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Climatic exterior walls in residential buildings of Yazd

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Abstract

This paper deals with evaluating the thermal behavior of exterior walls in dwellings of a particular place. Today, there is a huge increase in constructing multi-storey apartment buildings and single-family houses in the city of Yazd, a city with hot dry climate and a rich historical architecture in Iran. Unfortunately, the new methods that are used nowadays to make the envelopes of these dwellings are not suitable for the climate of the city, so they are not sustainable. The aim of this study is to evaluate the thermal properties of all types of applicable walls and recommend suitable exterior walls that are constructed of common materials in the region to improve comfort and energy conservation. The procedure of the research includes two parts: at first the climatic characteristics of Yazd is Studied. At the second part, to define the most suitable wall, effective thermal properties of the walls are calculated in none steady-state conditions. These properties are calculated for the walls with different types and thicknesses of common material layers in various positions. At last, a comprehensive compare between thermal properties of the different walls is done and sustainable envelopes ─exterior walls that are suitable for both cold and hot seasons in Yazd─ are defined. In the result section, the types, thicknesses, and positions of the layers of the recommended walls in four directions of acceptable building orientation (that is +15 degree towards east-south) are defined, and the needed amount of mass and insulation as well as their relative positions is discussed. Furthermore, sun porch as a suitable passive heating system for cold seasons is suggested in some directions.

Keywords: *Climatic exterior wall, Thermal properties, None-steady state conditions, Yazd.*

1. Introduction

The city of Yazd is located in the central desert of Iran. It has a rich historical architecture that is built of heavy mass, thick adobe walls, and vaulted roofs. The climate of Yazd is hot and dry with large diurnal temperature range, intense solar radiation, very low rate of raining, and relative humidity.

Some climatic characteristics of Yazd include the followings:

In summer, maximum mean temperature is 37.2°C; minimum mean temperature is 21.2°C, and mean daily range is about 15 to 17°C. In winter, maximum mean temperature is 16°C; minimum mean temperature is 2.6°C, and mean daily range is about 13 to 13.5°C. Maximum mean relative humidity is 73%, and minimum mean relative humidity is 12%. The amount of precipitation is about 61.5 mm in a year. The percent of sunshine hours is 63% in winter, 69% in spring, 83% in summer, and 75% in autumn. Also, the amount of heating degree days (1337.4) is more than cooling degree days (1190.1). Table1 shows Monthly Maximum and Minimum mean temperature in Yazd.

Today, there is a huge increase in constructing multi-storey apartment buildings and single-family houses in Yazd. Unfortunately, the new methods that are used nowadays to make the envelopes of these dwellings are not suitable for the climate of the city, so they are not sustainable. As explained, the aim of this paper is to recommend suitable exterior walls in Yazd.

2. Methodology

Nowadays 3 types of exterior walls are used in residential buildings: 20cm thick brick walls, 20cm thick clay block walls, and 30cm thick brick walls (for load-bearing walls). The insulation is applied rarely in dwellings.To reach the most sustainable ones, we need to evaluate thermal properties of applicable walls that are composed of the materials mentioned above. High daily temperature range makes it necessary to use materials with high heat capacity to reduce the indoor swing and to stabilize the indoor conditions. So this point has been regarded in the test walls investigated by the authors. Test walls (T-W) are some applicable walls (insulated and none-insulated) in Yazd. Details of them are shown in the Fig. 1 and 2.

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Table 1 Monthly Maximum and Minimum mean temperature in Yazd [1]

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Maximum mean temperature	12.3	15.5	20.2	26.5	32.1	37.7	39.4	37.9	34.3	27.5	19.9	14.3
Minimum mean temperature	-0.5	1.8	6.6	12.4	17.4	22.2	24.3	21.8	17.4	11.2	4.8	0.6
Mean daily range	12.8	13.7	13.6	14.1	14.7	15.5	15.1	16.1	16.9	16.3	15.1	13.7

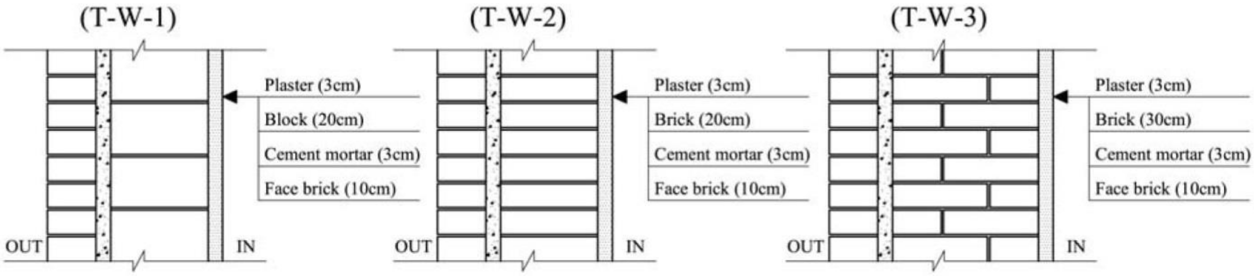

Fig. 1. Details of none-insulated exterior walls' structures

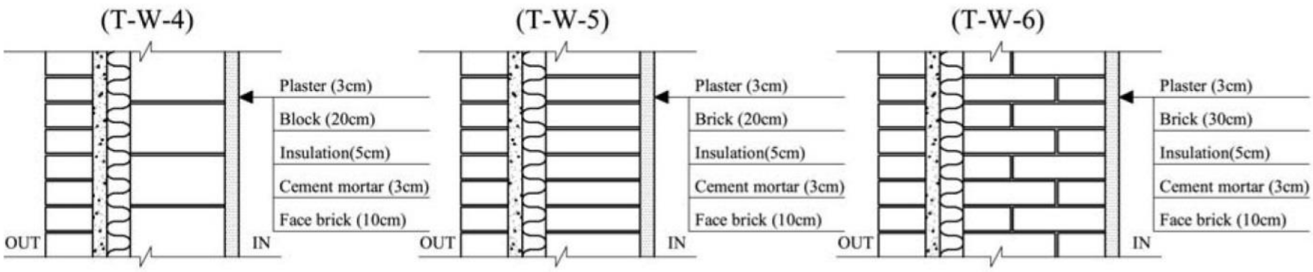

Fig. 2. Details of insulated exterior walls' structures

To evaluate thermal behavior of exterior walls, we need to answer the following 2 questions:

- What is the impact of dark color envelopes on the heat gain of the buildings in winter? (Is it useful to absorb maximum solar radiation on the external surface of the walls and transfer it to the interior space by conduction in cold months of the year?)

- Is it possible to keep the interior space always in a comfort zone by using walls consisting of high heat capacity materials or insulated external walls?

To answer the first question, the amount of solar energy striking and absorbed at the external surface of the walls are calculated in 3 directions of acceptable building orientation (south, west, and east), then sol-air temperature of them is estimated. To analyze the heat transferred through the walls, time lag and decrement factor are taken into account. The procedure of estimation is discussed later.

To answer the second question, a complete comparison between thermal performance of applicable walls (insulated and none-insulated) is done in none-steady state conditions and the most suitable walls are defined. Factors applied for comparing the test walls are presented later.

3. Calculating the Internal Surface Temperature of External None-Insulated Walls

In this section, the impact of dark-color exterior walls on the heat gain of the buildings is investigated. As mentioned before, the common walls in the region are made of bricks and cavity blocks, but the most usual façade materials for exterior walls are: face brick, granite stone, and kahgel (a mix of mud and straw used to cover the walls of the buildings in old Iranian architecture). It can be seen from the Table 1, that face brick has the most suitable thermal properties. Its heat capacity (product of density and specific heat) is more than kahgel, and its conductivity is less than stone. Furthermore, it is the most suitable one regarding the aspects of being in harmony with the urban view and historical region, easy application, and being economic. So in this research, face brick is chosen as a suitable facade material for the test walls. The interior finishing of the test walls is "plaster", which is common in the region. Fig. 1 shows the details of none-insulated exterior walls' structures.

Table 2 shows the test walls' decrement factor and time lag that have been calculated using thermal properties of the materials presented in the Table 1.

Table 2 The thermal properties of the structural components of the test walls

	density (Kg/m^3)	conductivity $(W/m.K)$	Specific heat $(J/Kg.K)$
face brick	1350	0.6	840
granite stone	2880	3.49	840
kahgel	720	0.23	840
Plaster	1680	0.81	840
Brick	1700	0.84	800
Clay block	1350	0.6	840
Cement mortar	1650	0.72	920

Table 3 Time lag and decrement factor of the test walls [2]

	T-W-1	T-W-2	T-W-3
Timelag	7.737	9.922	14.091
Decrement factor	0.376	0.281	0.124

In the next step, the amount of radiation striking and absorbed at the external surfaces and the sol-air temperature (T_{sa}) of the walls in 3 directions (south, east and west) are calculated using two various absorptivity of face bricks (a=0.4 for cream bricks and a=0.7 for brown ones). In calculating the sol-air temperature of the walls, the maximum temperature of the surface is taken into account. So time lag and decrement factor of a wall can determine the maximum temperature of internal surface and its time [2].

The results of estimations presented in Table 3 shows that even with brown face bricks, the maximum internal surface temperature (T_{in}) is less than the lower boundary of the human comfort zone. So the heat transferred through the walls by conduction does not have effective impact on heating the indoor spaces. Furthermore, from the practical aspect in the climate of Yazd with large diurnal temperature range, when direct radiation decreases in the early evening, outside temperature drops rapidly, so the heat stored in the external layers of the wall transfers to the outside.

Table 3 maximum sol-air temperature (T_{sa}) and maximum internal surface temperature (T_{in}) in°C for test walls, that is calculated in 15 December(outside temperature=14.3°C). [2]

	south			east			west		
Test walls	T-W-1	T-W-2	T-W-3	T-W-1	T-W-2	T-W-3	T-W-1	T-W-2	T-W-3
T_{sa}(a=0.4)	29.1	29.1	29.1	14.8	14.8	14.8	27.2	27.2	27.2
T_{in}(a=0.4)	10.94	8.18	3.61	5.6	4.2	1.8	10.2	7.6	3.4
T_{sa}(a=0.7)	43.3	43.3	43.3	16.6	16.6	16.6	38.8	38.8	38.8
T_{in}(a=0.7)	16.28	12.17	5.37	6.2	4.7	2	14.6	10.9	4.8

Investigating outdoor diurnal temperature range shows that in 3 months of the year, outdoor temperature is always below the limit of human comfort zone, and this causes heat transfer from inside to outside permanently. However, just in sunny days when the intense radiation strikes at the external surface of the walls, the flow of heat conduction from internal surface to external surface is reversed (outside-inside) due to solar radiation for a few hours, so none-insulated massive walls do not operate properly in cold months of Yazd.

4. Comparing The Thermal Properties Of Insulated And None-Insulated Walls:

In the previous part, thermal performance of none-insulated walls was evaluated in cold months of the year. In this part, some guidelines that indicate massive walls are not suitable as well in hot months are investigated as below:

- The studies of Olygay has shown that "when the mean outdoor temperature is expected to be 29°C or higher, heavyweight construction by itself will not stabilize temperatures in the comfort range [4]". In the climate of Yazd, in 3 months of the year, the mean outdoor temperature is higher than 29°C (29.95°C in June, 31.85°C in July and 29.85°C in August). So none-insulated walls do not operate properly in these months.

Givoni has recommended two concepts of required thermal resistance of the exterior walls ,R_{req}, and total mass of the building per unit area of the envelope ,M_{req/m^2}, that represents needed heat capacity of the walls in regions with hot dry climate as followings[5]:

$$R_{req} = 0.05\times\left(T_{(o)max} - 25\right) + 0.002\times\left(a\times I_{max}\right) \quad (1)$$

$$M_{req/m^2} = 2.5\times\left(T_{(o)max} - T_{(o)min}\right) + 0.1\times\left(a\times I_{max}\right) \quad (2)$$

In these formulas, $T_{(o)max}$ is the average maximum air temperature; $T_{(o)min}$ is the average minimum air temperature; I_{max} is the Global (horizontal) solar radiation, and a is the absorptivity of the external surface that is 0.4 for cream face bricks. The recommended thermal resistance of the exterior walls in Yazd - that is calculated by the authors using meteorological data- is 1.554 m².C/W and total mass of the building per unit area of the envelope is 358.576 kg/m³.

It can be seen from Table 4 that total mass of T-W-3 per unit area (M) is more than requested heat capacity in Yazd (M_{req}). The amount of M for T-W-2 is close to M_{req} and that for T-W-1 is less than M_{req}. Furthermore, resistance (R) of all none-insulated walls (T-W-1,2,3) is not enough for the climate of Yazd. As explained, the studies of Olygay and Givoni indicate that it is necessary to use insulation in the structures of the exterior walls to elevate thermal resistance of the envelope in this city. So 3 other test walls are recommended (T-W-4,5,6 shown in Fig. 2). In these test walls, the insulation layer is placed at the external part of TW- 1,2,3.

In the last part of the research in order to compare thermal behavior of the test walls, some more properties are calculated and presented in Table 4. The factors that are effective in none-steady state conditions are explained here: [6]

Volumetric heat capacity (C_v): describes the ability of a given volume of a substance to store internal energy while undergoing a given temperature change, but without undergoing a phase change. It is different from specific heat capacity in that the C_v depends on the volume of the material, while the specific heat is based on the mass of the material. It is obtained by multiplying the specific heat by the density of the substance.

Thermal diffusivity (U): Thermal diffusivity is the thermal conductivity divided by density and specific heat capacity at constant pressure. It measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy.

Thermal admittance (Y): The ratio of flow of heat between the internal surfaces of the structure and the environmental temperature in the space, for each degree of deviation of that temperature about its mean value.

Decrement factor (f) and Time lag (ф): The decrement factor is the ratio of the rate of heat flow through the structure, due to variations in the external heat transfer temperature from its mean value with the environmental temperature held constant, to the steady state conduction. The associated time dependency takes the form of a time lag.

Surface factor (F): The ratio of the variation of radiant heat flow about its mean value readmitted to the space from the surface, to the variation of heat flow about its mean value incident upon the surface.

Analyses of these factors show that Volumetric heat capacity (C_v), Thermal admittance (Y), and Surface factor (F) of all test walls are almost similar to each other. The longest time lag (ф) is related to T-W-6 and the shortest is related to T-W-1. All the insulated test walls (T-W-4,5,6) have the needed resistance,R_{req}, in the climate of Yazd (more than 1.554 m².C/W), but just T-W-6 has the needed M_{req}. However, the amount of M for T-W-5 is close to M_{req}.

Table 4 Thermal properties of the test walls. [2,3]

	R	M	Cv	U	Y	f	ф	F	TTC	DHC
T-W-1	0.76	270	1171.7	1.954	4.35	0.376	7.74	0.536	13.9	<150
T-W-2	0.67	340	1225.2	1.552	4.55	0.281	9.92	0.548	14.1	150
T-W-3	0.81	544	1186.1	1.184	4.55	0.124	14.1	0.547	26.4	>150
T-W-4	2.11	270	1119	0.267	5.11	0.391	10.3	0.475	48.3	<150
T-W-5	2.02	340	1119	0.245	4.68	0.344	11.4	0.53	54.3	150
T-W-6	2.16	544	1111	0.214	4.58	0.132	15.5	0.548	93.3	>150

There are two important composite properties that determine effective mass of a building. These factors are: TTC and DHC that are explained below[5]:

- Thermal time constant (TTC): TTC of an envelope element is the main property in un-air conditioned buildings, and it determines the effect of the element on the damping of the indoor temperature swing relative to the outdoor swing. It depends on the organization (sequence) of the layers of which the element is composed. When the insulation layer is external, TTC will increases. So in the test walls, insulation layer is recommended between façade material and internal mass.

- Diurnal heat capacity (DHC): The DHC of the building determines its capacity to absorb heat from the interior space and to release the absorbed heat back to interior air during the night hours. It depends mainly on the properties of the layer directly exposed to the interior air. So in the test walls, massive layer is placed close to interior space.

TTC and DHC of the test walls are calculated and presented in the Table 4. It can be seen that applying insulation layer and increasing the thickness of brick layer will significantly elevate TTC. Also, the amount of DHC depends on the thickness of the brick layer that is exposed to the interior air. So T-W-6 has the most amount of TTC, and DHC has the most effective impact on stabilizing indoor temperature.

5. Results and Discussion

As explained, there are 2 types of dwellings in Yazd: multi-storey apartments and row houses. In most of the row houses, exterior walls have the role of structural elements (load-bearing walls). Therefore T-W-6 could be a good choice for these types of residential buildings, but in multi-storey apartments, decreasing dead load weight of structure is one of the main purposes of the design. So if it is possible to provide needed mass via ceiling material (concrete), applying T-W-5 or even T-W-4 will seem more reasonable. However, they are not as effective as T-W-6. In this condition it is necessary to place the mechanical systems of the building (like pipes) on the floor. Also, false ceiling must be omitted.

As discussed, it is not possible to gain heat through exterior walls, so solar passive heating systems are investigated by the authors in order to increase heat gain in cold months. The most suitable passive heating system in hot-dry climate of Yazd is sunporch which can be applied just in southern side of the building. In row houses, if enough mass is provided in sunporches (to reduce temperature range), it will be possible to apply T-W-3 as common wall between sunporch and interior space. However, applying insulation layer improves thermal performance of exterior walls. In Table 5, sustainable exterior walls made of common materials are presented in 4 directions for the climate of Yazd.

Table 5 Sustainable exterior walls in the climate of Yazd

	South	West /East /South
Apartment buildings	T-W-4 (with or without sunporch)*	T-W-4*
	T-W-5 (with or without sunporch)	T-W-5
Row houses	T-W-6 (with or without sunporch)	T-W-6
	T-W-3 (just with sunporch)**	

*This type of wall is applied if only enough mass is provided by ceiling or other interior elements.

** This type of wall is applied if only sunporch with enough mass is accessible.

Notation

The Symbols used within this article are defined as follows.

- T_{sa} Maximum sol-air temperature (ºC)
- T_{in} Maximum internal surface temperature (ºC)
- $T_{(o)max}$ Average maximum air temperature (ºC)
- $T_{(o)min}$ Average minimum air temperature (ºC)
- I_{max} Global (horizontal) solar radiation (W/m^2)
- a Absorbtivity of the external surface (--)
- R_{req} Required thermal resistance (m².ºC/W)
- M_{req/m^2} Required total mass (kg/m³)
- M Total mass (kg/m³)
- R Thermal Resistance (m².ºC/W)
- C_v Volumetric heat capacity (J/m^3.K)
- U Thermal diffusivity (m²/s)
- Y Thermal admittance (W/m^2.K)
- f Decrement factor(--)
- ϕ Time lag (hrs)
- F Surface factor (--)
- DHC Diurnal heat capacity (W/m^2.ºC)
- TTC Thermal time constant (hrs)

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