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URBAN WIND-CONCENTRATOR TOWER FOR ENERGY CONVERSION

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Abstract. *In urban environments the wind speed can increase locally due to two effects acting like vents on the airflow: One is the surrounding natural landscape topology which might enforce a concentration of airflow under certain wheather conditions, the other effect comes from the existing development of cities due to their history. Often a checker-board pattern was starting point of the beginning urbanization. Since historical buildings were relatively low, wind didn't play a role in town-planning, however, nowadays, in particular in urban street canyons between skyscrapers gale-force like wind speeds can be reached. Besides an uncomfortable microclimate for pedestrians in regard to gusts and pollution at street level, high wind speeds can damage the urban infrastructure by high wind loads. Against the background of the climate change it can be expected that the kinetic energy in the atmosphere will increase in future, and, as consequence, wind speeds in urban canyons will further increase even more, causing more damages and other negative effects. The idea proposed here is to use the concentrated wind energy in the urban street canyons in order to lower the negative effects onto the urban environment and the pedestrian's thermal comfort, and, besides that to coincidentally produce electricity for local consumers, entertainment or commercial applications. Thereto, a slender wind-concentrator tower has been designed, which collects and redirects inflowing air to a vortical flow system, making the conversion of kinetic into electrical energy possible. This work is a CFD study to examine the feasibility of the proposed 20m high wind-concentrator tower, which has been especially designed for the urban environment. One goal is to analyse the developing flow within the tower and to determine the concentrated wind energy. An estimation of the efficiency in comparison to a conventional axial wind turbine is part of the study for the evaluation of the concept. An optimisation of the wind-concentrator tower is a future task.*

1 INTRODUCTION

The forth development of towns and cities has changed the urban environment over the time. In particular the industrialisation has forced the concentration of people on a limited place, and, as consequence, higher buildings have been build. This had have an crucial impact on the wind distribution within the cities, the wind speeds have been drastically increased at destinct locations. Additionally to the surrounding natural landscape topology which might enforce a concentration of the airflow under certain wheather conditions the new major effect on wind speeds comes from the canyoning of modern building development acting like a vent on the airflow: Often a checker-board pattern was starting point of the beginning urbanization. Since historical buildings were relatively low, wind didn't play a role in the old town-planning. But nowadays, building height has changed, and, in particular in urban street canyons, gale-force like wind speeds between skyscrapers can be reached [1]. Some places in New York are famous for the high wind speeds, Chicago is called the “Windy City”. One negative effect of high wind speeds is the uncomfortable microclimate at street level for pedestrians in particular due to gusts, pollution and airquality, see [5] and [13], but, even more, high wind speeds damage the urban infrastructure primarily by high wind loads and secondarily by transporting pollutant and dust. The kinetic energy of the wind in the street canyons is locally very high as measurements and models show [6]. Often vent like building development contrains the wind to coalesce onto a neuralgic point. Even more, the inhomogenious building development leads to gusts, hence, wind speeds are amplified and the probability of damaging wind loads is escalated. Storms are tightening the problem. Against the background of climate change with its higher kinetic wind energy in the atmosphere it reasonable assumption that the wind speeds in urban street canyons will also further grow [7], which consequentely will lead to even more damages onto the urban infrastructure. The fact that concentrated wind energy is existent in street canyons leads to the idea, now poposed here, to capture the wind energy in a tower in order to lower the negative effects onto the urban environment by redirecting the wind through the tower upwards and, hence, lowering wind speeds at street level. Further on, the wind energy shall be used to coincidentally produce electricity for local consumers, i.e. to refill batteries of electrical cars, to provide power for traffic light or Notstrom or, not at least, to play commercials on large LED arrays. Thereto, a concept of slender high wind-concentrator tower has been developed: The tower collects and redirects inflowing air to a vortical flow system, making the conversion of energy in the first place possible, and provides additionally electricity for local consumers. By using numerical flow simulation techniques (CFD) the feasibility of the proposed wind-concentrator tower concept is examined. One goal of the work is to analyse the developing and vortical flow structure within the tower in regard to the possibility to redirect air and extract energy. One focal point is the estimation of the potential of the concentrated wind energy for energy conversion and, eventually, the evaluation and comparison of the concept. Before going in details related work will be discussed in order to present the relevant background information for the concept and its evaluation. Then the flow concept of the wind concentrator tower will be introduced. Special attention is given to the constraints coming from the urban environment, i.e. the dimensions of streets or places, which, in consequence, limit the diameter of the tower. Thereafter, the CFD simulation setup is briefly explained, followed by the analysis of the flow simulation results of three wind concentrator tower variations. Their performance will be discussed and compared. Finally, the evaluation of the wind-concentrator tower concept in regard to energy conversion will be discussed.

2 Related Work

Conventional horizontal axis wind turbines (HAWT) consist of three major parts. One is a high tower which is typically made from tubular steel, concrete, or steel lattice. The second one is a rotor which consists usually of two or three blades mounted on a hub. The third part is the nacelle which sits atop the tower and contains the gear box, speed shafts, generator, controller and brake. The wind blowing over the blades generates lift and, therefore, rotation. The wind speed is directly correlated with the power output. Unfortunately, the drag of the ground surface leads to higher air boundary layers lowering the wind speed near to the ground level; upwind obstacles such as other hills, trees or buildings are further slowing down the wind at ground level. Therefore, in order to increase the production of electricity higher and higher wind towers and turbines with longer blades have been built, well knowing that wind speed increases with the seventh root of the altitude according to the wind profile power law [11]. Moreover, at higher altitudes the wind is more gusty and unsteady oncoming flow conditions lead to more disturbed flow fields in the vicinity of the blades. In consequence this enhances flow separation and the generation of vortices, which in turn affect the efficiency, durability, noise emissions and environmental impact of the wind turbine [10]. Especially the noise emission and the frequential shadow of the wind tubine blades is still a major concern for the installation of a HAWT in an urban environment. Nevertheless some concepts have or will be realised: One is the installation of three horizontal axis wind turbines between the Bahrain World Trade Center skyscrapers, see figure 1. Another impressive and unique example is the planned Anara Tower in Dubai, a giant wind turbine will be mounted on the top of tower, see figure 2. Even though the diameter of horizontal axis wind turbines and the onflow wind speed are the crucial design parameters with respect to the expected maximum of power conversion, see the derivation of Betz [2], a lot of other concepts have been tested in order to minimize the throat plane at constant power. In particular the idea of concentrating wind has been obvious. Often stator blade like devices commonly used in the power turbine technology are used to generate additional angular momentum whilst the flown-through area is even reduced, thus leads to an extraordinary increase of power output. The lesson from earlier studies is that decreasing the dimension of the apparatus might be essential, in particular in urban street canyons. Moreover, a further concentration of wind is also inevidently to further increase the wind speeds just before

Figure 1: Three integrated horizontal axis wind turbines between the Bahrain World Trade Center skyscrapers (WWW)

Figure 2: The planned new Anara Tower at Dubai City, integrated wind turbine on the top of the tower (WWW)

the actual conversion. Hence, the later presented design realises these aspects. The flow in urban street canyon itself can be really complex, lee-side vortices, i.e corner eddies, and also strong canyon vortices can occur. The expected wind speeds and, therewith, the wind energy potential depends strongly on the local wether conditions and building arrangement. Modelling the flow field in such urban canyons is difficult and a focal point of current work, see for example the work of Li and coworkers [9]. Even CFD modelling of the air flow and the air pollution prediction in urban street canyons is challenging as Neoftou et al. [12] show. Hence, measurements are still indispensable in order to get valid wind speed data. In this context the major aspect is that the experiments revealed that wind speeds from 10m/s to 15m/s at 2m hight from street level are commonly observable, in such cases the air flow boundary thickness is with 0.5m unexpected low. The resulting flow is really uncomfortable for pedestrians, but this is also promising for producing electricity with a small wind turbine. Assuming a radial flow-through area with a radius of $4m$, an air density of $1.2kg/m^3$ a wind speed of $10m/s$ a theoretical wind power of $30kW$ can be calculated by using

$$P = \frac{\pi \cdot \rho \cdot r^2 \cdot v^3}{2}, \tag{1}$$

with the air density ρ, the radius r of the actuator disc and the velocity magnitude v. Providing that the famous wind power law of Betz is valid in general [2], the maximum of a realistic power output is 16/27 of the theoretical value. Although the expected electricity is not much, the provided power of round about $17kW$ is high enough for supplying some local power consumers: Batteries of electrical cars could be refilled, maybe street lights or large LED screens can be supplied.

3 Wind-Concentrator Tower Concept

Before the results of the wind-concentrator tower study can be discussed the basic concept will be presented and explained. The section begins with major constrains for the wind-concentrator tower design, thereafter, the applied CFD method will be introduced followed by the explanation of the CFD simulation set-up.

3.1 Design Constrains for Wind Turbines in Urban Environment

The limitation of the urban environment comes from dimensions of the street canyons and the traffic within. In fact even small conventional horizontal wind turbine are not applicable in street canyons close to street level. Beside the performance losses due to the street flow boundary layer their rotating blades would be loud and at least dangerous for the people. Furthermore, their moving parts would irritate the traffic and the people in the surrounding. Although vertical wind turbines like the Darieus or Helix rotors may exhibit relatively small diameters these concepts would also irritate the traffic, they are loud and noisy, and finally, they can not be accepted for safety reasons due to its freely reachable rotating parts. Furthermore, those wind turbine types do not redirect the flow, hence, their impact on the urban microclimate would be negligible. In conclusion, the first major constrain for the wind turbine is that rotationg parts have to be encapsulated, the second major constrain is that the wind turbine has to redirect the oncoming flow in order to lower the flow speed behind the turbine. Not at least the wind turbine system must be small in diameter allowing an integration in an existing urban building development at street level. In particular the latter aspect is crucial, two lane streets are roughly 20m wide, in fact not wide enough for the installation of any classical horizontal or vertical axial wind turbine. However, bearing in mind that street canyons are often focussing to places or traffic islands those locations could be ideal candidates for placing a wind turbine system. The concept of the now presented wind-concentrator tower has been especially developed for such locations. Details of the design will be explained now.

3.2 The Wind-Concentrator Tower Design

The basic idea of the concept is to concentrate wind by using an air flow intake structure with an opening to the oncoming flow. Then the air flow is redirected. The tower is devided in two parts, a base part for air inflow and generating angular momentum in order to prepare the energy conversion, and a pipe part on top for the air flow redirection and the energy conversion itself. In the figure 3 a sketch of the basic two dimensional design of the base part is shown. Obviously the design is simple and not optimized, following the strategy to proof the concept at first. To complete the impression of the wind-concentrator tower concept figure 4 illustrates the whole three dimensional configuration. The spiral architecture sucks in air over a height of 8.6m and a width of 2m, the air flow is enforced to spiral into the inner part of the tower getting more and more angular momentum. In fact this part acts like a stator of a classical turbine. Over the base part three different

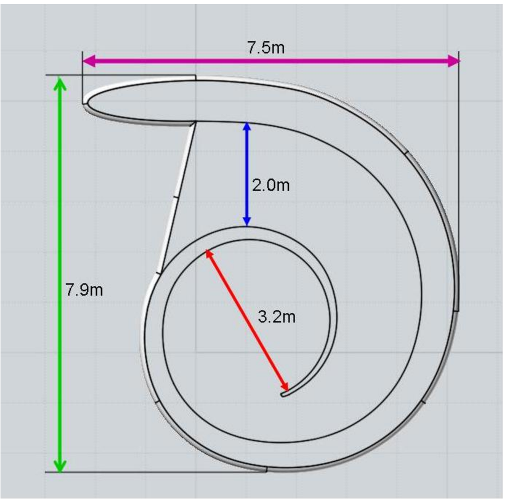

Figure 3: Elliptical shape of the wind-concentrator tower base.

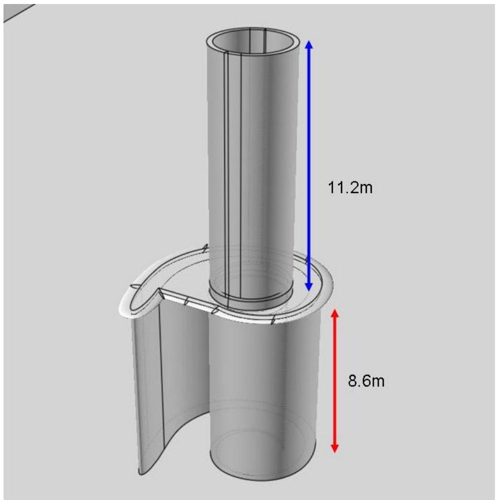

Figure 4: Wind-concentrator tower with a straight pipe.

configuration have been investigated. The first configuration is a simple straight pipe with a diameter of 3.2m and a height of 11.2m. The other two configurations are variations, one has a diffusor like pipe on top of the base, see figure 5 with a pipe diameter of 3.2m at the bottom and a top diameter of 5m. With the second variation possessing a vent like pipe, see figure 6, the opposite flow condition within the tower should be generated and, then, be analysed in order to identify performance trends. In this study rotational parts have not been part of the investigation due to the following reason: A rotational part like an impeller is a highly flow optimised configuration in particular designed for a certain operation point. Yet optimisation has not been a focal point in this early state of investigation.

3.3 Numerical Simulation Method

For the wind-concentrator tower study numerical flow simulations have been performed. Hereto, the DLR code Theta has been used to conduct the steady flow simulations. THETA is a finite volume code based on the well-known DLR-TAU code [4], but in contrast to TAU it is particularly designed for solving incompressible flow problems. Due to its dual-grid approach THETA is independent of all types of structured or hybrid, unstructured CFD grids: By performing a pre-processing step THETA is able to convert a variety of polygonal elements into a new edge based grid structure, on which then the transport equations are solved. The matrix free formulation of THETA has been applied to reduce the computational memory amount. The multigrid approach has been used to accelerate the solving of the linear equations even on fine grids. An efficient balancing algorithm for domain decomposition has been utilized to perform efficient computations on a DLR Linux-cluster. In this study the SIMPLE algorithm has been applied for

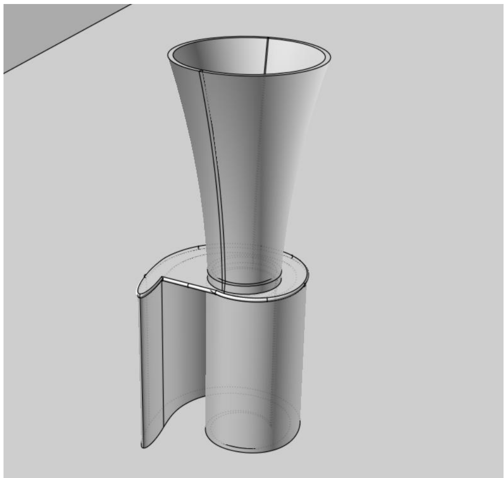

Figure 5: Wind-concentrator tower with a diffusor like pipe.

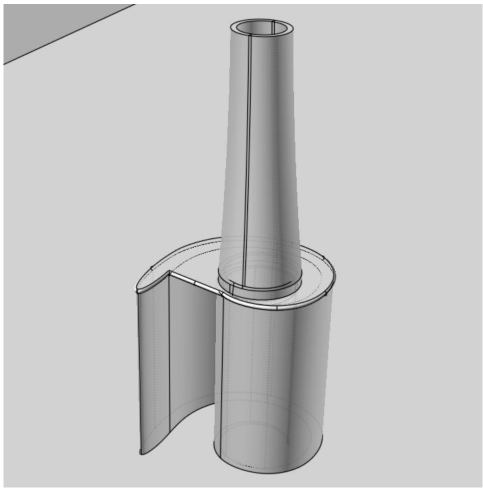

Figure 6: Wind-concentrator tower with a vent like pipe.

an efficient velocity pressure coupling. The well-known chequerboard instability of the pressure has been eliminated by a 4th-order stabilisation term. The spatial discretisation is done by using a second order quadratic upwind differencing scheme. The GMRES algorithm has been applied for solving the linear equations. Following the approach of [6] for turbulence modelling of urban street canyon flows the standard k-ω turbulence model has been utilised also knowing that turbulence modelling especially for wind turbine flows is a focal point of research, see the discussion in [8] and [10].

3.4 Simulation Setup for the Wind-Concentrator Tower Configurations

From the CFD point of view the proposed configurations are quite simple, however different physical flow scales have to be considered: For example the street boundary layer has to be resolved in order to get realistic onflow conditions for the tower, more over, the smaller boundary layer around and in the tower must be captured by the grid. Additionally the spatial grid resolution at the tip of tower pipe must be fine enough to resolve the flow separation and expected Venturi effects. Even the elliptical guiding wall region has to be resolved accurately in order to capture the expected spiraling flow motion. For those 3-D flow configurations large computational CFD meshes have been generated: The meshes have approximately 3.5 million vertices, they are unstructured and non regular, consisting of approximately 12 million volume cells, tetrahedra and non-convex prisms in 12 prism layers especially for resolving the boundary layers. The cell sizes range from roughly 0.5mm at the turbine wall to 4.0m in the farfield. The y+ is in average close to 15, hence, for accurate turbulence modelling, a generalised wall function has to be utilised. Impressions of the CFD surface grid triangulation are given in figure 7 and figure 8.

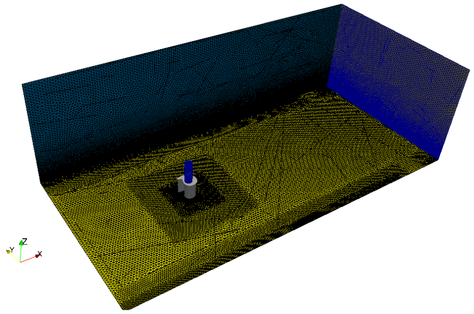

Figure 7: View onto the CFD surface grid of the wind concentrator with the straight pipe.

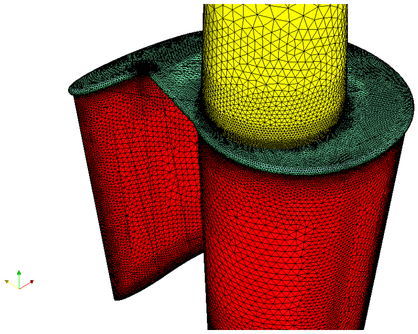

Figure 8: Details of the CFD surface grid of the wind concentrator with the diffusor pipe.

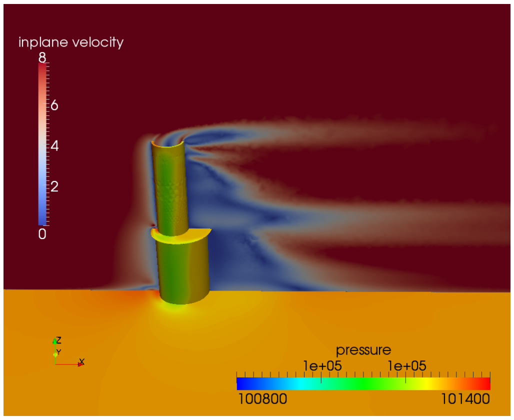

Figure 9: Inplane velocity magnitude of the flow around the straight pipe wind concentrator.

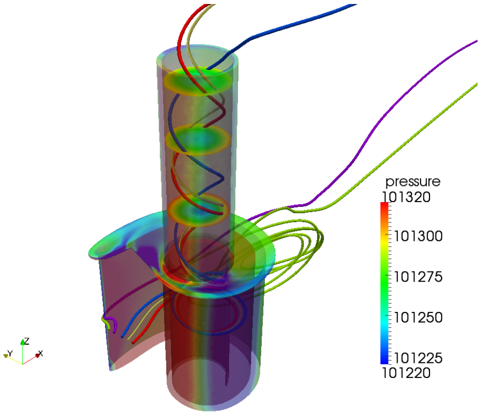

Figure 10: Streamlines are illustrating the flowfield of the straight pipe wind concentrator

4 Dominant Flow Structures in the Wind-Concentrator Towers

Starting point of the flow analysis is one main goal which shall be reached by the installation of the wind concentrator tower, lowering the wind speed on lee-side of the building. In figure 9 the inplane velocity on a sectional slice through the wind concentrator tower is depicted. Even though the wind speeds are significanlty lowered in the nearfield of the tower, the wind speed increases again further streamdown. The reason is that the surrounding buildings of a street canyon have not be taken into account in this numerical study. Buildings would block air flow coming from the outer sides, hence, they would prevent a flow restoration. Despite that in figure 10 streamlines illustrate that the onflowing air is sucted into the wind concentrator tower and spirals upwards. However, as the outer streamlines indicate, the shape of the intake is in no case optimized, there is a significant blockage of air at the tower entry leading to a strong redirection of the flow. Thus, performance losses due to the misshaped entry have to be expected. Even the figures 11, 12 and 13, which show isosurfaces of the velocity magnitude with an isovalue

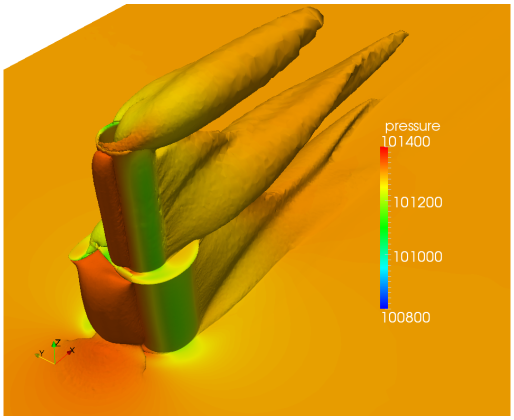

Figure 11: Iso-surface of the velocity magnitude of the flow around the wind concentrator with the straight pipe, iso-value 6.0m.

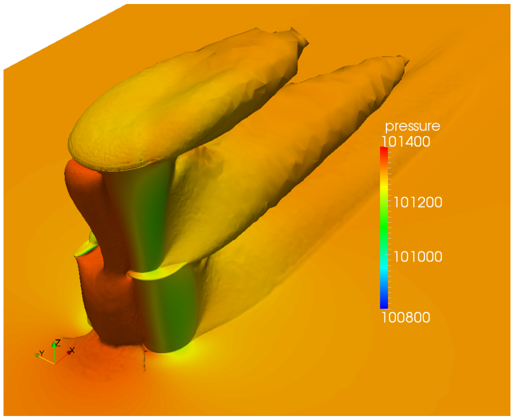

Figure 12: Iso-surface of the velocity magnitude of the flow around the wind concentrator with the diffusor pipe, iso-value 6.0m.

of 6m/s for the three tower configurations, are confirming this observation. Here would be a first starting-point for a future shape optimisation. A comparison of the iso-surfaces reveals a further significant detail: the diffusor type tower shows the largest domain of a reduced air flow at the top and the middle part of the tower. Due to its bigger cross sectional area the reversed cone blocks effectively the oncoming air. In street canyons this would positively effect the microclimate, as known from trees which crowns significantly change the local flow topology.

For all three wind-concentrator tower configurations the pressure distributions on horicontal sheets/cut planes at different heights have been compared. In the figures 14, 15 and 16 colour plots of the pressure indicate that flow within the towers has established a stable vortical flow field, and, hence, it can be assumed that the angular momentum of the air within the upper part tower is high. In particular, directly after leaving the spiral structure of the tower base the air flow the radial pressure gradients are maximal. This height seems to be the preferable position for any wind turbine installation.

5 Performance Analysis and Evaluation

The performance of the wind concentrator tower can only be roughly estimated, since the numerical simulation of the flow through rotational parts like the wind turbine propeller have not been part of the study. Here, focal point of the investigation and analysis are certain integral flow values for the different configurations. With those a first assessment of the results has been undertaken. The averaged pressure, the axial velocity and the averaged angular momentum distributions along the flow path within the wind concentrator tower configurations will be compared. In figure 17 the averaged pressure distribution on certain analysis sheets and at different tower heights are compared. As clearly shown on the analysis sheets, the spiraling flow stabilises within the upper tower and generates a typical radial pressure equilibrium. The radial pressure gradients are dis-

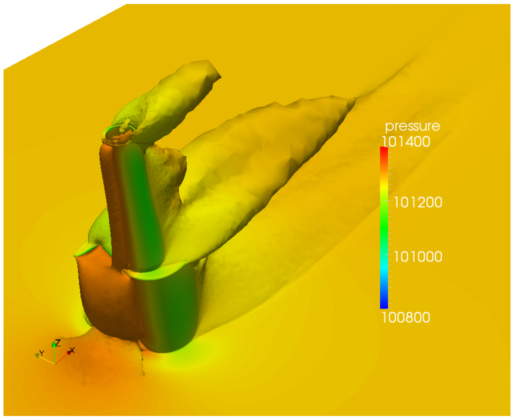

Figure 13: Iso-surface of the velocity magnitude of the flow around the wind concentrator with the vent pipe, isovalue 6.0m.

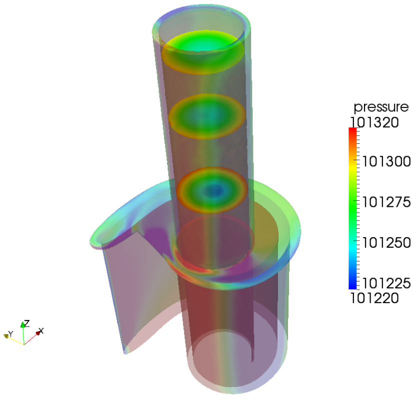

Figure 14: Pressure distribution on the wind conentrator tower and on analysis sheets in the straight pipe.

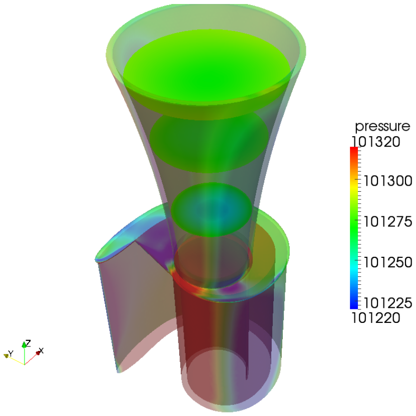

Figure 15: Pressure distribution on sheets in the diffusor pipe of the wind concentrator tower.

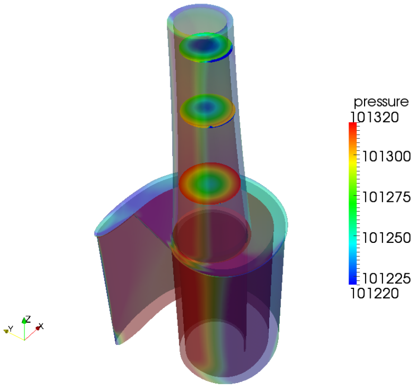

Figure 16: Pressure distribution on sheets in the vent pipe of the wind concentrator tower.

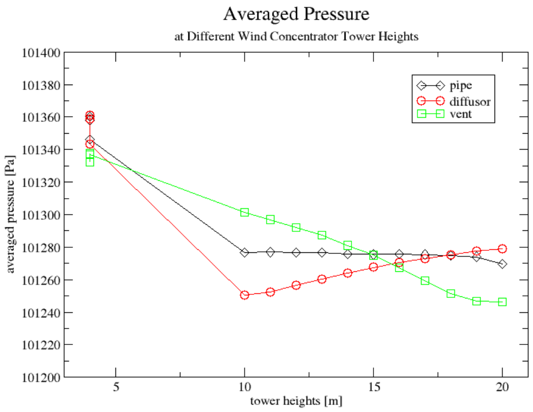

Figure 17: Comparison of the averaged pressure on perpendicular slices at different tower heights.

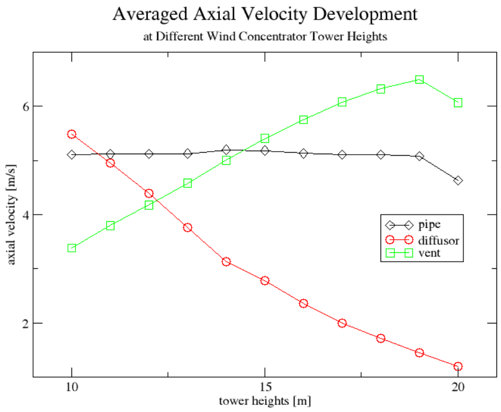

Figure 18: Comparison of the averaged axial velocity on perpendicular slices at different tower heights.

tinct and highly depend on the shape of the tower. As intended the diffusor tower shows a weak radial pressure gradient, the vent tower high gradients indicating a highly spiraling accelerated flow. This observation corresponds to the presented data in the following figures. In figure 18 the averaged axial velocity distribution on certain analysis sheets and at different tower heights are depicted. In the case of the pipe type tower the axial velocity distribution is nearly constant, which coresponds to the pressure distribution. As expected from the shape design significant distinctions are shown by the diffusor and vent tower types. The vent accelerates the flow in contrast to the deceleration by the diffusor. A comparison of the predicted wind power, which could be conversed, is shown in figure 20. The calculation follows equation 1. In fact, the performance of all wind-concentrator tower configurations is lower than expected, a clear sign that the simple shape design has a lot of optimisation potential. However, again the diffusor type tower performs best in relation to the other configurations. In particular, in regard to maximise the power output a position at the beginning of the diffusor part, especially the height of 10m, should be preffered when installing an impeller or turbine system. Further upwards losses due to friction are rapidly degrading the performance.

6 CONCLUSIONS

Based on own experiences with urban street canyon storm and the associated uncomfortable thermal microclimate the concept of a wind-concentrator tower has been developed. This tower seems to fulfill the primary task to redirect wind away from street level upwards into higher building levels. The local wind speeds can be reduced significantly which consequently increases the thermal comfort for pedestrians. Besides that the idea has been investigated that the wind-concentrator tower obsesses the ability to convert

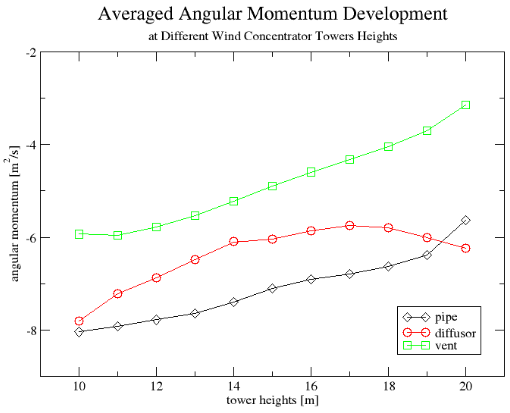

Figure 19: Comparison of the averaged angular momentum on perpendicular slices at different tower heights.

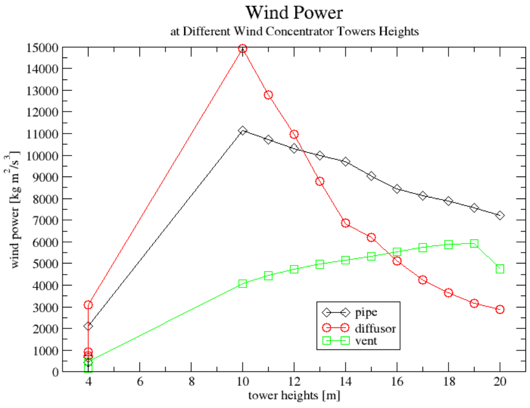

Figure 20: Comparison of the predicted wind power on perpendicular slices at different tower heights.

wind energy into electricity. From the beginning of study, it has been clear that the power output would be low, as simple power estimations for a reference horizontal axis wind turbine have shown. However, for specific and autonomous appliations the produced power can be benefitial. From the energetic point alone it would not make sense to realise the wind-concentrator tower concept, only a multiple use of the presented configuration could be benefitial and justify a realisation. For example the architectural structure opens the opportunity to further mount solar panels on the outer wall, or, as figure 10 indicates, the wind tower concentrator could be used to capture the air pollution, commonly highly concentrated on street level, at the side walls of its inner structure. As mentioned above, the presented tower configurations have not been optimised, thus further potential could be opened in future. In particular a special design for cleaning air might be worth for further investigations.

REFERENCES

[1] Baik, J.J., Kim, J.J., 1999: A numerical study of flow and pollutant dispersion characteristics in urban street canyons, Journal of Applied Meteorology, Vol. 38, pp. 1576-1589,

[2] Betz, A. 1926: Wind-Energie und ihre Ausnutzung durch Windmühlen. - Grebenstein: Öko-Buchverl., 1982, Nachdr. [d. Ausg.] Göttingen, Vandenhoeck u. Ruprecht.

[3] Chang, C., Meroney, R.N., 2003: Concentration and flow distributions in urban street canyons: wind tunnel and computational data, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 91, pp. 1141-1154.

[4] Gerhold, T., Evans, J., 1999: Efficient Computation of 3D-Flows for Complex Configurations with the DLR Tau-Code Using Automatic Adaptation, *Notes on Numerical Fluid Mechanics*, Vol. 72, Vieweg.

[5] Hunter, L.J., Watson, I.D., Johnson, G.T., 1991: Modelling air flow regimes in urban canyons, Energy and Buildings, Vol. 15, pp. 315-324

[6] Jeong, S.J. and Andrews, M.J., 2002: Application of the k turbulence model to the high Reynolds number skimming flow field of an urban street canyon. Atmospheric Environment, Vol. 36, pp. 1137-1145.

[7] Kasperski, M., 1999: Influence of a possible climate change on the specification of the design wind speed. Proceedings of the 10th International Conference on Wind Engineering, Kopenhagen 1999. Rotterdam, Balkema, pp. 229-236.

[8] Leishman, J. G. 2002: Challenges in Modeling the Unsteady Aerodynamics of Wind Turbines, AIAA-2002-0037, 21st ASME Wind Energy Symposium, Reno, NV, Jan. 14-17.

[9] Li, X-X, Leung, D.Y.C., Liu, C-H, Lam, K.M., 2008: Physical modeling of flow field inside urban street canyons. Journal of Applied Meteorology and Climatology, Vol. 47(7), pp. 2058-2067.

[10] Muljadi, E., Butterfield, C.P., Buhl, M.L., 1997: Effects of Turbulence on Power Generation for Variable-Speed Wind Turbines, *Proceedings of the 1997 ASME Wind Energy Symposium*, Reno, Nevada, Jan. 6-9.

[11] Peterson, E.W. and J.P. Hennessey, Jr., 1978: On the use of power laws for estimates of wind power potential, J. Appl. Meteorology, Vol. 17, pp. 390-394.

[12] Neofytou, P., Venetsanos, A.G., Rafailidis, S., Bartzis, J.G., 2006: Numerical Investigation of the Pollution Dispersion in an Urban Street-Canyon, Environ. Modell. Softw., Vol. 21, pp. 525-531.

[13] Stathopulus, T., Wu, H., Zacharias, J., 2004: Outdoor human comfort in an urban climate. Build. Environ. Vol. 39, pp. 297-305.