PERFORMANCE-BASED ENVELOPE DESIGN FOR RESIDENTIAL BUILDINGS IN HOT 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 due to poor thermal envelope performance. Implementing proper envelope thermal characteristics for residential buildings can significantly reduce energy consumption. The objectives of this paper are to evaluate the thermal characteristics of building envelope and consequently define those that improve the energy efficiency of residential buildings in Saudi Arabia. Under the climatic conditions of Dhahran and Riyadh, a base case residential building was simulated utilizing the energy simulation program: VisualDOE 4.1 when the air-conditioning (cooling and heating) is used throughout the year. Different envelope designs and four glazing types were evaluated. It is found that when proper envelope designs including high performance glazing and reduced air infiltration are selected, significant energy consumption is reduced in hot climates. The results of this study can be used as an alternative method of meeting prescriptive local requirements and international standards.

INTRODUCTION

In traditional buildings of Saudi Arabia, climatic thermal design of exterior building envelope was predominantly utilized to manipulate the indoor air temperature to achieve thermal comfort. Climatic thermal design such as thermal characteristics of building envelope and air leakage characteristics greatly influences the room air temperature and subsequently the energy consumption. As envelope-load dominated buildings, residential buildings are greatly influenced by the climatic conditions. In Saudi Arabia, the thermal load of building envelope (i.e. walls, roof and windows) is responsible for more than 70% of the total thermal load in a single-family house in Dhahran (Said and Abdelrahman 1989, Abdelrahman and Ahmed 1991, Ahmed and Elhadidy 2002). Residential buildings on average consume more than 51% of total consumed energy in Saudi Arabia in year 2002 with an annual growth rate of 8.1% (SEC, 2002). The majority of this consumption, measured to be more than 76% in hot-dry climate (Al-Arfag, 2002) and more than 62% in hot-humid climate of Saudi Arabia (Al-Najem, 2002), is used by mechanical cooling and heating systems to provide thermal comfort.

Many studies including site measurements, experiments, energy simulations and numerical studies have been conducted to evaluate the energy performance of residential buildings in Saudi Arabia. In hot-humid climate of Dhahran, Saudi Arabia, an experimental study using 10 roofs and 14 wall assemblies have been carried out to investigate the impact of varying insulation and construction approaches on the annual net heat flow (Said et al., 1997). The study has demonstrated that using 75 mm of extruded polystyrene in roof slab reduces the net heat flow by more than 80%. In wall assemblies, the reduction in net heat flow using 50 mm of thermal insulation ranges from 64-84% depending on the type of insulation and its placement within the building envelope. Annual energy consumption for three 2-story villas, one w/o insulation and others with different insulation materials, has been monitored in hot-dry climate of Madina, Saudi Arabia (Al-Maimani, 2002). The study has shown that insulation in both walls and roof contributed to actual savings of 48-80% in annual energy consumption. A parametric simulation analysis using DOE 2.1A for a single floor house in Dhahran has indicated that using thermal insulation for both roof and walls would contribute a reduction of 12.6% of the total annual energy consumption (Said and Abdelrahman, 1989). For the same climate, a similar study for a two-story detached single family house has shown that a reduction of 42% in total energy consumption can be utilized if walls and roof are insulated (Ahmed and Elhadidy, 2002). Utilizing PC-DOE program, (AL-Maziad, 1999) has investigated the impact of many building envelope design parameters in eastern province of Saudi Arabia, Dammam. He found that with insulated walls, electrical consumption for cooling purposes could be reduced by 23% compared to buildings without insulation. Al-Homoud has investigated the impact of different level and types of thermal insulation on thermal performance of residential and office buildings in hot-dry climate of Riyadh and hot-humid climate of Dhahran in Saudi Arabia by utilizing the hourly building energy simulation program “EnerWin” (Al-Homoud, 2004). The study has indicated that residential buildings are more sensitive to the level of thermal insulation in reducing the energy consumption. For the residential buildings in Riyadh, the reductions in the annual energy consumption due to the use of walls and roof thermal insulation ranges from 23.69% to 45.51%, while in the climate of Dhahran, the reductions are more and ranging from 25.29% to 50.24%.

BUILDING CHARACTERISTICS AND ENVELOPE SELECTION

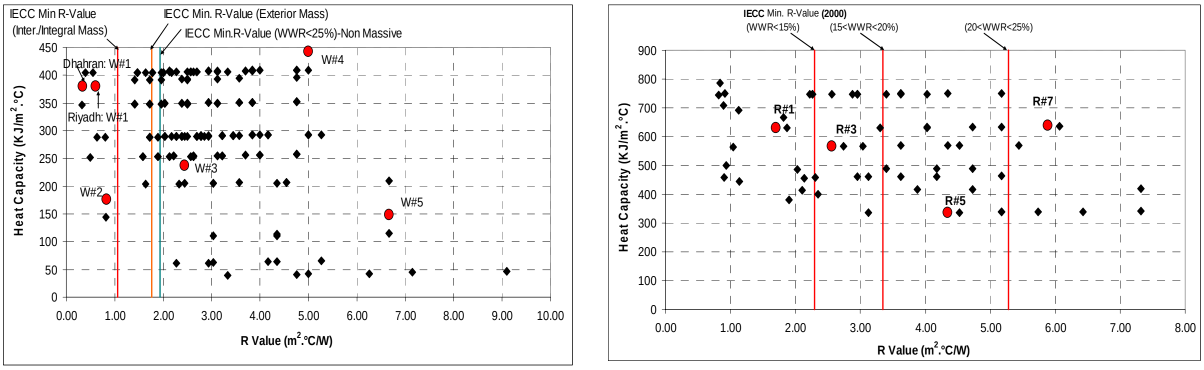
Energy simulation programs require many data inputs including floor plan, occupancy type, location, walls, roof and floor constructions; window area and type; HVAC system type; lighting and equipment power density. Many programs have databases that are available for easier input through the library and 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 and Riyadh is defined as shown in Table 1.

Table 1 Characteristics of Architectural System for a Typical Single-Family Residential Building in Dhahran and Riyadh

Characteristics	**Description of the Base Case**
Location	Dhahran (26.27 N latitude, 50.15 E longitude, and 17m above sea level), Riyadh (24.72 N latitude, 46.72 E longitude, and 612 m. above sea level)
Orientation	Front Elevation facing North
Plan Shape	Rectangular
Number of floor	Two
Floor to Floor Height	3.5 m (7.0 m for the two floors)
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 (98 m^2), Uniformly Distributed
Type of Glass	6 mm Single glazing
Solar Absorbance (for Exterior Surfaces)	0.55 for external walls (medium color) 0.35 for the roof (light color)
Exterior Walls	**Dhahran:** 15mm Stucco + 200 mm CMU Hollow Block + 15mm Stucco **Riyadh:** 15mm Stucco + 200 mm CMU Hollow Block (with insulation insert material) + 15mm Stucco
Roof	Tiles + 10 mm Mortar + 4 mm Membrane + 100mm LWC + 200 mm Hourdi Slab + 15 mm Cement Plaster
Floor	100 mm slab on grade
Occupancy Density	6 People
Lighting Power Density	10 W/m^2 (Ground Floor), 8 W/m^2 (1^{st} Floor)
Equipment Power Density	12 W/m^2 (Ground Floor), 5 W/m^2 (1^{st} Floor)
Infiltration	0.5 ACH
System Type	Residential System (Constant-Volume DX AC) with Electric Heating
Thermostat	Two-Position with Cooling & Heating
Thermostat Setting	25ºC for Cooling, 21ºC for Heating
COP	2.87
Weather File	Dhahran:2002, Riyadh: TMY (1983-1999)

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 as shown in Figure 1. The figures also show the minimum requirement for thermal resistance for walls and roofs assemblies with various window-to-wall ratios based on International Energy Conservation Code (IECC, 2000).

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 2 where Design#1 is the base case.



(a) (b)

Figure 1 Thermal Characterstics of Possible (a) Wall Assemblies and (b) Roof Assemblies in Saudi Arabia

Table 2 Selected Building Envelopes for Energy Simulation in Residential Buildings in Saudi Arabia

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

Internal heat gain emitted by people, lighting and appliances has a significant impact on total heat load and consequently energy consumption. For the purpose of this study, the number of people, their schedules and activity, lighting and appliances and their operation schedules is based on previous energy studies of residential buildings in Saudi Arabia as shown in Table 3. (Ahmed and Elhadidy 2002, Said and Abdelrahman 1989, and Ahmed 1991).

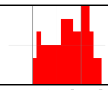
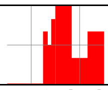
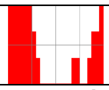
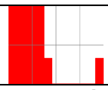
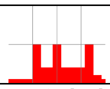
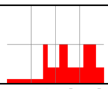
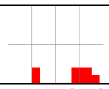
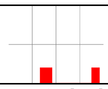
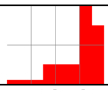
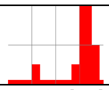
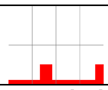
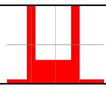
DISCUSSION OF RESULTS

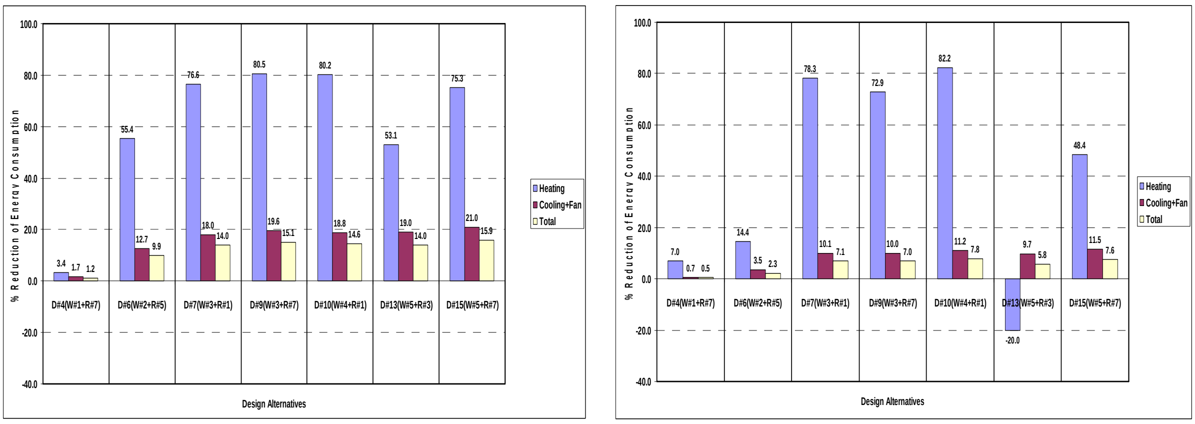
Utilizing VisualDOE4.1, the base case model for the residential building in Dhahran and Riyadh is simulated and the annual total energy consumption is 117,750 kWh and 101,450 kWh for Dhahran and Riyadh respectively. In terms of energy intensity, the energy index for residential building in Dhahran and Riyadh is 196 and 169 kWh/m^2/year respectively. For comparison purposes, studies in Dhahran show that the average energy intensity for poorly insulated residential buildings is 263 kWh/m^2/year and for properly insulated buildings is 153 kWh/m^2/year (Ahmed, 2004).

IMPACT OF ENVELOPE DESIGNS ON ENERGY PERFORMANCE OF RESIDENTIAL BUILDING

Figure 2 shows the impact of the selected eight designs (combination of wall and roof designs) on the annual heating, cooling and total energy consumption. In Dhahran, the reduction in energy consumption ranges from 1.2% for D#4 to 15.9% for D#15 as shown in Figure 2 whereas in Riyadh the reduction in energy consumption ranges from 0.5% for D#4 to 7.8% for D#10. While all envelope designs reduces both the heating and cooling energy in Dhahran, some designs perform better in reducing the heating energy and others are better in reducing the cooling energy. In Riyadh, the effect of both the low thermal mass in Wall#5 and the interior thermal insulation in Roof#3 on increasing the heating energy (20%) is clear. It is interesting to note that although Roof#1 is poorly insulated but performed well when combined with insulated wall designs. It is worth mentioning that all roofs are considered with light color as revealed from the questionnaire.

Table 3 Occupancy, Lighting, Equipment and Domestic Hot Water Profiles for Living and Sleeping Zones in Residential Buildings

	Living Area		**Sleeping Area**	
	Weekdays	**Weekends**	**Weekdays**	**Weekends**
Occupancy 100% (6 People)	 0% (23h-5h), 33% (6), 67% (7h), 50% (8h-12h) , 83% (13h-15h), 67% (16h-17h), 100% (18h-19h), 67% (20h), 33% (21-22h)	 0% (24h-8h), 67% (9h), 50% (10h), 83% (11h), 100% (12h-15h) , 33% (16h-19h), 67% (20h-23h)	 100% (23h-5h), 67% (6h), 33% (7h), 0% (8h-15h), 33% (16h-17h), 0% (18h-19h), 33% (20h), 67% (21-22h)	 100% (24h-8h), 33% (9h-10h), 0% (11h-21h), 33% (22h-23h)
Home Appliances 100% (12 W/m^2 for Living Area and 5 W/m^2 for Sleeping Area)	 5% (23h-5h), 50% (6h-7h), 20% (8h-10h) , 50% (11h-12h), 20% (13h-18h) , 50% (19h-20h), 10% (21h-22h)	 5% (24h-8h), 50% (9h), 20% (10h-12h) , 50% (13h-14h), 20% (15h-18h), 50% (19h-21h), 20% (22h-23h)	 0% (23h-5h), 20% (6h-7h), 0% (8h-15h) , 20% (16h-20h), 10% (21h-22h)	 0% (23h-7h), 20% (8h-10h), 0% (11h-20h) , 20% (21h-22h),
Lighting 100% (10 W/m^2 for Living Area and 8 W/m^2 for Sleeping Area)	 5% (23h-5h), 50% (6h-8h), 25% (9h-17h) , 100% (18h-20h), 75% (21h-22h)	 5%(1h-8h), 25% (9h-17h), 100% (18h-20h), 75% (21h-23h)	 5% (23h-5h), 25% (6h-7h), 5% (8h-15h), 25% (16h-17h), 100% (18h-20h), 50% (21h-22h)	 5% (24h-7h), 25% (8h-10h), 5% (11h-21h), 25% (22h-23h),
	All Days			
Hot Water 100% (1 gpm)	 5%(18h-4h), 100% (5h-6h), 30% (7h-15h) , 100% (16h-17h)			



(a) (b)

Figure 2 Impact of Envelope Designs on Energy Consumption of Residential Building in (a) Dhahran and (b) Riyadh

IMPACT OF GLAZING TYPES ON ENERGY PERFORMANCE OF RESIDENTIAL BUILDING

Glazed windows are becoming an important component of contemporary architecture and increasingly used in the design of buildings. With many benefits that the glazed windows do offer to the occupants and the designers, they are not free of introducing problems if they are not properly selected. While many glazing types are available in market today, four glazing types are evaluated to assess the impact of their thermal characteristics on energy consumption. The thermal and physical properties are presented in Table 4.

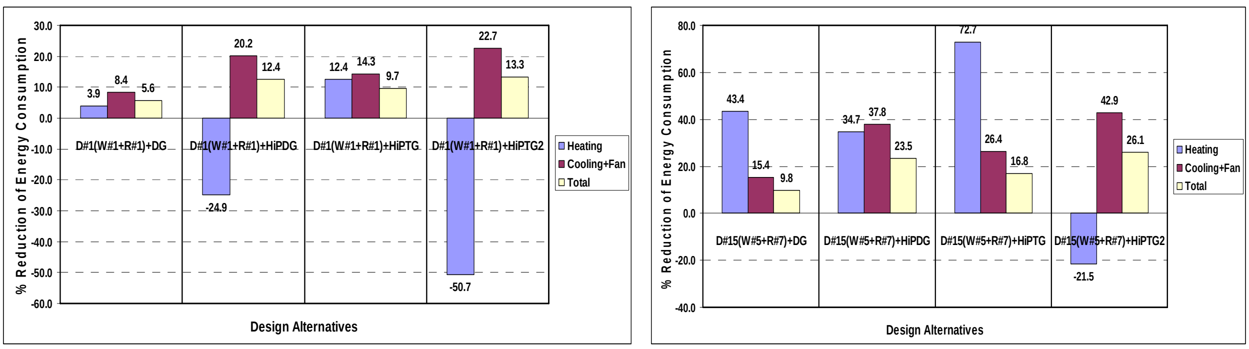
Table 4 Thermal and Physical Characteristics of Evaluated Glazing Types

Description	**# of glazing**	**U-Factor ($W/m^2.K$)**	**SC**	**SHGC**	**VT**
Single Clear 6 mm	1	6.172	0.95	0.82	0.88
DG 3/12/3 mm	2	2.788	0.71	0.613	0.743
HiPDG Tint Low-e4 Argon 6/12/6 mm (e2=0.04)	2	1.317	0.32	0.278	0.407
HiPTG-1 Clear 2Low-e1 Argon 3/12/3/12/3 mm (e2=e5=0.1)	3	0.772	0.55	0.471	0.656
HiPTG-2 Tint HM33 6/12/0/12/6 mm	3	1.198	0.17	0.149	0.168

Notes:

DG: Double Green Glazing
HiPDG : High Performance Double Glazing
SC: Shading Coefficient
VT: Visible Transmittance
HiPTG : High Performance Triple Glazing
SHGC: Solar Heat Gain Coefficient

Figure 3 shows the profile of heating, cooling and total energy consumption when various glazing types are applied to the base case (D#1) and to the well insulated design D#15 in Dhahran. As the thermal resistance of the glazing increases, the total and cooling energy consumption decreases. However and in some instances, heating energy increases due to high shading coefficient. For example, the triple glazing-1 has a thermal resistance that is more than that of the double glazing (50% more) but it admits more solar radiation to the space (high SHGC). As a result, triple glazing-1 performs better in terms of its heating energy (i.e. reduces heating energy due to the utilization of solar radiation for heating purposes in winter) but less improvement in reducing cooling energy is observed when compared to double glazing. When the thermal resistance and solar heat gain coefficient of triple glazing are reduced to the level of Double glazing (case: HiPTG-2), the heating energy increases with a significant reduction in cooling energy. It is noticed that the reduction in energy consumption for the well insulated designs are more than those achieved with poorly insulated designs. Therefore, the high performance glazing is more efficient with insulated designs than the poorly insulated design. It is clear that to achieve a significant reduction in total energy consumption, a proper combination of thermal resistance (R-value) and solar heat gain coefficient (SHGC) of glazing system is important. A similar discussion is also found when Riyadh climatic condition is considered.



(a) (b)

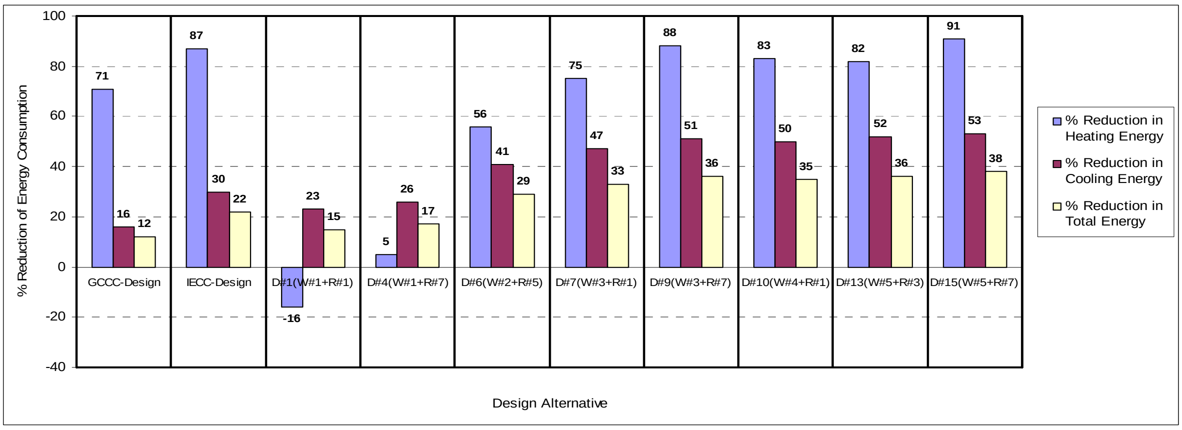
Figure 3 Impact of Glazing Types on Energy Consumption of (a) Base Case (D#1) and (b) Insulated Design (D#15) Residential Building in Dhahran

COMBINED EFFECT OF ENVELOPE DESIGN PARAMETERS ON ENERGY CONSUMPTION OF RESIDENTIAL BUILDING

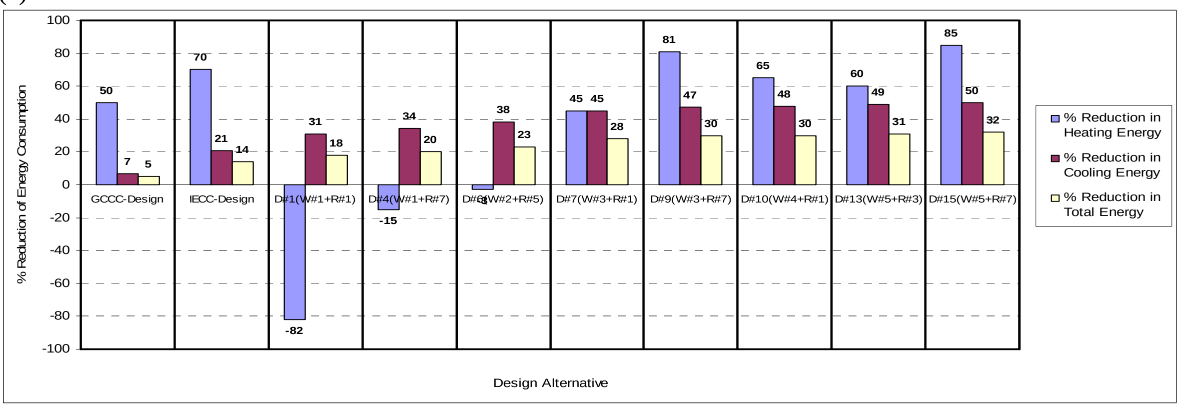
The impact of individual design alternatives on heating, cooling and total energy consumption has been investigated. This section evaluates the combined effect of the envelope designs and passive strategies on the energy consumption and is compared to the recommended envelope design requirements from the international energy conservation code (IECC 2000) and the Gulf Countries Cooperative Council (GCCC) thermal insulation requirement (1984). The GCCC regulations are prescriptive in nature and ignore the credit of glazing characteristics and the air infiltration limits.

For the base case (WWR=0.2) residential building to meet the IECC requirements, a wall with an R-value of 1.96 m^2.K/W, a roof with an R-value of 5.88 m^2.K/W and a window with a U-value of 3.321 W/m^2.K are selected in the design of the building envelope. For the same building to meet the GCCC regulations, a wall with an R-value of 1.43 m^2.K/W and a roof with an R-value of 2.041 m^2.K/W are selected keeping other parameters constant (0.5 ACH and single clear glazing). These designs are referred as IECC design and GCCC design. The selected eight designs are evaluated under a high performance double glazing (U-value= 1.317 W/ m^2.K, SHGC= 0.278) and a 0.35 ACH air infiltration.

Figure 4 shows the impact of envelope designs, high performance glazing, and reduced air infiltration on the reduction of heating, cooling and total energy consumption in Dhahran and Riyadh. The figure shows that reducing the air infiltration to 0.35 ACH and using a high performance glazing can reduce the total energy consumption by 15% for poorly insulated design (D#1) in Dhahran and 18% in Riyadh. For the well insulated design (D#15), the total energy consumption is reduced by 38% in Dhahran and 32% in Riyadh.



(a)



(b)

Figure 4 Combined Effects of Thermal Envelope Design Parameters on Energy Consumption of Residential Building in (a) Dhahran and (b) Riyadh

Table 5 shows the energy intensity of the base case residential building and the evaluated 8 envelope designs. The energy intensity of the base case residential building is 196 kWh/m^2/year and for well insulated design (D#15) is 123 kWh/m^2/year compared to 263 kWh/m^2/year for a typical non-insulated and well insulated residential housing in Dhahran (Ahmed, 2004). Under Riyadh climatic condition, the energy intensity of the base case residential building (D#1) is 169 kWh/m^2/year and for the well insulated design (D#15) is 115 kWh/m^2/year. Additionally, the energy intensity of the residential building with envelope design recommended by GCCC regulations and IECC is 172 and 153 kWh/m^2/year for Dhahran and is 161 and 145 kWh/m^2/year for Riyadh.

Table 5 Combined Effects of Thermal Envelope Design Parameters on Energy Intensity of Residential Building in Dhahran and Riyadh

Alternative	**Energy Intensity (kWh/m^2/year)**	
	Dhahran	**Riyadh**
Design#1(W#1+R#1)- Base Case (S-Glaz)	196*	169
Design (GCCC Regul.)	172	161
Design (IECC)	153	145
Design#1(W#1+R#1)+ Final Case	168	138
Design#4(W#1+R#7)+ Final Case	163	134
Design#6(W#2+R#5)+ Final Case	140	130
Design#7(W#3+R#1)+ Final Case	131	121
Design#9(W#3+R#7)+ Final Case	126	118
Design#10(W#4+R#1) +Final Case	128	118
Design#13(W#5+R#3) +Final Case	126	117
Design#15(W#5+R#7) +Final Case	123**	115

Notes:

* Energy Intensity of Typical non-Insulated Residential Building in Dhahran= 263 (kWh/m^2/year) (Ahmed, 2004)

** Energy Intensity of Typical insulated Residential Building in Dhahran= 153 (kWh/m^2/year) (Ahmed, 2004)

In Dhahran, when IECC envelope design is selected as a benchmark, the energy intensity is met with D#6 (wall R-value= 0.83 m^2.K/W and roof R-value= 4.35 m^2.K/W) onwards while GCCC regulation is met with D#1(wall R-value= 0.34 m^2.K/W and a roof R-value= 1.69 m^2.K/W). It is clear that the envelope design can meet the IECC requirement even when the roof is poorly insulated (R-value=1.60 m^2.K/W) as is the case for D#7. However, the wall R-value has to be at least equal to or more than 2.44 m^2.K/W with high performance glazing (U-value 1.317 W/m^2.K, SHGC=0.278) and reduced air infiltration (0.35 ACH). In Riyadh, it is observed that the poorly insulated design D#1 (wall R-value= 0.61 m^2.K/W and a roof R-value= 1.69 m^2.K/W) comply with both GCCC regulations and IECC requirements with the use of high performance double glazing and reduced air infiltration (0.35 ACH). If proper envelope designs are implemented in hot climates of Saudi Arabia, the total energy consumption of residential buildings can significantly be reduced by 20% below the International Energy Conservation Code (IECC) proposed design.

CONCLUSIONS

The base case residential building was identified through a questionnaire survey and was simulated under climatic condition of Dhahran and Riyadh. Eight envelope designs were selected to represent a wide variation of thermal characteristics in the design of building envelope. The energy performance of the selected envelope designs was evaluated under the climatic conditions of both cities. The reduction in annual total energy consumption ranged from 1.2% for D#4 to 15.9% for D#15 in Dhahran and ranged from 0.5% for D#4 to 7.8% for D#15 for Riyadh. Different high performance glazing types were also evaluated with poorly insulated design (D#1) and well insulated design (D#15). It was found that both thermal characteristics (R-value) and solar characteristics (SHGC) are to be carefully selected to achieve high energy reduction in hot climates. Additionally, it was found that high performance glazing is more efficient with well insulated designs than poorly insulated designs. The selected eight envelope designs with high performance double glazing were simulated when the air infiltration is reduced to minimum and compared to International Energy Conservation Code (IECC 2000) and Gulf Corporation Country Council thermal insulation requirements (GCCC 1984). For the building in Dhahran to meet the GCCC regulations, the wall R-value should be 0.34 m^2.K/W and the roof R-value should be 1.69 m^2.K/W. On the other hand, if the building is to meet the IECC requirements, the:

1) wall R-value should 0.83 m^2.K/W and the roof R-value should be 4.35 m^2.K/W.

OR

2) wall R-value is 2.44 m^2.K/W and the roof R-value should be 1.6 m^2.K/W.

For the same building in Riyadh to comply with both GCCC and IECC requirements the wall R-value should be 0.61 m^2.K/W and the roof R-value is 1.69 m^2.K/W. All above guidelines are applicable if high performance glazing with a U-value of 1.317 W/m^2.K and SHGC=0.278 is used and a reduced air infiltration (0.35 ACH) is achieved.

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