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Thermal Analysis of Tibetan Vernacular Building - Case of Lhasa

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***Abstract*—**Vernacular building is considered as sustainable in energy consumption and environment and its thermal performance is more and more concerned by researchers. This paper investigates the thermal property of the vernacular building in Lhasa by theoretical analysis on the aspects of building form, envelope and materials etc. The values of thermal resistance and thermal capacity of the envelope are calculated and compared with the current China building code and modern building case. And it is concluded that Lhasa vernacular building meets the current China building code of thermal standards and have better performance in some aspects, which is achieved by various passive means with close response to local climate conditions.

***Keywords*—**Climate, Vernacular Building, Thermal Property, Passive Means

I. INTRODUCTION

IT is commonly acknowledged that vernacular architecture represents local tradition, culture and climates, thus the difference between regions lead to the diversity of vernacular architecture. In despite of the diversity, vernacular building around the world share the common characters of energy saving and environment friendly, which are approached by local building material and climate responsive strategies etc. By the fact that no electric power could be used to achieve thermal comfort in ancient time, passive means are mainly applied in building to provide thermal comfort by intellectual manipulation of spatial form and building elements which utilize the advantages of climate or resist the disadvantages. The knowledge of passive means is concluded by the long period of trial and error instead of the scientific guidance. Although the vernacular building has been accepted by local people for long, it is still necessary for a scientific understanding of whether and how the vernacular building could achieve thermal comfort by traditional passive means.

China has great variations of vernacular building in different climate regions. This paper aims at a scientific analysis of the thermal performance of Tibetan vernacular building. The representative building form and element of vernacular building in Lhasa is studied to analyze its thermal performance according to the standard of China building code of thermal design and energy conservation.

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II. CLIMATE ANALYSIS

Lhasa is in the cold climatic region of China, in terms of the definition that the temperature between 0 to -10℃ in the coldest month and 90 to 145 days when mean temperature is below 5 ℃ [1]. Lhasa is located in the East-south of Tibet at the altitude of 3600 meters on Qingzang plateau with the typical plateau climate characters of annual low temperature, intensive and long solar radiation, high diurnal temperature range and low and concentrative precipitation.

A. Annual Low Temperature

According to the China Typical Year weather data[2], the annual mean temperature is 8.5℃, and in most period of the year, the mean exterior daily temperature is below the thermal comfort zone and the mean temperature is -1.4℃in January and 16.4 in July respectively. The low temperature indicates that winter insulation is the main requirement is Lhasa building design.

Fig. 1Monthly diurnal average temperature and thermal comfort zone

B. Intensive and Long Solar Radiation

The annual mean direct solar radiation is about, which is twice as much as other cities on the same latitude [3]. the minim direct radiation is in January at 7141wh/㎡, and the maximum is in June at 10039wh/㎡. The strong solar radiation results from the high altitude of Lhasa as well as its high coefficient of atmospheric transparency, which is above 0.8 [4]. Also the annual sunlight hour number in Lhasa is 3006 hours, which is among the maxim in China [3]. This leads to the contradiction of utilization of passive solar heat and solar shading.

C. High Diurnal Temperature Range

From the Figure2, it can be seen that both in winter and summer, the diurnal temperature range fluctuates between 13 ℃ to 17 ℃. The mean range is about 15℃, which is much higher than that of the other cities on the same latitude which is below 9℃. The occurrence of mean lowest temperature in winter is between 6:00-7:00am, and the highest in summer is 16:00pm. The reason for this phenomenon is that the air temperature rises because of the heat gained from the strong solar radiation in daytime and decreases quickly at night when heat is radiated back into the sky from the surface of building and earth, due to the high atmosphere transparency, the radiated heat is of great amount to decrease the air temperature quickly. Accordingly high thermal capacity of the building exterior envelope should be focused according to this climatic character.

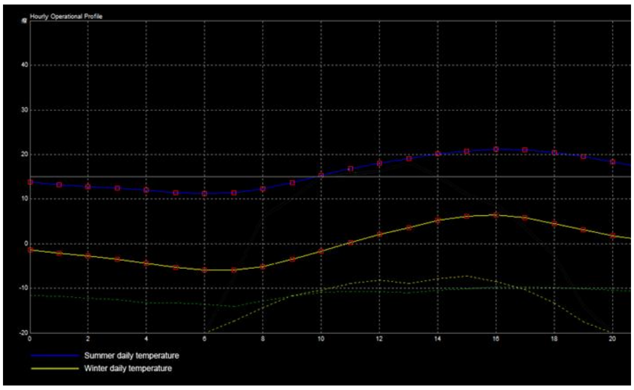

Fig. 2 Daily temperature in winter and summer

D. Low and Concentrative Precipitation

The rainy season in Lhasa is during June and September which takes 80% of the annual precipitation. Thus there is a distinguish time difference between rainy and arid season in the whole year. Thus water-proof is less considered in Lhasa than sun shading.

III. CHARACTERS OF LHASA VERNACULAR BUILDING

A. Building Materials

Materials used in Tibetan vernacular building mainly come from the local abundant and easily probable natural resource, like in many other cultures[5]. The materials include clay of high glutinosity which is used for wall and roof, stone slab for wall, sandstone, dried branch wood for insulation, and lath for floor. Dung is also used as weather proof for exterior walls. Locality and thrift are main requirements for building material; however glazing has also been employed in late vernacular building. Compared with all these materials, clay has the high density which is suitable for exterior envelop of high thermal capacity, and stone slab is also employed in exterior wall. However abundant local availability results in the feasibility of the heavy material portage.

B. Building Form and Opening

Tibetan vernacular building has very compact form of rectangle building plan, and the form is very simple with little variation. Courtyards are sometimes included in the plan of large residence building to allow daylight and solar radiation. The building height is generally between 2.2 to 2.6mters [6], which is much lower than modern standard of 3.3 meters. The compact form which can minimum the heat loss from the building envelop is the result of the local cold climate. However the compact form also reduces the solar heat gain in the daytime, thus south-oriented windows generally take large proportion of the south-side surface to allow winter sunshine inside, whereas those on the other sides are very small only for daylight and ventilation. Glazing is the part which causes the most heat loss in the building, thus thick curtain is used as insulation to prevent heat loss during night, and the space between functions as air-gap with high thermal resistance.

C. Massive Wall

Wall is the main envelop to define the interior space, In Tibet as a cold clime with high diurnal temperature range, wall also acts as heat storage to provide thermal comfort by the advantage of solar heat gain, which requires high density material and volume. The wall of Tibetan vernacular building ranges from 50 to 70 cm [6] , and in some non-domestic buildings such as temple; it could reach to 1 meter of width. There are two type of the massive wall, made of clay and stone slab of basalt and granite respectively [6]. In the clay wall type, stones are also partly employed in the foundation and quoins to avoid erosion of water, which is the general, mean for protection of soil wall in world-wide vernacular building [5], and clay is also used for cohesive purpose.

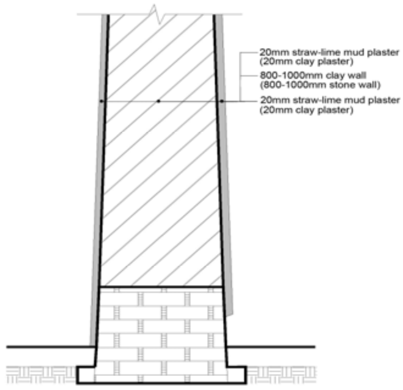

Fig. 3 Detail of exterior wall

D. Roof and Floor

Flat roof is the general type in most clime of Tibet of low precipitation including Lhasa, and is made of multi-layer structure of various materials of high R value. The high R value materials are employed to prevent heat loss from indoor to outside. Roof also acts as heat storage, but due to load limitation, roof has a thinner width and lower weight, with lower thermal capacity compared with wall. Two types of floor can usually be found in Lhasa vernacular building, one has the same structure as roof and in some higher standard building, and wood floor is used for softer and warmer surface by low heat absorption property.

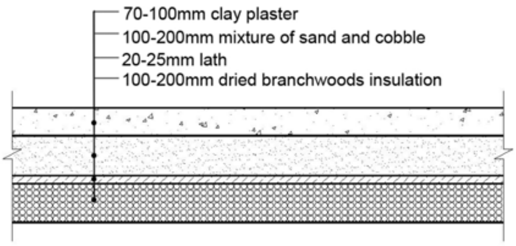

Fig. 4 Detail of roof

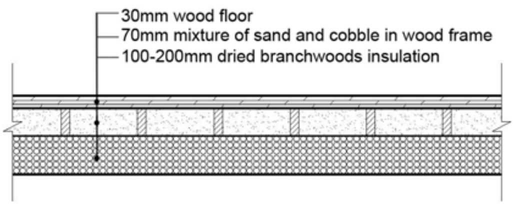

Fig. 5 Detail of floor

IV. Thermal Analysis of Representative Building

In Lhasa as a cold-arid clime with high diurnal temperature range and intensive solar radiation, use of thermal mass is the main passive strategy to achieve thermal comfort as well as minimum heat loss. According to the psychrometric chart, thermal comfort in Lhasa could be achieved by mass construction during summer and solar heat gain during spring and autumn passively. Meanwhile the level of insulation within the building envelope is directly correlated with the comfort zone by passive solar heating, which indicates that envelop of high thermal resistance is important for passive heating in this clime. Also active heating is still required during winter, and usually stove is placed in the central of room as the heating equipment in Lhasa vernacular building.

A. Surface-volume Ratio and Building Height

Surface-volume Ratio refers to the ratio of building envelop surface and the volume it embodies. This index has direct correlation with building energy consumption, the great the ratio means more surface exposed to the exterior which causes more heat loss. Thus the ratio is important in cold climate [9], which is the reason the compact form is generally employed in Tibet. According to China Design Standard for Energy Efficiency of Residential Building (GB 2006 Draft Version), the ratio of multi-storey domestic building for Lhasa region should be less than 0.55. For a typical two–storey vernacular building model with 15 meters wide and 8 meters length, the ratio is 0.58 which is slightly above the standard. The reason is that the total height of building is inversely correlated with SF ratio.

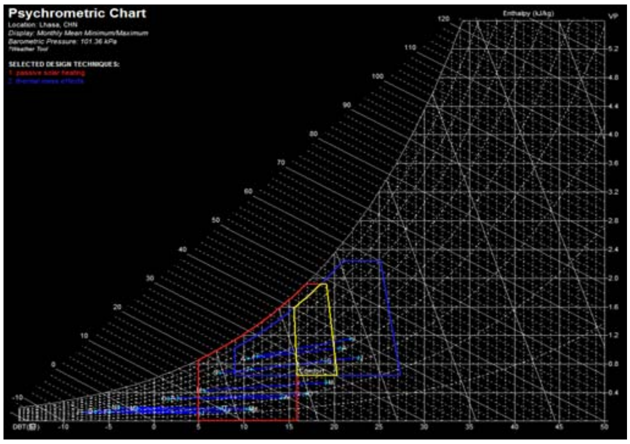

Fig. 6 Psychrometric chart

On the other hand, the lower building height reduces the exposed surface and the heat loss as well. According to the equation of energy consumption of heat transferred through the envelope.

$$q_{H.T} = (t_i - t_e)\left(\sum_{i=1}^{m} \xi_i \cdot K_i \cdot F_i\right) \Big/ A_0 \qquad (1)$$

Where F_i is the surface area of the building and A_0 is the 阿 area of building. If a is defined as the width of plan, b is the length, h is the storey height and n is the number of the stories, then equation(1) than can be transformed as:

$$q_{H.T} = (t_i - t_e)\left(\sum_{i=1}^{m} \xi_i \cdot K_i\right)\left(\frac{2(a+b)}{ab} \cdot h + \frac{1}{n}\right) \qquad (2)$$

It can be seen from the transformed equation that the $q_{H.T}$ value is correlated with h, which means the lower storey height causes less heat loss through the envelope.

B. Thermal Resistance

In terms of China thermal design code, a building of standard thermal insulation should achieve the following aspects as the basic standards: 1.the interior surface temperature above interior dew temperature 2. Minimize the cold radiation of interior surface 3.Minimum heat loss 4. Certain thermal capacity. According to the building design standards, the thermal resistance of envelop is the index to define the insulation capacity. And the minimum thermal resistance is defined as:

$$R_{0,\min} = \frac{(t_i - t_e)n}{[\Delta t]} R_i \qquad (3)$$

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Where t_i is winter indoor design temperature (℃), which is defined as 20℃ for high standard residence, t_e is winter outdoor design temperature (℃) which varies in terms of thermal inertia index, n is correction coefficient of temperature deviation whose value is 1 when the envelope has direct contact with exterior air, Δt is allowable temperature difference between internal surface of envelop and indoor air(℃) ,which is 6 for wall and 4 for flat roof in residence, R_i is internal surface thermal exchange resistance(㎡.K/W), which is defined as 0.11 ㎡.K/W.

According to the R comparison graph, it can be seen that both vernacular wall and roof meet the stand of minim thermal resistance in Lhasa, but vernacular wall does not have very good insulation property even at the thick width, of which clay wall has a better performance than stone wall, because that Roof is at the top of the building and of all building envelope is impacted most by climate [8].

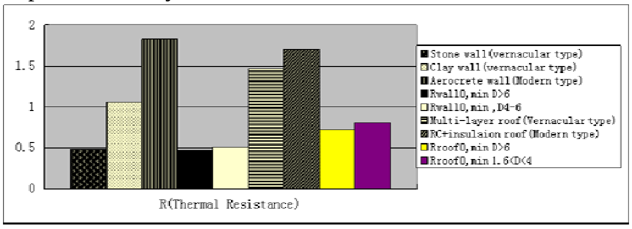

TABLE I
THERMAL COEFFICIENT OF MATERIALS*

Material	Rammed clay	Stone(granite)	Straw-lime mud	Dry branch	Sand	Reinforced concret	Aerocrete	Cement mortar
λ (W.m/K)	0.93	3.49	0.15	0.14	0.58	1.74	0.22	0.93
S(W/㎡.K)	11.03	25.49	2.8	3.58	8.26	17.20	3.59	11.37

*: Referred to China Building Code Of Thermal Design(GB 50176-93)

TABLE II
THERMAL PROPERTY OF ENVELOPE

Component		Width(mm)	Thermal Resistance(㎡.K/W)	Thermal Inertia
Vernacular Type	$wall_S$	600	0.48	4.91
	$wall_C$	600	1.06	7.86
	$Roof_{ver}$	525	1.46	19.72
Modern Type	$Wall_{Aerocrete}$	360	1.83	7.02
	$Roof_{RC}$	120+insulation	1.7	2.06

In order to meet the building code, two parameters of envelop are to be estimated, total thermal resistance and thermal inertia. The total thermal resistance of envelope is calculated by the equation:

$$R_0 = R_i + \Sigma \frac{d}{\lambda} + R_e \tag{4}$$

Where d is the width of envelop (m) and λ is the thermal conductivity coefficient of material (W.m/K) and the thermal inertia index is defined as:

$$D = R \cdot S \tag{5}$$

where R is the thermal resistance(㎡.K/W) and S is the thermal storage coefficient(W/㎡.K).

To better demonstrate the thermal property of vernacular building, a model of modern building case is applied for comparison. Therefore, in Lhasa domestic building the $R_{0,\ min}$ value of wall is 0.47 or 0.51㎡.K/W , when D value is above 6 or between 4-6, and that of roof is 0.72 or 0.80㎡.K/W, when D value is above 6 or between 1.6 - 4.

Roof receives no long wave radiation from other surfaces such earth or building, therefore the flat roof radiates heat back into the space without gaining, and may cause more heat loss during cold night. Thus high thermal resistance is essential for roof to minimum heat loss from inside to outside. Also it should be pointed out that the actual R value of roof will be greater than the calculated value because the air gap exists inside the layer of dried branch wood which will increase the thermal resistance.

C. Thermal capacity and time lag

Generally, in cold clime, thermal resistance is the key factor for insulation and thermal comfort by the hypothesis that interior temperature is stable and higher than exterior temperature. However in terms of Lhasa climate with strong solar radiation and high diurnal temperature range, thermal mass is a key passive mean to store solar heat in daytime and releases heat during night to moderate the internal surface temperature, on the other hand, thermal mass delays the cold temperature to reach the inside. Heavy wall and mass roof is employed in vernacular building for this purpose. Thermal capacity indicates the amount of heat absorbed by material to increase the [8], and is related with density and specific heat of a certain material.

$$Q = \rho \cdot c \quad (6)$$

Where ρ is the density (kg/m^3) and c is the specific heat (KJ/Kg.K)

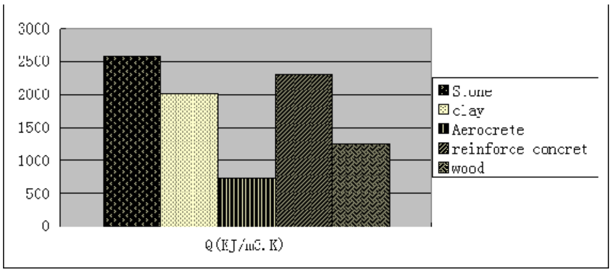

Fig. 8 Comparison of the Q value between different materials

Fig.8 shows the comparison of thermal capacity between vernacular and modern general used material. Apparent difference between the materials can be found, of which stone and clay have the pretty same performance as reinforced concrete, and much higher than aerocrete and they are much cheaper and more environmental friendly materials than the modern materials such as reinforced concrete, the abundant local availability also reduces the cost of manufacturing and transport. The two materials of vernacular building are suitable to achieve thermal mass effect in a sustainable way.

Thermal mass has the time lag effect of heat wave between the external temperature and internal surface temperature, which for example, causes the internal surface temperature decline after a time delay when the exterior temperature reaches its peak. The time lag is defined by the following equation:

$$\xi_0 = \frac{1}{15}\left(40.5\sum D + arctg\frac{Y_e}{Y_e + \alpha_e\sqrt{2}} - arctg\frac{\alpha_1}{\alpha_1 + Y_i\sqrt{2}}\right) \quad (7)$$

Where D is the thermal inertia, Y_e is the heat storage coefficient, α_i and α_e represent the coefficient of exterior and interior heat exchange respectively. The time lag of 600mm clay wall is therefore 19.8hours and that of stone wall is 12.5 hours.

In winter, time lag indicates how long it needs for the lowest temperature to get to the interior surface and then the interior surface temperature starts increasing to warm inside up or deduce the indoor heat load. The time lag also shows the difference of heat storage capacity between the two vernacular materials. According to Fig.2, as the lowest exterior temperature in winter is at 07:00, thus the lowest indoor surface temperature occurs at 03:00 the next day for clay wall and 19:30 for stone wall respectively. Vernacular wall does not have good insulation, which means more heat loss during cold night when indoor is actively heated, but the high thermal capacity decelerates the heat transfer from inside to outside, and when the internal temperature drops, the heat will radiate back into the inside room before it reaches the exterior surface. Thus high thermal capacity can be regarded as the compensation of low thermal resistance.

V. Conclusion

The main climate concerns in Lhasa are annual low temperature and high diurnal range, and the intensive solar radiation is the main climate advantage to utilize. Since fossil energy dependent system is hardly used to achieve thermal comfort, the main strategies are to minimum the heat loss and maxim the passive heat gain such as solar heat. Various passive means are employed to achieve this purpose, such as compact form, low storey height and thermal mass and local materials are made the best use of in the building envelope according to their thermal property as high heat storage and thermal resistance. By theoretical analysis, it is concluded that the thermal property of the building all meet the standards of current China building codes approximately for this clime, and even better performance in some aspects, by local materials and traditional technology. However further studies including on-site measurement are needed to fully understand the thermal performance of Tibetan vernacular building.

Acknowledgment

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