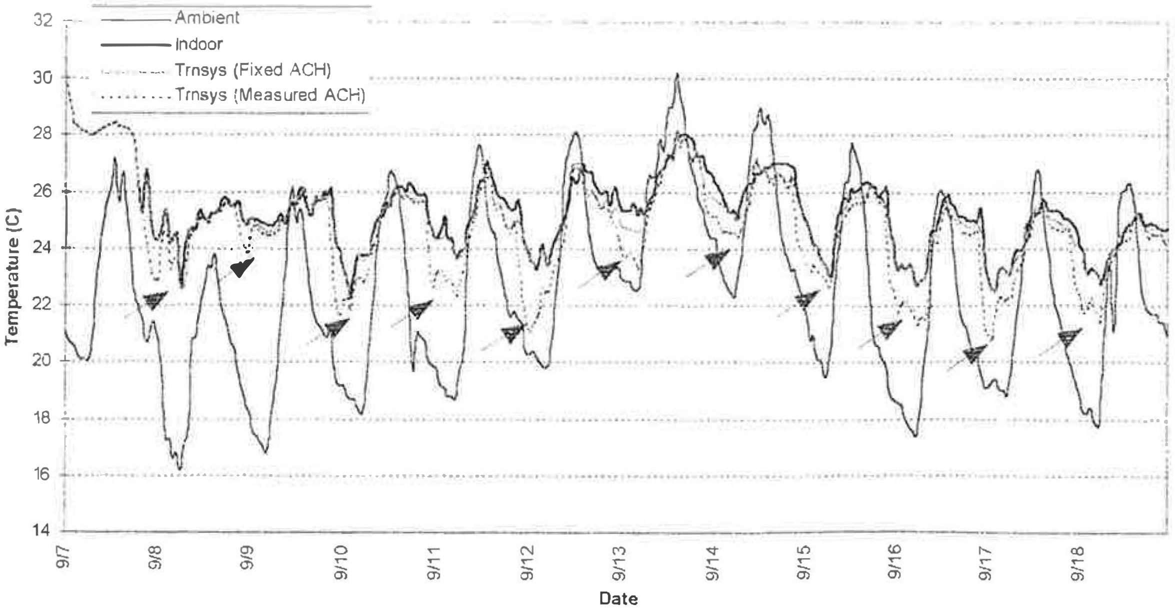

Fig. 16. Measured and simulated indoor temperatures ('NOA'—Summer 1996).

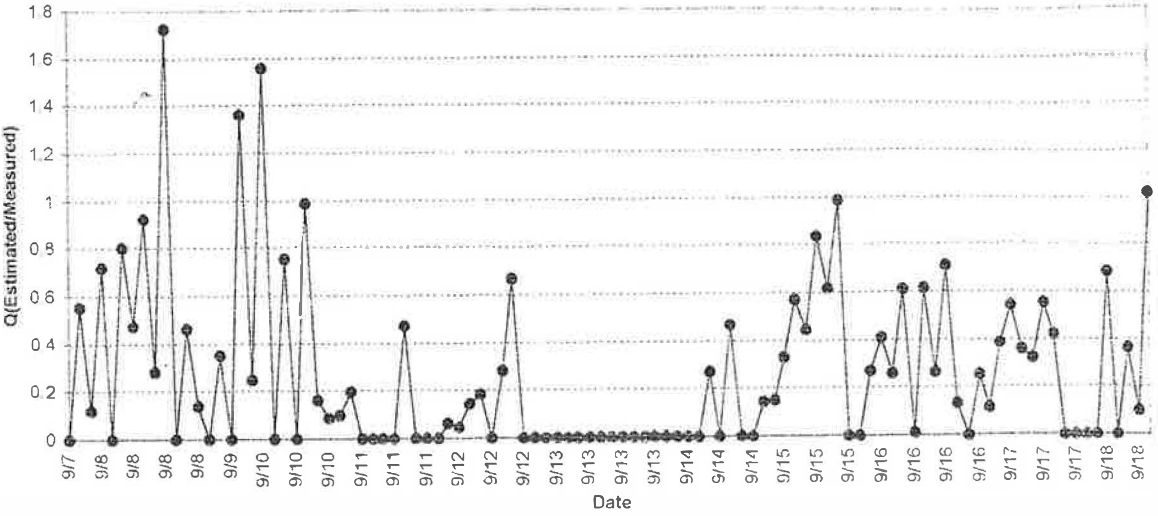

Fig. 17. Ventilation efficiency ('NOA'—Summer 1996).

ature data. As shown, almost a perfect agreement with the experimental data has been achieved.

The two data sets of the experimental and active air flow rates have been compared in order to evaluate the ventilation efficiency during the experiment. An index, Q (ventilation efficiency) has been calculated and the results are given in Fig. 17. The parameter, Q is defined as the ratio of the estimated to the measured air changes per hour. As shown, Q varies between 0 and 1.72. The 96% of the ventilation efficiency values are less than one, while its average value is close to 0.3. Therefore the 'active' air exchange rates that really contribute to decrease the temperature of the building's mass are much lower than the measured ones for almost the entire experimental period.

7. Conclusions

The efficiency of night ventilation is strongly related to three main parameters. The relative difference between indoor and outdoor temperature mainly during the night period, the useful air flow rate applied during the night period and the thermal capacity of the building.

As shown from the whole experimental procedure, the lower the outdoor temperature during night and the higher the fresh air supply, the higher is the efficiency of night ventilation. Additionally, the existence of important thermal–structural mass increases the efficiency of the technique since the inertia of the building is increased and the effect of the night ventilation can clearly be observed in the next day's indoor temperature profiles (lower and delayed peak indoor temperature). Additionally, the interior planning of the building plays a very important role, determining the flow and the 'paths' of the air flowing through the building. Finally, another important climatic parameter is the daily amplitude of the ambient temperature. When the amplitude is high, night ventilation techniques can be very effective (especially if the minimum ambient temperature is low).

In the present paper, night ventilation techniques have been applied in three real scale buildings, of different structure, ventilation, layout and regional characteristics. 'Meletitiki' building has important thermal mass and the first set of experiments (during 1995) has been performed during a period of very low internal gains, and without any operation of the air conditioning system. On the contrary, the 'University' building has a light structure and was monitored when internal gains were important and the air conditioning system was in use. The two case studies are extreme conditions and in a way they indicate the limits of the cooling potential of night ventilation techniques. Moreover, the second set of experiments in 'Meletitiki' (during 1996) was carried out under A/C operation and when the building was normally occupied. The observed differences between the first and the second set of experiments, permit to extract useful information on the cooling potential of night ventilation techniques. It was found that the use of night ventilation techniques, permits to decrease the next day peak indoor temperature, under free-floating conditions, by up to 3°C. Sensitivity analysis has shown that under the same conditions, the expected reduction of the overheating hours, varies between 39% and 96% for air flow rates between 10 and 30 ACH, respectively. Under A/C conditions the indoor air temperature during the early morning hours can be reduced by 0.8 to 2.5°C as a function of the considered set point temperature. Finally, sensitivity analysis has shown that under A/C conditions, the expected energy conservation, varies from 48% to 94% for air flow rates of 10 and 30 ACH, respectively. It was shown that the higher the air flow rate, the higher the calculated energy conservation due to night ventilation.

In the University building, it was found that under free-floating conditions, night ventilation techniques decrease the next day peak indoor temperature to about

0.2°C, while the 24-h average reduction of the indoor air temperature is close to 0.4°C. Increase of the air flow rate up to 30 ACH may decrease the peak indoor temperature up to 0.6 C, and the mean 24-h temperature up to 1.6°C. When the building operates under thermostatical control, the achieved reduction of the cooling load varies between 14% and 71% for air flow rates between 5 and 30 ACH, respectively.

The problem of efficient coupling of the air flow with the thermal mass of the building has been presented in the NOA building. Because of the short circuit air flow, convective exchanges between the fresh air and the building walls were very poor. The ventilation efficiency of the phenomena during the experiment has been calculated and is found to be close to 0.3.

In conclusion, night ventilation techniques can contribute to decrease significantly the cooling load of A/C and improve the comfort levels of free-floating buildings. The exact contribution of night ventilation for a specific building is a function of the building structural and design characteristics, the climatic conditions and the building's site layout, the applied air flow rate, the efficient coupling of air flow with the thermal mass of the building and the assumed operational conditions. Appropriate design of night ventilation systems requires exact consideration of all the above parameters and optimization of the whole procedure by using exact thermal and air flow simulation codes.

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