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Effect Of Roof Profiles On Wind Heat Loss Coefficient For Roof Top Solar Collectors In The Gulf Region

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Abstract: Nowadays solar collectors are constructed on roof tops very frequently for water heating, air heating or photovoltaic power generation. At a location the wind velocities increase as the elevation from the earth increases and its variation follow one-seventh power law. This variation plays a crucial role in determining the efficiency of roof mounted solar air heating collectors. Unglazed collectors are more affected by the wind than glazed collectors. Previous studies either neglected wind effects or used relations based on experiments conducted on flat surfaces to predict these losses. The subject matter of this paper is to predict the wind velocity induced thermal top-losses on roofs of different configurations through the use of computational fluid dynamics software. Wind data for the Arabian Gulf region in terms of wind velocity and direction has been used for the calculation of thermal top loss. Reynolds number of the order of $5x10^5$-$2x10^6$ is considered for the simulation. Several factors contribute for the heat loss coefficient from the roof surface. The results help in estimating the performance of solar collectors installed on roof tops and to choose the right type of roof.

Keywords: Wind heat transfer coefficient, Wind losses, Roof top collectors.

1. Introduction

The phenomenon of convective heat loss due to wind flow over roof top requires special attention when solar collectors are mounted on the roof because roof tops are becoming the preferred location for installation of solar collectors due to advantages like zero investment on land, nearness to energy consumption point and free from external interferences. Performance of solar thermal collectors is reduced due to wind induced top losses. However, solar photo-voltaic panels are at an advantage because the wind helps to reduce the temperature of the panels which increases its efficiency.

Earlier studies on wind losses were restricted to collectors mounted on flat roofs. Satish and Swami, 2009 used computational fluid dynamic (CFD) to evaluate convective heat losses over conventional solar air heaters on roof tops. Subodh et al, 1997 conducted experimental investigation on the effect of wind velocities on the top-loss coefficient of solar stills and box type solar cookers. A correlation for convective coefficient due to wind speed on a flat surface is given in McAdam, 1954. Suresh and Mullick, 2010 developed a linear equation for wind heat transfer over solar collectors with a flat surface. Most of the above studies used the standard procedure given by McAdam, 1954 to calculate wind losses on flat horizontal surfaces or used a constant value. However roof tops of recent origin have different layouts based on the architectural appeal and design. No formal study has been done to find the effect of wind flow over these types.

One of the earliest experimental studies on the forced convection heat loss from solar collectors mounted on inclined roofs was conducted by Onur, 1993. Wind speed from 2.5 m/s to 15 m/s was considered. The average heat transfer coefficients were determined for the sloping roof mounted collector. Panagiota et al, 2011 conducted CFD analysis and experimental validation of results for flat inclined roof with wind flow convective losses. The results indicated that the convective heat transfer coefficient approached values of that for horizontal surfaces at high Reynolds number flow.

Performance of photovoltaic panels or solar thermal collectors is highly influenced by the convective heat losses due to wind. The subject matter of this study is to make an analysis of the different factors that affect the convective heat loss in different types of roof designs with reference to the wind flow prevailing in the gulf region. The emphasis of this study will be to determine:

- The wind convective heat loss for different roof types, orientation and inclination angles due to wind and to
- Evaluate the effect of this heat loss on the annual performance of solar thermal and photovoltaic collectors

2. Wind flow pattern in the Arabian Gulf

Wind flow occurs from the North-West direction throughout the year in the Gulf region (Hussam Khonkar, 2009). It is seen that the wind speed from this direction is stronger in winter than in summer; this season lasts from November to March and reaches its maximum during the winter. The North-West wind commonly occurs following a cold front. In contrast, the summer North-West wind is weak and lasts from the beginning of June to the end of July.

3. Wind velocity and temperature variation

Most of the human activity occurs in atmospheric boundary layer in which the wind speed increase from the earth following power law variation. Dixon and Hall, 2010 has reported this variation in terms of $1/7^{th}$ law in which velocity of the wind (V) at a particular height (H) is given relative to the values of the reference velocity (V_{ref}) measured at reference height (H_{ref}) as given in equation (1).

$$V = V_{ref} \times \left(\frac{H}{H_{ref}} \right)^{1/7} \quad \ldots\ldots (1)$$

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01 Jan. 2016

Further the human activity is located within the lower strata of the troposphere in which the temperature of air decrease with the increase in altitude. David G Hull, 2007 has reported air temperature (T_a) variation with height (h) as given in equation (2)

$$T_a = T_{ref} + a \times (h - h_{ref}) \quad \text{......... (2)}$$

$$a = -0.0065^0 C/m$$

The temperature measured by the equation (2) represents the static temperature variation in the atmospheric boundary layer for the lower region of troposphere. The actual temperature in presence of dry wind is different. The temperature of air in presence of wind depends both on the static temperature and the wind speed. Sahin et al, 2006 uses the following relation for calculation of wind temperature.

$$T_w = 35.74 + (9.6215 \times T_a) - (35.75 \times V^{0.16}) + (0.4274 \times T_a \times V^{0.16}) \quad \text{... (3)}$$

In the above equation, the temperatures are in ^{0}F and V is in miles/hour.Even though the actual wind direction is changing the wind flow in this study is assumed to be parallel to the surface of the ground. Eq.1, 2 and 3 are used to determine the velocity and temperature of the wind at the location of the roof.

4. Effect of roof orientation and inclination on wind velocity

Roofs are usually oriented towards the north or south in order to maximize lighting. Since the direction of the wind is from the north-west throughout the year in the gulf region (Hussam Khonkar, 2009), the angle of flow is 450 to the line of orientation of the roof as shown Fig.1.

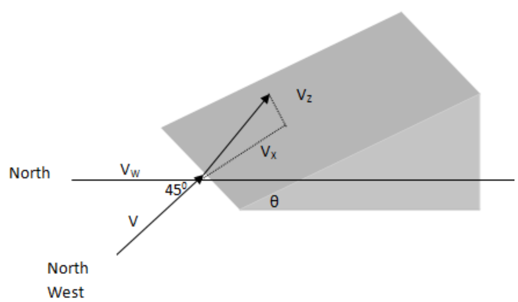

Fig.1 Velocity components for wind flow over roof surface

The resulting wind velocity in the direction along the roof and perpendicular to the roof are given by Eq.4 and 5.

$$V_X = V \times \cos(45^o) \times \cos(\theta) \quad \text{..................(4)}$$

$$V_Z = V \times \cos(45^o) \times \sin(\theta) \quad \text{..................(5)}$$

The actual velocity of wind flow over the roof is given by the term 'V_w'. Two cases of roof orientation are considered in this study, namely, north and south facing.

5. Roof style and angle of inclination

Fig.2 shows the different variations of the roof considered in this study. It also shows the sections used in the analysis. The following variations in the geometry of the roof are considered in this study.

- Mono roof with inclination angle of θ=45^0 and slope length of 10m
- Mono roof with inclination angle of θ=30^0 and slope length of 10m
- Common roof with inclination angle of θ=45^0 and slope length of 10m
- Common roof with inclination angle of θ=30^0 and slope length of 10m
- Arch roof with R/H=1 with R=6m
- Arch roof with R/H=1.5 with R=6m

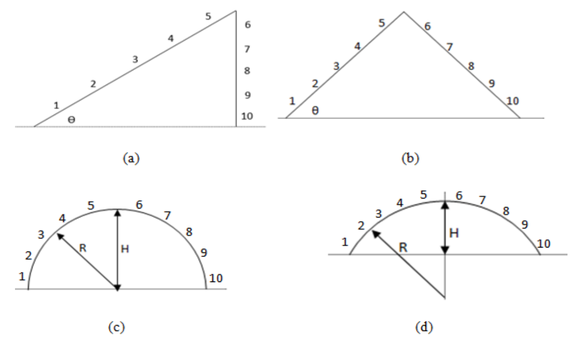

Fig.2 Different roof profiles and their sections for a) Mono b) Common c) Arch with R/H=1 and d) Arch with R/H=1.5

The three factors given above, result in the wind velocity over the roof surface to be in the final form as shown in fig. 2 and the components of velocity in the X and Z directions are given by eq. 3 and 4. The values of the X and Y components are given in Table.1. The total convective heat transfer coefficient is taken as the mean of the heat transfer coefficient due to the wind flow in the X and Z directions.

6. Simulation

A two-dimensional CFD simulation was performed with RNG - turbulence model using the finite volume method. The computational model was created using the modeling software and consisted of triangular grids. The computational domain includes the wind flow region between in spaced duct within which the roof shape is enclosed. A grid independence study was conducted by repeating the results for one such case for different grid sizes. Uniform grids were used in the two dimensional analysis. The inlet wall was fixed as velocity inlet and three velocity values of 2, 3 and 4 m/s were used at temperatures determined using Eq.2 and 3. The outlet was fixed as a pressure outlet with atmospheric pressure (1.013 x 10^5). The mass, momentum and energy equations were used for the simulation. The duct walls as taken to be impermeable with no slip boundary condition. The roof surface is subjected to a temperature of 333 K which is the normal operating range for solar collectors. The other walls are kept at adiabatic condition. Physical parameters of the air have been assumed to remain constant at mean bulk temperature. Semi-implicit method for pressure-linked equations (SIMPLE) algorithm was used to solve the governing equations of the system using second order upwind scheme.

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01 Jan. 2016

Renormalization-group model was used for the simulation. Convergence was achieved within 750 iterations in all the cases and the normalized residual remained constant.

7. Results and discussion

The two-dimensional velocity contours for the different roof profiles are shown in Fig.3 a - d. The velocity contours were considered in order to ensure that the upper duct wall does not have any effect on the velocity profiles at the roof region. For this reason a flat roof has been taken as reference. The flow structure shows that the flow behavior of different roofs is not affected and hence similar to the reality.

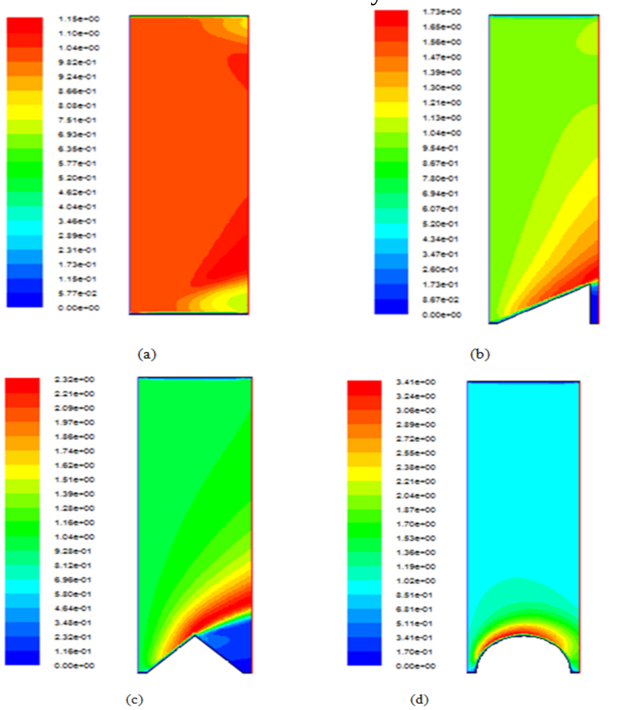
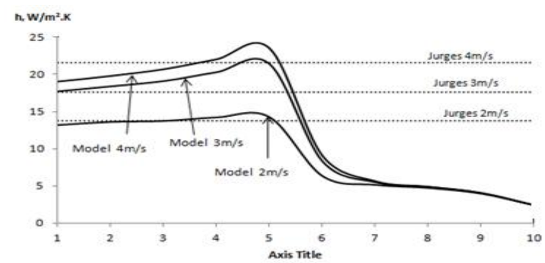


Fig.3 Velocity contours for flow over different roof profiles a) Flat b) Mono c) Common and d) Arch roof

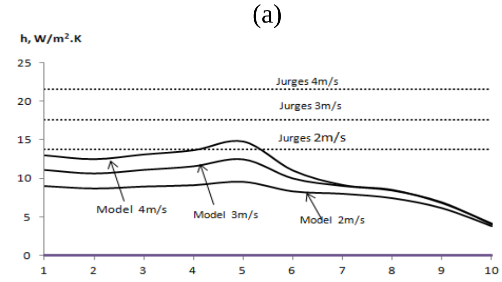
The evaluation of heat transfer coefficient was carried out for four roof types. The geometry is taken similar to that in Jurges, 1924. A comparison of heat transfer coefficient with the results for the flat roof, Jurges, 1924, has been indicated in all the figures for the purpose of comparison. The mono roof will behave differently with these types of winds and therefore this roof has been subjected to both these types of winds. In case of mono and common roof the effect of inclination has been considered by taking two slopes, 30^0 and 45^0, for these roofs. The investigation has been carried out at three wind velocities that are common in Riyadh. Fig. (4a,4b) show the total heat transfer coefficient (HTC) for mono type roof with inclination angles of 45^o and 30^o at the different sections numbered from 1 to 10 along the roof length. This figure shows the behavior of roof with respect to northerly winds when the roof orientation is towards north. The results show that heat transfer is more on forward face (1-5) of the roof than the backward face (6-10). Further the heat transfer increases linearly along forward face up to the peak of the roof and then it falls sharply towards the backward side. The heat transfer increases with the increase in wind speed. The heat transfer coefficient is 40 % more at 4 m/s than at 2 m/s wind speed. The backward face shows 80% lesser value of heat transfer than at the top. And values on backward face are almost independent of the wind speed. These results are different than that obtained by Jurges who obtained constant values all along the roof length for different wind speeds. On the forward side the values slightly match at 2 m/s except at the peak. However, it varies for higher velocities. The variation is 0-4% for wind velocity of 3 m/s and -25 to +25% for velocity of 4 m/s. On the backward side the heat transfer coefficient values are much lower than that of Jurges all along the backward side of the roof. In contrast to it when the same roof faces wind flow from the opposite direction (South-east), Fig. (5a, 5b), the maximum HTC occurs at the summit of the roof, section 5 and 6. The heat transfer coefficient falls to a minimum in section 1 to 5. For all the speeds the values of heat transfer coefficient show lower values than that obtained by Jurges. Therefore heat transfer in this case is lower than the flat roof.

Fig. 6(a) and (b) give the results for a common roof for inclination of $30^0$and 45^0. In this case also, three different wind velocities of 2, 3 and 4 m/s corresponding to Reynolds number of 8.84 x 10^6, 1.33 x 10^6 and 1.77 x 10^6 coming from north-west direction are considered. It is seen that the variation of HTC for 30^0 is comparatively more uniformly distributed than the 45^0 case. There is a difference of 20-30% in the HCT values compared to the Jurges equation for all the three wind velocities.

Fig.7 (a) and (b) show the results of the HTC for arched roofs for two different ratios of roof radius to height ratio(R/H). Fig. 7 (a) gives the results for the R/H=1 case. The flow velocities considered are 2, 3 and 4 m/s corresponding to Reynolds numbers of 7.5 x 10^5, 1.13 x 10^6 and 1.5 x 10^6. Fig. 7(b) gives the results for R/H=1.5 case. The flow velocities in this case are 2, 3 and 4 m/s corresponding to Reynolds numbers of 5 x 10^5, 7.5 x 10^5 and 1 x 10^6. Higher value of R/H gives HTC closer to the Jurges equation and the values are higher at the summit than that of the sides.



(a)



(b)

Fig.4 HTC profile along the roof for the different sections of the roof for mono type (a) 45^o and (b) 30^0 with roof orientation towards north direction.

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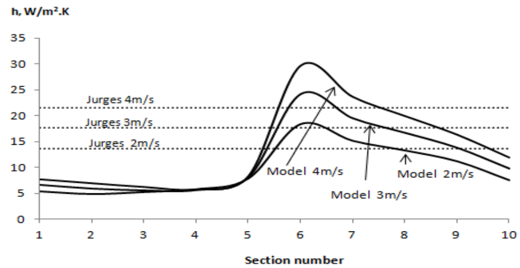
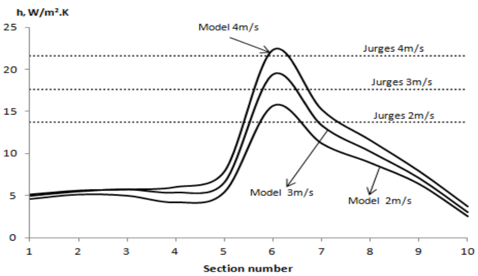
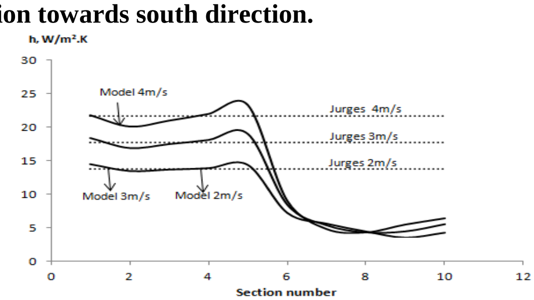


(a)

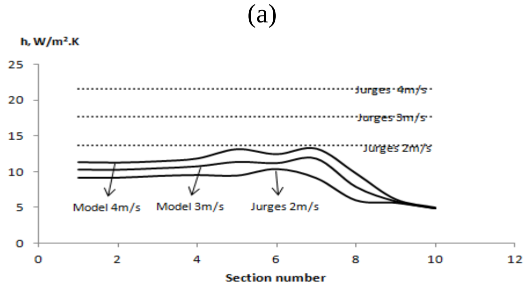


(b)

Fig.5 HTC profile along the roof for the different sections of the roof for mono type (a) 45^o and (b) 30^0 with roof orientation towards south direction.



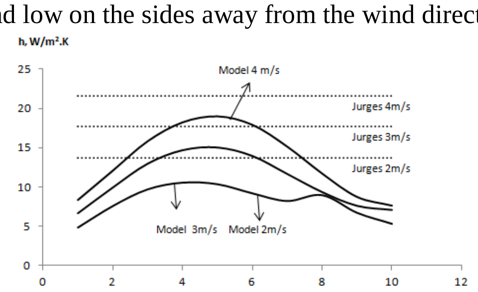
(a)



(b)

Fig.6 HTC profile along the roof for the different sections of the roof for common type (a) 45^o and (b) 30^0

Comparison of the results of the different roof types shows that mono and common type roofs with higher inclination angles with reference to the horizontal have high values of heat transfer coefficient. Heat transfer coefficient is high on the sides facing the wind and low on the sides away from the wind direction.



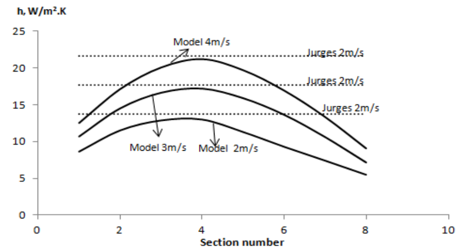


Fig.7 HTC profile along the roof for the different sections of the roof for arch type (R/H=1 and R/H=1.5) with roof orientation towards north direction.

8. Conclusion

A study about the convective heat loss from three different roof profiles has been made with the help of CFD. Roof profiles are subjected to different rates of convective heat losses depending on their geometry and orientation with respect to wind direction. Since mono roofs have higher losses at the summit region, it is ideally suited to install solar photo-voltaic systems in this region. Roofs facing the north-west direction have higher heat loss and hence more suitable for solar photo-voltaic installations. In contrast solar thermal collectors need reduced heat losses and hence the South-east direction is more advantageous for such systems. Common roofs with higher angle of inclination give higher values of HTC making them suitable for installation of photo-voltaic systems. Higher values of HTC occur at the summit of arch roofs and arch roofs with higher R/H values have more losses compared with one with lower R/H value. The above study gives a clear picture for making decisions to take advantage of or preventing heat losses in solar installations.

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