CFD modelling of transient thermal performance of solar chimney used for passive ventilation in a building

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Abstract. The paper analysed the 24 hour performance of a solar chimney placed on a building roof in Krakow, Poland. The solar chimney was an element of as a passive ventilation system allowing energy efficient night ventilation during the summer season. The chimney was built as an air duct. Three walls of the chimney were made of glass and faced toward the sun, the opposite wall was made of a concrete absorber. The system worked in two stages: day and night. The absorber located in the chimney was heated during the day, and cooled during the night. During the night phase, the released heat provided a draft contributing to passive ventilation.

Absorbers with different thermal capacities were studied. Simulations were conducted for three different absorber thickness 10 cm, 20 cm or 30 cm. The simulations were carried out using the Ansys Fluent simulation software. The hourly results of temperature distributions in the chimney allowed the authors to determine the optimal absorber thickness for the passive ventilation system. Calculations showed that the chimney with the absorber that was 10 cm thick was the optimal among analysed solutions. The absorber is warmed up to the highest temperature, up to 82°C, and induces air flow which lets removing even 3820 m³ of air during the night.

1. Introduction

Directives of the European Parliament introduce the idea of lowering energy consumption in Europe for heating purposes in winter, as well as for cooling in summer. One of the ways of lowering energy demand is the application of cooling systems that are based on natural ventilation systems. They are called passive cooling systems and help to improve thermal comfort without the use of an energy source. In summer, the walls of buildings accumulate heat, causing the building to maintain a higher inside temperature during the night than the outdoor air. Because of this, the indoor air does not cool down to the required temperature during the night which means that, during the day, more energy will have to be used to maintain indoor air quality.

To provide proper ventilation and night cooling, a system based on the application of a solar chimney can be used thanks to which the airflow used to cool the building is forced. It is constructed in the form of a duct with one or more sides made of glazing that allows the sun to heat an absorber on the opposite side of the duct. During the day phase the air inlet and outlet in the lower and higher chimney walls are shut. The absorber accumulates heat during the day and after opening the air inlet and outlet, it releases the air during the night phase. The air flow is created by the pressure difference...
in the night – air is induced out of the building through the chimney and fresh, cool air flows in from the open windows through the building and to the chimney.

The intensity of the ventilation caused by the chimney is strictly connected to its design and the solar radiation that heat it during the day. The best effects are gained when the radiation is the highest, which is why it is recommended that they are located in hot climates where the sun shines for long periods of time [1].

Solar chimneys in hot climates have been studied around the world and have proved to provide passive ventilation. The studies focused on the location of the absorber and of the chimneys’ geometry, as well as on its maximum effectiveness. Analysis of solar chimneys in Singapore [2] and Spain [3,4] showed that the location of the absorber being heated during the day is an important factor. Moreover, the studies proved that shorter chimneys with the absorber located on the roof of a building and inclined in the right angle were more effective, even though the chimney length was shorter and the pressure difference that drives the process should have been lower. Many other authors have shown that such chimneys have a positive effect on lowering energy usage. Jianliu and Weihua [5] designed a mathematical model of such a chimney used in South-East China. Their study showed that their model reflected the existing chimney. The same conclusions were made by Bassiouny and Koura [6], in whose study computer simulations were used to provide a detailed view of the airflow within the chimney. Neves et al. [3] analysed the angle of the absorber in the chimney and its influence on its effectiveness in Brasilia, Mahdavinejad et al. [7] studied the optimal angle of the chimney in Iran and Sakonidou et al. [8] did a similar analysis for the conditions in Greece.

The presented studies show that the matter of passive ventilation using solar chimneys is important and ongoing. What is more, computer simulations can reflect the conditions within a solar chimney. This is why in this paper it was decided to conduct a simulation for an absorber in such a chimney located on the roof of a building in Krakow, Poland. The purpose of the study was to see if it was possible to use a passive ventilation system in Poland’s cooler climate. The aim of the analysis was to gain the largest airflow through the system, so that the cooling would be as intensive as possible. Because the thermal capacity of the absorber is the crucial parameter in the solar chimney design, the thickness of the absorber was adjusted to determine which was the optimal for the ongoing conditions. Each case was simulated for the period of 24h to reflect the heating and cooling process throughout the day and night.

The simulations were conducted using the Ansys Fluent modeling software, widely used to conduct simulations on the topic of airflow, turbulence, heat transfer in complicated geometries. After the assumptions of boundary and initial conditions and solver settings, transient numerical calculations were performed.

2. Geometry of the solar chimney

The solar chimney was designed in such a way that maximum radiation could reach the absorber. It was designed as a duct with three glass walls and one wall with a concrete absorber. The glass walls were placed so that solar radiation could reach the absorber, the concrete wall was opposite the radiation. Figure 1 shows the detailed 3D geometry of the chimney designed in the Ansys geometry tool.

An inlet and outlet at the bottom and top chimney walls from were designed as throttling dampers that close and open automatically according to the day and night cycle. Each position was maintained for 12 hours. During the day, when the absorber was heated the inlet and outlet dampers were closed to prevent heat loss, while during the night, when passive ventilation occurred, they were both open. Thanks to this arrangement, the heated absorber released the accumulated energy and created a draft caused by the difference of temperature/density between the air in the chimney and inside the building.

Fresh air was provided by window vents located inside the building. Thanks to this, fresh, cool air entered and lowered the building’s temperature and improved indoor air quality. This was done without the use of a mechanical ventilation system meaning that such a system is a passive one. The only energy used was to provide the impulse for the dampers to change position between cycles.
Three different cases were studied; in each the thickness of the absorber differed. In figure 1, the thickness is shown as 20 cm, the other thicknesses include 10 cm and 30 cm. In each case the inlet and outlet sizes were the same. The thickness of the absorber determines its thermal capacity and the study will show which absorber is optimal.

Figure 2 shows the cross-section of the chimney along with the materials used and their dimensions.

**Figure. 1.** 3D geometry of the solar chimney

**Figure. 2.** Vertical cross section through the solar chimney – the absorber thickness 20 cm. Dimensions in centimetres. 1 – absorber, 2 – insulation of the absorber made of polystyrene, 3 – concrete support of the absorber, 4 – concrete support of the glazing, 5 – glazing, 6 – air in the chimney, 7 – inlet damper.
3. Mesh

The mesh created to conduct the calculation is an important step in the simulation process. It must be of high quality to prevent calculation errors. The mesh was created in Ansys meshing tool. Each analysed case had a mesh consisting in tetrahedral elements. The amount of elements in each mesh was around 223 000, 191 000 and 196 000 for the cases in which the absorber was 10 cm, 20 cm and 30 cm thick respectively.

The quality of the mesh was determined by two parameters: the aspect ratio and skewness. Their value was not larger than 1:5,5 and 0,85 respectively for each case. The more regular the mesh is the lower these parameters are, where the maximum values are 1:35 for the aspect ratio and 0.95 for the skewness. Both of these parameters are sufficient and the quality of the mesh is adequate for the case study.

4. Boundary conditions and simulation setup

To conduct the simulation, a series of input parameters had to be defined. One of them was the materials used for the study that created the solar chimney. The materials and their thermal properties shown in table 1 were used in the simulation.

| Material  | Thermal conductivity $\lambda$ (W/(mK)) | Density $\rho$ (kg/m$^3$) | Specific heat $c_p$ (J/(kgK)) |
|-----------|----------------------------------------|---------------------------|------------------------------|
| concrete  | 1.3                                    | 2200                      | 840                          |
| polystyrene | 0.04                                  | 30                        | 1460                         |
| glazing   | 1.0                                    | 2500                      | 840                          |

Another important aspect was the air turbulence model, as it determines how the air behaves throughout the heating and cooling process. The k-ε turbulence model was used to simulate air movement. It was also assumed that the physical properties of air changed in a linear way along with temperature change. Table 2 shows the air properties used in the simulation. Because the chimney’s 24-hour cycle was divided into two stages (the day stage, when the absorber was heated, and the night stage, when the absorber cooled and night ventilation took place) it was decided to divide the cycle into two sub-cycles that lasted 12 hours each. The day cycle lasted from 8:00 a.m. until 8:00 p.m. while the night cycle lasted from 8:00 p.m. to 8:00 a.m. of the next day. During the day, the inlet and outlet dampers were shut to maximize heat gain in the chimney, while during the night, they were open. To simulate solar radiation heating up the absorber, an hourly distribution of external air temperature as well as the daily sun route on the horizon were assumed for both for day and night stages. The outdoor temperature was chosen for a sunny day in Krakow according to hourly meteorological data. The external air temperatures for each hour are shown in table 3.

During the simulations it was also assumed that the absorber was facing south. To simulate the moving sun, the solar ray tracing model that reflects the movement of the sun during the day was used. The value for each phase was calculated with a time step equal to 300 s (5 min).

| Temperature ($^\circ$C) | Thermal conductivity $\lambda$ (W/(mK)) | Density $\rho$ (kg/m$^3$) | Dynamic viscosity $\mu$ (Ns/m$^2$) | Specific heat $c_p$ (J/(kgK)) |
|------------------------|----------------------------------------|---------------------------|------------------------------------|------------------------------|
| 10                     | 2.51·10$^{-2}$                         | 1.247                     | 1.76·10$^{-5}$                     | 1005                         |
| 20                     | 2.59·10$^{-2}$                         | 1.205                     | 1.81·10$^{-5}$                     |                              |
| 30                     | 2.67·10$^{-2}$                         | 1.165                     | 1.86·10$^{-5}$                     |                              |
| 40                     | 2.76·10$^{-2}$                         | 1.128                     | 1.91·10$^{-5}$                     |                              |
| 50                     | 2.83·10$^{-2}$                         | 1.093                     | 1.96·10$^{-5}$                     |                              |
| 60                     | 2.90·10$^{-2}$                         | 1.060                     | 2.01·10$^{-5}$                     |                              |
Table 3. External air temperatures for each hour.

| Hour | Temperature during the day phase [°C] | Hour | Temperature during the night phase [°C] |
|------|--------------------------------------|------|----------------------------------------|
| 8:00 | 17.4                                 | 20:00| 26.5                                   |
| 9:00 | 17.4                                 | 21:00| 23.0                                   |
| 10:00| 24.2                                 | 22:00| 20.6                                   |
| 11:00| 26.9                                 | 23:00| 19.2                                   |
| 12:00| 29.2                                 | 00:00| 15.2                                   |
| 1:00 | 30.8                                 | 1:00 | 14.5                                   |
| 2:00 | 32.6                                 | 2:00 | 13.8                                   |
| 3:00 | 34.2                                 | 3:00 | 13.2                                   |
| 4:00 | 35.3                                 | 4:00 | 12.6                                   |
| 5:00 | 36.1                                 | 5:00 | 12.5                                   |
| 6:00 | 35.8                                 | 6:00 | 12.2                                   |
| 7:00 | 33.5                                 | 7:00 | 12.4                                   |
| 8:00 | 30.2                                 | 8:00 | 12.4                                   |

5. Results for 24h work of the solar chimney

This chapter shows the results for the 24-hour phase in which the absorber is heated from 8:00 a.m. to 8:00 p.m. (12-hour day phase) with inlet and outlet dampers shut and then with passive ventilation working when the absorber is cooled (12-hour night phase). In the night the dampers were open from 8:00 p.m. to 8:00 a.m.

The average temperature of the absorber volume for 24-hour period is shown in figure 3. Figure 3 shows that the absorbers gain their maximum temperature around 4 p.m., the 8th hour after shutting the dampers. The absorber with the thickness of 10 cm heats up the quickest and also releases the most heat during the night stage due to the lowest thermal capacity. It reaches the temperature of 82°C, which is twice as hot as the temperature of 30 cm thick absorber.

The temperature contours on the cross section in the middle of the chimney for each absorber thickness at 4 p.m. are shown in figures 4 to 6.

![Figure 3](image_url)
Figure 4. Temperature distribution in the chimney (°C) with 10 cm thick absorber at 4:00 p.m.

Figure 5. Temperature distribution in the chimney (°C) with 20 cm thick absorber at 4:00 p.m.
Figure 6. Temperature distribution in the chimney (°C) with 30 cm thick absorber at 4:00 p.m.

In addition to the temperature contours, it was possible to achieve airflow for each case during the 24-hour period. The airflows are shown in figure 7.

Figure 7. Volumetric air flow rates through the solar chimney for each case for a 24 h cycle.

On the basis of the results shown in figure 7, the total amount of air that was removed from the building during the 12-hour period was the following:
- 3821 m³ of air in 12 h for the chimney with an absorber that was 10 cm thick,
• 3634 m$^3$ of air in 12 h for the chimney with an absorber that was 20 cm thick,
• 3222 m$^3$ of air in 12 h for the chimney with an absorber that was 10 cm thick,

The results show that the most air was removed through the system when the absorber was the thinnest (10 cm). It can be then stated that it is the best for a passive cooling system in Poland and can reduce the cooling energy consumption of the building.

6. Summary

The aim of this paper was to see if night passive ventilation applying a solar chimney would be possible for a building in Krakow, Poland, because the most studies that analysed such structures are mainly on cases for hot climates closer to the Equator.

The analysed chimney was located on the roof of a building and designed in such a way that the absorber, which purpose was to accumulate solar heat gains, was facing south. The rest of the structure was made of glazing. This was done to accumulate the maximum amount of solar radiation.

The chimney work was simulated using Ansys Fluent software in order to determine which thickness of the absorber is the optimal for the Central European climate. Three different cases that differed in the thickness of the absorber were studied: 10 cm, 20 cm and 30 cm. The calculations were conducted for two phases: the day phase, in which the absorber was heated up by the solar energy and the night phase, in which the absorber released the accumulated heat which contributed to the passive ventilation effect. The outside air temperature and solar radiation differed on an hourly basis.

The results of the simulations showed that the solar chimney with the thinnest absorber (10 cm) was the most efficient. It heated up the quickest and achieved the highest temperature – up to 82$^\circ$C. It also released the most heat during the night phase, which caused a draft to occur and generated the highest air flow through the chimney, 3820 m$^3$ in 12 h, meaning that the building would be ventilated more efficiently. The thicker absorbers (20 cm and 30 cm) heated up slower and accumulated less heat.

It must be highlighted that the results are dependent on weather conditions. This study was conducted for a sunny and warm day with no clouds that could lower the solar radiation received by the absorber. Thus the results are maximal to be reached for Krakow.

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