

Passive Cooling Strategies for Improved Thermal Performance of Residential Buildings in Hot-Humid Climates

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ABSTRACT: Residential buildings are characterized by being envelope-load dominated buildings, hence are greatly influenced by the outside climatic conditions. Due to the harsh climate of Saudi Arabia, residential buildings on average, consume more than half of the total consumed energy. The bulk of this energy is consumed by the air-conditioning system which is required to remove substantial amount of gained heat throughout the year due to poor thermal performance. Implementing proper passive strategies including ventilation strategies and different envelope designs can significantly improve the thermal performance of residential buildings in transition as well as in winter months. The objectives of this paper are to evaluate different ventilation strategies with various envelope designs to improve the thermal performance of residential buildings in hot humid climate of Saudi Arabia. Under the hot-humid climatic conditions of Dhahran, a base case residential building was simulated utilizing the energy simulation program: VisualDOE 4.1 when the air-conditioning is off in transition months (March, April, May, October and November) and in winter months (December, January and February). Different ventilation strategies coupled with various envelope designs were investigated. It is found that when proper ventilation strategies are implemented for different envelope designs, thermal performance is significantly improved. The results of this study can be used to develop smart ventilators or improved AC systems with economizer for residential buildings to improve thermal comfort in transition and winter months without using the traditional air conditioners.

Keywords: hot-humid climate, ventilation strategies, thermal comfort

1. INTRODUCTION

The exchange of air between the outdoor and indoor has equal benefits and drawbacks. In some climates, outside air is utilized for natural ventilation to

accomplish thermal comfort and hence reduce energy consumption. Using a validated computer program “QUICK”, different air change rates were investigated in low mass and heavy mass buildings in a hot climate region [1]. It was found that the

indoor air temperature in low mass building is less sensitive to the increases in air change rates but rather follow the outdoor temperature regardless of increased ACH. However, a reduction of 1.5°C in indoor air temperature was achieved in the heavy mass building when the air change rates increased during night time. An experimental study in hot climate has indicated that using a high air change rates in heavy mass buildings during night would keep the indoor air temperature 7.5 -10.5 K below the outdoor maximum temperature [2]. A field study in hot arid climate of Riyadh has concluded that a continuous day and night ventilation through outside windows is worse thermally than keeping the building closed without ventilation [3]. In a hot humid climate of Japan, the indoor air temperature of a ventilated courtyard house was dropped by 1.3°C with an air change rate range of 1.5 to 2.0 ACH [4]. In a warm humid day of Sri Lanka, a simulation study utilizing TRANSYS was utilized to investigate the impact of natural air change rates to reduce the indoor air temperature in residential buildings [5]. It was found that if windows are opened from 17:00 hrs to the next morning 8:00 hrs, the indoor air temperature is reduced from 30.2°C to 29.1°C. A simulation study using ENERGY was performed to investigate four level of night ventilation in different level of massive construction for a typical apartment building in hot-humid climate regions [6]. The night ventilation levels assumed in this study were: natural infiltration rate of 2 ACH (base case), natural night ventilation rate of 5 ACH, forced night ventilation of 20 and 30 ACH. The study concluded that it is possible to achieve a reduction of 3-6°C in a heavy constructed building without air conditioner. The reduction of indoor air temperature depends on the amount of thermal mass, the rate of night ventilation and the temperature swings between the day and night. Another simulation study for free-floating building in hot-humid regions

indicated that the nighttime-only natural ventilation reduces both the peak indoor air temperatures and daily indoor temperature fluctuation during summer and hence improves the overall building performance [7].

2. BUILDING CHARACTERISTICS AND ENVELOPE SELECTION

Energy simulation programs require many data inputs. Many programs have databases that are available for easier input through the library and templates. However, building designs are not readily available and vary from one climatic region to another. In this study, a questionnaire survey was distributed to design offices to define the physical and thermal characteristics of a typical residential building in Saudi Arabia. Based on the survey results, the architectural design of residential buildings in Dhahran is defined as shown in Table I.

Table I: Characteristics of Architectural System for a Typical Single-Family Residential Building in Dhahran

Characteristics	Description of the Base Case
Location	Dhahran
Orientation	Front Elevation facing North
Plan Shape	Rectangular
Number of floor	Two
Fl to Floor Height	3.5 m
Floor Area	300 m ²
Floor Dimension	15 x 20 m
Gross Wall Area	490 m ²
Window Area	20% of the gross wall area
Type of Glass	6 mm Single glazing
Solar Absorbance (for Exterior Surfaces)	0.55 for external walls , 0.35 for the roof (light color)
Exterior Walls	Stucco + 200 mm CMU Hollow Block + Stucco
Roof	Tiles + Mortar + Membrane + 100mm LWC + 200 mm Hourdi Slab + Cement Plaster
Floor	100 mm slab on grade
Occupancy Density	6 People
Light. Power Density	GF: 10 W/m ² , 1 st Fl: 8 W/m ²
Equip. Power Density	GF: 12 W/m ² , 1 st Fl: 5 W/m ²
Infiltration	0.5 ACH
Weather File	Typical Year 2002

Additionally, a series of possible wall and roof types that are normally used in the design practice of residential buildings in Saudi Arabia has been generated [8]. Five walls and four roofs are selected to represent the wide variations of the thermal characteristics of envelope designs. A combination of 4 roof and 5 wall designs make 20 possible designs. Some of these combinations are not practical or the variation in the thermal characteristics is not wide. Therefore, only 8 envelope designs are considered for further study as depicted in Table II where Design#1 is the base case.

Table II: Selected Building Envelopes for Energy Simulation in Residential Buildings in Saudi Arabia

	R#1	R#3	R#5	R#7
W#1	D #1 (Base Case)	D#2	D#3	D#4
W#2		D#5	D#6	
W#3	D #7		D#8	D#9
W#4	D #10			
W#5		D#13	D#14	D#15

3. LOCATION, CLIMATE AND THERMAL COMFORT ZONES

3.1 Location and Climate

Saudi Arabia lies between Latitude 16° and 32° North. This variance has resulted in different climatic conditions where tropical climate is between Latitude 16°-18° North, hot climate between Latitude 18°-30° North and a warm climate between Latitude 30°-32° North [9]. The model residential building is located in Dhahran, Saudi Arabia (Lat. 26° 17'N, Long. 50° 09'E, Alt. 24 m) (hot humid climate), which is situated about 10 km from the Arabian Gulf. The monthly average hourly outdoor temperature is shown in Figure 1. The shaded area in the figure shows that outdoor air can potentially be used in all months except in summer months (i.e. Jun, July and August) to remove the indoor

generated heat in buildings. A more careful approach has to be made in transitions months (i.e. April, May, September and October) where the outside air is hot during the day (above 29° C) and in winter months (i.e. December, January and February) where the outside air is chilly (below 15° C). The decision to introduce the outside cool air is not arbitrary and a proper analysis is required to evaluate the indoor thermal environment.

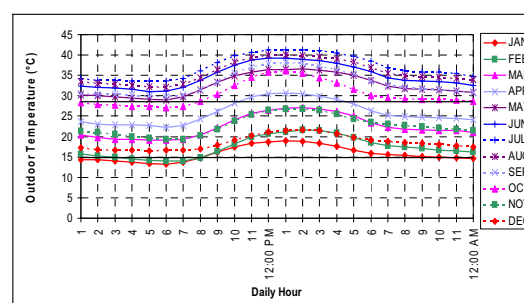


Figure 1: Monthly Average Outdoor Air Temperature for Dhahran City

3.2 Thermal Comfort Zones

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” [10]. ASHRAE has defined and recognized two thermal comfort zone criteria: (1) natural ventilation thermal comfort criterion, and (2) the thermal comfort criteria for mechanically operated buildings. Both of these methods are approved in the recent version of ASHRAE standards 55 [10]. The first method is applicable to the naturally ventilated buildings and is much dependent on the monthly average (Max and Min) outdoor air temperature which is entered in the following equation: $T_{\text{comfort}} = 0.31 T_{\text{outdoor}} + 17.8$. When using this equation for Dhahran, the thermal comfort zone is defined and differs from month to month as shown in Table III. This criterion is used in this study to evaluate the effectiveness of ventilation strategies on indoor thermal environment.

Table III: Thermal Comfort Zones Limit for Dhahran

Month	Average Outdoor Temp. (°C)	Thermal Comfort Zones (°C)
Jan	15.8	19.1-26.1
Feb	17.4	19.7-26.7
March	22.5	21.3-28.3
April	25.9	22.3-29.3
May	32.6	23.4-31.41
Summer	34.8	N/A
September	33.2	24.6-31.6
October	30.4	23.7-30.7
November	22.7	21.3-28.3
December	18.6	20.1-27.1

4. DISCUSSION OF RESULTS

Utilizing VisualDOE4.1, the base case model and different envelope designs for the residential building in Dhahran were simulated when Air Conditioner (AC) is off. Figure 2 shows the monthly average indoor air temperature of the base case and for the different envelope designs for a typical winter (i.e. December) and typical transitions months (i.e. March and May). It is clear that in winter where the outdoor air temperature is between 18°C and 22°C, mechanical air conditioner is required for some envelope designs to remove the gained heat. For example, the indoor air temperature of the well insulated envelope designs (D#13 and D#15) is out of thermal comfort zones from 10:00 AM to 10:00 PM. However, for the poorly insulated designs (i.e. D#1 (base case design) and D#4) are within thermal comfort zones. In transitions months, the indoor air temperature is partially within the thermal comfort zones for some months and outside the thermal comfort zones for others. In March for example, the indoor air temperature is within thermal comfort for the poorly insulated designs from 1:00 AM to 10:00 AM. However, the thermal performance of well insulated designs is

poor and air conditioner is necessary for the whole day.

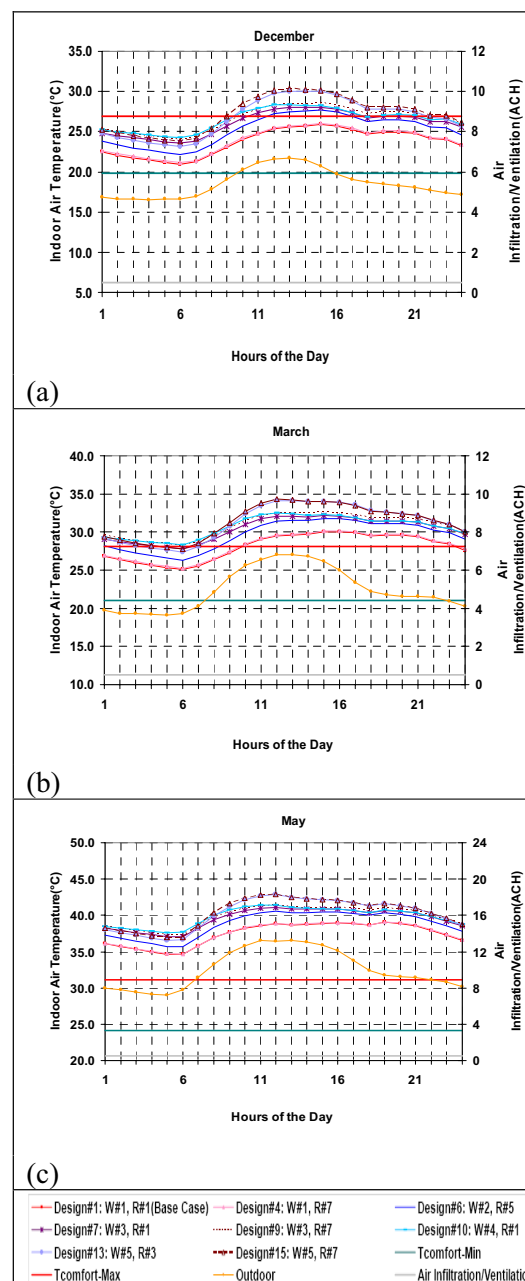


Figure 2: Monthly Average Indoor Air Temperatures for Different Envelope Designs in Dhahran under No Ventilation in (a) Typical Winter Month, (b) Typical Cool Transition Month and (c) Typical Warm Transition Month

Although the outside air temperature is within thermal comfort from 12:00 PM to 6:00 AM in May, the indoor air temperature is outside the thermal comfort zones for all envelope designs and air conditioner is therefore a necessity for a thermally comfortable environment.

5. IMPACT OF DIFFERENT VENTILATION STRATEGIES ON INDOOR THERMAL ENVIRONMENT

5.1 Preliminary Ventilation Strategies

The base case residential building with different envelope design alternatives is modelled to evaluate the effectiveness of ventilation strategies on the indoor air temperature. In order to develop preliminary ventilation strategy that improves the indoor thermal conditions, the outdoor air temperature should be within the thermal comfort zones when the indoor air temperature is outside the thermal comfort zones (i.e. above the max. limit). To meet this condition, a month by month analysis was conducted to evaluate possible air flows and proper timings to introduce outdoor cool air. As a result a preliminary ventilation strategy (ventilation strategy#1) was proposed as shown in Table IV. The quantity and timings of cool air is different from one month to another. Different ventilation strategies were then evaluated where the quantity of air flow is increased while the timings were fixed constant to evaluate the thermal performance of different envelope designs.

5.2 Thermal Performance of Envelope Designs

The percentage of thermal comfort in a year is used as an indicator of a thermal performance of envelope designs. This indicator is calculated by estimating the number of hours where the indoor air temperature is within thermal comfort zones divided by the number of hours in a year (8760 hours). For example, if the

indoor air temperature for an envelope design is 4000 hours in a year within thermal comfort zones then 45% of thermal comfort is achieved by that design.

Figure 3 shows that the thermal comfort is enhanced by introducing outside cool air. As the volume of cool air is increased, the thermal comfort increases. However, the thermal comfort deteriorates with the high air change per hour (Ventilation Strategy#4). This implies that introducing high volume of outside air randomly in winter months (December, January and February) and cool transition months (March and November) results in thermal discomfort and therefore poor thermal environment. Therefore, applying selective ventilation strategies such as daytime ventilation only during winter months (December, January and February) and cool transition months (March and November) and night ventilation only during warm transition months (April, May, and October) help to avoid the overcooling and overheating during cool and hot seasons respectively. It was found difficult to utilize the outside air to improve the thermal environment in September.

Proper ventilation strategies are derived for this building and corrected for wind speed and stack effect as listed in Table V for transition and winter months. This strategy is a combined ventilation strategy that is drawn from all ventilation strategies. The thermal comfort of envelope designs when no ventilation is applied varies from 27% for poorly insulated design (D#1) to 16% for super-insulated design (D#15). Applying proper ventilation strategies, the thermal comfort increases to 40% for the poorly insulated design and to 41% for the super-insulated design as shown in Figure 3. It is noticed that all envelope designs achieve similar thermal comfort level under this strategy. However, the improvement in thermal comfort is significant with the insulated designs (above 100%) compared to the poorly insulated design (45%).

Table IV: Preliminary Ventilation Strategies for Residential Building in Dhahran

Month	Ventilation Strategy# 1	Ventilation Strategy# 2	Ventilation Strategy# 3	Ventilation Strategy# 4
Jan	2 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	4 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	6 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	12 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00
Feb	4 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	8 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	12 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	24 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00
Mar	10 ACH (24 h)	20 ACH (24 h)	30 ACH (24 h)	60 ACH (24 h)
Apr	10 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	20 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	30 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	60 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00
May	10 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	20 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	30 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	60 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00
Sum.	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)
Sept	10 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	20 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	30 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	60 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00
Oct	10 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	20 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	30 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	60 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00
Nov	10 ACH (24 h)	20 ACH (24 h)	30 ACH (24 h)	60 ACH (24 h)
Dec	4 ACH: 08:00-17:00 0.5 ACH: 18:00-07:00	8 ACH: 08:00-17:00 0.5 ACH: 18:00-07:00	12 ACH: 08:00-17:00 0.5 ACH: 18:00-07:00	24 ACH: 08:00-17:00 0.5 ACH: 18:00-07:00

Winter Months
 Summer Months
 Changes on Vent. rate
 Cool Transition Months
 Warm Transition Months

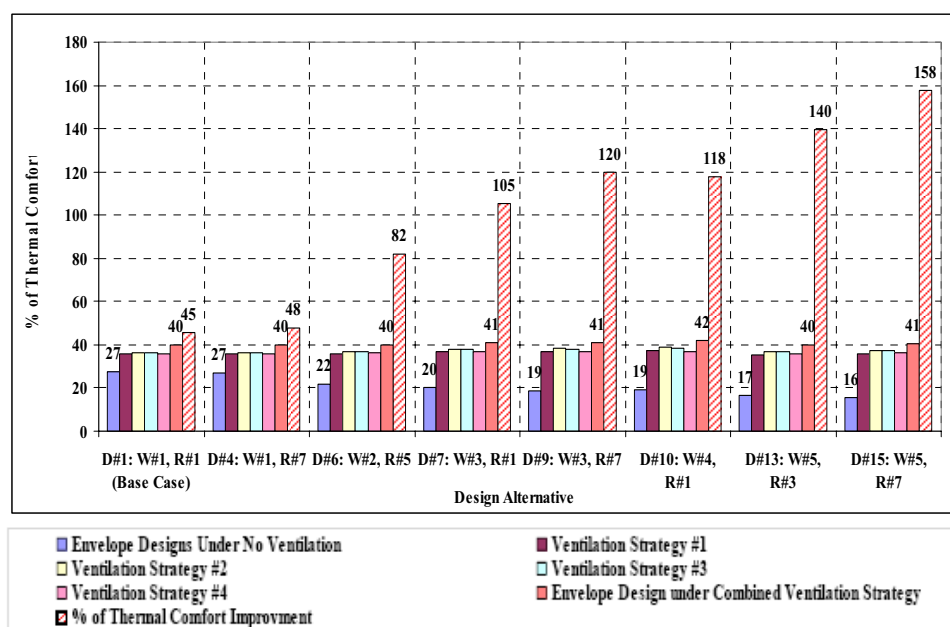
**Figure 3:** Impact of Different Ventilation Strategies on Thermal Comfort of the Residential Building in Dhahran under Various Envelope Designs

Table V: Combined Ventilation Strategies for Various Envelope Designs in Dhahran under Transition Months and Winter Months

	Dec	Jan	Feb	Mar	Apr	May	Oct	Nov
D #1 (B.C.) & D#4	2.5 ACH 08:00- 17:00, 0.3 ACH 18:00- 07:00	0.3 ACH (24 h)	0.3 ACH (24 h)	5.0 ACH 08:00- 18:00, 0.3 ACH 19:00- 07:00	5.5 ACH 16:00- 9:00, 0.3 ACH 10:00- 15:00	12 ACH 20:00- 6:00, 0.3 ACH 7:00- 19:00	8.5 ACH 20:00- 6:00, 0.3 ACH 7:00- 19:00	6 ACH 07:00- 18:00, 0.3 ACH 19:00- 06:00
D#6 D #7	2.5 ACH 07:00- 18:00, 0.3 ACH 19:00- 06:00	0.3 ACH (24 h)	2.70 ACH 08:00-18:00, 0.3 ACH 19:00-07:00	5.0 ACH 08:00- 18:00, 0.3 ACH 19:00- 07:00	5.5 ACH 16:00- 9:00, 0.3 ACH 10:00- 15:00	12 ACH 20:00- 6:00, 0.3 ACH 7:00- 19:00	8.5 ACH 20:00- 6:00, 0.3 ACH 7:00- 19:00	6 ACH 07:00- 18:00, 0.3 ACH 19:00- 06:00
D#9					5.5 ACH 16:00- 9:00, 0.3 ACH 10:00- 15:00			
D#10	2.5 ACH 07:00- 18:00, 0.3 ACH 19:00- 06:00	1.3 ACH 08:00-18:00, 0.3 ACH 19:00-07:00	2.70 ACH 08:00-18:00, 0.3 ACH 19:00-07:00	5.0 ACH 08:00- 18:00, 0.3 ACH 19:00- 07:00	11 ACH 16:00- 9:00, 0.3 ACH 10:00- 15:00	12 ACH 20:00- 6:00, 0.3 ACH 7:00- 19:00	8.5 ACH 20:00- 6:00, 0.3 ACH 7:00- 19:00	6 ACH 07:00- 18:00, 0.3 ACH 19:00- 06:00
D#13								
D#15								

	Poor Envelope Designs		Winter Months
	Insulated Envelope Designs		Cool Transition Months
	Super-Insulated Envelope Designs		Warm Transition Months

6. CONCLUSION

The base case residential building with different envelope designs was modelled under the hot humid climate of Dhahran, Saudi Arabia using VisualDOE 4.1 when air conditioner is off. In winter, indoor thermal environment was found satisfactory for poor insulated envelope designs (i.e. D#1 and D#4) and poor for insulated envelope designs when ASHRAE thermal comfort limits for naturally ventilated buildings is considered. All envelope designs performed poorly in transition months. Preliminary ventilation strategies were proposed and evaluated for different envelope designs including the base case. Introducing high volume of cool air in winter and cold transition months and high

volume of warm air in warm transition months had deteriorated the thermal environment and a selective ventilation strategy was proposed to avoid overcooling and overheating during these critical months. When this strategy is used for different envelope designs, thermal comfort was improved by 40% for the poorly insulated design and more than 150% for the well insulated designs. In addition to its well defined performance during the summer months, utilizing the outside cool air in winter and transition months has improved the performance of well insulated envelope designs.

ACKNOWLEDGEMENT

The authors would like to thank Sultan Qaboos University and King Fahd University of Petroleum and Minerals for its continuous encouragement and support of research activities.

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