

Increase of the Ventilation Effectiveness of Solar Chimneys with Consideration of Wind-Effects applying CFD Simulations and Measurements

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Abstract

Solar chimneys have been used for natural ventilation and cooling in the Middle East already hundreds of years ago. In modern buildings, the concept could contribute to energy savings and reduction of greenhouse gas emissions. An optimized system would enable a sustainable and permanent operation of this natural ventilation concept. This study analyzes the effect of wind and the possibilities to increase the ventilation effectiveness of solar chimneys by optimizing the design of the chimney outlet. Computational fluid dynamic (CFD) simulations have been used to investigate the general influence of the wind effects on a building which is naturally ventilated with solar chimneys. The results show that the air change rate increases or decreases depending on the predominating wind direction. To be able to accomplish a system which supports the natural ventilation irrespective of the wind direction, different wind cowls were tested at a test rig located at the University of Applied Sciences Munich. As a result of this study, the flow velocity can be shown as a square root function of the wind speed. An average flow velocity between 0.6 – 1.1 m/s can be reached by using turbine ventilation systems.

Keywords: Solar chimney, wind cowl, energy savings, natural ventilation, CFD simulation, ANSYS FLUENT

1. Introduction

Approximately 15 % of the total electrical energy demand of today's office and factory buildings is used by mechanical ventilation (EnOB 2016). The use of natural ventilation and natural cooling systems could be a possible solution to reduce the energy consumption in the building sector. This paper explores the concept and the potential of an enhanced solar chimney which uses just the sun and the wind as its driving forces. Therefore, no conventional sources of energy are used.

During sunshine, solar radiation enters the chimney through a transparent cover and heats up an absorber surface. The difference between the chimney temperature and the ambient air temperature generates a buoyancy effect. As a result, the air is drawn out of the building. To generate this buoyancy effect also during the night-time, for night cooling or periods with cloudy sky, the effectiveness of such a system needs to be increased. Permanent and sufficient ventilation could be provided by using wind effects with an optimized design of the chimney outlet and wind cowls in addition to the buoyancy effect.

Khan, Su and Riffat (Khan et al. 2008) give a good overview about historical wind towers and modern techniques for wind driven ventilation systems. Kistelegdi and Haber (Kistelegdi, Háber 2012) discuss the direction of wind towers and the design of their outlets for the natural ventilation of a plus-energy manufactory in the South of Hungary. Ismail and Rahman (Ismail, Rahman 2012) show possibilities for future configurations of wind turbines, fans and solar panels and combinations of static and dynamic systems.

To study the effect of wind and its benefit for a natural ventilation concept with a solar chimney, the investigation of this study contains two major parts. The first part describes the general impact of wind on a reference building which is naturally ventilated with solar chimneys. This analysis was done using CFD simulations to see the influence of wind direction and the positioning of the solar chimneys. Afterwards an experimental investigation was conducted to investigate different wind cowl systems which could be integrated in a solar chimney concept using measurement data from a test rig.

2. Impact of wind on natural ventilation of a reference building

2.1. Methodology and simulation set-up

The impact of wind on a building regarding the ventilation effectiveness is analyzed using a standard building model as a reference for the location of Munich, Germany. The reference model is a three story office building and it was taken from the VDI Norm 6009 (VDI 2001). The same model has been used in previous studies to investigate the viability of using solar chimneys for natural ventilation in Germany (Schwan et al. 2017a). A solar chimney was attached to the south façade of each floor, respectively. The inlet window sizes and building geometry for the three floors was identical to the reference model.

The building model was simulated with the software ANSYS workbench 16.2, which consists of different applications. The geometry of the building model was set up using the DesignModeler. In addition to the building, a surrounding area was simulated as well. Both, reference building and its surrounding area can be seen in Fig. 1.

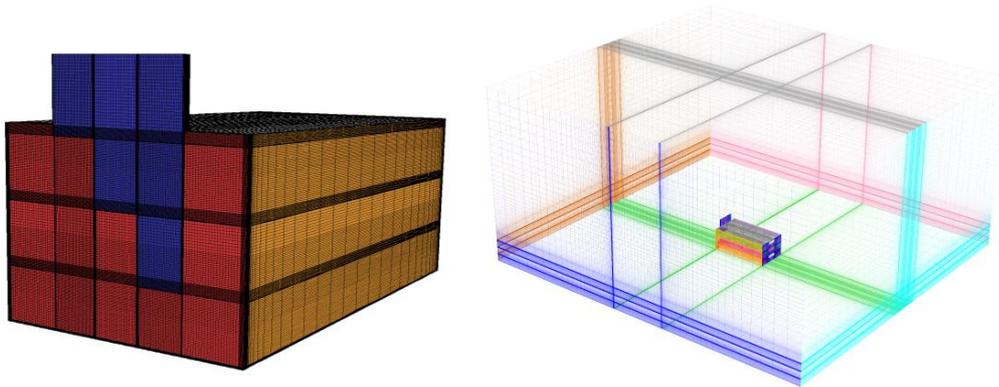


Fig. 1: Model of the reference building (left) and surrounding (right) developed in ANSYS FLUENT

The reference building is 30.6 m long and 16.6 m wide. The solar chimneys are 4 m, 8 m and 12 m high; depending to which floor they are attached to. Every solar chimney is 3 m wide and has an inside air gap of 0.3 m. In previous investigations an air gap of 0.3 m was found to be the ideal size for a maximum air flow without the appearance of backflows (Schwan et al. 2017b). The building, including the solar chimneys, has a height of $H = 16$ m. In every direction the building is $5H$ away from the boundaries of the surrounding, respectively. The simulation of the surrounding is necessary to be able to simulate the wind effect properly. It is limited to $5H$ to retain a manageable simulation time. The distance is chosen to be the same in all directions, because different wind directions are investigated. The parameters for the building and the solar chimneys (SC) can be seen in Table 1 and Table 2.

Table 1: Building parameters

Parameter	Symbol	Value	Unit
Height of building	H_B	16.00	m
Length of building	L_B	30.60	m
Width of building	W_B	16.60	m
Window size (north)	A_W	9.50	m ²
Area of each floor	A_F	507.96	m ²
Total floor area	$A_{F,ges}$	1523.88	m ²

Table 2: Solar chimney parameters

Parameter	Symbol	Value	Unit
Cross section area	A_{SC}	0.841	m ²
Height of SC ground floor	H_{SC1}	12	m
Height of SC first floor	H_{SC2}	8	m
Height of SC second floor	H_{SC3}	4	m

The major influence factor for the both, simulation time and the accuracy of the simulated results, is the applied mesh. For this investigation the software package ANSYS ICEM CFD was used for the mesh generation. High numbers of cells are used in the solar chimney and the building floors to provide reliable results in these areas. Lower numbers of cells are used in the surrounding area to reduce the calculation time. A hexahedral mesh was used due to lower numbers of cell element and a higher quality of the mesh compared to a tetrahedral mesh. The used mesh consists of more than 2,000,000 hexahedron cell elements. ANSYS FLUENT was used for the calculation of the fluid dynamics. The post processing and evaluation of the results have been done with ANSYS CFD Post. The investigations were performed with steady simulations for specific reference days to be able to reduce the simulation time. The turbulence of the air flow is calculated with the k- ϵ model, considering gravity and buoyancy effects. An enhanced wall treatment was used to compensate inaccuracies of the turbulence model for areas next to the walls. The air density was calculated using the Boussinesq model.

2.1. Investigated aspects

The ventilation effectiveness was studied according to the position of the solar chimney, the wind direction and the wind speed for different seasons. Steady simulations were conducted for three reference days (two in summer and one in winter) to be able to validate the impact of the wind on the natural ventilation system. The weather data for the city of Munich was taken from the German Test Reference Year (TRY) of 2010 for the chosen reference days (Deutscher Wetterdienst 2014). The used data can be seen in Table 3.

Table 3: Weather of used reference days

Month, day, time	July, 23 rd , 12 pm	August, 12 th , 5 pm	December, 5 th , 12 pm	Unit
Wind direction	260 (SW)	190 (S)	100 (SE)	°
Wind velocity (H = 10 m)	3	1	5	m/s
Wind velocity (H = 16 m)	3.70	1.23	6.16	m/s
Air temperature (H = 2 m)	24,8 297,95	32,8 305,95	-2,4 270,75	°C K
Air pressure	96,09	95,45	95,54	kPa
Direct solar irradiation	550	59	24	W/m ²
Diffuse solar irradiation	291	201	128	W/m ²

2.2. Comparison between reference days

The weather data of the three reference days are completely different, as it can be seen in Table 3. The largest influences on the buoyancy effect of the solar chimney are the height of the chimney and the temperature difference between the inner part of the solar chimney and the ambient air temperature.

On the December reference day, the temperature difference is high, because of the low ambient air temperature. As a result the air changes per hour (ACH) are high as well. All simulated results of the ACH for the three reference days can be seen in Fig. 2. The ACH will be even higher with an increased height of the solar chimney. Therefore, the ACH of the ground floor is higher than the ACH of the first and second floor. The wind has a positive effect on the results of the ACH for the December reference day. The ambient air temperature on the reference day in August is significantly higher than the temperature in the building. In addition, the solar irradiation is not strong enough to rise the temperature in the solar chimney. As a result, backflows occur in the solar chimney. Just the wind can balance that effect, although sufficient ventilation cannot be provided. On the July reference day, the ACH is higher and the effect of the height of the solar chimneys can be seen as well. The wind from south west has no significant positive effect of the ACH on that day. These results show the effect of the ambient air temperature as well as the effect of the wind.

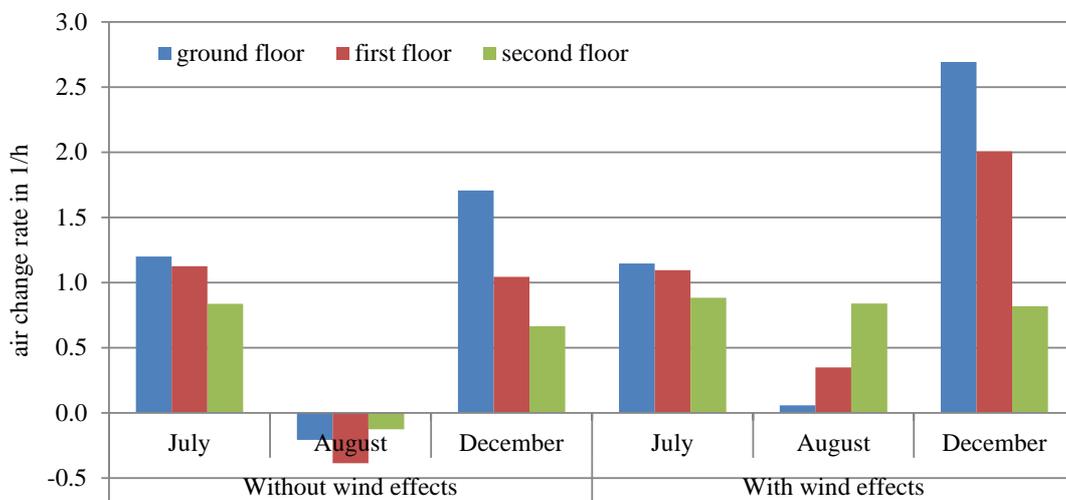


Fig. 2: Air changes per hour without and with wind effects for three reference days

2.3 Investigation of wind direction

Different wind directions have been investigated for the same reference day in July, to ensure a better comparability of the results to neglect the other effects. The considered wind directions can be seen in Fig. 3.

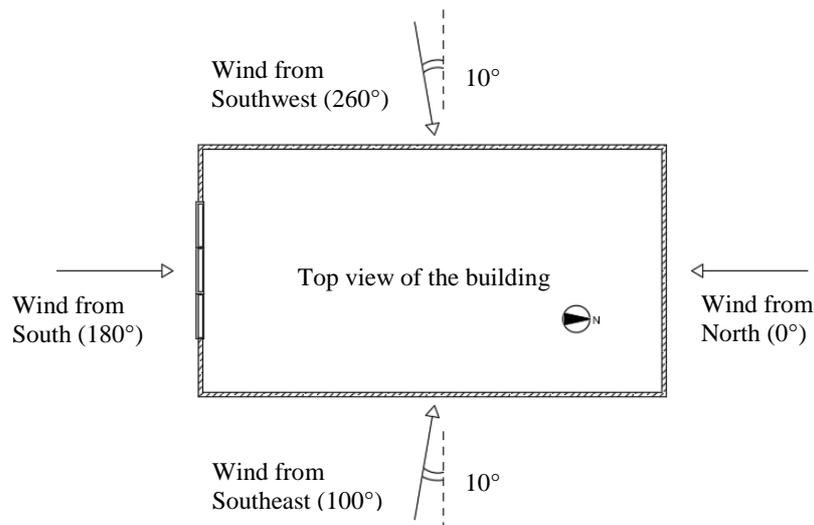


Fig. 3: Considered wind directions

The simulations have been conducted for the four wind directions. The results show that the effect of wind depends considerably on the wind direction. The results of the ACH can be seen in Fig. 4.

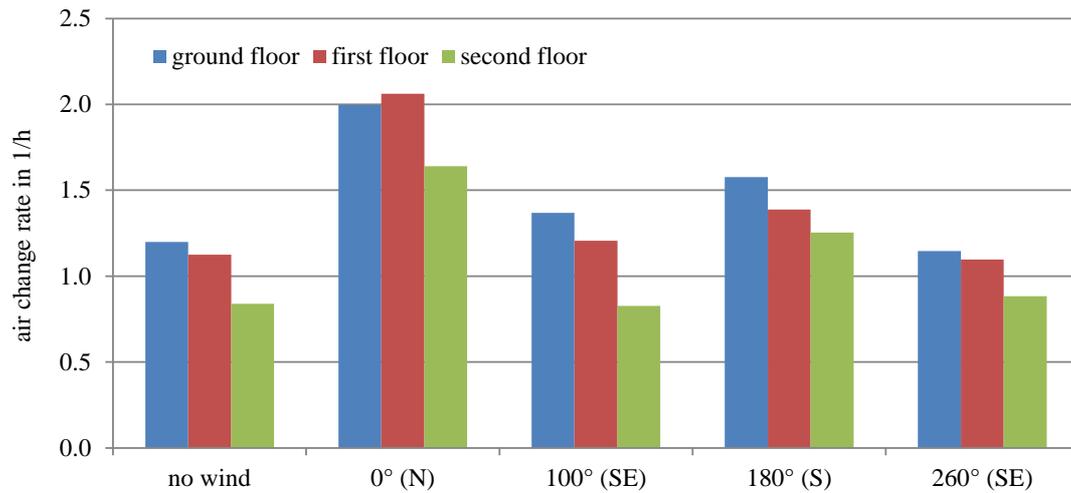


Fig. 4: Air changes per hour for different wind directions for a reference day in July

If the wind direction was North (0°) or South (180°), then a distinct wind profile occurs. The wind increased the provided volume flow in the solar chimney and therefore the ventilation effectiveness (compared to simulations without wind) for all three floors. A velocity profile for the air around the reference building and inside the chimney can be seen in Fig. 5. The air change rate is approximately 30 % higher compared to simulations without wind.

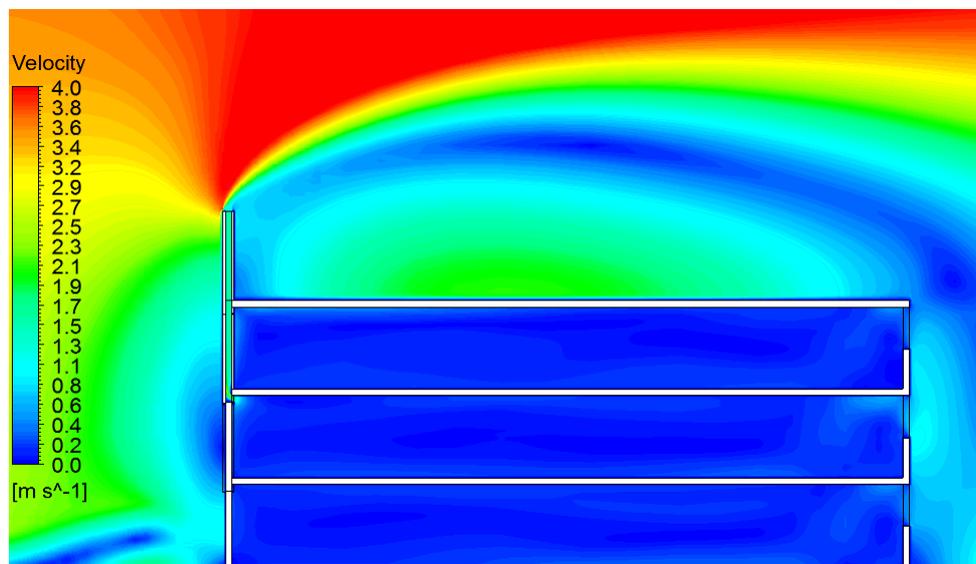


Fig. 5: Velocity profile for air around the reference building (wind direction: South)

If the wind direction is inclined and non-parallel to the small side of the solar chimney, for example for wind from South-West (260°) or South-East (100°), there is a significant change in the resulting air volume flows. At least in one of the three solar chimneys, a reduced volume flow occurred for these wind directions compared to simulations without wind. The air change rate was reduced by up to 10 % in these cases. These results highlight the importance to optimize the design of the solar chimney outlet in order to avoid negative influence of wind effects and rather use wind effects to enhance the ventilation effectiveness.

3. Optimization of the solar chimney outlet through integration of wind driven systems

3.1. Methodology and test-rig

Using wind-driven ventilation systems at the top of a solar chimney should offer permanent and sufficient ventilation and avoid negative influences on the performance of the thermally driven solar chimney. Therefore, different types of cowls and roof ventilation systems were analyzed for their contribution to natural ventilation. Only systems without additional gears (e.g. photovoltaic-wind driven systems) were considered. The systems work independent of the wind direction, which should avoid the problems discussed in the previous chapter. The experimental investigation was mainly focused on findings about the ventilation rate in general and as a function of the wind speed. Also, the influence by the thermal buoyancy effect and the solar radiation was part of the study.

With a height of 4.5 m, the chimney overlapped the adjacent building and enabled an incident flow from all directions. The length of the chimney was 1 m and the width 0.5 m. The diameter of the air inlet and outlet was 0.3 m. The test rig was located at the University of Applied Science in Munich and faced in southwestern direction. The test rig can be seen in Fig. 6.

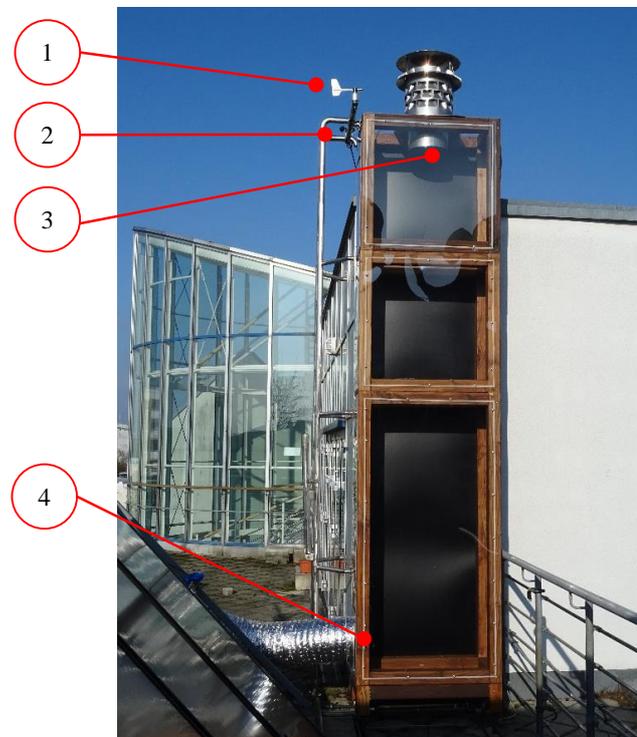


Fig. 6: Test rig at University of Applied Science Munich

A wind direction transmitter (1) and a vane anemometer (2) recorded the wind regimes. Inside the chimney, the flow velocity, pressure and temperature of the air were measured. Therefore, two thermoanemometers were installed at the air outlet (3) and inlet (4). Table 4 shows the installed measurement instrumentation and corresponding measuring range.

Table 4: Installed measurement instrumentation at the test rig

Measured variable	Measuring instrument	Measuring range
Wind speed	Vane anemometer	0 – 50 m/s
Wind direction	Wind direction transmitter	0 – 360 °
Air velocity, pressure and temperature	Thermoanemometer	0.08 – 2 m/s

On a test rig, three different types of dynamic turbine ventilation systems by Rotovent Systems (RS) and an inject nozzle by Euro Windkat were tested (see Fig. 7). The turbine ventilation systems differ from the shapes of their blades.

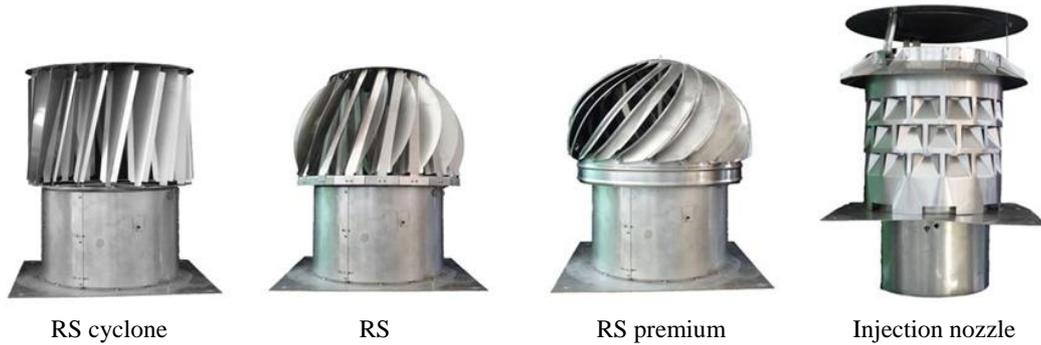


Fig. 7: Three different types of turbine ventilation systems (left) and an inject nozzle (right)

3.2. Correlation between wind speed, buoyancy effect and chimney airflow velocity

During the experimental investigation, global solar radiation, wind speed, the flow velocity inside the chimney, the temperatures inside the chimney and the ambient air temperature have been measured. For each wind cowl systems the data was recorded for at least two weeks to ensure to have different weather situations with varying intensities of wind and solar radiation.

Fig. 8 shows the global solar radiation, the wind speed and the resulting flow velocity in the solar chimney for an exemplary hour of the wind cowl system with straight blades (RS cyclone).

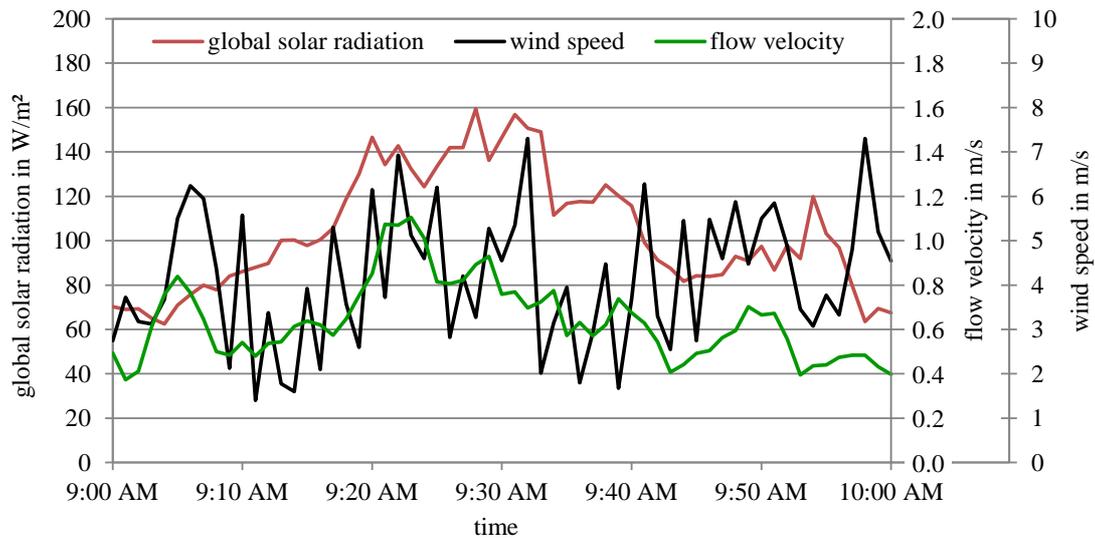


Fig. 8: Solar radiation, wind speed and flow velocity inside the solar chimney (18th March 2017, 9:00 – 10:00 am)

The buoyancy effect and the wind effect are the two major impact factors for the resulting flow velocity inside the solar chimney. The buoyancy effect is mainly influenced by the temperature difference between the ambient air temperature and the temperature inside the chimney and therefore indirectly influenced by the solar radiation as well. To quantify the share of both of these factors – wind and buoyancy – further investigations have been conducted, in which the thermal influence was neglected.

Fig. 9 shows the flow velocity inside the solar chimney as a function of the wind speed for the dynamic turbine ventilation system with straight blades. An average flow velocity more than 1 m/s can be reached. The development of the flow rate equates a root function. In comparison to the thermal buoyancy due to an increased absorber temperature, dynamic wind cowls show the same speed level. Therefore, the integration of wind-driven cowl systems in the concept of a solar chimney shows great promise.

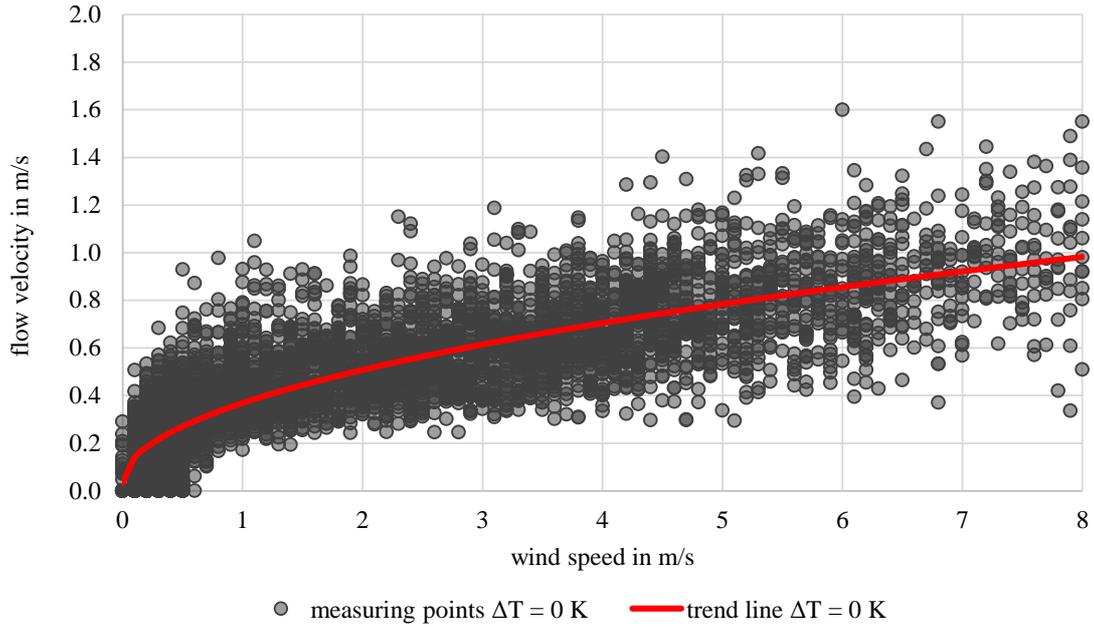


Fig. 9: Flow rate without thermal buoyancy for a turbine vent with straight blades (RS cyclone)

To consider the influence of the two driving forces wind and sun, the flow velocity can also be shown including the thermal buoyancy. Therefore, the air temperature difference between inlet and outlet was divided into six temperature ranges. Fig. 10 shows the flow velocity as a function of the wind speed and thermal buoyancy for a turbine ventilation system with straight blades. In comparison to Fig. 9 the flow velocity increased up to 1.8 m/s.

The measurements also illustrate, that the two driving forces interfere each other. For low wind speed, the impact of the thermal buoyancy is high. Otherwise the temperature differences between inlet and outlet decreased for increasing wind speed. This trend was noticed for all four ventilation systems.

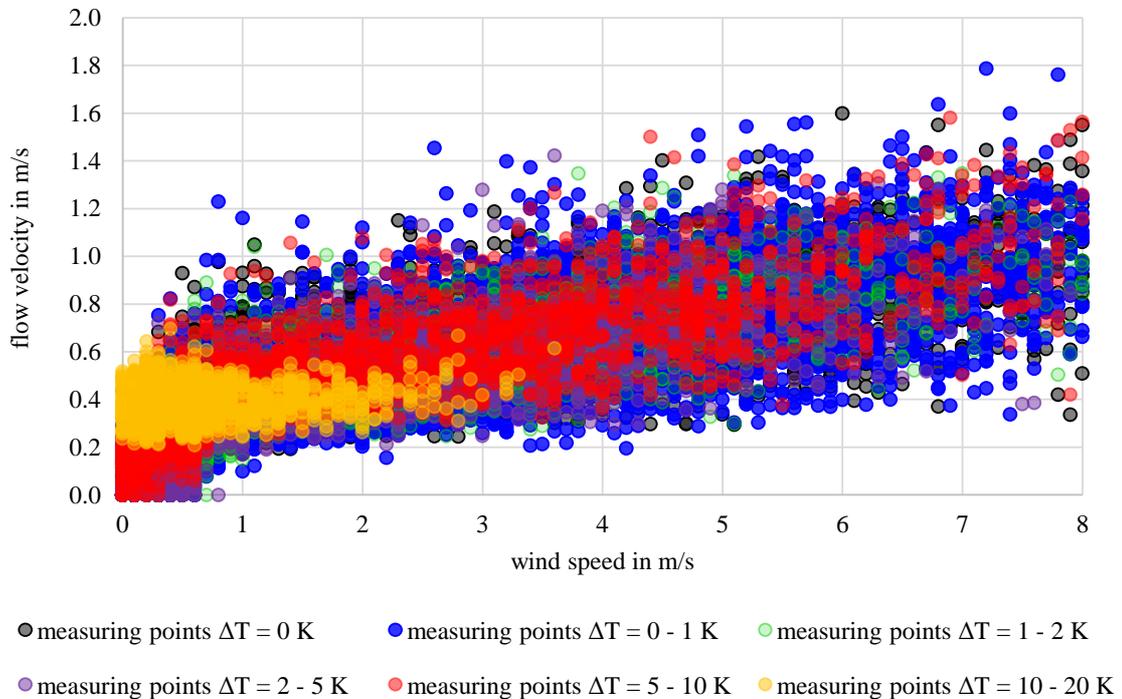


Fig. 10: Flow rate with thermal buoyancy for a turbine vent with straight blades (RS cyclone)

3.3. Comparison between different wind cowl systems

The flow velocity inside the chimney increases with higher wind speeds according to a square root function.

$$f(x) = a\sqrt{x} + b \quad (\text{eq. 1})$$

For time steps with a temperature difference between the inner part of the solar chimney and the ambient air, a buoyancy effect occurs. This results in positive flow velocity even in situations without wind with wind speed = 0 m/s. In eq. 1 this offset to the origin of coordinates is represented by the constant b. For time steps without buoyancy effect, the graph starts in the origin of coordinates. The gradient of the graph a is different for all four investigated systems. The different gradients and the trend lines of the measurement points of all four systems can be seen in Table 5 and Fig. 11.

Table 5: Gradient of graph and average flow velocity for a wind speed of 10 m/s for all wind cowl systems

Wind cowl system	Gradient of graph <i>a</i>	Average flow velocity for a wind speed of 10 m/s
RS	0.21	0.66 m/s
RS cyclone	0.34	1.08 m/s
RS premium	0.31	0.98 m/s
Injection nozzle	0.33	1.04 m/s

Based on the measurement results, it can be seen that the best values can be achieved with the RS cyclone system. The measured points of the injection nozzle have the highest deviation compared to the dynamic RS systems.

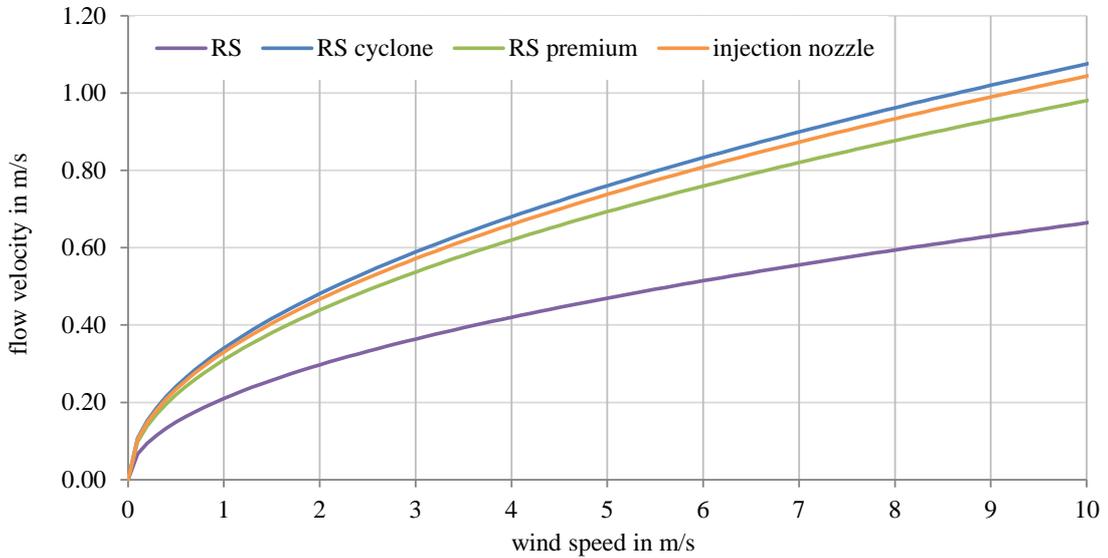


Fig. 11: Trend lines of the flow velocity without buoyancy effect for all four systems

4. Conclusion and Outlook

In this study the influence of wind effects on natural ventilation systems with solar chimneys has been investigated applying CFD simulations and measurements. The results showed the importance of considering wind effects for solar chimney projects and the huge impact of wind on the resulting air change rates. Especially the wind direction is important and can either lower or enhance the effectiveness of the solar chimney. A suitable solution to achieve a system which utilizes the wind effects irrespective of the wind direction, are wind cowl systems. Turbine vents showed the best performance and generated average flow velocities above 1 m/s. A higher effectiveness of solar chimneys can be reached through the integration of wind cowl systems. This offers a longer time of operation of the natural ventilation system, saves more energy and reduces greenhouse gas emissions.

In the future, the presented findings will be used in further research work to develop a planning tool for solar chimney projects. This planning tool should provide information about the expected ventilation rates and increase of the effectiveness of solar chimneys by using wind effects for the specific place of installation. Further research needs to be done to integrate the findings to a simplified calculation method to predict the effectiveness and efficiency of different solar chimney concepts.

5. References

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