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WIND HEAT TRANSFER COEFFICIENT FOR GLASS COVER OF SOLAR COLLECTORS IN INDOOR TESTING

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ABSTRACT

For designing and thermal performance evaluation of solar thermal collecting systems, the wind heat transfer coefficient is a major concern. For estimating the wind heat transfer coefficient (h_w) of a flat plate solar collector or solar box cooker, the glass cover temperature is needed. The measurement of glass cover temperature of flat plate solar collectors is not so easy, especially in outdoor conditions. In outdoor conditions the glass cover temperature is measured using a thermocouple which yields an error as it's junction is directly exposed to the solar radiation. The other way of estimating the wind heat transfer coefficient is to use the available correlations as a function of wind velocity. There is considerable difference in the value of h_w obtained from different correlations at the same wind velocity. Arbitrary selection of a correlation will cause a substantial uncertainty in the thermal analysis.

In the present work a method is proposed to estimate the wind heat transfer coefficient from the outer surface of the glass cover of a flat plate solar thermal collector. An unglazed heated plate, almost of same size of collector or cooker aperture, can be used to estimate the wind heat transfer coefficient of a flat plate solar collector. The unglazed heated plate can be placed near the collector for the measurement of wind heat transfer coefficient, exactly in the same conditions. Some indoor experiments were performed on a single glazed flat plate collector and unglazed heated plate, both are heated electrically from underside. Similar wind conditions were maintained on the collector as well as on heated plate by a large fan. Under similar wind conditions the values of wind heat transfer coefficient from the unglazed plate and collector are within 3% rms error.

KEYWORDS: Flat Plate Solar Collector, Thermal Performance, Glass Cover Temperature, Wind Heat Transfer Coefficient, Unglazed Heated Plate

Symbols and Abbreviations

A_p = Area of the absorber plate of collector or unglazed plate (m^2)

h_{rga} = Radiative heat transfer coefficient between glass cover and ambient (w/m^2k).

h_w = Wind heat transfer coefficient (w/m^2k).

K_g = Thermal conductivity of glass (w/mk).

K_{gw} = Thermal conductivity of glass wool (w/mk).

Q_b = Bottom heat loss per unit area per unit time (w/m^2)

Q_{in}= Input heat supplied per unit time (w)

Q_t = Top heat loss per unit area per unit time (w/m^2)

T_p = Plate temperature (^{o} C).

T_a = Ambient temperature (^{o} C).

T_{gi} = Inner surface temperature of the glass cover (^{o} C).

T_{go} = Outer surface temperature of the glass cover (^{o} C).

U_{ga} = Heat transfer coefficient between glass cover and ambient (w/m^2K).

U_{pa} = Heat transfer coefficient between unglazed plate and ambient (w/m^2K).

V = Wind velocity (m/s).

Greek Symbols

δ_g = Thickness of the glass cover (m)

δ_{gw}=Thickness of the glass wool (m)

ε_g = Emittance of Glass

ε_p = Emittance of unglazed plate

σ =Stefan's-Boltzman constant (w/m^2K^4)

Subscripts

a = atmosphere
p = absorber plate
g = glass cover
i = inner
o = outer

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Introduction

In order to design a solar thermal collector or to evaluate the thermal performance of the system under different operating conditions, the heat loss factor must be known. The overall heat loss factor, U_L, is the sum of top heat loss factor (U_t) and bottom and sides heat loss factors (U_b and U_s). In a well-insulated collector the bottom and side losses are small. The top heat loss factor of a collector (with single or double glazing) is a function of the basics variables: plate temperature (T_p), ambient temperature (T_a), plate emittance (ε_p), air spacing (L), collector tilt (β) and wind heat transfer coefficient (h_w).

For estimating the wind heat transfer coefficient (h_w) of a flat plate solar collector, the glass cover temperature is needed. The measurement of glass cover temperature of a flat plate solar collector is not so easy, especially in outdoor conditions. In outdoor conditions the glass cover temperature is measured using a thermocouple which yields an error as it's junction is directly exposed to the solar radiation.

Presently the wind heat transfer coefficient, from outer glass cover of a flat plate solar collector, is determined using the following correlations,

i. McAdam's Correlation (1954)

$$h_w = 5.7 + 3.8\ V \qquad \text{-----------} \ (1)$$

ii. Watmuff's Correlation (1977)

$$h_w = 2.8 + 3.0\ V \qquad \text{-----------} \ (2)$$

iii Test et al. (1980)

$$h_w = (8.55 \pm 0.86) + (2.56 \pm 0.32)\ V \qquad \text{-----------} \ (3)$$

iv. Subodh et al. (1997)

$$h_w = 10.03 + 4.687\ V \qquad \text{-----------} \ (4)$$

These correlations are based on wind tunnel tests of isolated plates. But wind flow over a flat plate solar collector (or solar box cooker) is not always well represented by wind tunnel flow. In actual outdoor conditions the collector will sometimes be exposed directly to the wind and othertimes will be in the wake region. Moreover different correlations give different values of wind heat transfer coefficient at the same wind velocity. Although a small approximation in the wind heat transfer coefficient will not cause too much error, but arbitrary selection of a correlation will cause substantial error in the thermal analysis. Values of the wind heat transfer coefficient were calculated using the four correlations (as given by the eqns. 1 to 4) for wind velocity range 1-5 m/s. The wind heat transfer coefficient was plotted against the wind velocity as shown in the following Figure 1.

Therefore these correlations are not correctly applicable for determining the h_w for thermal modeling of flat plate solar collectors. There is a need of the measurement of wind heat transfer coefficient in the similar conditions during testing of flat plate collector. An unglazed heated plate of almost of same size of collector aperture was used to measure the wind heat transfer coefficient. The plate is well insulated at the bottom and sides to compel most of the heat to flow through upward. The plate is painted dull black at the upper side.
The unglazed heated plate can be placed near the flat plate solar collector for the measurement of wind heat transfer coefficient.

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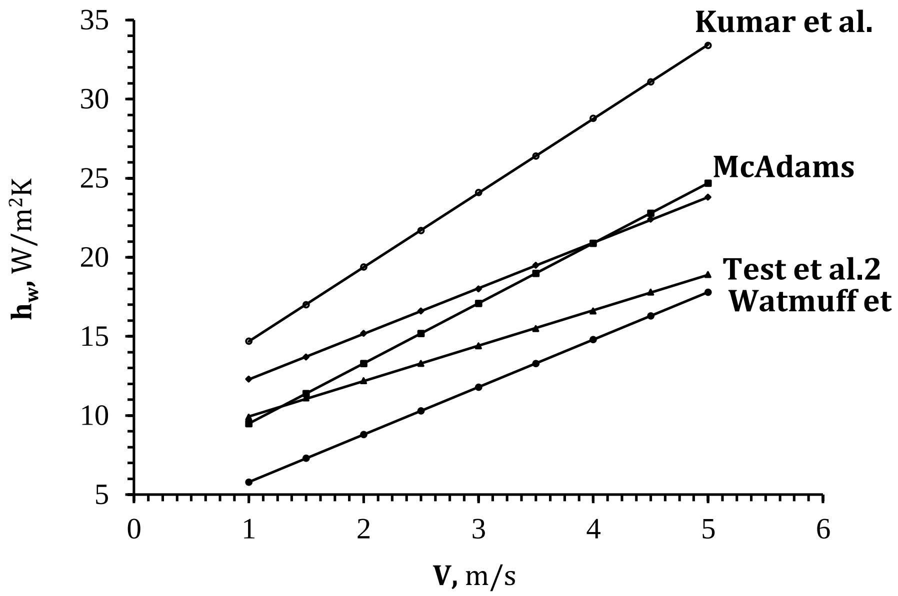

Figure 1: h_w at Various Wind Velocities from different Correlations

Indoor experiments were performed on a single glazed flat plate collector and unglazed heated plate (both are heated electrically from underside) under similar wind conditions set by a large fan. The glass cover temperature of the collector is measured using a thermocouple embedded in a slot made on inner surface of the glass cover.

Experimental Set-up and Experimentations

A. Indoor Flat Plate Collector

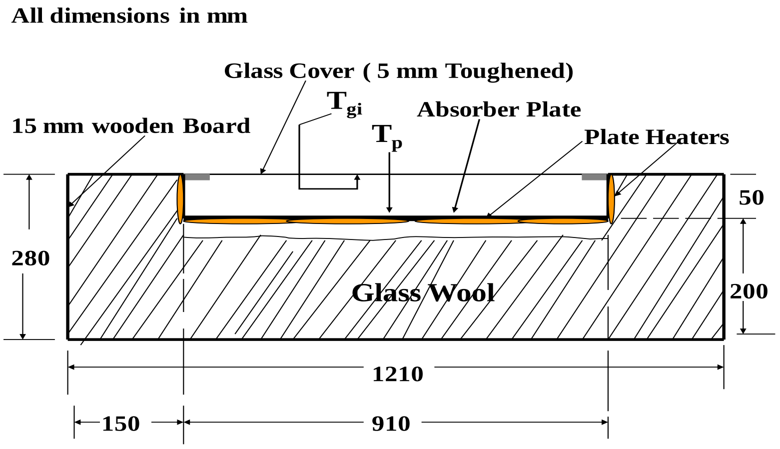

Figure 2: Indoor Experimental Single Glazed Collector

The experimental flat plate collector (Single glazed) consists of a copper plate 910 mm X 910 mm in size and 2 mm thickness coated with dull black paint. A plate type electric heater was attached on the underside of the copper plate (covering the entire area) for supplying the input energy. The electric heater was connected to a servo-stabilizer for constant voltage supply. A calibrated

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wattmeter was used to measure the power input to the heater. A large fan of about one meter diameter was used to produce wind. For any particular set of readings the wind speed was set using a variac. A 3-cup anemometer using chopper type sensor was used for the measurement of wind velocity. Bottom and sides were well insulated by using glass wool. Calibrated chromel-alumel thermocouples (type K) were attached to the absorber plate and glass cover for temperature measurements. The ratio of aperture area (910mm X 910 mm) to the plate-glass air spacing (50 mm) is large; therefore the side losses are small. As further precautions a low power guard heater is provided on four sides to cut-off the heat losses from the sides by balancing the temperatures.

During the experiments constant energy inputs were supplied to the main heater as well as the guard heater through variacs. The fan was set at a constant input voltage to obtain a constant wind velocity. For each set of observation, about 7 to 8 hours are required to attain a good steady state. Experiments were performed at different sets of input supply (Q_i) and wind velocity (V) ranging from 0.5 m/s to 2.5 m/s and following quantities were measured until steady state condition.

1. Plate Temperature measured at the centre of the plate (T_p)
2. Inner Surface Temperature of the Glass Cover (T_{gi})
3. Ambient Temperature (T_a)

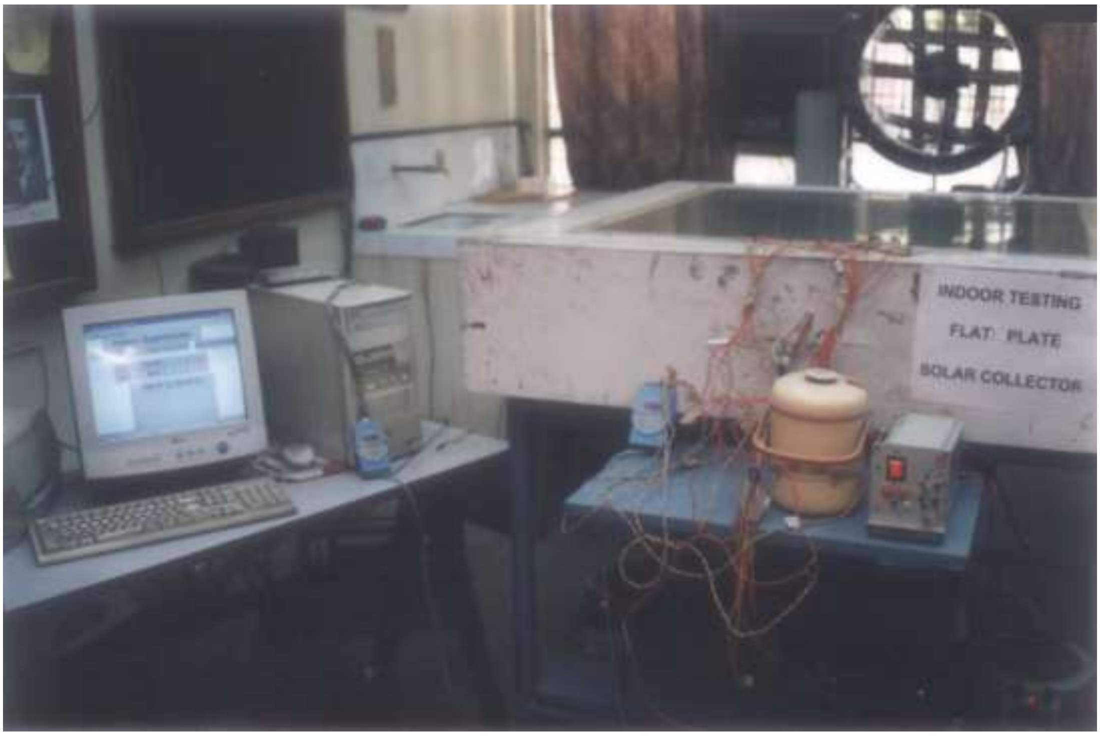

Figure 3: Experimental arrangement for indoor experiments

Nature of Air Flow

The nature of flow of air, for the velocity range under study, was checked by calculating the Reynolds number (Re). For the flow of wind over the horizontal outer surface of the glass

Cover, Re is given as;

$$Re = \frac{V \times L}{\nu}$$

V = velocity of the wind over the glass surface (m/s)

L= characteristic dimension of the collector in the direction of flow (m)

ν = kinematic viscosity of air (m/s^2)

Table 1: Experimental data for indoor single glazed collector

V m/s	**Q_i** W	**T_p** °C	**T_{gi}** °C	**T_a** °C	**Re**
0.5	300.0	94.7	52.6	30.6	$0.236 x 10^5$
0.7	300.0	93.5	52.3	30.6	$0.332 x 10^5$
0.8	300.0	92.7	51.8	30.5	$0.380 x 10^5$
1.0	400.0	107.3	56.5	30.5	$0.458 x 10^5$
1.2	400.0	106.6	55.2	31.1	$0.549 x 10^5$
1.5	400.0	105.5	54.0	30.5	$0.690 x 10^5$
2.0	400.0	104.0	51.6	30.5	$0.923 x 10^5$
2.5	350.0	93.5	53.5	37.1	$1.157 x 10^5$

Since,
$Re < 2 \times 10^5$ therefore for this range of wind velocity, the flow is Laminar over the entire length of glass cover of the collector or unglazed plate.

B. Indoor Unglazed heated Plate

2 mm thick aluminum sheet of size 910 x 910 mm (same as aperture area of the collector) is painted dull black and its underside, plate heaters are provided covering the entire area of the plate. Asbestos sheet of thickness 4 mm is attached below the heaters as shown in the Figure 4. The combination is fixed over an insulated pad comprises a 50 mm glass wool layer and 50 mm thermocole layer. The electric heater was connected to a servo-stabilizer for constant voltage supply. The other instruments and their arrangement, for measuring the power input, temperatures and wind velocity, were same as in the case of experiments on collector.

Experiments were performed at different sets of input supply and wind velocity (same values as taken in collector case) ranging from 0.5 m/s to 2.5 m/s. For each set of observation, about 3 to 4 hours are required to attain a good steady state. The following quantities were measured until the steady state was reached.

1. Plate temperature (T_p) measured at the centre on the underside of the plate.
2. Temperatures (T_1 and T_2) across the glass wool layer.
3. Ambient Temperature (T_a)

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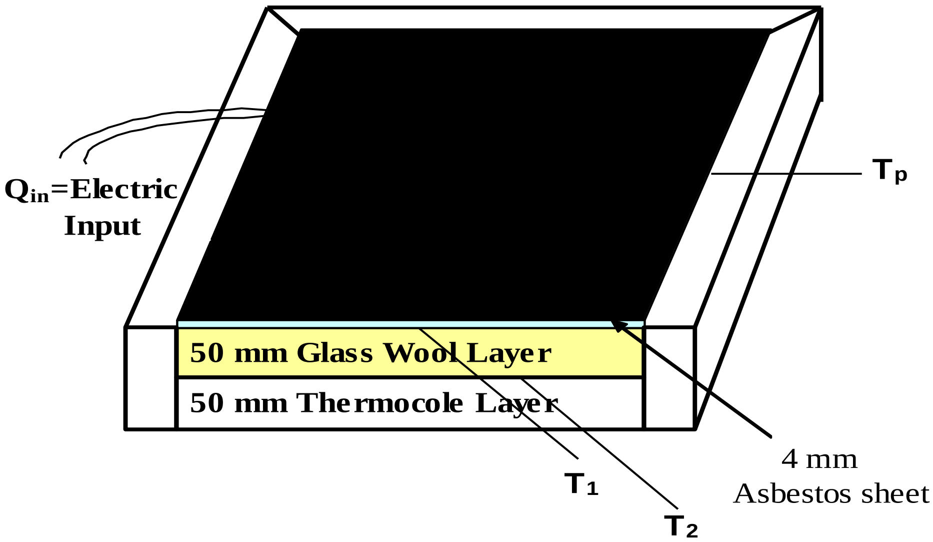

Figure 4: Indoor Unglazed Heated Plate

Table 2: Experimental Data for Indoor Unglazed Heated Plate

V m/s	Q_{in} W	T_p °C	T_1 °C	T_2 °C	T_a °C
0.5	300.0	55.6	77.0	56.6	33.0
0.7	300.0	52.7	75.1	55.7	31.0
0.8	300.0	52.0	74.7	54.6	31.3
1.0	300.0	51.0	73.5	54.1	31.7
1.2	300.0	48.8	71.6	53.3	30.0
1.5	300.0	49.0	72.0	54.0	31.0
2.0	300.0	45.8	68.6	53.2	30.7
2.5	300.0	47.8	70.5	53.0	33.0

Analysis

From the experimental date of Table-1, for each set of observations at the steady state, the heat balance at the collector (equations 1.1 to 1.6, Appendix-I) gives the value of wind heat transfer coefficient from the outer glass cover of the flat plate collector.

Similarly from the experimental date of Table-2, for each set of observations at the steady state, the heat balance at the unglazed plate (equations 2.1 to 2.5, Appendix-II) gives the value of wind heat transfer coefficient from the unglazed plate.

The values of wind heat transfer coefficient obtained from the outer glass cover of the flat plate collector and those from the unglazed heated plate are tabulated and plotted against the wind velocity. The plot compares the wind heat transfer coefficient from the outer glass cover of the collector and that from unglazed heated plate as shown in the following Figure 5.

The deviation of the values of wind heat transfer obtained from the unglazed heated plate and from those of the collector was studied. For the velocity range under study, the root mean square deviation is 0.34 W/m^{2}K as shown in the following Table 3. For wind heat transfer coefficient ranging from 8-18.5 W/m^{2}K, the rms deviation of 0.34 W/m^{2}K indicates a good accuracy of the results.

Table 3: Comparison of h_w of Collector and Unglazed Plate

V m/s	**h_w W/m^{2}K** Collector	Plate	**Δh_w**	**$(\Delta h_w)^2$**
0.5	8.1	8.3	-0.200	0.040
0.7	9.2	9.3	-0.100	0.010
0.8	10.2	10.0	0.200	0.040
1.0	11.7	11.3	0.400	0.160
1.2	12.3	12.0	0.300	0.090
1.5	13.6	13.0	0.600	0.360
2.0	16.0	16.5	-0.500	0.250
2.5	18.5	18.5	0.000	0.000
Average h_w=12.5 W/m^{2}K		**rms Value=0.34 W/m^{2}K, rms error=2.7%**		

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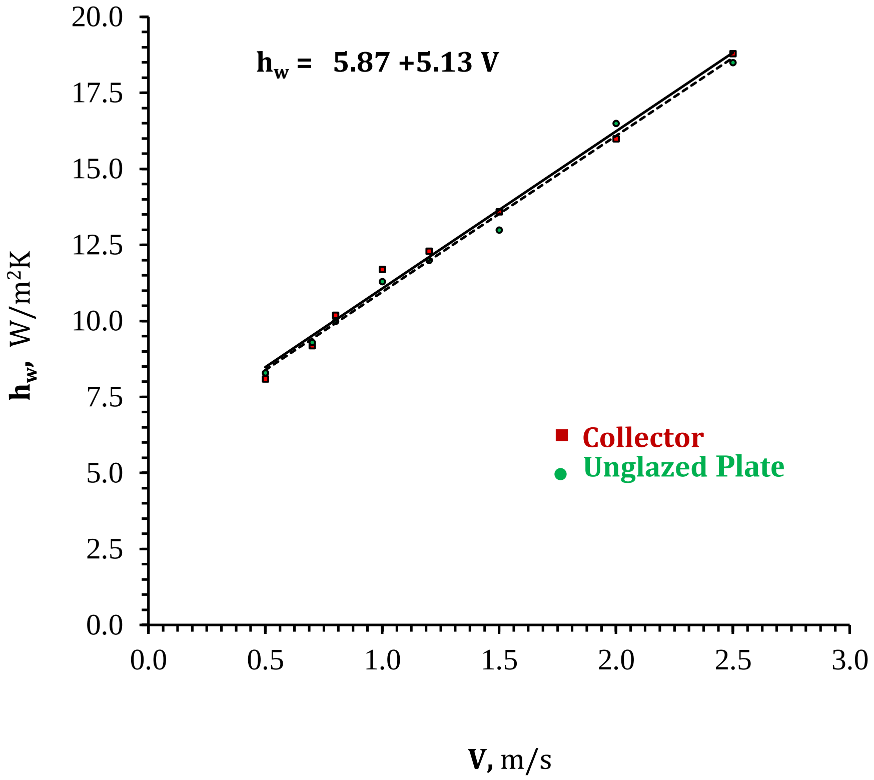

Figure 5: Deviation of h_w of Collector from that of Unglazed Plate

By the linear regression of two curves of plot between wind heat transfer coefficient and wind velocity (Figure 5), a single linear equation of h_w is obtained. The values of wind heat transfer coefficient of flat plate collector were analytically verified using obtained equation.

Table 4: Validation of h_w of single Glazed Collector

V m/s	h_w **Heat Balance** W/m²K	h_w **Linear Relation** W/m²K	Δh_w	$(\Delta h_w)^2$
0.5	8.1	8.4	-0.341	0.116
0.7	9.2	9.5	-0.267	0.072
0.8	10.2	10.0	0.219	0.048
1.0	11.7	11.0	0.692	0.479
1.2	12.3	12.0	0.266	0.071
1.5	13.6	13.6	0.025	0.001
2.0	16.0	16.1	-0.142	0.020
2.5	18.5	18.7	-0.200	0.040
Average h_w=12.5 W/m²K		**rms Value=0.325 W/m²K, rms error=2.6%**		

RESULTS AND DISCUSSION

At the same indoor wind conditions, the values of wind heat transfer coefficient from the outer glass cover of the collector was found to be very close to the values obtained from an unglazed plate of the same size. In indoor testing and thermal performance evaluation of a flat plate collector (also solar box cooker) the wind heat transfer coefficient from its outer glass cover can be approximated by the wind heat transfer coefficient from an unglazed plate of the same size.

The wind heat transfer coefficient obtained from the heat balance at the collector and plate under similar wind conditions are within 2.7% rms error. The values of wind velocity and corresponding wind heat transfer coefficients, for collector and unglazed plate are merged all together and plotted to obtained a single linear function of h_w with V. The wind heat transfer coefficients of the collector are within 2.6% rms with the corresponding values obtained from combined linear function.

Conclusion

From the above analysis and discussion it can be concluded that in indoor testing and thermal performance evaluation of a flat plate collector (also solar box cooker) the wind heat transfer coefficient from its outer glass cover can be approximated by the wind heat transfer coefficient from an unglazed plate of the same size. The use of this proposed method for the estimation of h_w eliminates the measurement of glass cover temperature or the use of velocity based correlations, which create a substantial amount of uncertainty. The adoption of proposed method will minimize the uncertainties (due to $h_{w)}$, in the thermal analyses of flat plate collectors or solar box cookers.

References

[1] McAdamas W.H., (1954). Heat Transmission, New York: McGraw-Hill, p.249.
[2] Hollands K. G. T., Unny T. E., Raithby G. D., Knoick L., 1976, Free convective heat-transfer across inclined air layers, ASME Journal of Heat Transfer, 98, pp.189- 192.
[3] Watmuff J. H., Charters W.W.S. and Proctor D., 1977, Solar and Wind Induced External coefficients for Solar Collectors, COMPLES, 2(56).
[4] Test F.L., Lessmann R.C. and Johary A., 1980, Heat Transfer During Wind Flow Over Rectangular Bodies in Natural Environment, Trans. ASME Journal of Heat Transfer, 103, pp 262-267.
[5] Subodh K., Sharma,V.B., ,Kandpal,T.C. and Mullick S.C., 1997, Wind Induced Heat Losses from Outer Cover of Solar Collectors, Renewable Energy, 10(4), pp 613-616.
[6] Khan S.Y., 2010, "Uncertainty in the Estimation of Glass Cover Temperatures and Top Heat Loss Factor of Flat Plate Solar Collectors", Proc. 16th ISME Conference on Mechanical Engineering for sustainable development, I. I. T. Delhi, New Delhi, India, Session 6 , Thermal Engineering-III (5).

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Appendix-I

Determination of h_w of Indoor Collector

At the steady state;

Bottom heat loss flux

$$Q_b = \frac{K_{gw}(T_p - T_a)}{\delta_{gw}} \quad \text{---------- (1.1)}$$

Top heat Loss flux

$$Q_t = \frac{O_{in}}{A_p} - Q_b \quad \text{-------- (1.2)}$$

Outer surface temperature of the glass cover

$$T_{go} = T_{gi} - \frac{(Q_t \times \delta_g)}{K_g} \quad \text{------------ (1.3)}$$

Heat transfer coefficient between glass cover and ambient,

$$U_{ga} = \frac{Q_t}{(T_{go} - T_a)} \quad \text{------------ (1.4)}$$

Radiative heat transfer coefficient from glass surface to the ambient

$$h_{rga} = \varepsilon_g \sigma \{(T_{go})^2 + (T_a)^2\}(T_{go} + T_a) \quad \text{--- (1.5)}$$

Wind heat transfer coefficient over the outer surface of the glass cover

$$h_w = U_{ga} - h_{rga} \quad \text{------------ (1.6)}$$

Appendix-II

Determination of the h_w of Unglazed Plate

At the steady state;

Bottom heat Loss flux

$$Q_b = \frac{K_{gw}(T_p - T_a)}{\delta_{gw}} \quad \text{-------- (2.1)}$$

Top heat loss flux

$$Q_t = \frac{O_{in}}{A_p} - Q_b \quad \text{------ (2.2)}$$

Heat transfer coefficient between plate and ambient,

$$U_{pa} = \frac{Q_t}{(T_p - T_a)} \quad \text{-------- (2.3)}$$

Radiative heat transfer coefficient from plate surface to the ambient

$$h_{rpa} = \varepsilon_p \sigma \{(T_p)^2 + (T_a)^2\}(T_p + T_a) \quad \text{-------- (2.4)}$$

Wind heat transfer coefficient

$$h_w = U_{pa} - h_{rpa} \quad \text{-------- (2.5)}$$