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Effect of various parameters on sol-air temperature

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Abstract

The sol-air temperature is an important parameter in building heat transfer. This is estimated based on solar radiation and outdoor air temperature ($T_{Outdoor}$). This work aimed to find the effect of various parameters on sol-air temperature. A theoretical sol-air temperature has been predicted with various ranges of parameters like solar radiation, material absorptivity, convective heat transfer coefficient. As per ASHRAE guidelines, the ratio of absorptivity to the convective heat transfer coefficient values ranges from 0.026 to 0.052 also considered to estimate the same. In this work, the wide range of $T_{Outdoor}$ from 15°C to 50°C was considered and the solar radiation maximum of 1000 W/m^2 was considered. The results show that the theoretical sol-air temperature reaches 102°C with maximum solar radiation of 1000 W/m^2 and the absorptivity to the convective heat transfer coefficient ratio of 0.052.

Keywords : Sol-air temperature, outdoor air temperature, absorptivity, solar radiation, convection heat transfer coefficient

Introduction

The sol-air temperature ($T_{Sol-air}$) is the outdoor temperature ($T_{Outdoor}$) at which the rate of heat transfer through building enclosures (wall, window glazing and roof) by the combined effect of $T_{Outdoor}$ and incident solar radiation. In addition to that, the building material property absorptivity and building enclosures outside convective heat transfer coefficient play a significant role [1, 2]. The external surface temperature is more or less equal to $T_{Sol-air}$, Building cooling load is calculated based on the $T_{Sol-air}$ which is also based on the thermal mass of the building materials [3]. The high building material reflection factor shows less cooling load than the low reflective materials. The difference in the $T_{Sol-air}$ increased by 60°C as increasing the aspect ratio [4]. For estimating indoor thermal comfort, building enclosures inside surface temperature is essential. Based on the temperature difference between the inside enclosure's surface temperature and indoor air temperature, the flow of convective heat transfer exists. Higher the difference higher heat transfer and lower the difference lower heat transfer either the way. Many researchers used $T_{Sol-air}$ for estimating the inside enclosure's temperature for thermal comfort prediction [5-8]. The movement of air-conditioned passenger train compartment subjected to receive solar radiation from all direction. The effect of parabolic heat gain to the comportment through wall varies time to time. A dynamic numerical analysis has conducted with $T_{Sol-air}$ in order to maintain thermal comfort inside the train compartment [9]. The sol-air estimation is not only applicable to human interaction buildings, it also plays a vital role in many industries like Broiler houses. At different weather conditions, broiler house convective heat gain was predicted by using $T_{Sol-air}$. In this work, it has been reported that during the measurement period the maximum $T_{Sol-air}$ and surface temperature exceed the air temperature. Also, it has been reported that in order to predict the external surface temperature sol-air temperature is the most appropriate one than the $T_{Outdoor}$ [10].

Basically, the buildings are constructed with different shapes and size based on the space availability, usage and energy perspectives. But most of the buildings are constructed in rectangular, square shape. [11]. Different building geometries on four climatic seasons at different building orientations were simulated to control the heat gain of a double façade building [12]. The building wall materials effects on the indoor thermal comfort, it is reported that the clay brick wall provides 5°C less than the concrete wall in Jordan [13]. Indoor air temperature of a building largely varies at different levels, the vertical temperature gradient is different at various levels [14]. The temperature variation has noted as 20°C in some cases [15], depends on that indoor air temperature also varies. It is also reported that, during summer cooling days in hot and dry climatic conditions, the impact of $T_{Sol-air}$ on the rectangular buildings are high. These buildings have been estimated to lose 41% of total cooling energy loss during summer days. It was also reported as square shape and east-west orientation buildings has low impact on $T_{Sol-air}$ [16].

Cost benefit investigation has conducted on US residential buildings with switchable integrated system (SIS). This analysis shows there is a strong correlation between sol-air temperature and heating/cooling days. The energy saving potential in US under different environmental conditions with SIS has estimated as minimum of 14 kWh/m^2 to maximum of 51 kWh/m^2 [17]. Saudi Aribia is one of the hottest countries in the world, for cooling the buildings 66% of energy been utilized. In terms of cooling load calculations sol-air temperature is used for calculating air handling units (AHUs) loads. With phase change material, the energy usage decreases 14% of the total energy utilized for indoor cooling [18]. Many solar based application (like solar air heat, solar water heater, parabolic trough collector, etc.) estimation of $T_{Sol-air}$ plays significant role in equipment performance [19]. Still, many researchers trying to estimate $T_{Sol-air}$ through various methods. The dynamic environmental impact on $T_{Sol-air}$ in transient condition has estimated [20-22].

In many countries building regulations are not implemented and few countries building regulations are implemented recently. Hence in most of the existing buildings while estimating the cooling and heating load at different locations it is essential to estimate $T_{Sol-air}$. The primary objective of this work is to predict the $T_{Sol-air}$ theoretically by considering the parameters $T_{Outdoor}$, solar radiation, material absorptivity and convective heat transfer coefficient as per ASHRAE guidelines. The secondary objective of this work is to predict $T_{Sol-air}$ beyond the limits according to the environmental conditions.

Methodology

The source of heat to the environment is the sun. The buildings are receiving heat from the sun by means of solar radiation as long and short waves. These waves heat up the building enclosures, along with that many factors influencing the rate of heat transfer to the buildings. The equation is used for estimating the building heat transfer per unit area or heat flux is mentioned below.

$$\frac{q}{A} = a\, I_{Total} + h_0 \left(T_{Outdoor} - T_{Surface}\right) - \varepsilon\, \Delta R \qquad (1)$$

Where, the heat flux in W/m^2 is q/A, a is absorptivity, I_{Total} is the total irradiance and h_0 is the convective heat transfer co-efficient, $T_{Outdoor}$ is the outdoor temperature, $T_{Surface}$ is the surface temperature of the building, the surface emissivity is ε and the difference between the solar radiation (long wave) to the radiation emitted (surface) by the blackbody at $T_{Outdoor}$ is ΔR. The below equation is used for estimating the building heat transfer rate in terms of sol-air temperature.

$$\frac{q}{A} = h_0 \left(T_{Sol-air} - T_{Surface}\right) \qquad (2)$$

The sol-air temperature ($T_{Sol-air}$) can be expressed as follows

$$T_{sol-air} = T_{Outdoor} + \frac{a\, I_{Total}}{h_0} - \frac{\varepsilon\, \Delta R}{h_0} \qquad (3)$$

The value of $\frac{(\varepsilon\, \Delta R)}{h_0}$ is mostly varies between 0 to 4 according to the orientation. When the surface is horizontal, the value may be 0 and in case of vertical its value becomes 4 [23]. In this work horizontal surface is considered, hence the value of $\frac{(\varepsilon\, \Delta R)}{h_0}$ becomes 0. The above equation can be remodified as mentioned below.

$$T_{sol-air} = T_{Outdoor} + \frac{a\, I_{Total}}{h_0} \qquad (4)$$

However as per the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) fundamental guidelines, the ratio of absorptivity (a) and convection heat transfer co-efficient (h_0) is ranging from 0.026 to 0.052 [24].

$$T_{sol-air} = T_{Outdoor} + (a_h\, I_{Total}) \qquad (5)$$

Where a_h is the ratio of absorptivity and convection heat transfer co-efficient (a/h_0).

Further all environmental conditions are not always within the prescribed limit as per ASHRAE standard guidelines. Many cases, environmental conditions may deviate drastically for the standard values. One such extreme conditions are also discussed here under by considering different values of convective heat transfer coefficient (10 W/m^{2}K to 2 W/m^{2}K), absorptivity (0.1 to 0.9) and solar radiation (200 W/m^2 to 1000 W/m^2).

Results and discussion

As per the ASHRAE guidelines the sol-air temperature has estimated with absorptivity and convection heat transfer co-efficient ratio, ranges from 0.026 to 0.052. Fig. 1 shows the temperature of outdoor air versus $T_{Sol-air}$ at ratio of 0.026 with different values of solar radiation. As expected, it is clear from the figure that $T_{Outdoor}$ and $T_{Sol-air}$ has linear relationship. Increase in $T_{Outdoor}$ increases the $T_{Sol-air}$, as well as increase in solar radiation also increases $T_{Sol-air}$. When the ratio of absorptivity and convection heat transfer coefficient ratio is 0.031 at $T_{Outdoor}$ is 15°C, the $T_{Sol-air}$ is predicted as 20.2°C for 200 W/m^{2}K solar radiation. At the same time, every 5°C raise in $T_{Outdoor}$ increases 5°C in the $T_{Sol-air}$. The rise in solar radiation increases the sol-air temperature in all cases of $T_{Outdoor}$. For the solar radiation 400, 600, 800 and 1000 W/m^{2}K, the rise in $T_{Sol-air}$ variations is estimated as 25.7%, 20.5%, 17.0% and 14.5% respectively for outdoor air tem$T_{Outdoor}$perature 15°C. An increase in $T_{Outdoor}$ decreased the percentage of $T_{Sol-air}$ rise. In case of 1000 W/m^{2}K solar radiation, the $T_{Sol-air}$ rise is estimated as 12.7%, 11.4%, 10.2%, 9.3%, 8.6%, 7.9% and 7.3% from 20°C to 50°C for every 5°C. In case of lower solar radiation 400 W/m^{2}K, the $T_{Sol-air}$ rise is estimated as 20.6%, 17.2%, 14.8%, 12.9%, 11.5%, 10.4% and 9.4% from 20°C to 50°C for every 5°C.

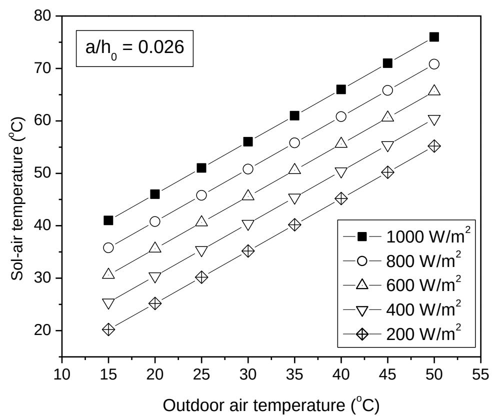

Fig. 1 Outdoor air temperature versus Sol-air temperature at a/h_0 ratio 0.026

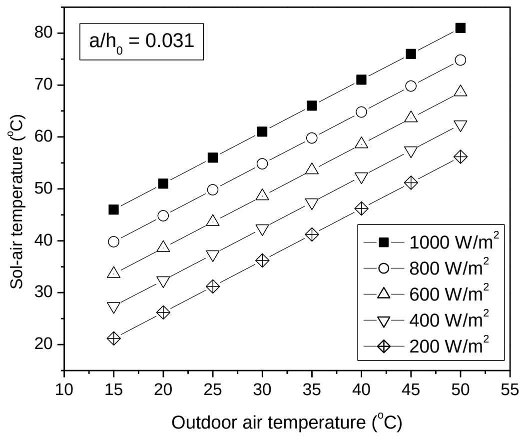

Fig. 2 Outdoor air temperature versus Sol-air temperature at a/h_0 ratio 0.031

The temperature variation between $T_{Outdoor}$ versus $T_{Sol-air}$ at the ratio of 0.031 with different values of solar radiation is shown in fig. 2. When the ratio of absorptivity and convection heat transfer coefficient ratio is 0.031 at $T_{Outdoor}$ is 15°C, the $T_{Sol-air}$ is predicted as 21.2°C for 200 W/m^{2}K solar radiation. At the same time, every 5°C raise in $T_{Outdoor}$ increases 5°C in the $T_{Sol-air}$. The rise in solar radiation increases the $T_{Sol-air}$ in all cases of $T_{Outdoor}$. For the solar radiation 400, 600, 800 and 1000 W/m^{2}K, the rise in $T_{Sol-air}$ variations are estimated as 29.2%, 22.6%, 18.5% and 15.6% respectively for $T_{Outdoor}$ 15°C. An increase in $T_{Outdoor}$ decreased the percentage of $T_{Sol-air}$ rise. In case of 1000 W/m^{2}K solar radiation, $T_{Sol-air}$ rise is estimated as 13.8%, 12.4%, 11.3%, 10.4%, 9.6%, 8.9% and 8.3% from 20°C to 50°C for every 5°C. In case of lower solar radiation 400 W/m^{2}K, $T_{Sol-air}$ rise is estimated as 23.7%, 19.9%, 17.1%, 15.0%, 13.4%, 12.1% and 11.0% from 20°C to 50°C for every 5°C.

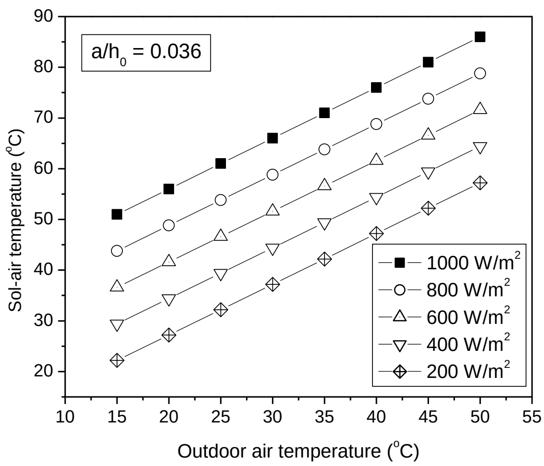

Fig. 3 Outdoor air temperature versus Sol-air temperature at a/h_0 ratio 0.036

The temperature variation between $T_{Outdoor}$ versus $T_{Sol-air}$ at the ratio of 0.036 with different values of solar radiation is shown in fig. 3. When the ratio of absorptivity and convection heat transfer coefficient ratio is 0.031 at $T_{Outdoor}$ is 15°C, $T_{Sol-air}$ is predicted as 22.2°C for 200 W/m^{2}K solar radiation. At the same time, every 5°C raise in $T_{Outdoor}$ increases 5°C in $T_{Sol-air}$. The rise in solar radiation increases $T_{Sol-air}$ in all cases of $T_{Outdoor}$. For the solar radiation 400, 600, 800 and 1000 W/m^{2}K, the rise in $T_{Sol-air}$ variations are estimated as 32.4%, 24.5%, 19.7% and 16.4% respectively for $T_{Outdoor}$ 15°C. An increase in $T_{Outdoor}$ decreased the percentage of $T_{Sol-air}$ rise. In case of 1000 W/m^{2}K solar radiation, $T_{Sol-air}$ rise is estimated as 14.8%, 13.4%, 12.2%, 11.3%, 10.5%, 9.8% and 9.1% from 20°C to 50°C for every 5°C. In case of lower solar radiation 400 W/m^{2}K, $T_{Sol-air}$ rise is estimated as 26.5%, 22.4%, 19.4%, 17.1%, 15.3%, 13.8% and 12.6% from 20°C to 50°C for every 5°C.

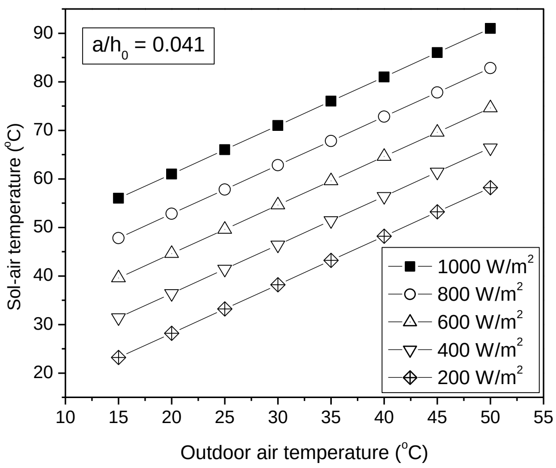

Fig. 4 Outdoor air temperature versus Sol-air temperature at a/h$_0$ ratio 0.041

The temperature variation between $T_{Outdoor}$ versus $T_{Sol-air}$ at the ratio of 0.041 with different values of solar radiation is shown in fig. 4. When the ratio of absorptivity and convection heat transfer coefficient ratio is 0.031 at $T_{Outdoor}$ is 15°C, $T_{Sol-air}$ is predicted as 23.2°C for 200 W/m^{2}K solar radiation. At the same time, every 5°C raise in $T_{Outdoor}$ increases 5°C in $T_{Sol-air}$. The rise in solar radiation increases the $T_{Sol-air}$ in all cases of $T_{Outdoor}$. For the solar radiation 400, 600, 800 and 1000 W/m^{2}K, the rise in$T_{Sol-air}$ variations are estimated as 35.3%, 26.1%, 20.7% and 17.2% respectively for $T_{Outdoor}$ 15°C. An increase in $T_{Outdoor}$ decreased the percentage of $T_{Sol-air}$ rise. In case of 1000 W/m^{2}K solar radiation, the $T_{Sol-air}$ rise is estimated as 15.5%, 14.2%, 13.1%, 12.1%, 11.3%, 10.5% and 9.9% from 20°C to 50°C for every 5°C. In case of lower solar radiation 400 W/m^{2}K, $T_{Sol-air}$ rise is estimated as 29.1%, 24.7%, 21.5%, 19.0%, 17.0%, 15.4% and 14.1% from 20°C to 50°C for every 5°C.

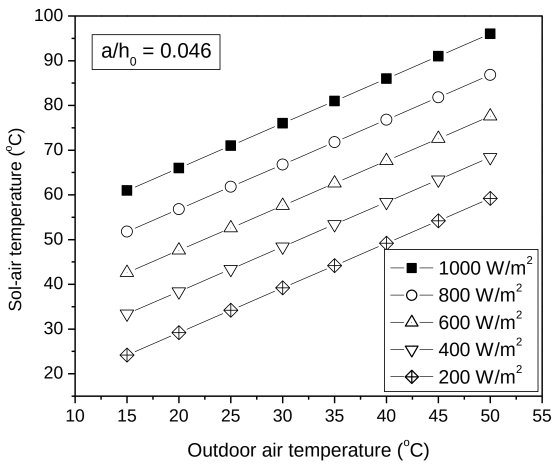

Fig. 5 Outdoor air temperature versus Sol-air temperature at a/h$_0$ ratio 0.046

The temperature variation between $T_{Outdoor}$ versus $T_{Sol-air}$ at the ratio of 0.046 with different values of solar radiation is shown in fig. 5. When the ratio of absorptivity and convection heat transfer coefficient ratio is 0.031 at $T_{Outdoor}$ is 15°C, $T_{Sol-air}$ is predicted as 24.2°C for 200 W/m^{2}K solar radiation. At the same time, every 5°C raise in $T_{Outdoor}$ increases 5°C in $T_{Sol-air}$. The rise in solar radiation increases $T_{Sol-air}$ in all cases of $T_{Outdoor}$. For the solar radiation 400, 600, 800 and 1000 W/m^{2}K, the rise in $T_{Sol-air}$ variations are estimated as 38.0%, 27.5%, 21.6% and 17.8% respectively for $T_{Outdoor}$ 15°C. An increase in $T_{Outdoor}$ decreased the percentage of $T_{Sol-air}$ rise. In case of 1000 W/m^{2}K solar radiation, $T_{Sol-air}$ rise is estimated as 16.2%, 14.9%, 13.8%, 12.8%, 12.0%, 11.2% and 10.6% from 20°C to 50°C for every 5°C. In case of lower solar radiation 400 W/m^{2}K, $T_{Sol-air}$ rise is estimated as 31.5%, 26.9%, 23.5%, 20.8%, 18.7%, 17.0% and 15.5% from 20°C to 50°C for every 5°C.

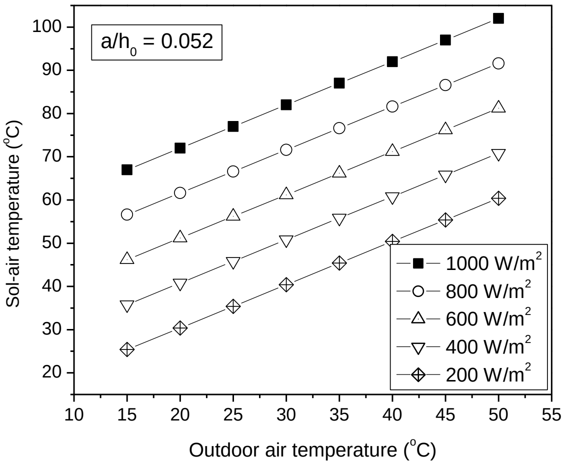

Fig. 6 Outdoor air temperature versus Sol-air temperature at a/h$_0$ ratio 0.052

The temperature variation between $T_{Outdoor}$ versus $T_{Sol-air}$at the ratio of 0.052 with different values of solar radiation is shown in fig. 6. When the ratio of absorptivity and convection heat transfer coefficient ratio is 0.052 at $T_{Outdoor}$ is 15°C, $T_{Sol-air}$ is predicted as 25.2°C for 200 W/m^{2}K solar radiation. At the same time, every 5°C raise in $T_{Outdoor}$ increases 5°C in $T_{Sol-air}$. The rise in solar radiation increases $T_{Sol-air}$ in all cases of $T_{Outdoor}$. For the solar radiation 400, 600, 800 and 1000 W/m^{2}K, the rise in $T_{Sol-air}$ variations is estimated as 40.9%, 29.1%, 22.5% and 18.4% respectively for $T_{Outdoor}$ 15°C. An increase in $T_{Outdoor}$ decreased the percentage of $T_{Sol-air}$ rise. In case of 1000 W/m^{2}K solar radiation, $T_{Sol-air}$ rise is estimated as 16.9%, 15.6%, 14.5%, 13.6%, 12.7%, 12.0% and 11.4% from 20°C to 50°C for every 5°C. In case of lower solar radiation 400 W/m^{2}K, $T_{Sol-air}$ rise is estimated as 34.2%, 29.4%, 25.7%, 22.9%, 20.6%, 18.8% and 17.2% from 20°C to 50°C for every 5°C.

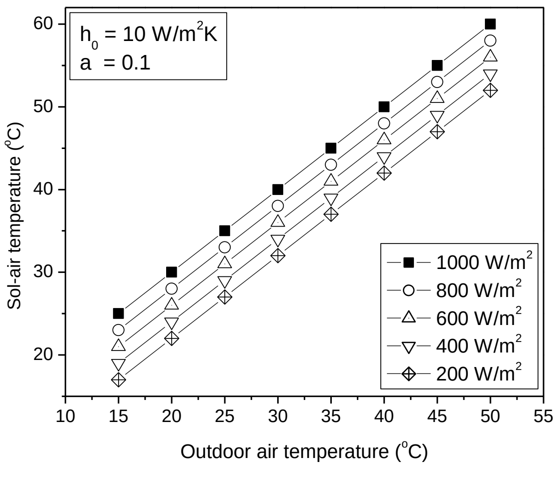

Fig. 7 Outdoor air temperature versus Sol-air temperature at a = 0.1 and h$_0$ = 10 W/m^{2}K

Further all environmental conditions are not always within the prescribed limit as per ASHRAE standard guidelines. Many cases, environmental conditions may deviate drastically for the standard values. One such extreme conditions are discussed here under by considering different values of convective heat transfer coefficient (10 W/m^{2}K to 2 W/m^{2}K), absorptivity (0.1 to 0.9) and solar radiation (200 W/m^2 to 1000 W/m^2).

The outdoor temperature versus $T_{Sol-air}$ with different values of solar radiation at constant absorptivity of 0.1 and convective heat transfer coefficient of 10 W/m^{2}K is shown in fig. 7. The figure shows outdoor temperature and $T_{Sol-air}$ have linear relationship, increase in $T_{Outdoor}$ increases $T_{Sol-air}$ at all cases of solar radiation. The minimum temperature estimated as 17°C at 200 W/m^{2}K at 15°C of $T_{Outdoor}$. An Increase in solar radiation increases $T_{Sol-air}$ for all cases of $T_{Outdoor}$. For the solar radiation 400, 600, 800 and 1000 W/m^{2}K, the rise in $T_{Sol-air}$ variations is estimated as 11.8%, 10.5%, 9.5% and 8.7% respectively for $T_{Outdoor}$ 15°C. An increase in $T_{Outdoor}$ decreases the percentage of $T_{Sol-air}$ rise. In case of higher solar radiation (1000 W/m^{2}K), $T_{Sol-air}$ rise is estimated as 7.1%, 6.1%, 5.3%, 4.7%, 4.2%, 3.8% and 3.4% from 20°C to 50°C for every 5°C. In case of lower solar radiation 400 W/m^{2}K, $T_{Sol-air}$ rise is estimated as 9.1%, 7.4%, 6.3%, 5.4%, 4.8%, 4.3% and 3.8% from 20°C to 50°C for every 5°C.

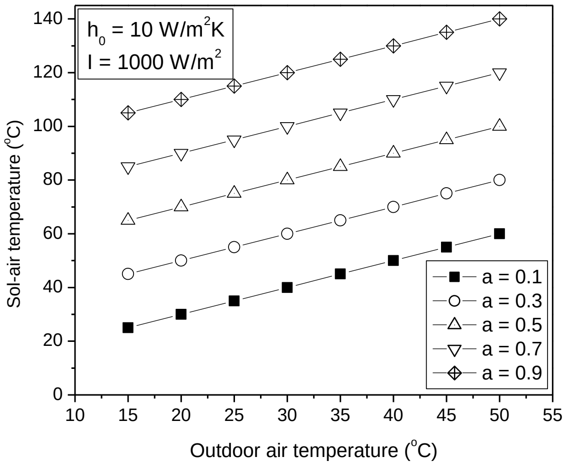

Fig. 8 Outdoor air temperature versus Sol-air temperature at I = 1000 W/m^2 and h_0 = 10 W/m^{2}K

The outdoor air temperature versus $T_{Sol-air}$ with different values of absorptivity at constant solar radiation of 1000 W/m^2 and convective heat transfer coefficient of 10 W/m^{2}K is shown in fig. 8. The minimum temperature estimated as 25°C for a = 0.1 and 1000 W/m^2 at 15°C of $T_{Outdoor}$. An Increase in absorptivity increases $T_{Sol-air}$ for all cases of $T_{Outdoor}$. For the absorptivity 0.3, 0.5, 0.7 and 0.9, the rise in $T_{Sol-air}$ variation is estimated as 80.0%, 44.4%, 30.8% and 23.5% respectively for $T_{Outdoor}$ 15°C. An increase in $T_{Outdoor}$ decreases the percentage of $T_{Sol-air}$ rise. In case of absorptivity (a = 0.9), $T_{Sol-air}$ rise is estimated as 22.2%, 21.1%, 20.0%, 19.0%, 18.2%, 17.4% and 16.7% from 20°C to 50°C for every 5°C. In case of lower absorptivity 0.1, $T_{Sol-air}$ rise is estimated as 66.7%, 57.1%, 50.0%, 44.4%, 40.0%, 36.4% and 33.3% from 20°C to 50°C for every 5°C.

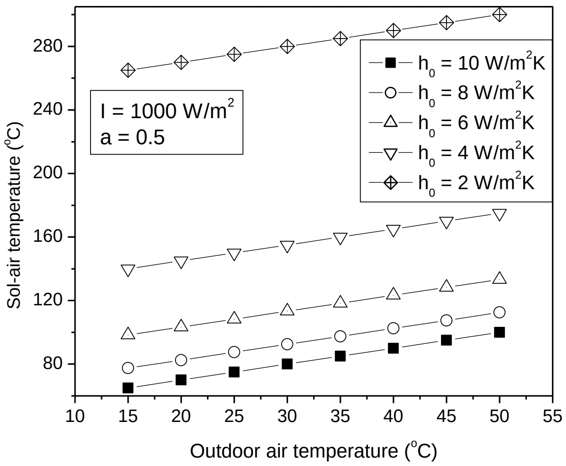

Fig. 9 Outdoor air temperature versus Sol-air temperature at I = 1000 W/m^2 and a = 0.5

The outdoor air temperature versus $T_{Sol-air}$ with different values of convective heat transfer coefficient at constant solar radiation of 1000 W/m^2 and absorptivity of 0.5 is shown in fig. 9. The minimum temperature estimated as 65°C for 1000 W/m^2 and heat transfer coefficient of 10 W/m^2 K at 15°C of $T_{Outdoor}$. A decrease in heat transfer coefficient increases $T_{Sol-air}$ for all cases of $T_{Outdoor}$. For the heat transfer coefficient 10, 8, 6, 4 and 2, the rise in $T_{Sol-air}$ variation is estimated as 19.2%, 26.9%, 42.4% and 89.3% respectively for $T_{Outdoor}$ 15°C. An increase in $T_{Outdoor}$ decreases the percentage of $T_{Sol-air}$ rise. In case of higher heat transfer coefficient (10 W/m^2 K), $T_{Sol-air}$ rise is estimated as 17.9%, 16.7%, 15.6%, 14.7%, 13.9%, 13.2% and 12.5% from 20°C to 50°C for every 5°C. In case of lower heat transfer coefficient 2 W/m^2 K, $T_{Sol-air}$ rise is estimated as 86.2%, 83.3%, 80.6%, 78.1%, 75.8%, 73.5% and 71.4% from 20°C to 50°C for every 5°C. Unlike other case the increase in heat transfer coefficient value the decreases $T_{Sol-air}$ 40.2%, 12.7% and 6.0% from lower level to higher level.

Conclusion

The sol-air temperature estimation within the ASHRAE guidelines, increase in $T_{Outdoor}$ decreases the percentage rise of $T_{Sol-air}$. Based on the ASHRAE recommendations $T_{Outdoor}$ and $T_{Sol-air}$ has linear relationship. For every 5°C rise in $T_{Outdoor}$ increases 5°C in the $T_{Sol-air}$ as well as Increase in $T_{Outdoor}$ increases $T_{Sol-air}$. Further increase in solar radiation also increases $T_{Sol-air}$ at all the cases. According to the environmental conditions, the variation of absorptivity, coefficient of convective heat gain and solar radiation had significant impact on $T_{Sol-air}$. In particular lower coefficient of convective heat gain increases $T_{Sol-air}$, the maximum temperature rise has estimated as 86.2% for 2 W/m^{2}K from 4 W/m^{2}K. At the same time, absorptivity and solar radiation rise increases the $T_{Sol-air}$ as well. On comparing both the cases environmental variables increases $T_{Sol-air}$. In addition to this, urban plan, shading devices, thermal mass of the wall, colour and surface coating also impact on the sol-air temperature.

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