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A SCREENING METHODOLOGY FOR CLIMATIC EVALUATION OF THE COOLING POTENTIAL OF NIGHT VENTILATION IN BUILDINGS

Akhilesh Reddy Endurthy
Energy Engineer, Lincus Inc
Monrovia, CA, USA

T Agami Reddy
The Design School and School of
Sustainable Engineering in the Built Environment,
Arizona State University
Tempe, AZ, USA

ABSTRACT

Night ventilation is a well known strategy for passive cooling of residences and small commercial buildings. The building's thermal mass can be cooled at night by ventilating the inside of the space with the relatively lower outdoor air temperatures, thereby lowering indoor temperatures during the warmer daytime period. Numerous experimental and theoretical studies have shown the effectiveness of the method to significantly reduce air conditioning loads or improve comfort levels in those climates where the night time ambient air temperature drops below that of the indoor air. One could develop/adapt computer programs with detailed mathematical component models to simulate and evaluate the performance of night ventilation strategies in a specific location for a particular building. A more basic problem is to develop a methodology whereby potential designers can screen various climatic locations and regions in order to perform a preliminary evaluation of which months of the year are good candidates for implementing such a scheme. Only after completion of such a phase is a detailed evaluation warranted for specific buildings. In this paper, effectiveness of night ventilation is quantified by a parameter called the Discomfort Reduction Factor (DRF) which is the index of reduction of occupant discomfort levels during the day time from night ventilation. Two different thermal network models which provide such insights are evaluated. Daily and monthly DRFs are calculated for two climate zones and three building heat capacities for the whole year. It is verified that night ventilation is effective in seasons and regions when day temperatures are between 30 °C and 36 °C and night temperatures are below 20 °C. The accuracy of these preliminary screening models may be lower than using a detailed simulation program but the loss in accuracy in using such tools is more than compensated by the insights provided, along with better transparency in the analysis approach and results obtained.

NOMENCLATURE

A - area of the inner surface of external wall (m^2)
A_i - amplitude of fluctuation of indoor air temperature (^oC)
A_o - amplitude of fluctuation of outdoor air temperature (^oC)
$A_{sol-air}$ - amplitude of fluctuation of sol-air temperature (^oC)
C- heat capacity of material (J/kg ^oC)
C_a - heat capacity of air (J/kg ^oC)
C_m - heat capacity of the internal thermal mass (J/kg ^oC)
E - effective total heat power (W)
K - thermal conductivity of material (W/m K)
M - mass of internal thermal mass (kg)
q - ventilation flow rate (m^3/s)
R_o - heat resistance of external wall (m^2 K/W)
t - time (h)
T_E - air temperature rise due to the inner steady state heat source (^oC)
T_i - indoor air temperature (^oC)
T_o, T_a - outdoor air temperature (^oC)
$T_{sol-air}$ - sol-air temperature (^oC)
$\overline{T}i$ - mean indoor air temperature (^oC)
$\overline{T}o$ - mean outdoor air temperature (^oC)
$\overline{T}_{sol\_air}$ - mean sol-air temperature (^oC)
α_i - total heat transfer coefficient of inner surface (W/m^2 K)
α_o - total heat transfer coefficient of external surface (W/m^2 K)
λ - heat transfer number

ρ_a - density of air (kg/m^3)
τ/ TC - time constant (h)
ξ_i - time lag of indoor air temperature with respect to outdoor air temperature (h)
$\varphi_{sol\text{-}air}$ - phase shift of sol-air temperature with respect to outdoor air temperature (radians)
ω - frequency of outdoor temperature variation (h^{-1})

BACKGROUND

Night ventilation is a passive cooling strategy which could be widely used in several parts of the world. It involves ventilating the inside of a building at night with the relatively cooler outdoor air so as to cool the building thermal mass. This cooling can subsequently be used to offset some of the thermal discomfort which occupants are likely to experience during the daytime in a non-air-conditioned residence. Alternatively, for air-conditioned spaces, some of the electricity needed for mechanical cooling can be reduced. The effect of night ventilation strategy can be observed in the reduced and time-delayed peak indoor air temperature the next day. The efficacy of a night ventilation cooling strategy would depend: (i) on the thermal mass of the structure which is a function of building construction parameters, and (ii) on diurnal ambient air temperature profiles.

Previous researchers have stated that night ventilation is applicable to regions where daytime temperatures are between 30 ^{o}C and 36 ^{o}C and the night temperatures are below 20 ^{o}C (Givoni, 1994). Several design and construction options are available that can provide the thermal mass necessary for nocturnal/ night cool storage. These include mass of the building such as walls, partitions, floors, furniture, etc., embedded air spaces / passages within floors, ceilings and/ or walls through which outdoor air is circulated, specialized storage such as a rock bed or a water tank with embedded air tubes. Thus, the efficacy of a night ventilation strategy will vary not only with the thermal mass of the structure but also from one day to another during the cooling season (time of the year).

OBJECTIVES AND SCOPE

Numerous experimental and theoretical studies have shown the effectiveness of the method to significantly reduce air conditioning loads or improve comfort levels in those climates where the night time ambient air temperature drops below that of the indoor air (Artmann et al., 2010, Geros et al.,1999). Though detailed modeling and experimental studies are available in the literature (Pfafferott et al.,2003), the specific intent of this paper is to propose a methodology to perform a preliminary screening of whether a particular location is suited for night cooling, and if so, at what specific times of the years. Such a first step would justify whether more detailed investigations are warranted or not. This paper proposes and discusses such a screening methodology.

The scope of this research is limited to unconditioned but mechanically ventilated spaces. All the models are evaluated for a sample structure of (50 ft x 50 ft x 10 ft) dimensions assumed to be a single zone. A fully mixed space i.e., air temperature uniform throughout zone, is assumed. Effects of only dry bulb temperature are explicitly considered, while humidity effects are ignored. Analysis of the results of the models is done for two similar hot and dry weather locations, Phoenix, AZ and Albuquerque, NM. The effect of thermal mass capacity has been studied by assuming buildings with two time constants representative of the lower and upper values of typical construction. A Discomfort Reduction Factor (DRF) has been proposed so as to quantify the comfort benefits which night ventilation can provide to the occupants. This parameter helps the engineers or architects or building owners to identify the days/ months of the year where night ventilation will be effective. Each of the models used/ developed in this research have certain specific limitations and they are discussed in their respective sections.

NETWORK MODELS ASSUMED

Heat transfer by convection of night ventilation air at the internal thermal mass, and heat transfer occurring by convection and conduction through the building envelope are ways by which sources of different temperatures exchange heat. Heat transfer energy balance occurring among these surfaces will allow calculation of unknown parameters such as indoor air temperature. Heat transfer analysis of building envelopes can be done by different methods such as harmonic response method, Z transfer function method and response factor method (Yam et al., 2003). In this paper, two slightly different thermal network models are assumed.

(a) Zhou et al. model and modifications

For naturally ventilated buildings, Zhou et al. (2008) proposed a model (an extension of a previous study by Yam et al., 2003) to estimate the impact of external and internal thermal mass. Parameters like the time constant of the system, the dimensionless convective heat transfer number and temperature increase induced by internal heat source are used to analyze the effect of thermal mass. A harmonic response method is proposed by which the inner surface temperature of the external building mass can be estimated. The model also allows one to determine the amount of internal thermal mass needed to meet a certain pre-stipulated temperature variation range. Modeling the internal thermal mass by a single capacitor network implies a uniform temperature distribution of the internal thermal mass. Further, the network assumed implies that this thermal mass is equal to indoor air temperature (infinite value of the convective coefficient). This makes thermal diffusion heat transfer more dominant than convective heat transfer at the wall surface. This assumption allows calculating the heat exchange between external thermal mass and internal thermal mass, while the radiation between these two bodies can be described by a total heat transfer coefficient. A lumped heat source term, E, is used to represent all sources of heat gain and heat generation in the building. The solar heat gain through apertures and radiation heat exchange between heat source and other surfaces are ignored. From the above assumption and details, the heat balance at the internal thermal mass can be stated as follows:

Heat supplied by ventilated air
+ Heat supplied by external wall
+ Power from internal heat source generated in the room
= Internal energy increase of the internal thermal mass

or $$\rho_a C_a q(T_O - T_i) + \alpha_i A(T_w - T_i) + E = MC_m \frac{dT_i}{dt}$$ (1a)

where $T_o = \bar{T}_o + A_o \cos[\omega t]$

$T_{sol-air} = \bar{T}_{sol-air} + A_{sol-air} \cos[\omega t - \varphi_{sol-air}]$

Using the harmonic response method and considering steady state, the closed form solution of the average inner surface temperature of external wall is derived as:

$$T_i = \bar{T}_i + A_i \cos[\omega(t - \varepsilon_i)]$$

where $$\bar{T}_i = \frac{\bar{T}_O + T_E + (\frac{\lambda}{\alpha_i R})\bar{T}_{sol-air}}{1 + (\frac{\lambda}{\alpha_i R})} \qquad (1b)$$

$\lambda = \frac{\alpha_i A}{\rho_a C_a q}$ is the convective heat transfer number

$\tau = \frac{MC_m}{\rho_a C_a q}$ is the time constant of the system

$T_E = \frac{E}{\rho_a C_a q}$ is the temperature increase induced by internal heat source.

In this study the parameters α_i, and "q" (assumed constant by Zhou et al.) are now varied so as to represent more accurately the fact that ventilation during hours with and without night ventilation are different. Varying these two parameters in turn effects λ, τ and T_E which subsequently impacts average indoor temperature, damping factor and time lag. These impacts will in turn influence the indoor air temperature calculation.

(b) Feuermann and Hawthorne model and modifications

Feuermann and Hawthorne (1991), in their study on the potential and effectiveness of passive night ventilation cooling, proposed a simplified thermal approximation (one capacitor and three resistor networks or 1C3R model) for buildings. This thermal network did not include factors like solar radiation, solar aperture and internal heat gains. Further, the network does not include a term for the thermal mass in the exterior building envelope, while assuming internal thermal mass to be dominant. Also, indoor comfort temperature is assumed to be constant even though the building considered is naturally ventilated. This RC network has also been modified to the one shown in Figure 1. Note that R_1 is the effective resistance made up of two resistances in parallel $\frac{1}{\alpha_o A_o}$ and $\frac{1}{\rho_a C_a q}$ and another resistance in series, namely $R_2 = \frac{1}{\alpha_i A}$. This thermal network was solved to determine T_i in terms of other parameters by using a finite difference scheme (Reddy, 1989).

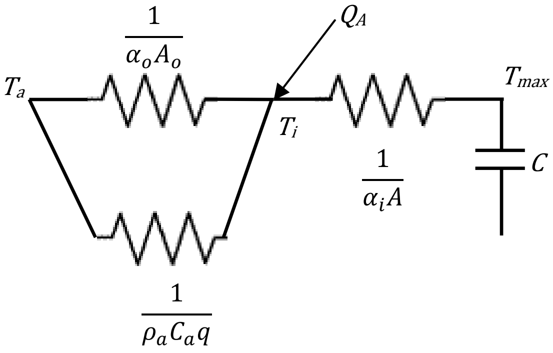

Figure 1. Thermal network model assumed by Feuermann and Hawthorne (1991)

(c) Adaptive model for indoor human comfort

For non-conditioned spaces which are naturally ventilated, indoor comfort temperatures can be modeled as follows

$T_i = 0.26 * T_o + 15.5$ (2)

where T_i (°C) is the indoor operative temperature,

and T_o (°C) is the mean monthly outdoor air temperature.

Equation 2 is eastimated from the graph "Figure 5.3 Acceptable operative temperature ranges for naturally conditioned spaces." Considering 80% acceptability limts (ASHRAE Standard 55, 2004)

(d) Model assumptions and limitations

The following assumptions are used in this study

(i) Thermal resistance to heat flow of the external wall is $R_o = 1.8$ m^2 K/W. This ia based on wall composition of typical light wall made of 200 mm foam concrete, 30 mm ploysterene on the outside, 20 mm stucco on the inside.

(ii) Time lag of inner surface temperature with respect to indoor air temperature is estimated as 0.0193 (h).

(iii) Because of insufficient data on wall properties and solar radiation, solar air temperature and its amplitude of fluctuation are assumed to be represented by those of outdoor air temperature. One ACH (Air Changes per Hour) was considered during the occupied hours. This was determined by considering 30% additional fresh air than that required by ANSI/ ASHRAE 62.1-2007, which is also stiipulated in LEED BD+C (2009).

(iv) So as to achieve a time constant of 15 hrs and 6 hrs, corresponding to one ACH, the building envelope parameters described earlier were kept constant but the interior thermal mass was altered by varying the volume of furniture. The time constant and other non dimensional terms are calculated assuming density of wood to be 600 kg/m^3 and its heat capacity to be 2.5 kJ/kg K, density of air to be 1.2 kg/m^3 and its heat capacity to be 1.005 kJ/kg K.

(v) A heat transfer coefficient of 8.29 W/m^{2}K corresponding to 3 ACH (Zhou et al., 2008) is assumed. Equation 3 (Kreider et al., 2005) is adopted which relates convective heat transfer coefficient (α_i) with velocity of flow over smooth surfaces results

$$\alpha_i = 6.2\left(\frac{v^4}{L}\right)^{\left(\frac{1}{5}\right)} \qquad (3)$$

where v is the indoor air velocity in meters/second and L is the length of plane or the wall surface in meters.

These models are simplified approximations of the dynamic behavior of a building structure subject to night ventilation. For example, the interaction between thermal mass and ventilated air is treated in a simple manner. Since the thermal capacity of the building is approximated by a single capacitance, its sensitivity to thermal mass behavior may be improperly captured. All sources of heat gain inclduing solar heat gain in the building are lumped, and considered as a single heat source. The distribution of heat gain may affect the distribution of indoor air temperature. This simplified model may affect the accuracy in predicting the indoor temperature profile and in computing the discomfort reduction factor.

ANALYSIS METHODOLOGY

Modified Zhou et al.(2008) and Feuermann and Hawthorne (1991) models were used for the test building assumed to be located in two different climates Phoenix, AZ and Albuquerque, NM. The analysis was done for two different values of building thermal mass capacitance. Results in terms of daily and monthly Discomfort Reduction Factor (DRF) are compared and analyzed. The reduction in the discomfort (in case there is no A/C) is quantified by a Discomfort Reduction Factor (DRF) as described in Equation 4.

$$\text{Monthly DRF}= \frac{\Sigma_{30\ \mathrm{days}}(T_{\mathrm{room}}-T_{\mathrm{comf}})^{+}_{\mathrm{no\ NV}}-\Sigma_{30\ \mathrm{days}}(T_{\mathrm{room}}-T_{\mathrm{comf}})^{+}_{\mathrm{NV}}}{\Sigma_{30\ \mathrm{days}}(T_{\mathrm{room}}-T_{\mathrm{comf}})^{+}_{\mathrm{no\ NV}}} \qquad (4)$$

A DRF value of 1 indicates that, with help of night ventilation, 100% indoor comfort can be achieved. A DRF value of 0 indicates night ventilation does not play any role in achieveing indoor comfort. To calculate DRF in buildings operating only during certain hours of day, equation 4 can be modified by only summing during the period of operating hours rather than 24 hours. To calculate DRF in buildings operating only during certain hours of day, equation 4 can be modified by summing only during the period of operating hours rather than 24 hours. In this study, for one of the models, DRF is calculated for the period from 9 AM to 9 PM during which the building is assumed to be occupied, and results are analyzed and compared to DRFs calculated for 24 hours period. A commercially whole building energy simulation model was also used to validate night ventilation effectiveness.

Table 1 specifies the volumetric air flow and interior convective heat transfer coefficient for scenarios with and without night ventilation and for different ACH values. The values of ACH and convective heat transfer coefficients are assumed following Equation 3. The time constant for a particular thermal mass is determined by maintaining constant loads in the building and step changing the forcing function (outdoor temperature) by an abrupt step change. The time taken for the response function (indoor temperature) to reach to 36.8% of its asymptote value is calculated. This was achieved when internal capacitance is set to 87,500,000 J/ ^{o}C (24.30 kWh/ ^{o}C). Similarly 15 hrs and 25 hrs time constants were achieved for internal capacitances of 60.26 kWh/ ^{o}C and 88 kWh/ ^{o}C respectively. A simulation code was developed for both the Zhou et al.(2008) and Feuermann and Hawthorne (1991) models to calculate indoor air temperature, daily and monthly DRF using Equation 4.

Table 1 – Air changes per hour (ACH) and convective heat transfer coefficients during day time and night time for scenarios with and without night ventilation

		ACH	q (m^3/sec)	α_i(W/m^2 K)
With Night Ventilation	Night	10	1.97	12
	Day	1	0.2	7.22
Without Night Ventilation	Night	0.5	0.1	6
	Day	1	0.2	7.22

ANALYSIS AND RESULTS

(a) Effect of location – Phoenix, AZ and Albuquerque, NM

In order to study the effect of weather data on night ventilation, indoor temperature dynamics can be simulated from which DRF for daily and monthly time scales can be determined. This was done for two locations, Phoenix, AZ and Albuquerque, NM using the TMY3 weather data. Figures 2 and 3 are plots of monthly DRF for Phoenix, AZ and Albuquerque, NM respectively, obtained by both models for time constant of 15 hours. Figure 4 is the plot of daily peaks and swings in ambient temperature for Phoenix, AZ and Figure 5 is its corresponding daily DRF.

From these figures, it can be observed that for Phoenix, AZ night ventilation will be effective from January to April and October to December (both models give consistent results). These are the months with relatively lower peak temperatures and larger swings in temperature. This is in agreement with Givoni (1994) who stated that night ventilation is applicable to regions/ seasons where daytime temperatures are between 30 ^{o}C and 36 ^{o}C and the night temperatures are below 20 ^{o}C. The Discomfort Reduction Factor (DRF) is largest during the months of March and November with a value of 0.40 using Zhou et al. (2008) model. However, the largest DRF is 0.48 in March and 0.41 in November using Feuermann and Hawthorne (1991) model. This discrepancy in DRF values between both models has been pointed out earlier. From Figures 2 and 3, it can be observed that in Albuquerque, NM, night ventilation is effective from April to October, which is different from that in Phoenix, AZ. Beyond the months of April to October, the daily peak temperatures are very cold and night ventilation is not an effective strategy. During April to October, most of the daily peak temperatures are below 36 ^{o}C and temperature swings are relatively larger. Between April to October, DRF values are largest during months of May, September and October and lowest during June and July.

For buildings, especially office buildings, which are only occupied during certain periods of day, the calculation of DRFs should be done only for hours when the building is occupied. Figure 6 is a plot which allows comparison of monthly DRFs calculated only from 9 AM to 9 PM against those for the entire 24 hour period for Phoenix, AZ using the Zhou et al.(2008) model for a building with time constant of 15 Hrs. From Figure 4 it can be noticed that both plots are quite close, with a slight decrease in DRFs (max is less than 8%) for the case of occupancy assumed between 9 AM to 9 PM. This is due to the fact that, benefits of night ventilation are accounted for 24 hour time periods even during non-occupancy hours when DRFs are calculated over 24 hour time periods.

(b) Effect of time constant – 25 , 15.5 and 6 hrs

Time constant is defined as time taken for a response to attain 1/e ~0.368 of its final steady state value when subject to a step change in the forcing function. The longer the time constant of a building, the longer it takes to cool down or warm up the building structure. Thus, time constant is reflective of the thermal capacity of the building. Thermal capacity of the building plays a significant role in night ventilation. When the building is ventilated at night, its cooling capacity increases with increase of thermal capacity or time constant, so that this cooled mass can delay the increase of indoor temperature for the next day. Three time constants of 25 hrs, 15.5 hrs and 6 hrs were used to test the effectiveness of night ventilation. These time constants were achieved by varying the capacitance of internal thermal mass. Figures 7 is the plot of Monthly DRFs for time constant of 25 hrs, 15 hrs and 6 hrs for Phoenix, AZ and Albuquerque, NM, respectively calculated using the Zhou et al.(2008) model. Figures 8 is a similar plot, but using the Feuermann and Hawthorne (1991) model.

From Figures 7 and 8, it can be observed that irrespective of the geographic location, buildings with higher time constants are more attractive for implementing the night ventilation strategy as compared to one with lower time constants since their DRFs are higher. Higher time constants signify larger thermal capacity where buildings can better hold the cold temperatures during the nights and release it when the space tries to warm up the next day. This property will delay the increase in the indoor temperatures with respect to outdoor temperatures. Also, it can be noticed that sensitivity to time constant is greater in Phoenix, AZ in both the models. However, there is a variation in sensitivity levels among the model, and this is discussed in comparison of these models. In Zhou et al. (2008) models, the difference between both model predictions in peak DRF values for Phoenix, AZ is 10% whereas for Albuquerque, NM it is 4%. Further research could be directed to finding the relation between ambient weather and sensitivity of time constant; the sensitivity to time constant on DRF values may also decrease with higher values of time constant.

(c) Effect of ACH – 20, 10 and 5

Air Changes per Hour (ACH) is a measure of how many times the air within a defined space (normally a room or house) is replaced with outdoor air. In this study, the peak ACH considered during the operating hours of night ventilation is varied and its effect on DRFs is observed. Peak ACH of 20, 10 and 5 are assumed for both climate locations of Phoenix, AZ and Albuquerque, NM using both the Heat Transfer the Feuermann and Hawthorne (1991) models. The monthly DRF values are shown in Figures 9 and 10. We note that DRFs increase as ACH increases. However, it is observed that the increase in DRF by increasing ACH is not as pronounced as that when the time constant is increased.

(d) Inter-comparison of both models

Both the Zhou et al. (2008) and Feuermann and Hawthorne (1991) models are similar except for resistance ($\frac{1}{\rho_a c_a q}$). This factor accounts for the capacity of ventilation air and is coupled differently in either model; it is in parallel to all other resistors in the Zhou et al. (2008) model whereas, it is coupled in parallel to the conduction and convection resistance of the exterior envelope, in series with the convective resistance of the internal thermal mass. Ascertaining which is more realistic would probably depend on the specific building. Also, the Zhou et al.(2008) model is a closed form solution while the Feuermann and Hawthorne (1991) model is solved using numeric methods.

Discomfort Reduction Factors (DRFs) have been calculated following both models for both locations. Figures 11 and 12 indicate that there is a difference in the monthly DRF values though, the patterns are quite similar. The variation in DRF values is due to the difference in how the coupling of thermal mass and night ventilation in buildings is approximated in both models.

SUMMARY, CONCLUSIONS AND EXTENSIONS

Thermal network models, similar to the two adopted in this paper, are more appropriate for architects/ engineers as a means for preliminary assessment of the potential of night ventilation as a strategy to implement in their specific location. A Discomfort Reduction Factor (DRF) is proposed as an index which provides such an assessment. From the calculated indoor temperature dynamics, the reduction in air-conditioning load may be estimated when night ventilation is used in conditioned buildings. Though these models are analyzed for a prototype small office building, the methodology used in analyzing and developing these models may be extrapolated to larger sized buildings.

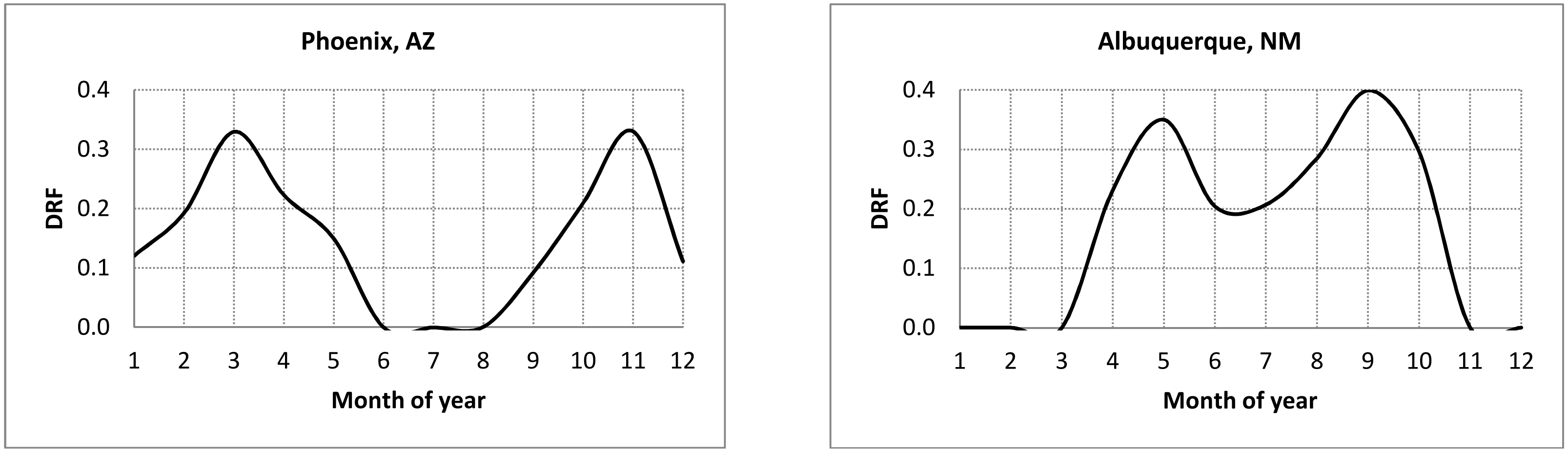

Figure 2. Monthly Discomfort Reduction Factors for Phoenix, AZ and Albuquerque, NM using the Zhou et al.(2008) model with time constant of 15 hrs

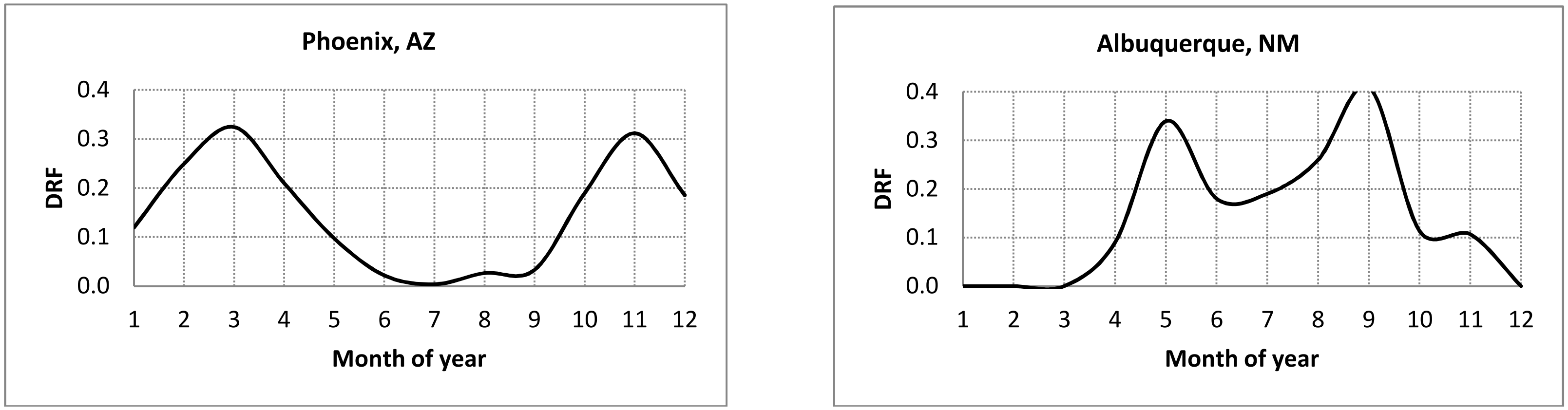

Figure 3. Same as Figure 2 but using the Feuermann and Hawthorne (1991) model

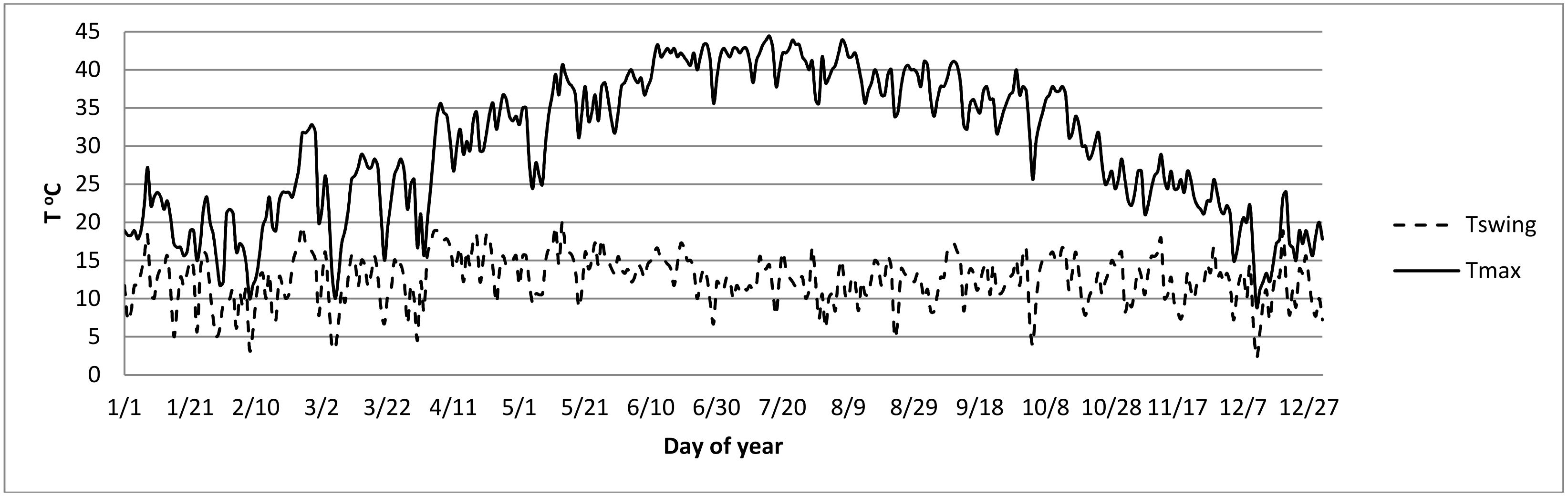

Figure 4 – Variation in daily peaks and swing in ambient temperature for a whole year in Phoenix, AZ using TMY3 data

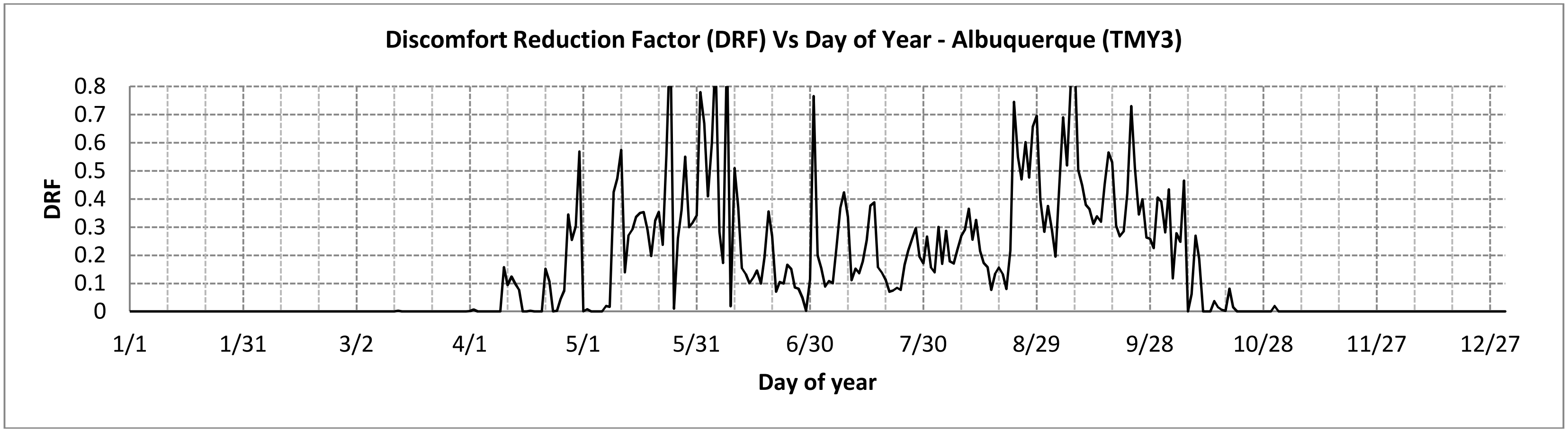

Figure 5 – Daily Discomfort Reduction Factors for Phoenix, AZ using the Zhou et al.(2008) model with time constant of 15 hrs

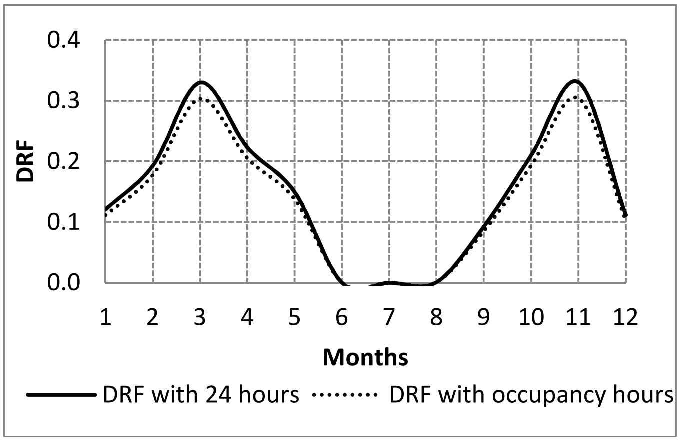

Figure 6. Comparison of monthly DRFs calculated assuming occupancy hours (9 AM to 9 PM) and for 24 hour period. Phoenix, AZ with the Zhou et al.(2008) model used to simulate building dynamics with time constant of 15 hrs

These models were used to evaluate the night ventilation effectiveness for two climate zones, Phoenix, AZ and Albuquerque, NM, for three time constants of 25 hrs, 15 hrs and 6 hrs and three peak air changes per hour (ACH) of 20, 10 and 5. It was observed that night ventilation is effective when day time ambient temperatures are between 36 ^{o}C and 30 ^{o}C and night time ambient temperatures below 20 ^{o}C.

Implementing night ventilation between January to April and October to December are best for Phoenix, AZ when the weather is pleasant and not too hot. On the other hand, night ventilation strategy is more effective for Albuquerque, NM during the period April to October when its weather is pleasant and not cold. As expected, it was observed that DRFs increased with increase in time constants. 25 hrs of time constant resulted in higher DRFs compared to 15 hrs which, in turn, has greater DRFs compared to 6 hrs. Similar kind of results were observed when ACH was increased. DRF values predicted by the Zhou et al. (2008) model and the Feuermann and Hawthorne (1991) model differ to some extent due to the manner in which each of the models treat the coupling of thermal capacity of ventilation air with internal thermal mass and the methodology of solving the equations. The results from these models are partially validated with whole building energy simulation program.

Future extensions of this work would include improving the network models, sensitivity analysis of night ventilation effectiveness with thermal mass and volume of night ventilation air, including the fan power required to implement the night ventilation strategy, and optimizing for the operation hours of ventilation so as to minimize energy. These models and the methodology should then be extended to air conditioned buildings so that estimates of the cooling energy reduction from night ventilation can be ascertained and climatic mapping methodology of the cooling potential of night ventilation in residential and commercial buildings for numerous arid climates worldwide should be explored. Humidity may be considered in the analysis in both comfort point of view and also architectural point of view (fromation of molds, etc.). The expertise required to develop the models, generate and analyze the results are less than that required for performing whole building simulation models. Though the accuracy of results is slightly compromised, the loss in accuracy using these tools more than compensates for the insights such as analysis provides as well as the transparency in the analysis approach.

ACKNOWLEDGEMENTS

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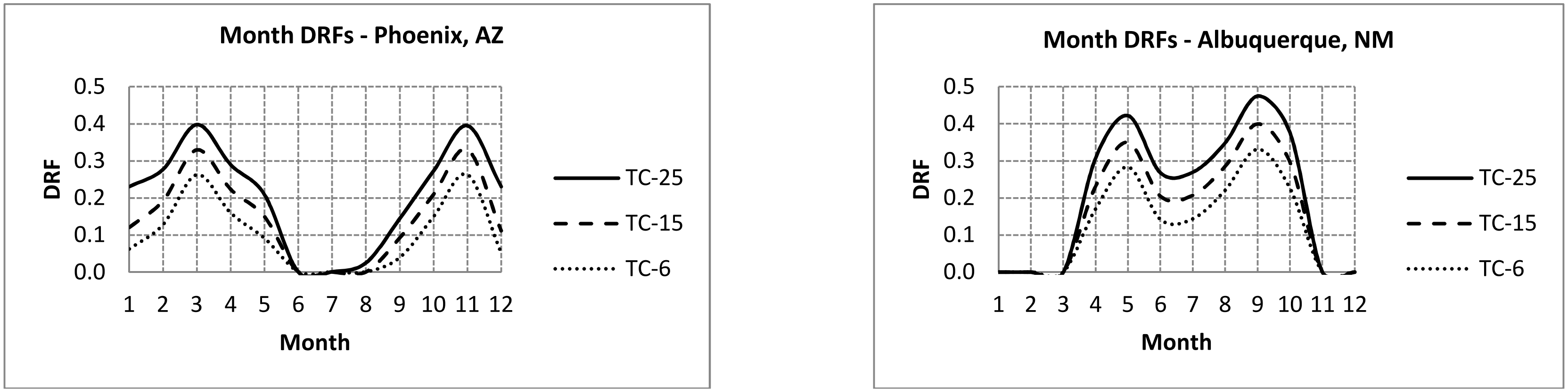

Figure 7. Monthly DRFs for peak ACH of 5, 10 and 20 for Phoenix, AZ and Albuquerque, NM using the Zhou et al.(2008) model

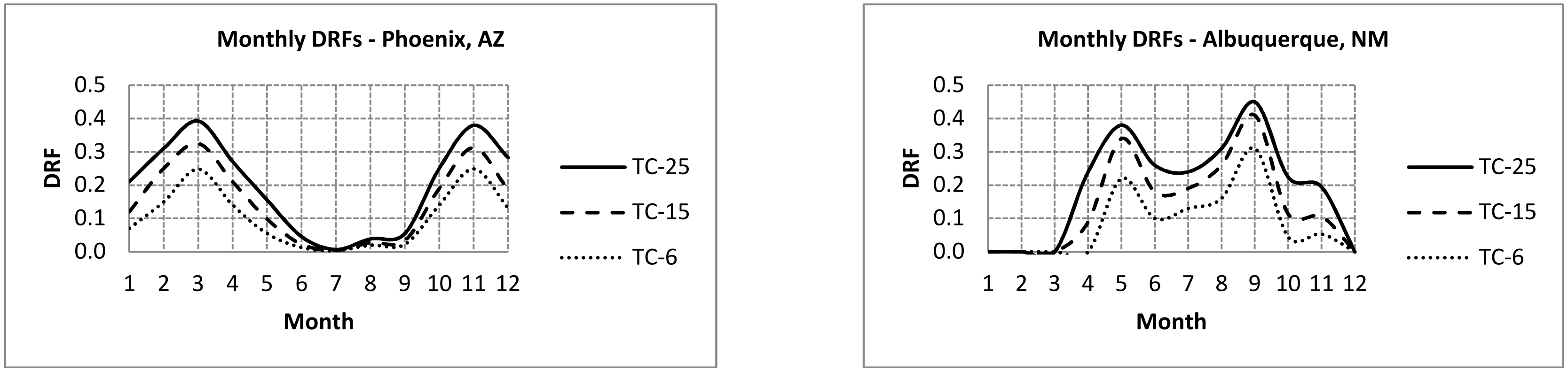

Figure 8. Same as Figure 5 using the Feuermann and Hawthorne (1991) model

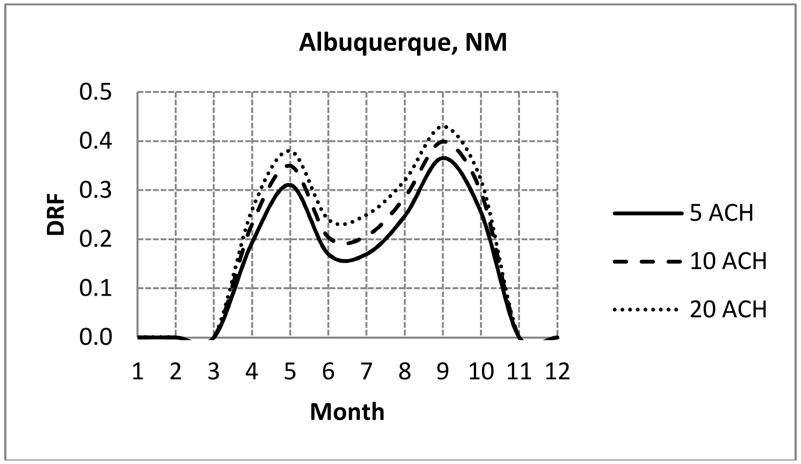

Figure 9. Monthly DRFs for peak ACH of 5, 10 and 20 for Albuquerque, NM using the Zhou et al.(2008) model

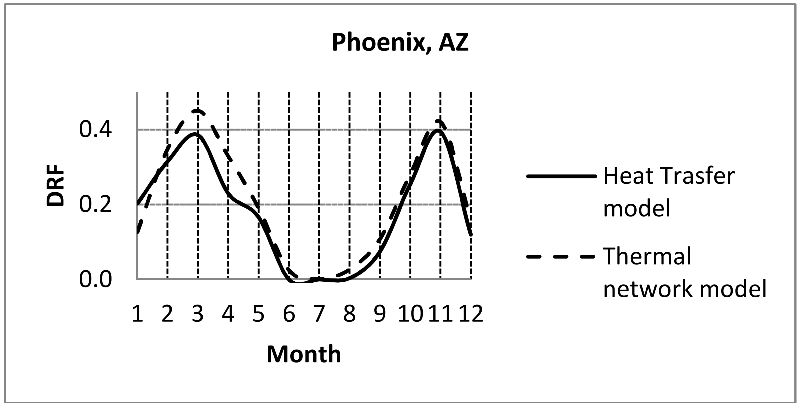

Figure 11. Comparison of variability in DRFs following the Zhou et al.(2008) model and the Feuermann and Hawthorne (1991) model for Phoenix, AZ for a time constant of 15 hrs and peak ACH of 10.

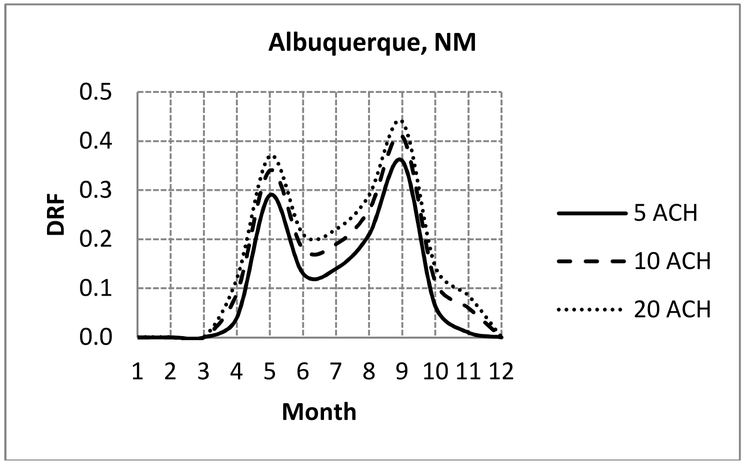

Figure 10. Same as Figure 7 using the Feuermann and Hawthorne (1991) model

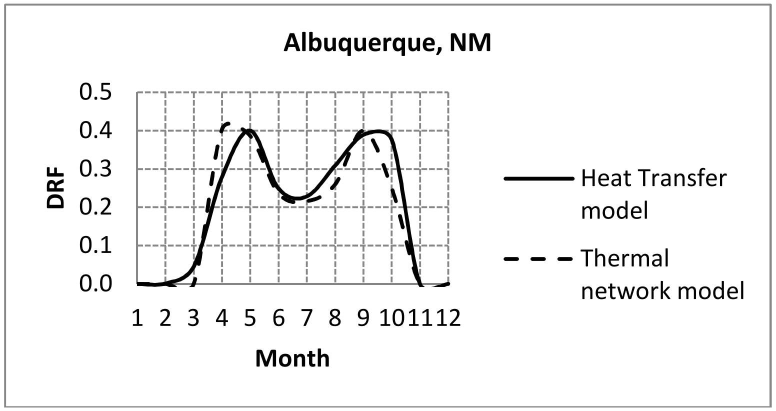

Figure 12. Same as Figure 9 but for Albuquerque, NM