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Model tests of dynamic action on the atmospheric boundary layer – concentric configuration of ventilation towers with a central ventilation chimney

Badania modelowe dynamicznego oddziaływania na warstwę przyziemną atmosfery – konfiguracja koncentryczna wież wentylacyjnych z centralnym kominem wentylacyjnym

Abstract
This paper describes model tests conducted in the Wind Engineering Laboratory of Cracow University of Technology on dynamic action on the atmospheric boundary layer in order to reduce the effects of air pollution and smog in urban areas. The paper focuses on vertical exhaust (ventilation chimney) and cooperation between a concentric system of ventilation towers and a ventilation chimney. The tests were conducted for different shapes and heights of ventilation chimneys, different diameters of the concentric system and different wind speeds provided by the ventilation towers. A heavy smoke visualisation was performed in order to qualitatively evaluate the efficiency of different solutions. The performed tests confirmed a sufficient level of efficiency of cleaning an area where the circular system is located.
Keywords: wind engineering, smog reduction, environmental engineering, urban ventilation, ventilation chimney, smoke visualisation

Streszczenie
Artykuł opisuje badania modelowe przeprowadzone w Laboratorium Inżynierii Wiatrowej Politechniki Krakowskiej dotyczące dynamicznego oddziaływania na warstwę przyziemną atmosfery w celu redukcji zanieczyszczenia powietrza i smogu w obszarach zurbanizowanych. Praca skupia się na pionowym wylocie powietrza (kominie wentylacyjnym) i współpracy pomiędzy koncentrycznym systemem wież wentylacyjnych i tym kominem. Pomiary zostały przeprowadzone dla różnych kształtów i wysokości komina, różnych średnic pierścienia wież wentylacyjnych i różnych prędkości powietrza podawanych przez wentylatory. Wykonano wizualizację dymową dla określenia jakościowego wydajności różnych rozwiązań. Badania potwierdziły wystarczającą wydajność systemu do wyczyszczenia obszaru, w którym się znajduje.
Słowa kluczowe: inżynieria wiatrowa, redukcja smogu, inżynieria środowiska, przewietrzanie miast, komin wentylacyjny, wizualizacja dymowa

1. Introduction

The deterioration of air quality is caused by the growth of industry, transportation and population, and is exacerbated by the blocking of natural ventilation channels [1]. To improve the conditions of urban areas, an idea of ventilation by dynamically forcing the movement of air mass in urban areas has been developed. However, it is crucial to examine the phenomenon of dynamic action on the atmospheric boundary layer as well as to determine whether such an action is feasible and effective.

The initial research determined the possibility of creating and maintaining an air stream through the placement of ventilation towers, either on an individual basis or arranged in a series of three parallel lines, even with large distances between the towers and with each of them producing a relatively low wind speed. It also proved to be effective on rough terrain, which simulated an urban area [2].

Despite the initial research supporting the efficiency of ventilation towers, longitudinal ventilation has its limitations due to the deterioration of the air quality as the stream length increases. Adding vertical ventilation provides an exhaust system that expels the polluted air to higher levels of the atmosphere by penetrating the smog layer which blocks natural air circulation. With this objective in mind, the idea of elevating a high chimney with fans (ventilation towers) on the bottom was developed. These fans should be able to create an airstream strong enough to penetrate the temperature inversion layer. A number of chimney shapes were tested in the Wind Engineering Laboratory of Cracow University of Technology with varying lean angles of the inlet ventilation towers and varying levels of permeability of the lower part of the chimney structure.

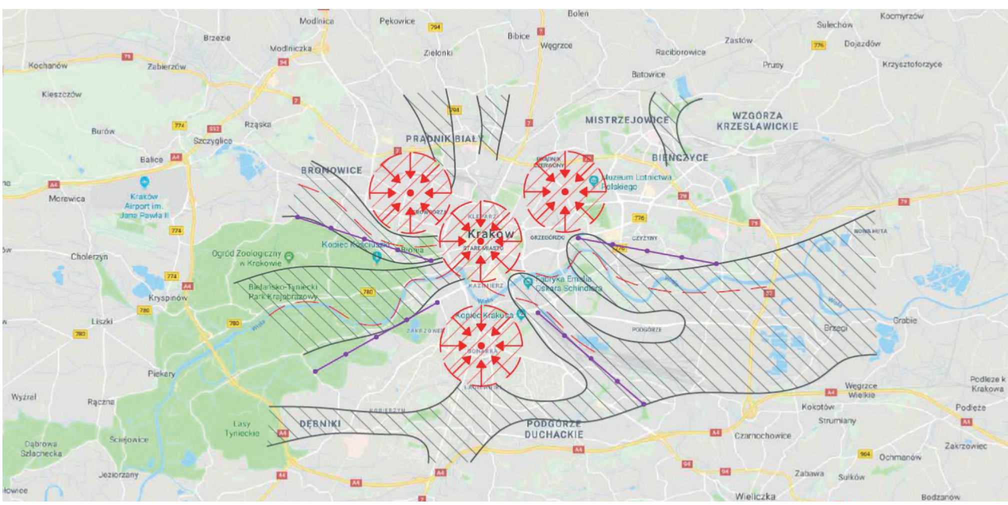


Fig. 1. Concept sketch for locating the areas for horizontal radial air stream generation and the central ventilation vertical exhaust systems on the example of an air exchange and regeneration system for Cracow [3]: black – natural ventilation channels of the city; purple – potential locations of rows of ventilation towers; red – potential location of ventilation chimneys with their supporting ventilation towers in concentric configurations

The presented system would potentially be an active solution for the smog problem. It would not limit the emission of the pollution, but would improve the aero-sanitary conditions. It would act on the polluted air or even before pollution has had a chance to accumulate by moving the air masses during wind calms. There are two basic goals of the system:

- to improve the air quality on the ground level by dispersing polluted air,
- to penetrate and break through the smog layer to enable natural air circulation.

In order to enable the results to be put into practical use, the efficiency of cooperation between the ventilation towers and the central ventilation chimney also had to be examined. A system consisting of the central ventilation chimney and an outer ring of ventilation towers located around the chimney at a certain distance from it was tested in different configurations.

The most effective and economically feasible places for the location of the system are natural ventilation channels formed by topographical and urban development. Based on the map of an air exchange and regeneration system for Cracow, Poland [3], an example of possible locations of the discussed systems is shown in Fig. 1.

2. Models, measuring devices and test method

2.1. Models

Substitute ventilation towers were used and rather than having eight to ten ventilator units uniformly distributed on both sides of the tower, these were each comprised of a single ventilator with an equivalent output of the total of the eight to ten ventilators they were substituting. These substitute ventilation units were made using 60 x 60 mm CPU fans. This resulted in 1:833 scale models. Due to the different proportions between the height and the width of the fans and the ventilation towers (80 x 20 m), only the vertical size was correctly proportioned at this scale.

The ventilation chimney was modelled as a thin shell positioned over the eight inlet ventilation towers placed under the chimney, with lean angles of 0° and 47° (see Fig. 2). The base of each chimney had a diameter of 240 mm. Four different ventilation chimney shapes were tested (see Fig. 3).

Another parameter taken into consideration were different variants of chimney shapes A & B. These variants were created by removing 25% and 50% of the height of the chimney from the top (see Fig. 4). Such variants were tested as they may prove to be vastly more economically and technically feasible to create at full scale.

The system, consisting of a ventilation chimney and ventilation towers, was planned on an octagon with eight ventilation towers located around the central chimney at distances of 150 cm and 120 cm in different series of tests. Each ventilation tower was placed on a different path and directed towards the chimney (see Fig. 5a).

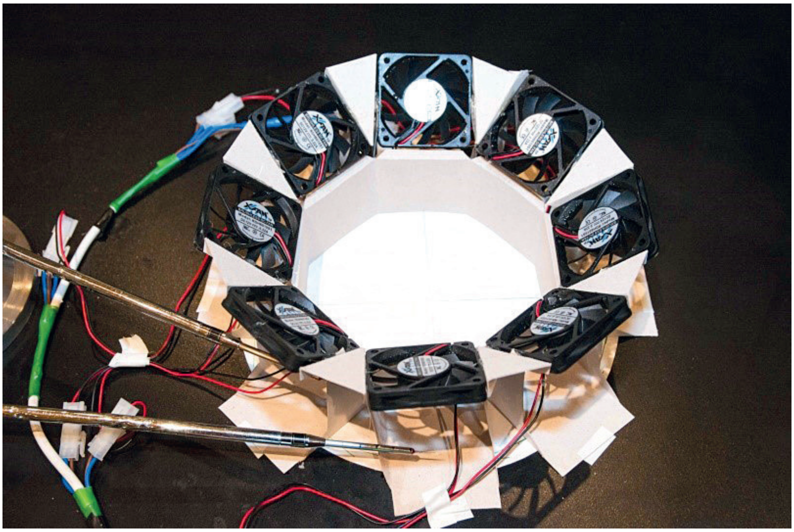


Fig. 2. Bottom of the ventilation chimney with inlet ventilation towers

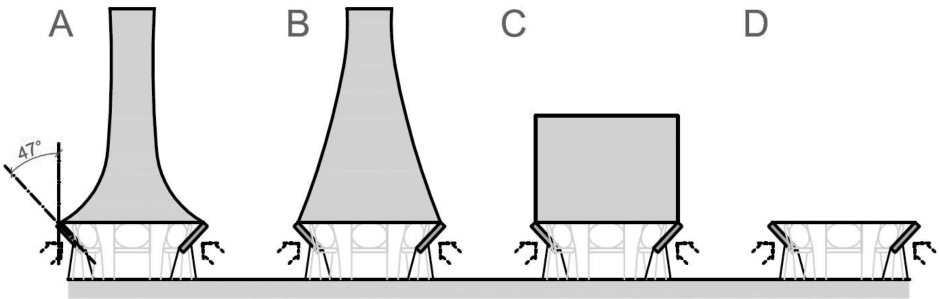


Fig. 3. Tested shapes of ventilation chimneys with inlet towers

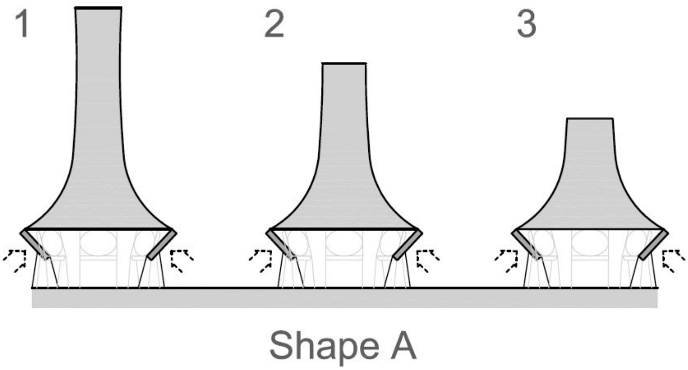


Fig. 4. Different variants of chimney shape A

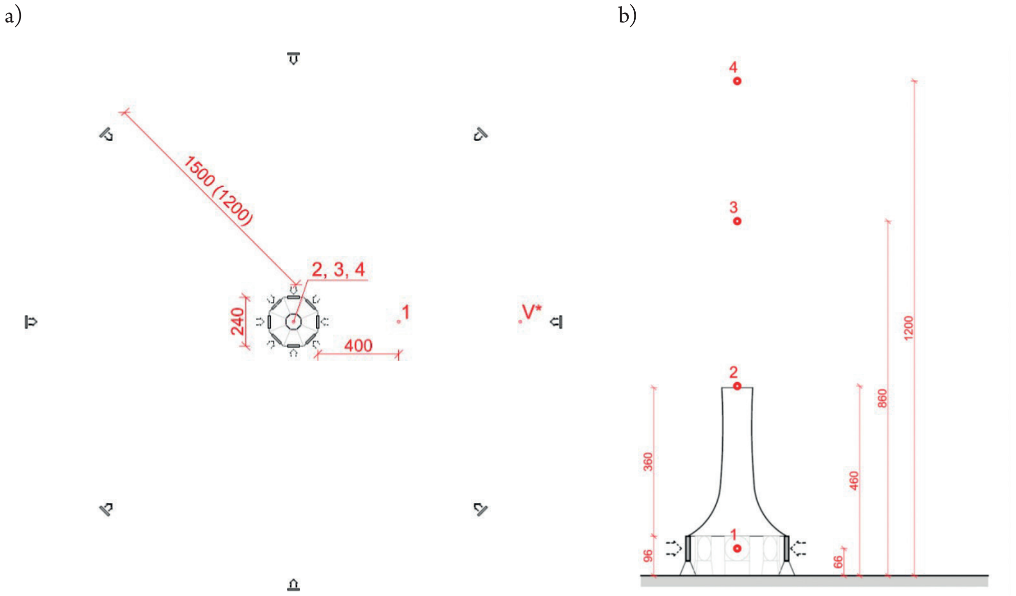


Fig. 5. Location of hot-wire probes on the model of concentric system: a) top view, b) side view

2.2. Test method and measuring devices

The main scientific aims of the investigations were:

- to find the most efficient, practical and feasible solution for the ventilation chimney, taking into account parameters such as shape, height, permeability and angle of inlet ventilation towers,
- to determine the continuity of air streams generated by ventilation towers and the possible upward exhaust resulting from combining the towers with the chimney.

This was achieved by measuring the wind speed at four different points along the path of the stream. The first measuring point of the horizontal wind speed was placed 400 mm from the outer edge of the chimney structure, along the path of one of the ventilation towers. Three other points were measuring the vertical wind speed at heights of 460 mm above the ground level (right above the chimney outlet), 860 mm above the ground level (start of the temperature inversion layer which has to be penetrated by the generated stream [4]) and 1200 mm (1 km above the ground at full scale). For a broader overlook on the location of each measuring point, see Fig. 5.

The velocity of the generated air stream was measured using ATU 2001 monofilament hot-wire anemometers. The air stream was generated through the use of CPU fans produced by *Xfan*, model: RDH6010S1 with a nominal voltage of 12 V, 0.22 A. These were powered by a stabilised DC power supply. The level of generated wind speed was controlled by adjusting the voltage provided to the fans.

2.3. Smoke visualisation

Qualitative studies were conducted using a heavy smoke generator. The ground of the workspace was clouded in heavy smoke to simulate urban air pollution (Fig. 6). The stream generation system was then turned on (Fig. 7) to observe the efficiency and thoroughness with which the area would be cleared of smoke (Fig. 8).

The smoke was made of vapour and dry ice to simulate a dense layer of smog and was dispersed uniformly in accordance with real-world urban conditions [5].

Fig. 6. Heavy fog covering ground (system turned off)

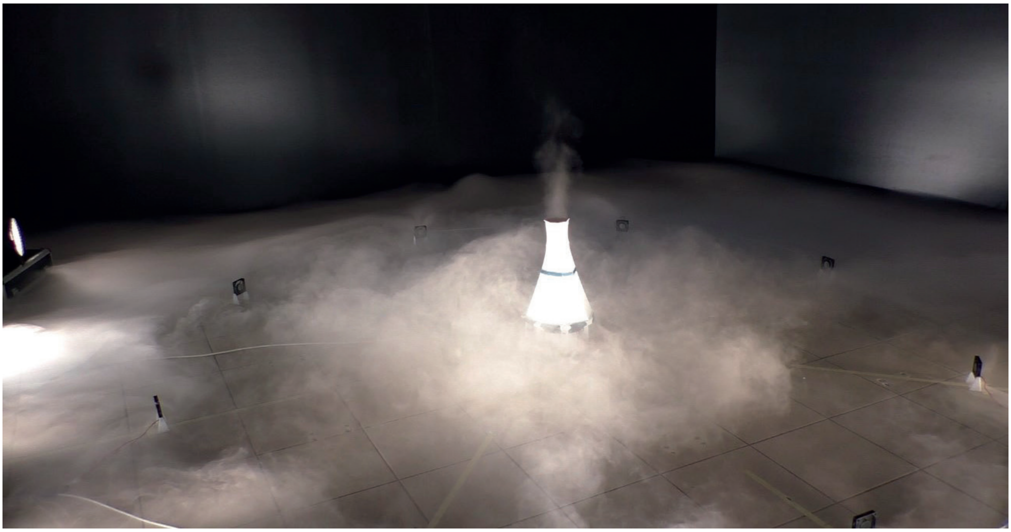


Fig. 7. Moment of turning on the system showing a visible circular gap in the fog forming due to the air movement

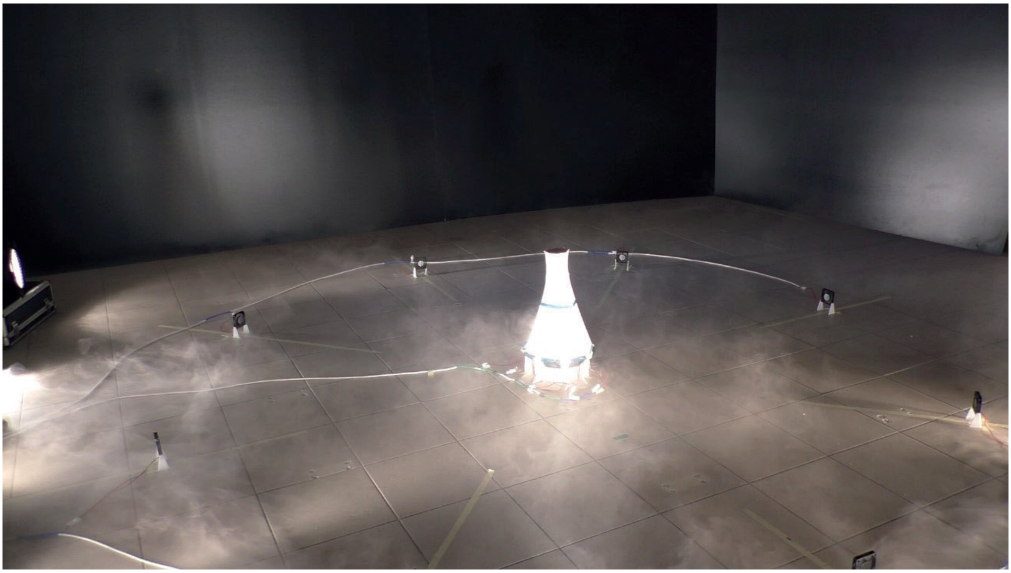


Fig. 8. Cleaned air within the circular system

During the smoke tests, a strong leak of air was observed at the bottom of the chimney. The shape of the chimney was designed to allow a sufficient level of air compression for the airstream to pass through the narrow end. A high difference of the inlet and outlet pressure was deemed to be the cause of the air leak between the fans. For this reason, tests with different types of permeability between the inlet towers have been performed. These different permeability types are shown in Fig. 9. In cases 1, 2 and 4, strong airstream leaks were observed. The best results were obtained for the third case, which was used in all of the subsequent tests [6].

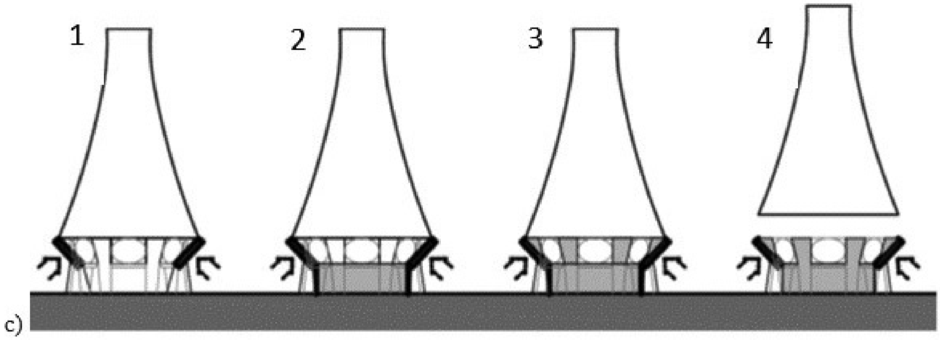


Fig. 9. Different types of permeability between the inlet ventilation towers: 1 – open space; 2 – closed space between the towers below fans level; 3 – whole space closed; 4 – whole space closed with the chimney elevated above the fans

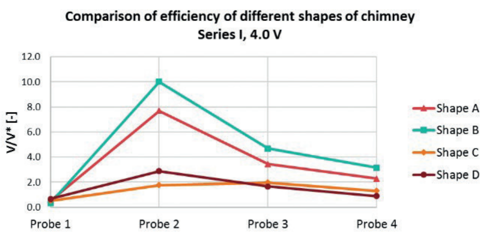
3. Model tests and their results

The air stream velocity and continuity investigations were conducted in the three different series presented in Table 1 [7].

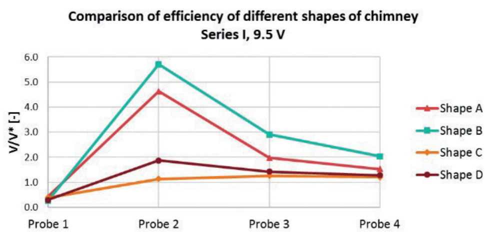
Table 1. Details of model test series

Series No.	Distance of 1st row of towers from the chimney	Shapes of chimney	Variants of shapes
Series I	1 500 mm	A, B, C, D	1
Series II	1 200 mm	A, B, C, D	1
Series III	1 200 mm	A, B	1, 2, 3

Each series was tested with three different wind speeds generated by the fans resulting from supplied voltages of 4.0 V, 9.5 V and 13.6 V. Comparison between the results obtained for each chimney shape at each voltage provided to the ventilation towers for Series I and II is presented in Figs. 10 and 11, respectively. The results are provided in a non-dimensional scale [8] – each velocity value is related to *V** which is the reference wind speed measured for each velocity provided by the fans at a distance of 200 mm from the outer ring of fans where the influence of the internal fan turbulence was deemed negligible. The form of the graphs (probes on horizontal axis, lines joining each points) was used solely for the purpose of presentation clarity and the lines are not meant to be interpreted as any kind of interpolation between each point.



a)



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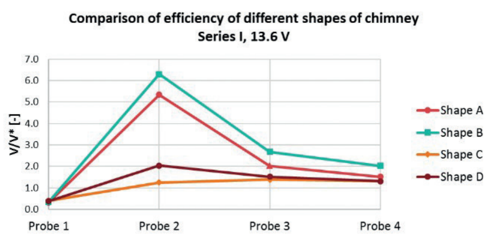

c)

Fig. 10. Comparison between results obtained for different shapes of the chimney for Series I for a set voltage provided to the fans: a) 4.0 V, b) 9.5 V, c) 13.6 V

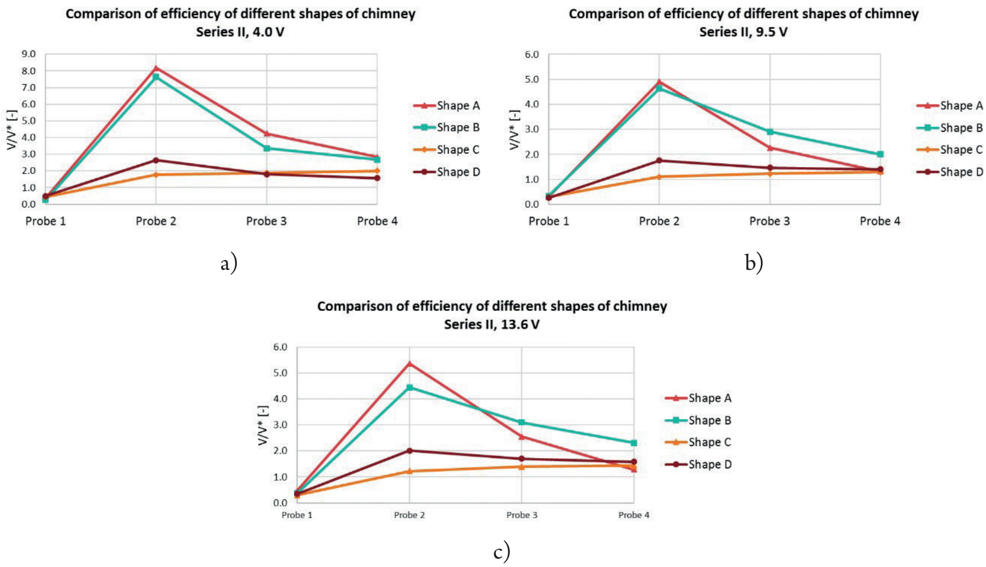

Fig. 11. Comparison between results obtained for different shapes of the chimney for Series II for a set voltage provided to the fans: a) 4.0 V, b) 9.5 V, c) 13.6 V

In order to determine the influence of the Reynolds number on the investigated phenomenon, a comparison between the results for different voltages provided to the fans (thus, different wind speeds) was performed. This comparison is shown in Figs. 12 and 13, for Series I and Series II, respectively.

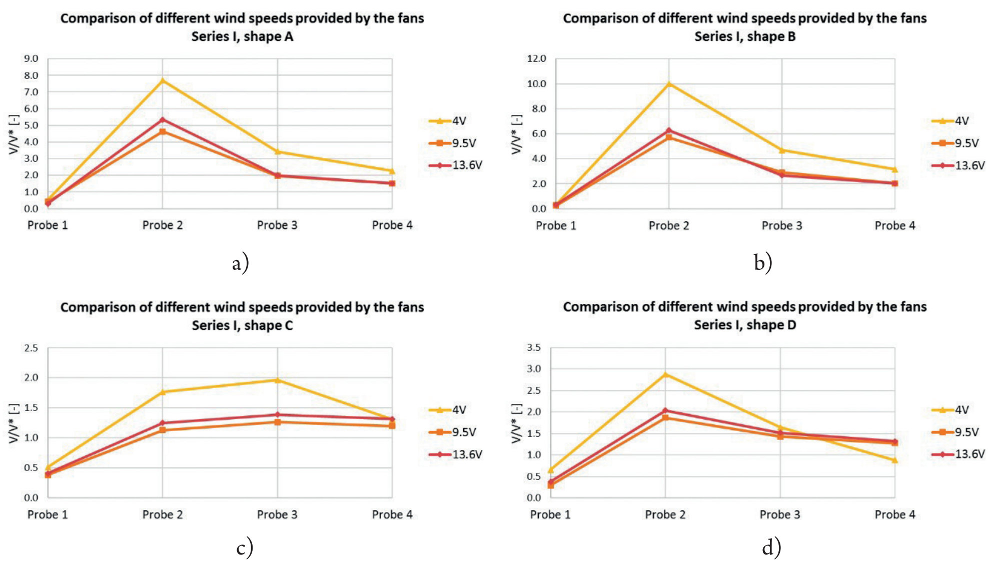

Fig. 12. Comparison between results obtained for varying voltages provided to the fans for each chimney shape – Series I: a) chimney shape A, b) chimney shape B, c) chimney shape C, d) chimney shape D

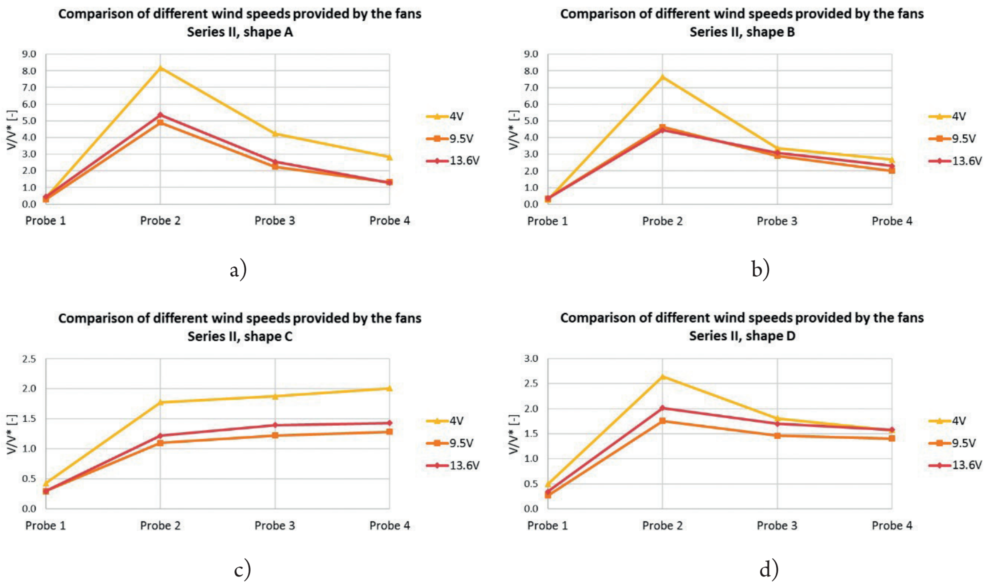

Fig. 13. Comparison between results obtained for varying voltages provided to the fans for each chimney shape – Series II: a) chimney shape A, b) chimney shape B, c) chimney shape C, d) chimney shape D

To investigate the influence of the distance of the outer ring of ventilation towers from the centre of the system, comparisons between Series I and II have been made (see Figs. 14-16).

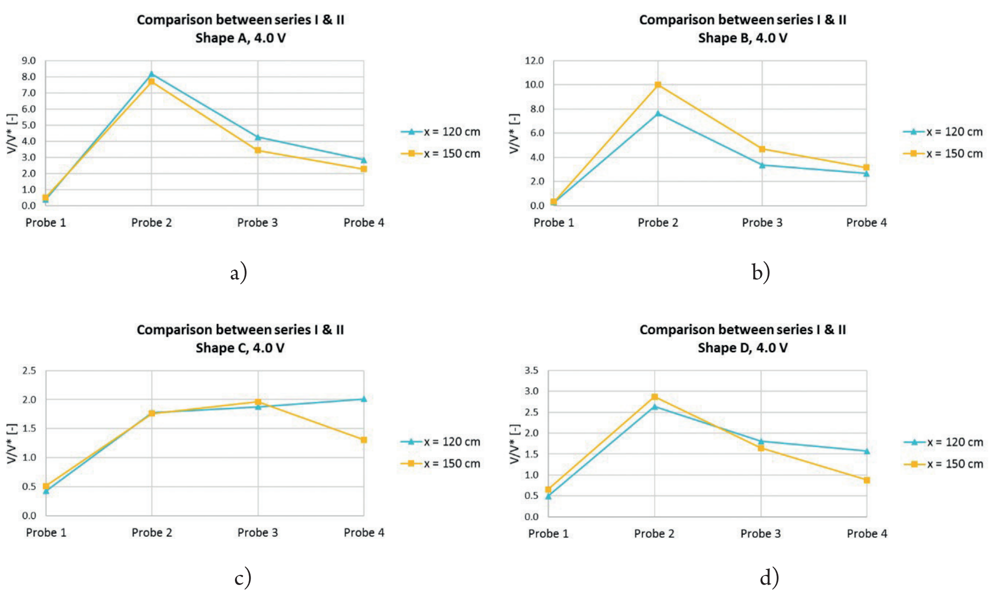

Fig. 14. Comparison between results for Series I & II for a voltage of 4.0 V: a) chimney shape A, b) chimney shape B, c) chimney shape C, d) chimney shape D

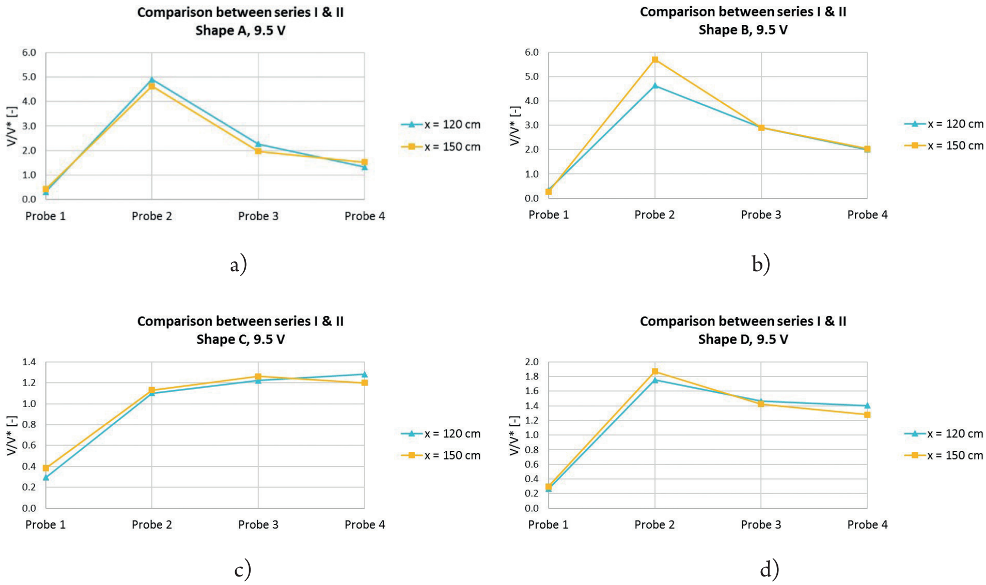

Fig. 15. Comparison between results for Series I & II for a voltage of 9.5 V: a) chimney shape A, b) chimney shape B, c) chimney shape C, d) chimney shape D

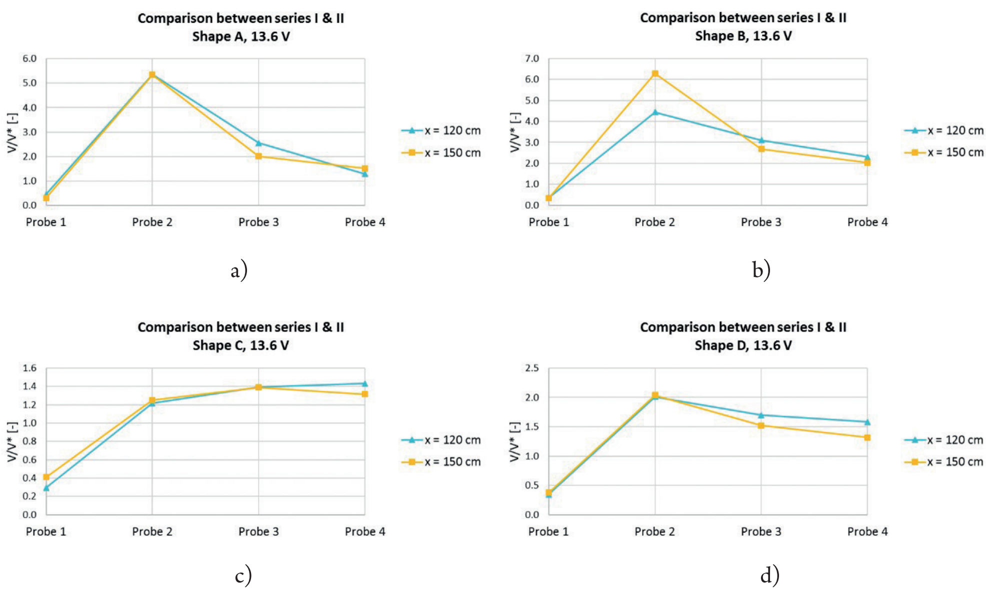

Fig. 16. Comparison between results for Series I & II for a voltage of 13.6 V: a) chimney shape A, b) chimney shape B, c) chimney shape C, d) chimney shape D

Comparisons between different variants of shapes A & B, which were conducted in Series III of the tests, are shown in Figs. 17 and 18.

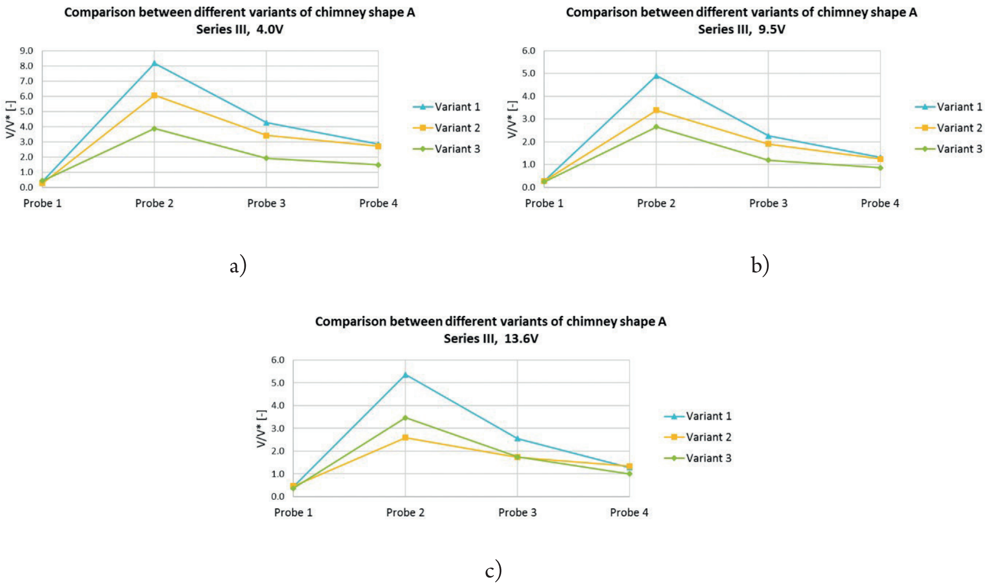

Fig. 17. Comparison between results for different variants of chimney shape A for varying voltages provided to the outer ring fans: a) 4.0 V, b) 9.5 V, c) 13.6 V

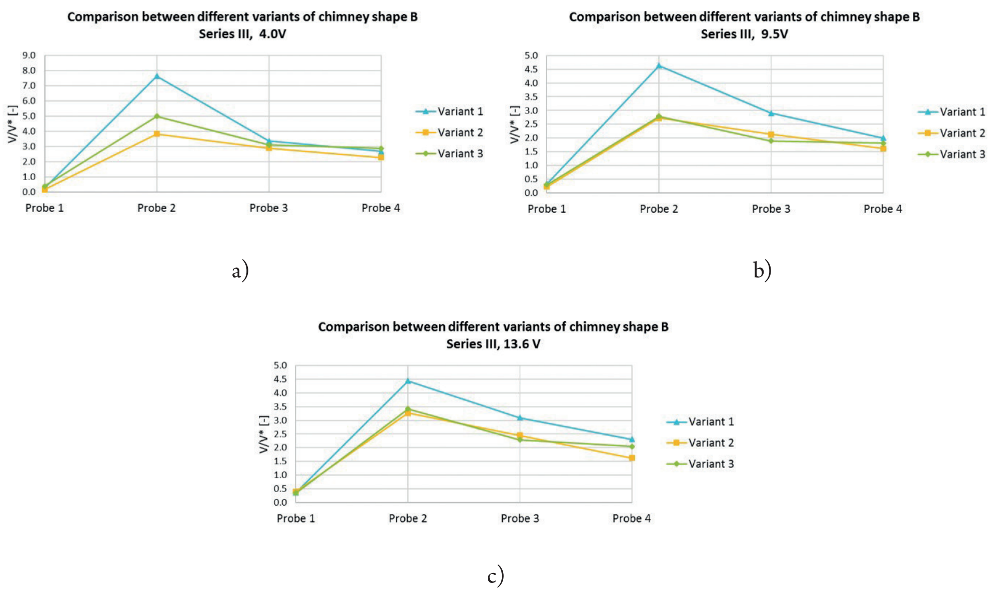

Fig. 18. Comparison between results for different variants of chimney shape B for varying voltages provided to the outer ring fans: a) 4.0 V, b) 9.5 V, c) 13.6 V

4. Results analysis and conclusions

Probe no. 1 was located at the point where the stream generated by the ventilation tower of the outer ring weakens, yet there is no noteworthy suction from the chimney inlet fans. Achieving a noticeable wind speed at this point means that there is interference between the outer ring of the ventilation towers and the inlet fans of the chimney. In practice, this would mean that the ventilation towers are able to supply the polluted air into the central vertical exhaust as a continuous airstream. For the two tested distances between the chimney and the first row of the outer ventilation towers, its influence on maintaining the continuity of the generated air stream is negligible. **The continuity was achieved** with both tested distances.

On probes no. 2 and 3, the highest wind speeds were achieved for chimney shapes A and B, which perhaps results from their forms resembling confusors. However, a similar wind speed on probe no. 4 was also achieved for shape D, which has no physical chimney at all. If verified at a larger scale, this solution would be the most advantageous for practical implementation. However, it may result in the vertical stream having too much turbulence and no longer being able to penetrate through the inversion layer. Shape C produced the most disappointing results on each measuring point in terms of wind speed; in most cases, this was slightly below the level of shape D.

The comparison of dimensionless velocity values for each tested voltage showed similarity between the graphs for 9.5 V and 13.6 V. There is a significant difference in the graph for the lowest voltage of 4.0 V, which shows there is **little influence of the Reynolds number** on the phenomenon in the investigated range of the Reynolds number for the lower values of air stream velocity. This provides the highest relative wind velocities above the chimney; however, this would not be feasible to accomplish at full scale as this wind velocity level would be too low.

Investigations of different variants of chimney shapes A and B showed that shape A produces lower wind speeds with each modification, while shape B might be **trimmed to up to half of its size with no significant deterioration of its efficiency**; furthermore, there is almost no difference between variant 2 and 3.

The most satisfying results were achieved for chimney shapes B (**highest velocity at the output of the chimney and at the inversion layer level**) and D (**most feasible solution as there is no chimney, yet the results are satisfying**). These shapes shall be tested in the forthcoming stages of the tests. At the level of temperature inversion (probe no. 3), the vertical stream achieves satisfying values of wind speed that should be able to **penetrate through the inversion layer**.

Another consideration which needs to be taken into account in future tests is the noise level generated by working ventilation towers as this may be disturbing to people. However, the estimated time of work for the fans would only be several hours a day during wind calms. Furthermore, the produced wind speed would be still at a very low level of up to 4 m/s; thus, the generated noise should not be too intrusive for people.

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