International Journal of Engineering & Technology, 7 (3) (2018) 991-995

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET
doi: 10.14419/ijet.v7i3.9530
Research paper

A Study on the solar radiation incident upon the overhead water tanks in Saudi Arabia with different configurations

Hassan Khurshid *, Karthik Silaipillayarputhur

King Faisal University, KSA
**Corresponding author E-mail: hkhurshid@kfu.edu.sa*

Abstract

Saudi Arabia is one of the warmer countries in the Middle East region. In the summer months, the ambient temperature reaches 50°C on regular basis. This high temperature has a direct effect on the elevation of water temperatures inside the domestic and commercial overhead tanks. The tanks are predominantly installed on the roof of the buildings without any shade or insulation and are exposed to the direct irradiation from the sun. The tank material is not capable of reducing the effect of solar radiation. Therefore, water gets very hot in the afternoon that it is impossible for the occupants of the residential buildings to take a shower or even wash their hands. This paper studied the effect of solar irradiation on the water temperature in the over-head storage water tanks during the summer months. The temperature rise in the water storage tank was considered for different cases, (i.e.) a free standing tank exposed to direct sun's irradiation, a tank with shade, a tank with fiber glass insulation, and a tank having insulation along with shade. An analytical model was developed to study the effects of sun's irradiation and the results were compared with that of experimentation. The results from the water storage tank having insulation exhibited encouraging results.

Keywords: *Solar Radiation; Heating of Domestic Storage Water Tank; Insulation; Shade.*

1. Introduction

Water is an important commodity and it is always important for humans to store it somehow and later on to use it for different purposes such as drinking, washing, cleaning etc. Most common method to store water is the usage of over head storage tanks. The tank material has been evolved since its inception from, wood to pottery and from steel to Polyethylene. Water tanks available in Saudi markets are usually made up of linear low density polyethylene (LLDPE). This tank wall comprises of four layers of LLDPE. Each layer has its own significance. External layer blocks UV rays that could result in material degradation. Second layer that is usually black makes the tank opaque thus preventing the growth of microorganism. Third layer is foam which provides the insulation. The inner most layer prevents any accumulation of impurities or bacterial growth inside the tank.

It is evident that the ready-made tanks are having some mechanism that helps to insulate the tank in order to decrease the inside tank water temperature as compared to the ambient temperature. Still this insulation is not enough for the regions like Saudi Arabia. The solar radiation incident upon Saudi Arabia especially in the months from April till October is very high as shown in table 1. One of the main implication of the solar radiation during summer is that the water temperature in the water storage tank gets to very comfortable temperatures throughout the day. It is impossible to take shower and to use the water for other purpose during this time. There is a serious danger of getting burns if one is not very careful in handling the domestic tank water in these timings. In order to overcome this problem there are different ways that people use, for example, storing water in buckets in the night and let them cool for the later usage, installation of cooling system on the over-head water tank and constructing shade over the tank. The cost of the cooling system and the construction of proper shade is anywhere from 1000 to 3000 Saudi Riyals. In case of the cooling system there is an extra maintenance and running cost.

The design of a domestic water storage tank and the effects of solar radiation on the domestic water storage tank are not widely reported in the available literature. However, some pertinent research work are discussed herein. Sahoo and Sahoo [1] studied the design of water tank, wherein the theory behind the design of liquid retaining structure using working stress method is detailed. The design of a circular water tank and a rectangular underground water tank were analyzed in this research work. The results from the work were then compared with the existing data. Meier [2] published a comprehensive book developed by members of the American Water Works Association (AWWA). This in-depth reference describes the use of steel tanks for potable water storage and includes details on tank sizes, capabilities, styles, construction, appurtenances, site selection, design, operation, maintenance, inspection, and security. Air force manual [3] provides the design criteria for water storage requirements at military facilities, gives a typical design analysis for tanks and reservoirs, and provides guidance on the procedures to be followed while selecting sites for such storage works. The manual covers requirements for treated water storage in the distribution system. This manual covers all elements of planning and designing of water storage systems.

Dwivedi and Counsell [4] concentrated on the thermal modelling and control of a domestic hot water tank. They evaluated the retrofitted or modified single hot water cylinder performance and as-

sessed its feasibility to meet the "dedicated solar volume" requirement. Cruickshank and Harrison [5] studied the heat loss characteristics for a typical solar domestic hot water storage system. Tests were conducted on a typical thermal storage used in solar domestic hot water (SDHW) applications and included a cool-down test and a heat diffusion test sequence. The values derived from these test sequences were then compared to computer predictions based on estimated thermal properties. Devore et al. [6] discussed the design and the analysis for improving thermal stratification in a domestic hot water storage tank. Niskanen [7] detailed the design, construction, and maintenance of a gravity fed water system in the Dominican Republic. Herein, the water source is from a naturally occurring mountain spring. The project describes the design of a 10,000 gallon water storage tank that is erected to serve a community consisting of 75 residential units. Hepbasli and Alsuhaibani [8] presented a key review on present status and future directions of solar energy studies and applications in Saudi Arabia. They pointed out that if a major breakthrough was achieved in the field of solar energy conversion, Saudi Arabia could become a leading producer and exporter of solar energy in the form of electricity. Likewise, Al-Masoud and Gandayh [9] discussed the future of solar energy in Saudi Arabia, wherein they proved that the cost of solar energy would be less than the cost of fossil fuel energy. The last two mentioned references provided the available solar irradiation in the Eastern region in Saudi Arabia. Abdullah [10] presented a numerical simulation of water temperature fluctuations in over-head water tanks commonly used in water supply system. Two types of over-head water tanks were modelled in his study. The author did not study the effect of shade and insulation on the water temperature inside the tank. Al- Juruf et al. [11] investigated the possibility of using dry leaves of date palm fronds and suitable binders to obtain thermal insulating products. Fouli et al. [12] evaluated the use of palm based insulators for reducing peak water temperatures during summer season. Though researchers have used some natural insulating materials to reduce the temperature but there is no study that uses the industrial insulation (glass wool) on the water tank in Saudi Arabia climatic conditions.
In order to incorporate the effect of using shade over the tank some papers were surveyed that discussed this aspect. Heisler [13] reported that under clear skies, a mid-sized sugar maple tree reduced about 80 % of irradiation and nearly 40% when leafless. Effects of other types of trees were also studied. Mohammad et al. [14] carried out a research on the comparative effectiveness of two types of trees. Their results indicated that heat filtration due to these trees were 93% and 70% respectively. Based on the described studies, the color of the shade was chosen for the domestic storage water tank.
Literature survey indicates that there is less work done in the heat transfer analysis of over-head tanks in Saudi Arabia. Though the problem is recurring, there is no systematic study on the effect of insulation and/or shade on the water temperature in the tank. The current study was divided into different parts. Firstly, analytical model to calculate the water temperature inside the tank was developed using heat transfer equations. Heat transfer calculations for the free tank (no insulation, no shade) were performed for the month of April analytically. Secondly, experiment was performed using four tanks on a domestic house to record the temperatures at different times of the day for the free tank, tank with insulation only, tank with shade only and tank with insulation + shade. The experimental readings of the free tank were compared to the analytical calculations and were found in close agreement to the analytical calculations. Finally, it was observed that there was a decrease in the tank inner water temperature when different configurations were used as compared to the free tank. The purpose of this study was to identify the factors that could reduce the water temperature in the tank so it can be used inside the house safely.

2. Analytical model

An analytical model was developed to understand the effects of solar irradiation on the domestic water storage tank. Therein, the principles of conduction, convection and radiation were employed to understand the temperature rise in water tank. The modeling involves radiation heat transfer from the sun to the tank's outer surface, natural convection occurring on the outer surface of the tank, conduction heat transfer through the tank wall and natural convection heat transfer from the inner surface of the tank to the water.
The following are the assumptions employed in the study:

a) Steady state conditions are assumed
b) The solar irradiation is assumed constant at all times
c) The incident solar irradiation on the tank is assumed to be uniform on all surfaces
d) The thermo physical properties of water and tank are constant

The study site is in the eastern city of Hofuf, Al Ahsa. The solar irradiation (I) in the Al Ahsaa region in Saudi Arabia is described in website of solar electricity handbook [15]. The heat flux due to solar irradiation on the water tank may be described as

$$q'' = I\,\frac{\text{kW h}}{\text{m}^2\ \text{day}} \times \frac{1}{24\ \text{h}}\,\text{day} \times 1000 \quad (1)$$

The material and color of the tank is such that it reflects about 75% of the total irradiation that is incident upon the tank. Therefore the heat flux due to the irradiation from the sun may be then be given as

$$q''_{radiation} = q'' - 0.75 \times q'' \quad (2)$$

Apart from the solar irradiation, natural convection cooling occurs between the outer surface of the water storage tank and the surrounding ambient air. Therein, the Grashof number, a dimensionless number that approximates the ratio of the buoyancy to viscous force acting on a fluid may be given as follows [16]

$$Gr_D = \frac{g\ \beta D^3\ \Delta T}{\nu^2} \quad (3)$$

Where

g - The acceleration due to gravity (m/s^2)
ν - Kinematic viscosity of air (m^2/s)
ΔT - Difference in the temperature between the tank's surface and ambient conditions (K)
D - Outer diameter of the tank (m)

β - $\frac{1}{T_{avg}}$ (K^{-1}); T_{avg} is the average temperature between the tank's surface and ambient conditions
The Nusselt number (Nu_D) may then be determined by the following empirical equation [16]

$$Nu_D = 0.36 + \frac{0.518(Gr_D\ P_r)^{0.25}}{\left[1+\left(\frac{0.559}{P_r}\right)^{0.5625}\right]^{-0.444}} \quad (4)$$

Where

P_r - Prandtl number for air at T_{avg}
The natural convection heat transfer coefficient is related to the Nusselt number as follows [16]

$$h = \frac{Nu_D\ k}{D} \quad (5)$$

Therefore, the rate of the natural convection cooling may then be described as [17]

$$q''_{convection} = h\,(\Delta T) \tag{6}$$

Thus, the net heat flux on the tank's surface may then be given as

$$q''_{net} = q''_{radition} - q''_{convction} \tag{7}$$

The relationship between the net heat flux, the tank's surface temperature and the ambient conditions may be described as follows

$$q''_{net} = \sigma\,[T_{s,out}{}^{4} - T_{surrounding}{}^{4}] \tag{8}$$

Where

σ: is Stefan Boltzmann constant (W/m^2K^4)
From Equation (8), the outer surface temperature of the water tank may be readily determined.
Conduction heat transfer occurs through the wall and the inner surface temperature of the water tank may be determined by applying the heat conduction equation. For a cylindrical water tank, the rate of conduction heat transfer may be given as follows [16]

$$q = \frac{2\pi L[T_{s,out} - T_{s,in}]}{\frac{\ln(d_{out}/d_{in})}{K}} \tag{9}$$

Where

$q = q_{net}$" x A (W)
$A = \pi d_{out} L$ (m^2)
$T_{s,out}$ - The outer surface temperature (K)
$T_{s,in}$ - The inside surface temperature (K)
L - The length of the wall (m)
K - Thermal conductivity of the tank (W/mK)
d_{out} - Outside diameter of the water tank (m)
d_{in} - Inside diameter of the water tank (m)
From Equation (9), the inside surface temperature of the water tank can be readily determined. Natural convection heat transfer occurs between inner surface of the water tank and the stored water. The water temperature in the tank can be readily determined by employing Equations (3) through (6), and while accounting for appropriate tank dimensions and fluid properties. The tank's physical and thermal properties are described in Table 1. The ambient conditions are described in Table 2 and the results from the analytical calculations are described in Tables 2 through 4. It must be noted that the analytical calculations were performed for a free standing tank exposed to the direct sun's irradiation.

Table 1: Tank Dimensions

Volume V (Litre)	300
Length L (m)	0.85
Width w (m)	0.77
Height H (m)	0.78
Thickness t (m)	0.054
Thermal Conductivity (W/mK)	0.15

Table 2: Ambient Conditions

Time	Irradiation ($kwh/m^2/day$)	$q''_{radiation}$ (W/m^2)	$T_{ambient}$ (°C)
09:00	6.2	64.6	40.5
11:00	6.2	64.6	43
13:00	6.2	64.6	45
15:00	6.2	64.6	45.5

Table 3: Rate Of Heat Transfer at the Tank's Surface

Time	T_{amb} (°C)	$q''_{radiation}$ (W/m^2)	$q''_{convection}$ (outer surface) (W/m^2)	q''_{net} (W/m^2)
09:00	40.5	64.6	27.06	37.51
11:00	43	64.6	26.19	38.38
13:00	45	64.6	25.52	39.05
15:00	45.5	64.6	25.36	39.21

Table 4: Temperature Distribution in the Free Standing Water Storage Tank

Time	Ambient temp. T_{amb} (°C)	Outer surface temp of the tank $T_{s,out}$ (°C)	Inner surface temp of the tank $T_{s,in}$ (°C)	Water temp T_{water} (°C)
09:00	40.5	45.73	44.13	44.06
11:00	43	48.23	46.62	46.55
13:00	45	50.22	48.61	48.55
15:00	45.5	50.72	49.11	49.04

3. Experimental setup and measurements

For experimentation, four domestic tanks having the specifications as described in Table 1 were installed on the roof of a residential building. Readings were taken in the month of April at different time intervals of the day. Four distinct cases were considered, i.e., a free standing tank, tank with 1" fiber glass insulation, tank with green shade , and tank having green shade and insulation. All the tanks were set up side by side and readings were recorded from each tank at the same time at different time intervals. The readings (temperatures) were recorded for twenty days and then averaged out. Tables 5 and 6 describe the experimental results for all the four cases considered in this study.

Table 5: Water Temperature in the Tank – All Cases (Experimental Results)

Time	Ambient temp. T_{amb} (°C)	Temp. of water in free tank (°C) Case 1	Temp. of water in tank with insulation only (°C) Case 2	Temp. of water in tank with shade only (°C) Case 3	Temp. of water in tank with insulation + shade (°C) Case 4
09:00	40.5	43.3	40.2	42.5	40.6
11:00	43	45.7	42.6	45.0	42.9
13:00	45	47.2	44.7	47	45.1
15:00	45.5	48.5	45.2	47.5	45.4

Table 6 illustrates the reduction in the water temperature in the overhead tanks for three different configurations as compared with the free standing tank. The three different configurations considered are tank with insulation, tank with shade, and tank with insulation along with shade.

Table 6: Percentage Reduction in Water Temperature for Different Configurations

Time	% Reduction in water temperature with respect to free standing tank		
	Tank with insulation only Case 2	Tank with shade only Case 3	Tank with insulation + shade Case 4
09:00	7.2%	1.9%	6.2%
11:00	6.8%	1.5%	6.1%
13:00	5.3%	0.4%	4.4%
15:00	6.8%	2.0%	6.4%

It can be clearly seen that the maximum decrease in the inner water temperature is achieved when the tank was insulated only. The average decrease is about 6.5% as compared to 1.5 % and 5.8% for the shaded tank and tank with insulation + shade respectively. It is evident from these figures that the type of shade that is used is little effective in reducing the effect of solar radiation on the water. Contrary to the expectation the insulation + shaded configuration is not as productive as the insulated one. Good results are obtained by simply insulating the water tank.

It must be recognized that the analytical model was employed only for the free standing tank, i.e., case 1 and can be readily extended for the other cases as well. The results from analytical model matched reasonably well with the experimental results. The minor discrepancy can be attributed to the assumption that the storage water tank is operating under steady state conditions. Also, it must be recognized that the irradiation from the sun is an average data obtained from the solar electricity handbook and doesn't reflect the exact conditions on a specific day and time.

Table 7: Percentage Difference between Analytical Model and Experimentation – Case 1

Time	Ambient temp. T_{amb} (°C)	Water temp (°C) Experimentation Case 1	Water temp (°C) Analytical Study Case 1	% Difference
09:00	40.5	43.3	40.2	7.1
11:00	43	45.7	42.6	6.8
13:00	45	47.2	44.7	5.3
15:00	45.5	48.5	45.2	6.8

Fig. 1: Overhead Water Storage Tank with Insulation (Case 2).

Fig. 2: Overhead Water Storage Tank with Shade (Case 3).

Fig. 3: Overhead Water Storage Tank with Insulation and Shade (Case 4).

4. Discussion

In the Kingdom of Saudi Arabia, where the solar irradiation is very high during the summer, the water stored in the domestic and commercial water tanks naturally gets warm beyond the tolerable limits. To mitigate the effects of radiation, and to have the stored water at bearable temperature limits, it is a common practice to install refrigeration units for the water storage tanks. Installation and continuous operation of refrigeration units incur considerable set up, operational and maintenance costs. Therefore, establishing such refrigeration systems for domestic water storage tanks is not feasible for regular income groups. In addition, in Saudi Arabia, there has been a considerable increase in the energy costs due to the collapse in oil prices and therefore it is becoming increasingly difficult and expensive to install such systems in commercial buildings.

Though the elevation of water temperatures in domestic and commercial water tanks is a broad issue in summer, no research work has yet been reported on this subject in the available literature. The current research concentrates on the effects of solar radiation in summer and attempts to develop cheap methodologies to attenuate the effects of solar radiation. This study, exhibits encouraging results. The research work is certainly beneficial for the residential community and for the light commercial establishments in Saudi Arabia.

A popular residential water storage tank was chosen for this study. The temperature rise in the domestic water storage tank was analysed for a free standing water tank, water tank with one inch thick fiber glass insulation and as a tank with one inch thick fiber glass insulation along with shade. The temperature rise in these water tanks were recorded at different time intervals and the results from the study were reported in the form of tables. In this basic study, it was observed that adding insulation to water tank reduces the temperate rise by about 7%. From the tables it is clear that the best results in the reduction of the temperature are given by using only insulation.

Based on the results reported by Stamps [17], the shade chosen for this study was a green protective cloth. As described before, the analysis was performed on popular kind of a domestic storage water tank using one-inch fiber glass insulation. It is to be noted that this particular type of shade has not much of a good effect to reduce the temperature of water tank as compared to the insulation. Use of permanent shades over the tanks made from blocks should be explored but it will add to the cost which is not the objective of the study.

Insulating the tank is a viable option not only from the point of view of thermal aspects but also from the financial side. The cost of insulation in Saudi Arabia is very less as compared to the installation & operation of a cooling unit on the over-head tank and the cost of building a shade that may take anything from 1500 to 3000 Saudi Riyals. Whole insulation of the water tank was done in just 275 Saudi Riyals where as the price of the cooling unit can be anywhere from 1000 to 3000 Saudi Riyals depending on the make and the capacity of it.

5. Conclusions

The effect of solar radiation on domestic water storage tanks in the Kingdom of Saudi Arabia is considered in this paper. Saudi Arabia, due to its geographical location receives higher solar irradiation during the summer months. This creates unwanted heating up of domestic water storage tanks in summer. Though this issue is of concern for the residential and industrial community, no such research work has yet been reported in the available literature. The study focuses on the use of insulation and shade to curtail the effects of solar radiation. A simple analytical model has been proposed that gives very close results to the experimental data. It has also been demonstrated that, insulation could reduce the inside tank water temperature considerably. In order to get better results thickness of the insulation material can be increased to a specific extent. To conclude, insulating the tank can be a cheap financial solution to the existing problem. Other options like shading the tank will not be economical as the cheap cloth shade has not shown any promising results to decrease the temperature.

References

[1] Sahoo, N., Sahoo, S.K., 2008, “Design of water tank”, B.E., Project work, Dept. of Civil Engineering, NIT, Rourkela, India.

[2] Meier, S., 2010, “Steel Water storage Tanks: Design, Construction, Maintenance, and Repair”, ISBN: 9780071549387, American Water Works Association.

[3] Air Force Manual, 1985, “Water supply, water storage”, TM 5-813-4, AFM 88-10, Vol 4, Departments of the Army and the Air Force, Washington DC.

[4] Dwivedi, V., Counsell, J., 2009, “Thermal Modeling and Control of Domestic Hot Water Tank”, Master’s Thesis, Dept. of Mechanical Engineering, University of Strathclyde, United Kingdom.

[5] Cruickshank, C.A., Harrison, S.J., 2010, “Heat loss characteristics for a typical solar domestic hot water storage”, Energy and Buildings, Volume 42, Issue 10, pp 1703-1710. https://doi.org/10.1016/j.enbuild.2010.04.013.

[6] Devore,N., Yip, H., and Rhee, J., 2013, "Domestic Hot Water Storage Tank: Design and Analysis for Improving Thermal Stratification, “*Journal of Solar Energy Engineering”* ,Vol. 135 Issue 4. https://doi.org/10.1115/1.4025517.

[7] Niskanen, M., 2003, “The Design, Construction, and Maintenance of a Gravity Fed Water System in the Dominican Republic”, Master’s Thesis, Dept. of Civil Engineering, Michigan Technological University.

[8] Hepbasli, A., Alsuhaibani, Z., 2011, “A key review on present status and future directions of solar energy studies and applications in Saudi Arabia”, Renewable and Sustainable Energy Reviews, Volume 15, pp 5021-2050. https://doi.org/10.1016/j.rser.2011.07.052.

[9] Al-Masoud A.H., Gandayh, M. H., 2015, “Future of solar energy in Saudi Arabia”, Journal of King Saud University – Engineering Sciences, Volume 27, pp 153-157.

[10] Abdullah S. G., 2010, "Numerical simulation of water temperature in intermittent water supply systems", International Journal of Civil and Environmental Engineering, Vol 10, no. 2.

[11] Al-Juruf R. S., Ahmed, F. A., Alam, I. A., and Abdel Rahman, H.H., 1988, "Development of heat insulating materials using date palm leaves", Journal of Building Physics, Vol 11, No. 3. https://doi.org/10.1177/109719638801100304.

[12] Fouli, H., Alshaikh, A. A., Nurdin, J., Alam, S., and Alnaimat, H., 2014, "Evaluating the use of palm based insulators for reducing peak water temperatures during summer and for saving energy during winter in existing overhead storage water tanks", Arabian Journal for Science and Engineering, Vol 39, Issue 6.

[13] Heisler, G.M., 1986, "Effects of individual trees on the solar radiation climate of small buildings", Urban Ecology, Vol 9. https://doi.org/10.1016/0304-4009(86)90008-2.

[14] Mohammad F.S., Salleh, E., and Musatafa, K.M.S., 2007, "Effect of tea canopies on solar radiation filtration in a tropical microclimatic environment", PLEA2007 Conference, Singapore.

[15] http://solarelectricityhandbook.com/solar-irradiance.html, acessed on 11.48am, December 3, 2016.

[16] Incropera, F. P., Dewitt, D. P., Bergman, T. L., and Lavine, A. S. 2006. Fundamentals of Heat and Mass Transfer, fourth Edition, John Wiley & Sons, Inc., New York.

[17] Stamps, R.H., 2009, "Use of colored shade netting in horticulture", HortScience, Vol 44, No. 2.