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A Scientific Study on the Performance of Iranian Ice-Pits

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Abstract

Functional use of sustainable energies has been significantly shown in Iranian traditional architecture. The old ice-pits are among the most extravagant architectural elements of the Iranian desert architecture indicating architects' precision and discerning towardsthe optimal use of green energies, the use of climate-friendly building materials, the use of clear sky radiation process at night to produce ice, benefiting cooling properties of domed roofs and underground warehouses, proper cooling to maintain the ice, and so forth. The main purpose of this study is to investigate scientifically the performance of Ice-pits which has been conducted as a case study in Iran. The present research as a descriptive-analytical studyassesses the various parts of ice-pits and the impact of each part on cooling performance of them. Finally, the experiments in the architecture of Iranian old ice-pits are compared with the numerical analysis.

Keywords: Sustainable development, ice-pits, sky radiation.

Introduction

Diverse climatic conditions of Iran have caused policies to be pondered for benefiting the facilities and coping with adverse weather conditions. In fact, there are many problems in the desert regions of Iran that the majority of them include water shortage, expansion of desert, blowing "winds of 120 days" in the Central Plateau, and exhausting heat. Since a long time ago, inhabitants of these lands have taken advantage of special measures to improve the conditions, cope with unfavorable climate, and optimally use the natural resources. All these measures have been based on the facilities found in the environment. There are still great ice-pits, although a few, around Iran resisted against thepassage of time and natural disasters such as earthquake and caused admiration and surprise[1].

Throughout the territory of Iran especially in desert regions with hot simmers and exhausting heat, ice has been considered as one of people'sessentials used for keeping foods safe in addition to cooling the drinking water. In this study, various parts of Iranian ice-pits are scientifically assessed. Actually, the results indicate the creativity of former Iranians. figures-1 and 2 showexamples of these extraordinary works:

The architecture of ice-pits: Any ice-pit is composed of three parts: the long shadowing wall, the ice making ponds, and the ice reservoir.

The long shadowing wall: The long shadowing wall has been a long wall extending from east to west. The height of this wall sometimes reached up to 10 meters so that frozen waters in the ponds could be prevented from the sunlight at day. In the case of being exposed to the sunlight from the east or west, lateral shadowing walls connected to the main wall were built in these places[2].

Figure-1
An ice-pit in Meybod-Iran

Figure-2
An ice-pit Shahroud-Iran

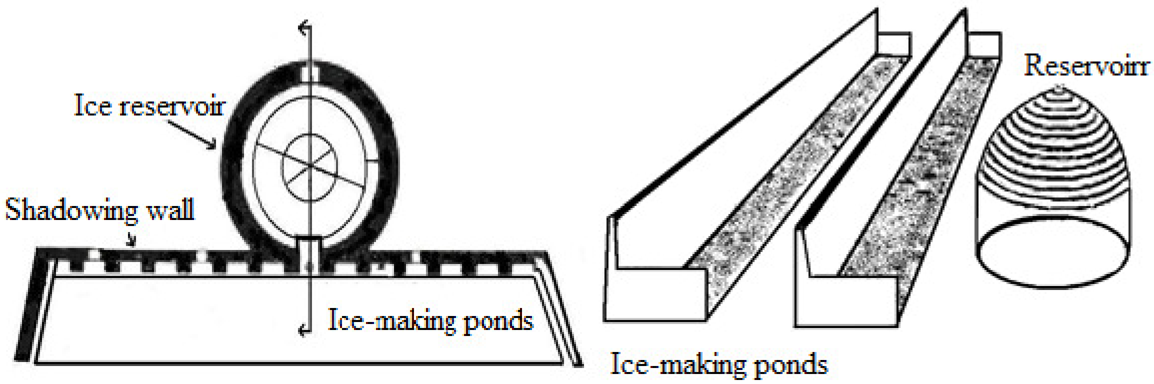


Figure-3
A general cross-section of an ice-pit and its different parts

The ice making ponds: Each pond is a rectangular pit dug parallel to the shadowing wall and in the northern part of it. The length of each pond is slightly smaller than the shadowing wall and its depth reaches 30-50 cm and sometimes more than 50 cm.The ponds were used to make ice at cold winter nights; such a manner that at they were filled with water in special intervals and when a layer of water was frozen, a new layer of water was added to the previous one to be frozen; then,in the morning the ice was chopped and collected in the reservoir. Depending on the cloudy or clear sky at night, the thickness of each frozen layer varied from 5mm to 1cm. The optimal thickness of ice layersin desert conditions has been reported equal to 6mm. In the following, the freezing of ponds water in different conditions has been explained. The findings of this study are consistent with experimental results[3].

Methodology

In many hot desert regions, the minimum temperature is not lower than 6^0C at the cold winter nights. In fact, this temperature is not sufficient to make ice; but it is interesting to know that old Iranians found a way to make ice in such circumstances. They took advantage of absorbing properties of the desert sky to easily make ice, because the clear sky of desert acts as a black object at night and significantly decreases the ambient temperature through absorbing the energy of surrounding environment. Here, the technique is explained:

The equation of energy exchange in the layer of water poured in the ponds is as follows:

$$\dot{Q} = \dot{Q}_r + \dot{Q}_e + \dot{Q}_c + \dot{Q}_g \quad (1)$$

Where: $\dot{Q}_r$: The exchanged heat per $\frac{W}{m^2}$, $\dot{Q}_g$: The Amount of heat which is transferred from the ground surface to the pool, $\dot{Q}_e$: The Amount of heat lost through evaporation which is ignored in the equation., $\dot{Q}_c$: The Amount of exchanged heat which is proportional to the water level, the temperature differences between the water surface and the environment $(T_p - T_{env})$, and the heat transfer coefficient.

$\dot{Q}_r$: The heat exchange as radiation between the water surface and "the sky and walls". In fact, $\dot{Q}_r$ shows more than 85% of heat exchanges in the equation-1. The indices of r, c, and e respectively stand for "radiation", "exchange", and "the surface evaporation of water". Here, the sky radiation at night is explained:

The heat exchanged between two surfaces (with temperatures of $T_1 and T_2$and areas of$A_1 and A_2$ through radiation so that there is no other surface between them) is obtained through following equation:

$$\dot{q}_{12} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F_{12}} + \frac{(1-\varepsilon_2)A_1}{\varepsilon_2 A_2}} \quad (2)$$

Where: σstands for Stefan Boltzmann's constant and is equal to $5.67 \times 10^{-8}\frac{W}{m^2k^4}$., $\varepsilon_1 and \varepsilon_2$ stand for emission coefficients of surfaces 1 and 2, respectively. F_{12}stands for the shape factor of surface 1 to surface 2.

It should be noted that two radiation processes are considered for each pond: from the pond to the sky and from the pond to the wall.

The clear sky acts as a black object at nights without clouds that the effective temperature of sky is calculated according the following equations:

$$T_{sky} = T_{env}(0.08 + 0.004\, T_{dp})^{1/4} \quad (3)$$

$$T_{sky} = (0.0552)\, T_{env}{}^{1.5} \quad (4)$$

Where: T_{env}: The environmental temperature per Kelvin, T_{dp}: The drop point temperature per ^{0}C

According to equation-2, it is observed that the effective temperature of sky reaches about -28° C even when the environmental temperature is higher than freezing temperature of water. Thus, this black object can easily absorb the thermal energy of the water pond. The equation of radiation from the pond to the sky is as follows:

$$\dot{q}_{rp\to sky} = h_{r(p\to sky)}\left(T_p - T_{sky}\right) \quad (5)$$

Where: $h_{r(p\to sky)}$ stands for heat transfer coefficient of radiation and is obtained from the following equation:

$$h_{p\to sky} = \frac{A_p\sigma\left(T_p^2+T_{sky}^2\right)\left(T_p+T_{sky}\right)}{\frac{1-\varepsilon_p}{\varepsilon_p}+\frac{1}{F_{p\to sky}}+\frac{\left(1-\varepsilon_{sky}\right)}{\varepsilon_{sky}}\left(\frac{A_p}{A_{sky}}\right)} \quad (6)$$

The indices of p and sky respectively stand for the pond and the sky. $F_{p\to sky}$ stands for the shape factor of the pond to the sky which is reported equal to 1. Since the area of sky is so greater than the area of the pond $\left(F_{p\to sky} = 1\right)$, it is possible to use the approximation of $A_p \big| A_{sky} \approx 0$ to simplify equation 6 into equation-7:

$$h_{r(p\to sky)} = \varepsilon_p\sigma\left(T_p^2 + T_{sky}^2\right)\left(T_p + T_{sky}\right) \quad (7)$$

Equation 8 is resulted from substituting the equation 7 into the equation 5:

$$E_q.8: \dot{q}_r(p \to sky) = \varepsilon_p\sigma\left(T_p^4 - T_{sky}^4\right) \quad (8)$$

Equation 9 is resulted from substituting the equation 8 into the equation-2:

$$\dot{q}_r(p \to sky) = \varepsilon_p\sigma T_p^4\left(1 - 9.3\times 10^{-6}T_p^2\right)\frac{W}{m_v^2} \quad (9)$$

The minimum heat which should be obtained from the pond to freeze its water is calculated from the following equation:

$$Q = mcT_{\epsilon nv} + mL_f \quad (10)$$

The thickness of water layer frozen per hour is obtained from the following equation:

$$h = \frac{\varepsilon_p\sigma T_p^4 tA_p\left(1-9.3\times10^{-6}T_0^2\right)}{p_w c\, T_p+p_u L_f} \quad (11)$$

In above equation, h, “p_{ic} , p_w ”, C,L_f, t, and A_p stand for the height of frozen layer, densities of water and ice, heat capacity of water, latent heat of fusion, length of night, and the area of pond, respectively. Taking into account that at least 80% of the heat obtained from the pond is as the result of radiation;the thickness of water frozen per hour is obtained about 6mm. The experimental results show that the thickness of frozen water is about 5mm-1cm which are consistent with the numerical calculations. This indicates how creatively old Iranians have used the mentioned techniques[4].

Results and Discussion

Dome-shaped reservoirs: These reservoirs have been usually located behind the shadowing wall, in the southern part of it, and connected to the ice-making ponds (in the northern part) by one or more entrances. The cover of these reservoirs has been usually made of clay wall or adobe. Also, to reduce the pressure from the dome to the base, architects have built them stepped.

The height of reservoirs entrances and exits has been low. The entrance of each reservoir has been usually located near the ice-making ponds(facing north) and connected to the ponds using an inclined planeto easily transfer the ice from ponds to the reservoir. The exits are located in front of entrances and have the way out through a small room. The owners of ice-pits poured straw or wheat stems among the ice layers while storing them. This helped them to take the ice pieces easily in the summer. In some regions such as Isfahan-Iran, they used sedge, a type of plant growing along rivers, and covered the ice layers with it. In some other desert regions, the ices layers were covered with a layer of mud, and then the entrances were completely blocked with thatch[5].

Why have the reservoirs roofs been built as dome-shape?: The amount of radiation on the spherical surfaces is far less than the flat ones. In the following, the radiation intensity and energy received from the sun are calculated:

To calculate the radiation intensity and energy received from the sun, it is firstly needed to know about the radiation intensity in the upper atmosphere and before hitting the atmosphere. In this regard, the concept of solar constant was firstly proposed by Poilet in 1837, and then the method of its calculation was provided by Lankham in 1881. The solar constant (G_{SC}) is defined as the amount of solar energy obtained at a distance equal to the mean distance between the Earth and the Sun per unit of time and per unit of surface that is perpendicular to the radiation in the upper atmosphere[6]. This amount was reported equal to $1353\frac{W}{m^2}$ by the International Solar Energy Society in 1970. The radiation intensity in the upper atmosphere per each day of the year is calculated using the following equation:

$$G_{on} = G_{sc}\left(1 + 0.033cos\left(\frac{360n}{365}\right)\right) \quad (12)$$

G_{on} stands for the total radiation intensity in the upper atmosphere for the N-th day of the year. Equation 13 is used for calculatingthe radiation intensity in the upper atmosphere per each day ofsolar year:

$$G_{on} = G_{sc}\left(1 + 0.033cos\left(\frac{360(N+80)}{365}\right)\right) \quad (13)$$

The part of solar radiation that directly reaches the Earth's surface is called “Direct Solar Radiation” and the component of solar radiation that is dispersed while passing through the atmosphere is called “Diffuse Solar Radiation”. The sum of direct and diffuse radiations components is called total solar radiation. The momentary reduction of direct solar radiation compared to the radiation in the upper atmosphere is obtained from the following equation:

$$I_{bn} = G_{on} \exp\left(\frac{-B}{cos\theta_z}\right) \quad (14)$$

The above equation is similar to the equation used forspectral radiation in which $\theta_z, G_{on}, and\ B$ stand for the sun ridge angle, momentary solar radiation, and the atmospheric extinction coefficient, respectively. According to the mentioned equations, direct transmission coefficient (shown asτ_b) while passing the atmosphere is calculated using the following equation:

$$\tau_b = \exp\left(\frac{-B}{cos\theta_z}\right) \quad (15)$$

Hottle has provided a simple method for evaluating the direct solar radiation on the earth at the days with clear sky. In fact, considering the sun ridge angle and the height above sea level for areas with four different climates, he has provided the following equation in which the direct transmission coefficient τ_b is equal to the ratio of $\frac{I_{bn}}{G_{on}}$:

$$\tau_b = \alpha_0 + \alpha_1 \exp\left(\frac{-K}{cos\theta_z}\right) \quad (16)$$

In above equation,I_{bn} stands fordirect radiation on earth and the constants of K,$\alpha_1, \alpha_0$are used for places with height less than 2 km, standard atmosphere, and visibility equal to 32 km or 5 km. Thus, the direct solar radiation in clear sky conditions is calculated using the following equation:

$$I_b^{cf} = G_{on}\tau_b \quad (17)$$

The direct radiation in clear sky conditions on the horizon is obtained using the following equation:

$$I_{bh}^{ci} = G_{on}\tau_b Cos\theta_z \quad (18)$$

The studies conducted by Liu and Jordan regarding the direct solar radiation suggest the following equation to show the relation between diffuse and direct radiation transmission coefficients in clear sky conditions:

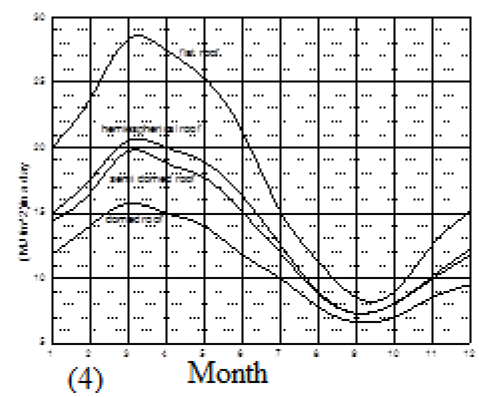
$$\tau_d = 0.271 - 0.2939\tau_b \quad (19)$$

In above equation, τ_d stands for diffuse radiation transmission coefficients showing the ratio$\frac{I_d}{G_o}$ $or \frac{I_d}{I_o}$; in other words, it indicates the ratio of diffuse radiation to the radiation in the upper atmosphere on a horizontal surface.

Regarding the ice-pits, it is needed to calculate the solar radiation on complex three-dimensional surfaces especially regarding the tall buildings located in close proximity to each other. In architecture, due to the variation in buildings roofs (such as spherical, domed, and semi domed roofs), the scheduler distribution of solar radiation is uniform contrary to what is being shined on flat roofs; in other words, the solar radiation is a function of the surface position to the sun; therefore, to assess the energy exchange of curved surfaces, it is needed to consider the solar radiation on them[7].

Changes in solar radiation intensity on a domed roof arecalculated using Hottle's model.The amount of daily radiation per square meter is of the main criteria for the calculation of heat that according to the equations of Hottle's model and the specified directions of elements compared to the surface, it is possible to calculate the heat at different hours and obtain the total heat per a day.

Using the mentioned equations, the amount of daily solar radiation on various surfaces was calculated in a year[8]. Figures 4and 5 respectively show the changes in amount of solar radiation on various roofs in Gachsaran-Iran and Yasooj-Iran in a year.As the figures show, flat surfaces absorb more solar radiation energythan the surfaces with other geometric shapes[9].In addition, the results indicate that the domed surfaces averagely absorb the least amount of radiation energy; in other words, more portions of domed surfaces are in the shadow at a day compared to the other roofs[10].



Figures-4
The changes in daily solar radiation on various roofs in Gachsaran-Iran

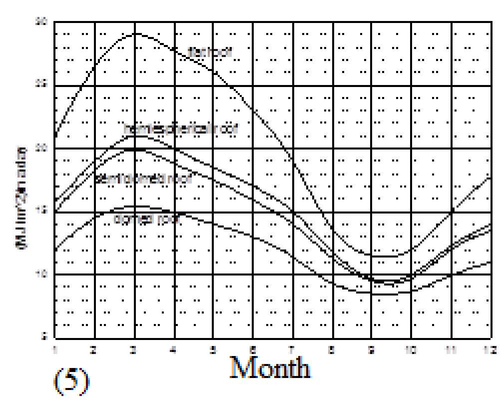


Figure-5
The changes in daily solar radiation on various roofs in Yasooj-Iran during a year

The other issue affecting the lower heat absorption of domed roofs is their lower heat transfer rate in comparison with other types of roofs[11].

The heat transfer rate of an object with the cross-section of A and heat transfer coefficient of K which is located between two thermal sources of T_H, T_C is calculated using following equation[12]:

$$\dot{Q} = -KA\frac{(T_H - T_C)}{L} \qquad (20)$$

As can be seen in the equation, there is a direct relation between the heat transfer rate and the area of the surface while the relation between the heat transfer rate and the length of the object is inverse.If the equation is used for other roofs, the following results will be obtained regarding the ratio of thermal conductivity of these surfaces[13]:

$$\left(\frac{\dot{Q}domed}{\dot{Q}flat} = \frac{\pi\sqrt{5}\,\alpha^2}{20\,\alpha^2} \approx 0.35\right) \qquad (21)$$

$$\left(\frac{\dot{Q}domed}{\dot{Q}semispherical} = \frac{\pi\sqrt{2}\,\alpha^2}{2\pi\,\alpha^2} \approx 0.7\right) \qquad (22)$$

According to the above equations, the heat exchange of domed surfaces is lower than the similar flat or semi domed ones. As a result, the domed ice-pits show higher efficiency than the similar samples in terms of maintaining the internal temperature of ice-pits[14].

Conclusion

Today, the issue of environment is tied with green energies consumption. It was attempted by the traditional Iranian architects to optimally use all climatic and natural elements to provide the cooling while designing the old ice-pits so that the ice required by natives of desert regions was provided. Although, today, the traditional architecture of ice-pits is not used anymore, the design principles of these ice-pits can be applied for improving the cooling systems of buildings in desert regions of Iran; on the other hand, this helps for reducing the consumption of fossil energies and preventing further destruction of nature[15].

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