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Ventilation Performance of a Solar Chimney with an External Tinted Glass Wall

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Abstract

To reduce the effects of increasing electricity load on account of global warming, researchers have proposed different configurations of solar chimney for enhancing natural ventilation in buildings. In this study, a modified solar chimney is investigated wherein the exterior glass panel is tinted to different heights (full height, quarter, half and three-fourth from the top and bottom respectively) and with different absorptivities (25%, 50%, 75% and linearly varying respectively). Simulations are performed for the different cases using ANSYS Fluent, and the mass flow rates at the inlet of the solar chimney are calculated. It is found that the flow rates are affected largely by the height to which the glazing is tinted, rather than the absorptivity level. An optimum case that results in the best ventilation performance is determined.

Introduction

With global warming on the rise, it is necessary to reduce our carbon footprint. Extreme summers and winters are now a common scenario, resulting in an increase in the electricity load. With world population on the rise, it can lead to worse situations.

Solar chimney, a now widely researched topic, can help to reduce the electricity load by allowing passive heating and cooling. Buildings are usually designed to provide a certain level of natural ventilation. There are two types of natural ventilation: temperature driven and wind driven. Stack ventilation is one that is driven by a temperature difference, as opposed to a pressure difference caused by wind. The transparent wall or roof of the solar chimney allows solar energy to heat up the air within it, resulting in a temperature variation between the ambient and the inside of the chimney, leading to an air density difference [6]. The solar chimney takes advantage of the temperature variation created within the building, enhancing the effect of stack ventilation.

Various forms of solar chimneys have been put forward by researchers to further improve the ventilation performance. While some have introduced changes to the geometric design, others have considered the materials used for specific parts like the absorber or glazing. These investigations all focus on one main goal, that is, improving the mass flow rate through the solar chimney.

Mathur et al. (2006) investigated the performance of a solar chimney in hot climatic conditions by varying the absorber height and air gap width, and identified the most optimum combination out of the nine different configurations considered. They reported that the air flow rate increases with incoming solar radiation and the air gap width for all the cases, and the convective flow is less restricted at larger air gap widths, resulting in higher velocities.

Khanal and Lei (2012) investigated the formation and effects of flow reversal: the absorber wall absorbs the heat and acts as a thermal storage, resulting in a thermal boundary layer forming over it; the thin boundary layer causes entrainment of air from both upstream and downstream sides, creating a reverse flow at the top of the chimney, lowering the mass flow rate in effect. An inclined solar chimney reduces this reverse flow and in turn improves the mass flow rate.

Hosien and Selim (2017) evaluated different types of cover materials including glass, concrete, gypsum board and aluminium. They found that concrete having the highest absorptivity results in the greatest cover temperature, followed by gypsum, glass and aluminium. In contrast, the temperature of the absorber wall is the highest with glass due to its transmissivity. The authors concluded that any of these alternative materials may be used if cheaper construction costs and safety are sought after since all of them provide greater than the required ventilation rate [1]. Instead of using different cover materials, Leng et al. (2014) examined the effects of different absorber materials such as copper, cast iron, PVC, cast concrete, aluminium and glass. They reported that copper leads to the highest air velocity. It was suggested that copper or aluminium be used in solar chimney to increase the flow rate and velocity.

Khanal and Lei (2011) took radiation into account and observed that a thermal boundary layer is formed adjacent to both the glazing and the absorber instead of only near the absorber wall due to the radiation heat exchange. In the case of zero surface emissivity, a reverse flow is observed at the exit of the chimney due to entrainment of air from the outside. However, with an emissivity of 0.9, no reverse flow is observed, but a region of separation near the inlet is seen due to the relatively stronger inflow of air into the chimney when radiation transfer is considered.

The present study uses the above result as a starting point. The conventional solar chimney is modified by introducing tint on the inside of the glass surface, and the effect of this modification on the resultant air flow rate is quantified. A number of simulations for different tint levels, height and positions are performed through computational fluid dynamics using ANSYS FLUENT 17.1. The simulated velocity and temperature fields and the flow rates within the tinted solar chimney will be compared with the conventional one without any tint. The results would shed light on determining an optimal model that provides superior ventilation performance.

Numerical Details

A two-dimensional model is considered in the present study. A schematic of the model is shown in Figure 1. The dimensions of the solar chimney are presented in Table 1.

Table 1: Dimensions of the Solar Chimney

Component	**Dimension**
Absorber Wall	0.4 m
Inlet Height	0.1 m
Air Gap Width	0.1 m
Total Chimney Height	0.5 m

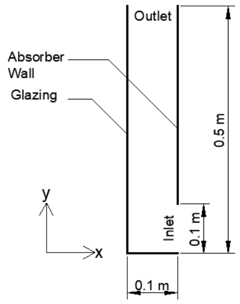


Figure 1: Schematic of solar chimney under consideration.

Methodology

A steady, pressure based solver is adopted to solve the governing Navier-Stokes and energy equations. Only laminar flow is considered. Radiation and turbulence effects are neglected. Gravity is specified in the y direction with a value of -9.81 m/s^2. The material is air with a density of 1.225 kg/m^3. Boussinesq assumption is made in this study.

The SIMPLE scheme, with a second-order upwind spatial discretization is used for momentum and energy equations and PRESTO! is used for pressure. The under-relaxation factors used are 0.3 for pressure, 0.7 for momentum and 1 for density, body force and energy. The convergence criteria are 10^{-7} for energy equation and 10^{-4} for continuity and velocity. In case the steady model does not converge, a transient calculation is carried out with a time-step 0.01s.

For the linearly varying tinting configurations, a user defined function is created to linearly increase or decrease the heat fluxes on the glazing and the absorber wall.

Boundary Conditions

Pressure inlet and outlet boundary conditions are specified at the inlet and exit of the solar chimney respectively.

The absorber wall and the glazing are given a heat flux corresponding to the case considered for each simulation. The external losses are neglected; therefore, the heat flux on the absorber would be the difference of the incoming solar radiation and the heat flux absorbed by the tint. The bottom wall is taken as no-slip condition with no heat loss. The glazing, if tinted is done only till the height of the inlet, below which it is considered to have a heat flux equal to zero. Figure 2 shows the boundary condition used for each component of the solar chimney.

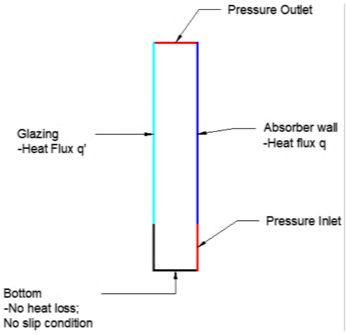


Figure 2: Boundary conditions.

Mesh Sizing

Three different mesh sizes are tried as shown in Table 2; based on computation time and accuracy, the 0.5mm × 0.75mm mesh size (0.5mm for the top and bottom; 0.75mm for the sides) is chosen. The mesh is made finer towards the walls, with a bias factor of 10. Face meshing is done to create a structured quadrilateral mesh.

Table 2:Mesh Sensitivity Analysis

Mesh Size	0.75mm x 1.00mm	0.50mm x 0.75mm	0.30mm x 0.55mm
Mass Flow Rate (kg/s)	0.00385	0.004419	0.004498

Results

As mentioned above, different configurations of tinted solar chimney are simulated. The results are summarised in Table 3. The results are grouped according to the height of tinting. It includes the calculated mass flow rate and the Air Changes per our (ACH). ACH is the volumetric flow rate divided by the volume of the room, which is assumed to be 3m × 3m × 3m.

Table 3: Mass Flow Rates and ACH of Different Cases

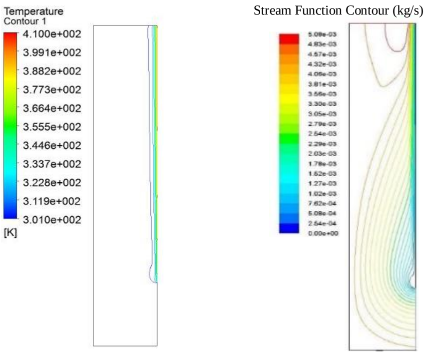
Case	**Tinting percentage**	**Mass flow rate (kg/s)**	**Air Changes per Hour (ACH)**
No Tint	-	0.0044	0.48
Full height tint	25%	0.0097	1.06
	50%	0.0101	1.10
	75%	0.0106	1.15
1/4 height from top	25%	0.0030	0.33
	50%	0.0030	0.33
	75%	0.0030	0.33
1/4 height from bottom	25%	0.0097	1.06
	50%	0.0101	1.10
	75%	0.0106	1.15
1/2 height from top	25%	0.0019	0.21
	50%	0.0019	0.21
	75%	0.0019	0.21
1/2 height from bottom	25%	0.0097	1.06
	50%	0.0105	1.14
	75%	0.0111	1.21
3/4th height from top	25%	0.0087	0.95
	50%	0.0090	0.98
	75%	0.0093	1.01
3/4th height from bottom	25%	0.0097	1.06
	50%	0.0100	1.09
	75%	0.0124	1.35
Linearly Increasing Tint	-	0.0094	1.02
Linearly Decreasing Tint	-	0.0119	1.30

When a uniform heat flux of 500 W/m^2 is applied on the absorber with no tint on the glazing, there is only one thermal boundary layer forming on the absorber surface. In this case, distinct reverse flow is observed. The mass flow rate is found to be 0.0044 kg/s, equivalent to only 0.48 ACH for a typical 3m × 3m × 3m room.

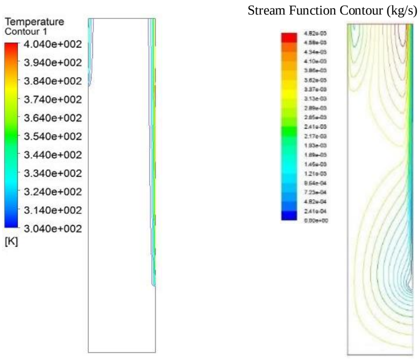
The presence of tint creates an additional thermal boundary layer on the glazing side. While comparing the fully tinted case with the base configuration, there is no reverse flow in this case. However, there is increased recirculation at the inlet. When the level of tinting is varied with 25, 50 and 75% absorptivity, it is observed that the case where the tint absorbs 75% of the incident radiation creates the maximum flow rate.

When the glazing is tinted for a quarter height and half height from the top, additional reverse flow is created towards the outlet, resulting in lowered mass flow rates compared to the reference case. This is not the case when the glazing is tinted three-quarters from the top, which results in larger flow rates.

Generally higher air flow rates are observed when the glazing is tinted from the bottom; and the highest flow rate is achieved when the glazing is tinted three-quarters from the bottom. Figure 3 shows the contours of the temperature and stream function of some representative cases.



(a)



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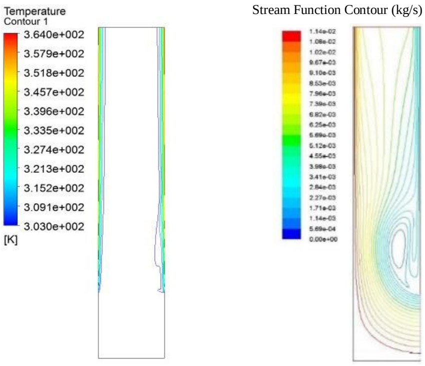

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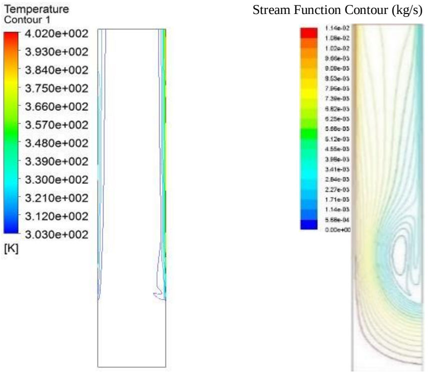

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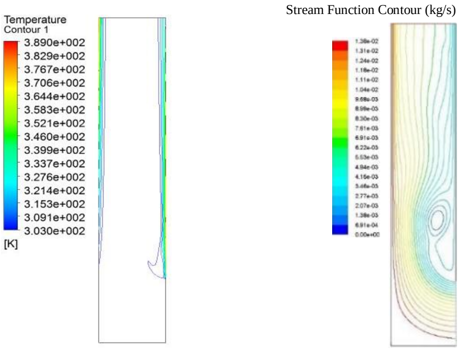

(e)

Figure 3: Temperature and stream function contours of (a) No tint (the reference case) (b) Tinted 1/4th height from top – 75% tint (c) Tinted the entire height - 75% tint (d) Tinted 3/4th height from bottom – 75% tint (e) Linearly decreasing tint.

Discussion

Having performed all the simulations to determine the ventilation performance when the glazing is tinted, the maximum flow rate is obtained when the glazing is tinted with a 75% absorptivity at a three quarter height from the bottom. A greater recirculation area is present near the inlet when compared to the reference case, indicating higher kinetic energy of the flow and hence a higher flow rate.

The flow rates of all the calculated cases surpass the base case, except for the case when the glazing is tinted a quarter height and a half height from the top, in which the extent of the reverse flow is much greater than that in the reference case. Reverse flow, in general, occurs due to the entrainment of air from the external environment, causing a reduction in the mass flow rate (Khanal and Lei, 2012). Additional reverse flow towards the glazing for the cases considered is created due to the heating effect at the top of the glazing resulting from the tinting. This constricts the air flow from the chimney to the outside, resulting in a much lower flow rate compared to the case where no tint is applied. Tinting for three quarters of the height, i.e., 0.3m from the top, has no reverse flow, and performs better than the base case. This may be because the extension of tinting length towards the bottom attracts the air flow towards it, causing a uniform distribution of the flow within the chimney channel with no reverse flow from the top. This is similar to the fully tinted case, but to a lesser extent; the air has to travel a certain distance before being entrained by the thermal boundary layer forming on the tinted surface.

Figure 4 shows the variation of the normalised flow rates with the height of tinting from the top. The flow rates are normalised by the flow rate of the base case (with no tint). It is clear in Figure 4 that the same trend is observed for all tinting levels when the height of tinting is varied. However, when the tinting height is kept constant and the absorptivity is varied, the difference in the flow rates vary from being identical to distinct. Variations of the performance with the level of tinting are noticeable for the three quarter height and full height tinting configurations, while for the other two tinting configurations the variations are almost indistinguishable. This is because the level of reverse flow for the quarter and half height tinting configurations is the same for all three tinting levels; the recirculation area for the three quarter and full height tinting increases marginally with tinting level, giving rise to increased flow rates.

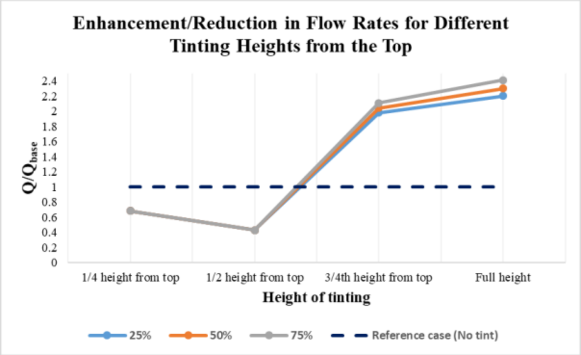

Figure 4: Variation of the predicted flow rates under different tinting configurations (the glazing is tinted from the top).

When the glazing is tinted from the bottom, the performance of all the cases are better than the reference case, as can be seen in Figure 5. No reverse flow is observed in any of these cases. However, an increased recirculation is observed near the inlet. As the tinted glazing is heated, it results in the air flow being drawn towards the glazing side, causing a large recirculation within the chimney, above which the flow of air splits between the two sides. This re-circulation area causes an increase of the flow velocity, and hence a greater flow rate. Further, it is observed that all the cases with the glazing tinted from the bottom have better performance than the fully tinted case. This may be because the change in the temperature distribution (caused due to heat flux) between tinted and non-tinted portions of the same side attracts greater flow. The greater the tint level, the higher the created heat flux and temperature difference, resulting in enhanced flow. The flow rates remain fairly constant across all the tinting heights. However, anomalies are present when it is tinted 50% and 75% at a 3/4th height from the bottom.

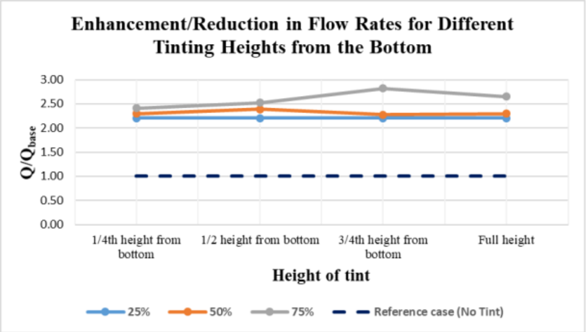

Figure 5: Variation of the predicted flow rate under different tinting configurations (the glazing is tinted from the bottom).

When the two linearly varying tinting cases are compared, the one in which the glazing is tinted with a linearly decreasing tint from bottom, i.e., 500 W/m^2 at the bottom to 0 W/m^2 at the top is found to perform better. This is similar to all the previous cases when the glazing is tinted from the bottom, in which the flow rates are generally higher than those when the glazing is tinted from the top. The higher heat flux at the bottom half causes more air to be attracted to it, leading to higher flow rate than the case with linearly increasing tinting from the bottom.

In summary, the performance of a solar chimney is enhanced when tinted, and the performance depends on the positions, height and level of tinting. This finding may greatly help in improving the energy efficiency of a building. Greater ventilation rates lower the dependence on external electrical appliances.

Conclusion

Research recognizes solar chimney as an effective means of providing passive ventilation and improving the energy efficiency of buildings. This report presented a modified design of the solar chimney to further improve the ventilation performance. The introduction of tinting on the glazing proved to be an effective technique to improve the aeration efficiency. By varying the position, height and absorptivity of the tint, a number of simulations have been carried out, and the mass flow rates are obtained. The performance of the various configurations is then represented in terms of Air Changes per Hour and a normalised flow rate Q/Q_{base}. It is found that the maximum air flow rate is attained when the glazing is tinted three-quarters of the height from the bottom at a tinting absorptivity of 75%. In this case the ventilation rate is 2.8 times that of the reference case with no tinting. For all the other cases, the linearly decreasing tint from the bottom is found to perform well relative to other configurations. However, the obtained flow rates do not differ much to the fully tinted case; for better aesthetics, the fully tinted case may be chosen. The enhanced ventilation performance is due to the weakening or suppression of the reverse flow with the adoption of tinting. It is worth noting that the present investigation does not consider the effect of external losses to the surroundings, which will be accounted for in future research. Further, an experimental validation is required for this project.

References

[1] Hosien, M. A. & Selim, S. M., Effects of the Geometrical and Operational Parameters and Alternative Outer Cover Materials on the Performance of Solar Chimney Used for Natural Ventilation, *Energy and Buildings*, **138**, 2017, 355-367.

[2] Khanal, R. & Lei, C., Numerical Investigation of the Ventilation Performance of a Solar Chimney, *Anziam*, **52**, 2011, C899-C913.

[3] Khanal, R. & Lei, C., Flow Reversal Effects on Buoyancy Induced Air Flow in a Solar Chimney, *Solar Energy*, **86**, 2012, 2783-2794.

[4] Leng, P. C., Ahmad, M. H., Ossen, D. R. & Hamid, M., Towards Sustainable Architecture: The Effect of the Solar Chimney Material on Thermal Performance Based on CFD Simulation, *International Conference on Sustainable Urban Design for Liveable Cities,* 2014.

[5] Mathur, J., Bansal, N. K., Mathur, S., Jain, M. & Anupma, Experimental Investigations on Solar Chimney for Room Ventilation, *Solar Energy*, **80**, 2006, 927-935.

[6] Ong, K.S & Chow, C.C., Performance of a Solar Chimney, *Solar Energy*, **74**, 2003, 1-17.