Optimization measures for the utilization of solar chimneys in regions with temperate climate

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Abstract

Different optimization measures have been investigated and evaluated to improve the ventilation effectiveness of the solar chimney concept for natural ventilation of buildings in regions with temperate climate. Improvement measures include an optimization of the chimney geometry and chimney outlet, improvement of the absorber system as well as the additional use of waste heat by integrating a heating circuit into the absorber wall. All measures have been investigated with building simulations for the course of a year. The air volume flow inside the solar chimney has been investigated with computational fluid dynamic simulations (CFD) and measurements at test facilities regarding the applied measure, respectively. The solar chimney concept could replace common mechanical ventilation systems and therefore save energy and reduce greenhouse gas emissions. The present study gives an overview of the different measures and their impact on the ventilation effectiveness of the natural ventilation with solar chimneys.

Keywords: Solar chimney, natural ventilation, optimization, energy savings, CFD

1. Introduction

The emissions of global greenhouse gases have increased considerably in the last years. Worldwide, there is consensus on the need to reduce the greenhouse gas emissions due to the risks and impacts of global climate change. Since November 2015, 195 countries have signed the Paris Convention on Climate Change, to limit the increase in global average temperature to well below 2 °C above preindustrial levels and take measures to reduce the increase to 1.5 °C (United Nations 2015; European Parliament 10/25/2012). The European Union aims to reduce primary energy consumption by 20 % by 2020 compared to 2007 (European Parliament 10/25/2012). The energy consumption in the building sector can be reduced or at least stabilized worldwide by 2050 (IPCC 2013). The building sector is currently responsible for 39 % of the global CO_2 emissions and 36 % of the global final energy consumption (International Energy Agency 2018). In order to achieve the ambitious goals, a wide range of potential savings must be identified and utilized.

A contribution to the reduction of energy consumption in the building sector can be achieved by saving ventilation power. Natural ventilation can be provided either by using wind or by thermal buoyancy effects. These effects have already been used in traditional buildings with solar chimneys in the Middle East and have been implemented in modern architecture in recent years. In a solar chimney, an absorber surface is heated by incident solar radiation. The irradiative heat increases the temperature inside the chimney and thus the temperature difference to the ambient air. The resulting buoyancy effect is used to ventilate the building. In regions with temperate climate and fluctuating weather conditions the potential of such concepts has been limited so far. In a preliminary study (Schwan et al. 2017a), the usability of solar chimneys in Germany is investigated. Therefore, the solar radiation and the resulting airflow for ventilation are analyzed using a reference building with three floors and an attached solar chimney per floor respectively. The viability study shows that during specific time periods in summer, the air volume flow is to small using traditional solar chimneys due to high ambient air temperatures and low solar radiation (Schwan et al. 2017a).

The temperature difference between the inner part of the solar chimney and the ambient air needs to be increased during those times. This can be achieved with an optimal geometry, an optimized chimney outlet and an additional thermal activation of the solar chimney by integrating a heating circuit to the absorber wall. An improved and adapted solar chimney concept can contribute to energy savings and thus to the reduction of greenhouse gas emissions. For a reliable use of the system, it is necessary to increase the ventilation effectiveness of the solar chimney and to ensure year-round operability.

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2. Methodology

This study gives an overview and summary over different optimization measures to improve the ventilation effectiveness of the solar chimney concept for natural ventilation of buildings in regions with temperate climate. The work is based on a dissertation in which the topic is described in more detail (Schwan 2019). Various optimization measures are presented to ensure a year-round operation of the natural ventilation concept. Chapter 3 deals with the geometric optimization of the solar chimney. The investigations are carried out with the aid of a modifiable laboratory test rig and computational fluid dynamic (CFD) simulations. Based on the results of the geometric optimization, Chapter 4 first examines the possibility of thermal activation of the chimney using building simulations. Second, various absorber systems are investigated experimentally with a test facility. The schematic of a solar chimney with heating pipes is shown in Fig. 1. Afterwards, optimization measures for the chimney outlet are shown. The design of the chimney outlet should ensure a positive wind effect on the natural ventilation concept. Finally, the different measures are summarized.

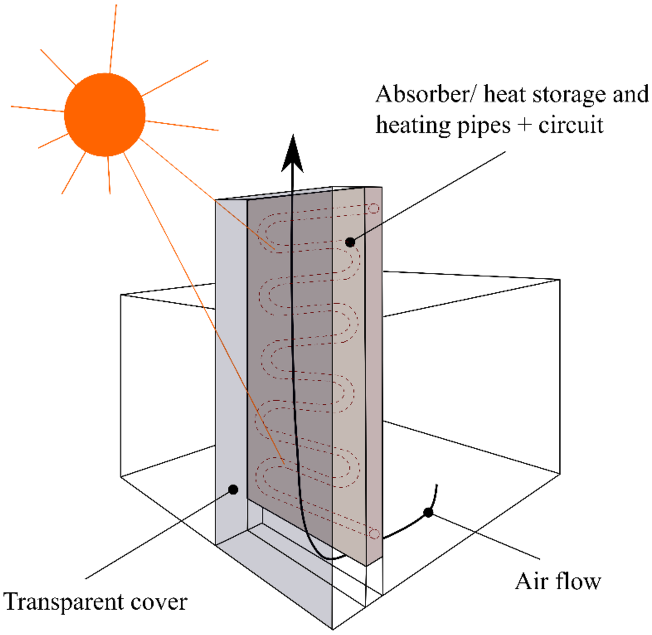

Fig. 1. Schematic of a solar chimney with heating pipes (Schwan et al. 2017b)

3. Optimization of the geometry

The geometry of the solar chimney has a strong influence on its performance. The chimney height, aspect ratios, angle of inclination and other geometric dimensions were investigated experimentally, numerically and analytically in previous studies. The height of the solar chimney has a direct and linear effect on the pressure difference for thermal buoyancy. The solar chimney height is therefore important for the expected air volume flow. The depth of the chimney also has a major effect on the characteristics of the airflow profile inside the chimney. With regard to the optimum chimney depth, the previous studies came to different results.

In his experiments, Bouchair (Bouchair 1994) discovered that for a chimney depth of 0.1 to 0.3 m a complete upward flow is present, whereas for a chimney depth greater than 0.5 m a backflow occurs in the center of the solar chimney. At a chimney depth of 0.5 m, only 125 mm on each wall side is used by the upward flow. The upward airflow at the chimney outlet is the result of the room airflow, but also of the circulated airflow. This results in a higher airflow at the chimney outlet than at the chimney inlet. Flow measurements should therefore be carried out at several points (Bouchair 1994). Other publications confirm that a chimney depth between 0.1 and 0.3 m is most suitable (Ong and Chow 2003; Arce et al. 2009). In contrast, studies by Burek and Habeb (Burek and Habeb 2007) describe a continuous increase of the volume flow with increasing chimney depths from 0.2 m to 1.1 m.

Due to the contradictory values in the literature, the influence of the geometry was verified with own preliminary investigations by using experiments and simulations (Schwan et al. 2017b). The mean values of the inlet air velocity and the volume flow are summarized for air gaps of 0.1 m, 0.3 m and 0.5 m in Table 1.

Table 1. Mean values for the inlet air velocity and volume flow for an air gap of 0.1 m, 0.3 m and 0.5 m (Schwan et al. 2017)

Depth	Velocity (CFD simulation)	Velocity (Experiments)	Volume flow (CFD simulation)	Volume flow (Experiments)
0.1 m	0.40 m/s	0.32 m/s	188 m³/h	171 m³/h
0.3 m	0.19 m/s	0.21 m/s	319 m³/h	339 m³/h
0.5 m	0.15 m/s	0.10 m/s	262 m³/h	266 m³/h

The values show a good correlation with experimental results of a test rig. Fig. 2 shows the resulting velocity vectors of the CFD simulations for different chimney depths. If the chimney depth is too low, the flow resistance of the chimney is too high, whereas a too deep chimney causes the risk of back flows in the center of the solar chimney. The volume flow for a solar chimney with a depth of 0.5 m is approx. 20 % smaller than for a solar chimney with a depth of 0.3 m. This phenomenon should be taken into account in the design and planning of all types of solar chimneys as well as in their calculation and dimensioning (Schwan et al. 2018a).

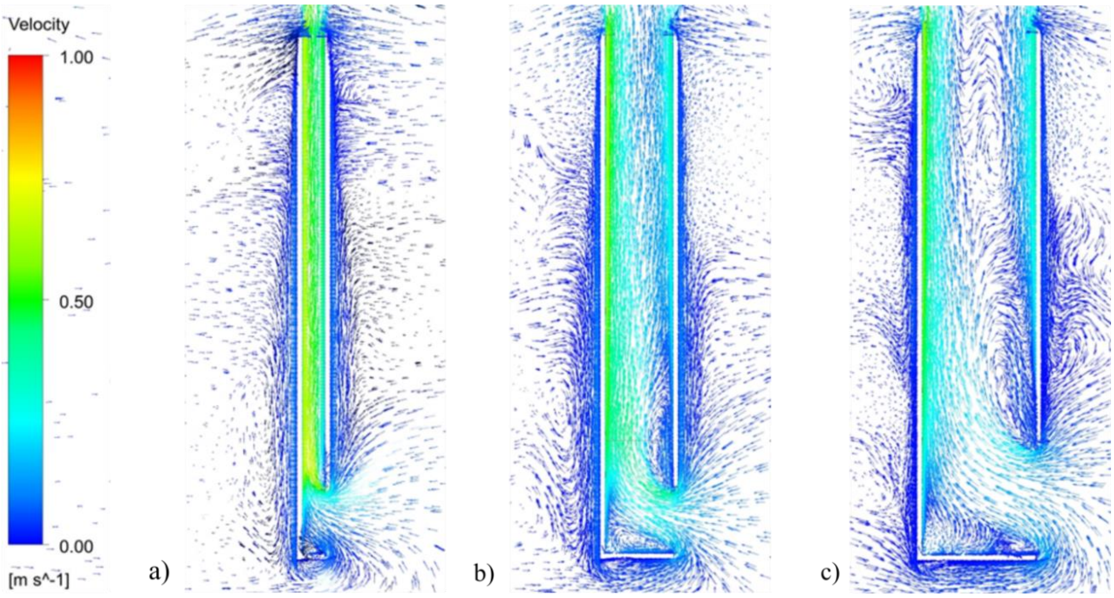

Fig. 2. Simulated velocity vectors for different chimney depths: a) 0.1 m; b) 0.3 m; c) 0.5 m (Schwan et al. 2017b)

4. Optimization of the absorber and use of waste heat

The main purpose of the absorber wall of a solar chimney is to absorb a maximum amount of solar radiation and transfer the heat to the air in order to maximize the buoyancy effect. The material of the absorber and the corresponding heat transfer coefficients are important for the overall efficiency. The longwave emission coefficient determines the radiative heat transfer to the glazing and other walls of the chimney. The impact of different absorber wall structures was investigated with the help of annual simulations with the building simulation software TRNSYS. Seven different wall structures were analyzed and compared to each other (Schwan et al. 2018b).

The best results were achieved with the insulated absorber wall structure shown in Fig. 3b). The results show the importance of high surface temperatures of the absorber wall and a high amount of radiative heat transfer for regions with temperate climate. The copper layer enables high absorber temperatures and good radiative exchange with an appropriate coating. A wall structure with additional thermal storage, which can be seen in Fig.3c) would lower the temperatures during the day. The thermal storage should be just considered for scenarios with a high demand of night cooling and high ventilation requirements during the night.

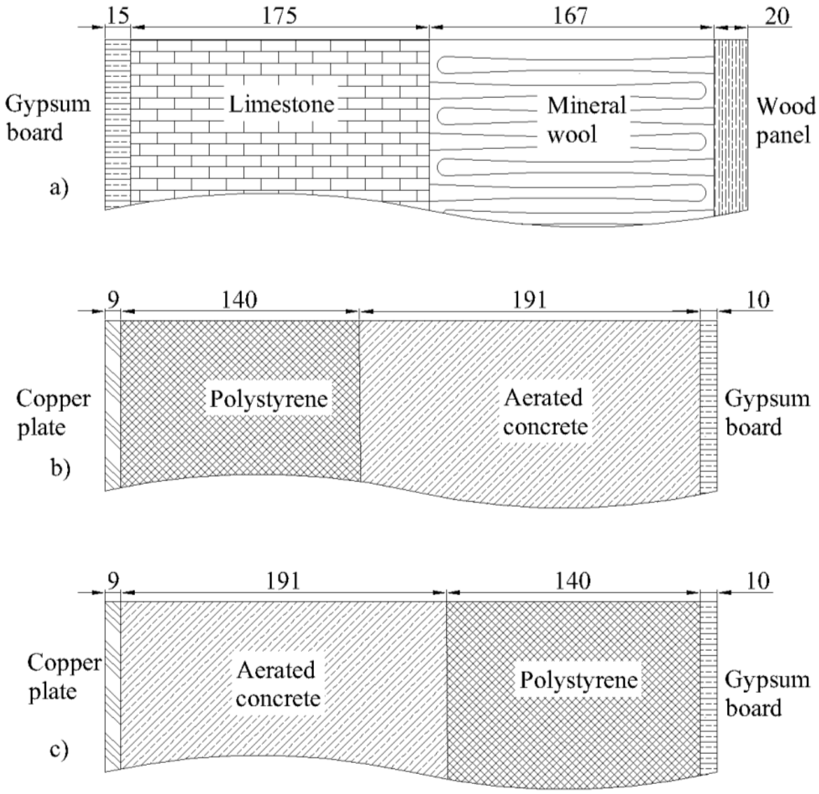

Fig. 3. Structure of investigated absorber walls - layer thickness in mm (Schwan et al. 2018b)
a) external wall (TRNSYS default) b) insulated absorber wall c) absorber wall with thermal mass

With the knowledge of the optimal geometry and materials for the absorber wall, the effectiveness of the solar chimney can be increased by an additional thermal activation for regions with temperate climate. The thermal buoyancy can be increased by integrating a heating circuit into the absorber surface. This new type of application offers the potential for further energy savings if the additional heat can be provided by waste heat. The impact of this additional heating was investigated first with the help of annual simulations. It can be shown that the volume flow required for sufficient ventilation can be provided for the whole year with the exception of a few points in time.

Experimental investigations and CFD simulations have been used to analyze different absorber systems with integrated heating circuits. Schematics of the investigated absorber systems are shown in Fig. 4. (Schwan et al. 2018b).

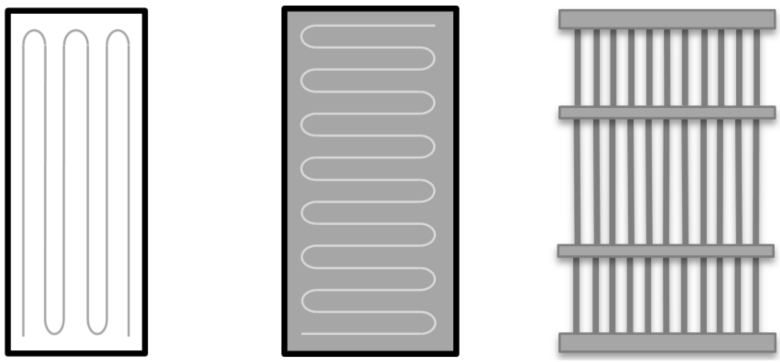

Fig. 4. Schematics of the investigated absorber systems (Schwan et al. 2018b)
a) Panel heating; b) Solar absorber; c) Capillary tubes

The absorber systems have been tested under the same boundary conditions. The panel heating system was investigated with and without additional fins. The geometry and material properties of the resulting four systems are summarized in Table 2.

Table 2. Investigated absorber systems (Schwan et al. 2018b)

System	Material	Area	Flow	Pipes (d/ l)	Supplementary notes
1 – Panel heating (P.h.)	copper (front)	2.5 m²	serial	8.0 mm / 22 m	Gypsum backside
2 – P.h. with fins	copper (front)	3.5 m²	serial	8.0 mm / 22 m	1 m² due to fins
3 – Solar absorber	copper	2.9 m²	serial	8.0 mm / 27 m	Solar paint
4 – Capillary tubes	polypropene	3.0 m²	parallel	2.6 mm/ 2.3 m	125 pipes

The results of the experiments indicate an asymmetric distribution of the air velocity inside the chimney. The asymmetry can be seen for all investigated absorber systems. Fig. 5 shows the measured air velocities inside the chimney for all absorber systems. The air velocity is considerably higher next to the absorber surface compared to the center of the solar chimney and the air velocity next to the glass cover for all four systems. Nevertheless, the copper-based systems achieve lower air velocity values compared to the capillary tube system due to the lower emissivity of the absorber material.

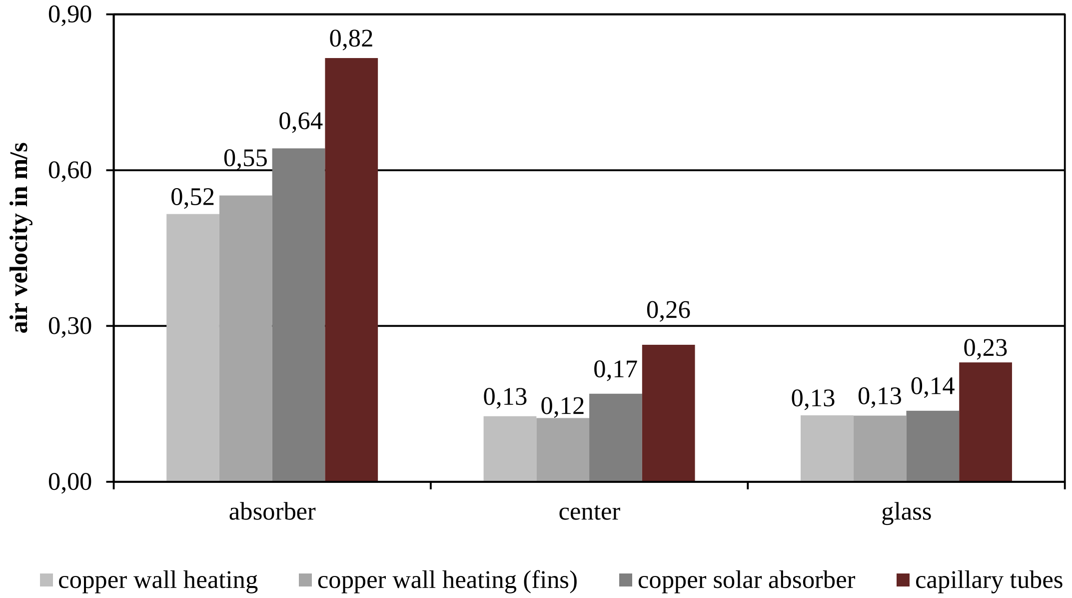

Fig. 5. Air velocity for different absorber systems (Schwan et al. 2018b)

Therefore, the maximum volume flow can be achieved with the capillary tube system. A maximum air volume flow of 700 m³/h can be generated in the test rig with a 2.5 m high solar chimney. The absorber systems made of copper can be improved with additional fins. Nevertheless, in addition to high absorption values of the absorber, the radiative heat exchange between the absorber surface and the glazing is of major importance. Higher temperatures of the inner surface of the surrounding glazing lead to a more symmetric temperature distribution and therefore to a more symmetric distribution of the air velocity inside the chimney.

The additional use of waste heat and an optimized absorber system make it possible to bridge the times when sufficient ventilation was not possible with the previous solar chimney concept.

5. Optimization of the chimney outlet

The effect of wind on buildings using solar chimneys for natural ventilation was investigated in detail in a previous study (Schwan et al. 2017c). The results show a strong dependency of the provided volume flow on the predominating wind direction with the traditional solar chimney design. For wind direction with a uniform wind profile, the volume flow can be increased by the wind. Fig. 6 shows the velocity profile of a reference building. The direction of the wind is north. On the north side are also the inlet openings. In this case the volume flow can be increased by approximately 30 %.

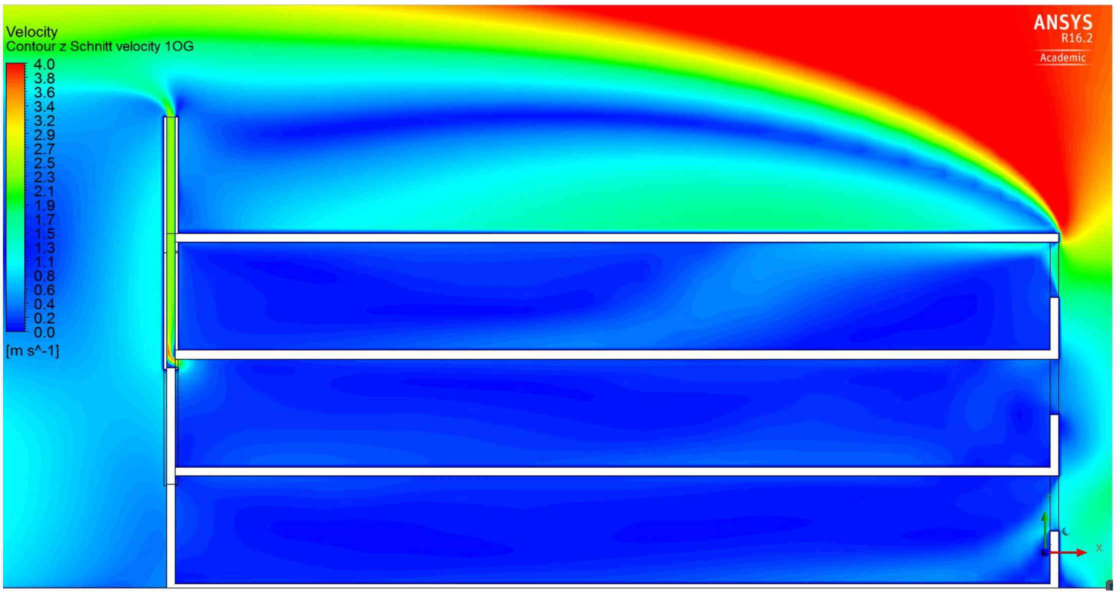

Fig. 6: Velocity profile for air around the reference building; wind direction: North (Schwan 2019)

In other cases, the air change rate decreases due to an unfavorable wind direction. The solar chimney outlet needs to be adapted with an additional wind cowl to ensure an operation of the system irrespective of the wind direction. Two schematics of exemplarily chimney wind cowls can be seen in Fig. 7.

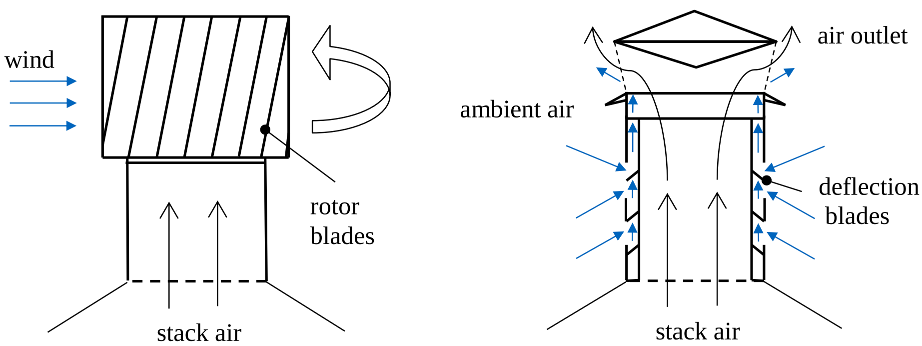

Fig. 7. Schematics of two chimney cowls (Schwan 2019)
a) Wind driven roof ventilator according to Rotovent Systems (b) Injection nozzle according to Windkat

The wind cowls ensure an operation of the solar chimney irrespective of the wind direction. Furthermore, a ventilation is possible without temperature difference and buoyancy effect, which increases the operation time of the natural ventilation system compared to the initial solar chimney concept. The volume flow increases with increasing wind speed for times without thermal buoyancy. A detailed comparison of three different types of turbine ventilation systems and an inject nozzle are described in a previous publication (Schwan et al. 2017c).

6. Conclusion

In this paper, different optimization measures are presented and summarized from previous investigations to increase the effectiveness of solar chimneys. The combination of the measures enables a utilization of solar chimneys in regions with temperate climate. The geometry, the choice of suitable materials of the absorber as well as an optimization of the chimneys outlet have a strong influence on the performance of the natural ventilation system. An optimal chimney depth can be identified. If the depth is to large backflows occur in the center of the chimney. The absorber material should have high absorption values as well as high convective and radiant heat transfer coefficients to the air and the surrounding chimney glazing. The additional heating circuit of the absorber increases the effectiveness of the system and extends the operation time. With the help of additional wind cowls, a positive wind effect can be ensured during the operation irrespective of the wind direction. Additional mechanical ventilation can be avoided. The new application of a thermal activated solar chimney contributes to energy savings and a reduction of greenhouse gas emissions.

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