UNIVERSITÀ DEGLI STUDI DI PALERMO

Meccanica dei Materiali e delle Strutture
Vol. 3 (2012), no.2, pp. 1-8
ISSN: 2035-679X
Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, Dei Materiali
DICAM

BI-STABLE FLOWS IN WIND PRESSURES ON VERY SLENDER CIRCULAR TOWERS: A STOCHASTIC DILEMMA ?

Francesca Lupi[*], Claudio Borri[*], Hans-Juergen Niemann[†]

[*] Dipartimento di Ingegneria Civile e Ambientale (DICeA)
Università degli Studi di Firenze
Via S.Marta 3, 50139 Firenze, Italy
e-mail: francesca.lupi@dicea.unifi.it; dir-criaciv@dicea.unifi.it

[†] Windingenieurwesen und Strömungsmechanik (WiSt)
Ruhr-Universität Bochum
Universitätsstraße 150, 44801 Bochum, Germany
e-mail: hans-juergen.niemann@rub.de

(Ricevuto 10 Giugno 2012, Accettato 10 Ottobre 2012)

Key words: Circular cylinders, bistable flow, wind pressures, Solar Updraft Towers.

Parole chiave: Cilindri circolari, flusso bistabile, pressioni indotte dal vento, Torri Solari.

Abstract. *The paper deals with an experimental evidenced stochastic property of wind induced pressures, which has been recently detected by analyzing slender (vertical) circular cylinders in turbulent flow. In the critical regime of Reynolds number it is well known that the transition of the boundary layer from laminar to turbulent conditions on an only one side of the cylinder produces an asymmetric and bistable flow condition. This phenomenon is very sensitive to the Reynolds number, turbulence in the flow and surface roughness on the cylinder. The paper shows that by applying a certain number of ring beams along the height of a finite length circular cylinder, a bistable flow can occur even at moderately high Reynolds numbers (> Re_{crit}). The case study of the investigation is a cylindrical shell for Solar Updraft Towers.*

Sommario. *L'articolo descrive una proprietà stocastica misurata sperimentalmente delle pressioni indotte dal vento su un cilindro circolare di lunghezza finita immerso in un flusso turbolento. E' noto in letteratura che nel regime critico del numero di Reynolds la transizione da strato limite laminare a turbolento può avvenire su un solo lato del cilindro, producendo un flusso asimmetrico e bistabile. Questo fenomeno è molto sensibile al numero di Reynolds, alla turbolenza del flusso e alla rugosità superficiale del cilindro. L'articolo mostra che posizionando un certo numero di anelli lungo un cilindro di lunghezza finita si induce un flusso bistabile anche a numeri di Reynolds moderatamente elevati (> Re_{crit}). Il caso di studio è un guscio cilindrico per torri solari a camino.*

1 INTRODUCTION

Circular cylinders represent a classic and widely studied topic in fluid-dynamics; the high dependence of the state of the flow on the Reynolds number (Re) has attracted the interest of many researchers for tens of years. However, the very high sensitivity of the state of the flow to many influencing parameters (beside Re, also turbulence of the flow, slenderness ratio, surface roughness, blockage, free-end effects…) together with the experimental difficulty in reproducing trans-critical conditions, produced a very large scatter of results in literature.

In the critical regime of Re the transition of the boundary layer to turbulent conditions is around the separation point and a bi-stable flow condition can occur (Schewe, 1983). That is an asymmetric effect on a perfectly symmetric body in smooth flow. The phenomenon is very sensitive to any disturbance of the flow, which is able to initiate reattachment on an only one side of the cylinder. This produces a laminar separation bubble on that side. It only occurs for a very narrow range of Re just before the critical value.

Civil engineering structures such as cooling towers are far beyond the critical regime. A wide investigation of wind effects on these large and thin concrete shells was performed in the past, both in the wind tunnel and in full-scale. Today, the experience on cooling towers is the base of the very recent wind tunnel investigation on challenging engineering structures for producing renewable energy: solar updraft towers.

Solar updraft towers are huge reinforced concrete shells (up to 1000-1500 m in height), stiffened along the height by stiffening rings. The latter have in important structural role, because they reduce the ovalling deformations of the cross-section and guarantee a better distribution of internal forces. During the experimental investigation in the wind tunnel, the ring beams along the height turned out to be responsible for a bi-stable flow condition, even far beyond the critical Re. The effect is completely stochastic and independent on any local distortion of the flow. In fact, the phenomenon has been cross-checked in two wind tunnels, at WIST-Ruhr University Bochum and CRIACIV-University of Florence. Although trans-critical conditions of Re are only achieved by surface roughness on the circular cylinder, it has not been detected, so far, any tendency for which the phenomenon should disappear at high Re.

2 BISTABLE FLOW AROUND CIRCULAR CYLINDERS - LITERATURE

The Reynolds number governs the transition from laminar to turbulent flow and this may generate, in certain conditions, an asymmetric and bistable flow even around symmetric structures which are sensitive to Reynolds effects, such as circular cylinders.

The discovery of the existence of a stable asymmetric pressure distribution around circular cylinders is very far in time. It was at first observed by Eisner in 1925 (Figure 1). Eisner measured mean pressure distributions around both sides of a circular cylinder and discovered a stable asymmetric pressure distribution in the critical range of the Reynolds number. The low and high pressure on the two sides of the cylinder interchanged in different runs. Because of that, this flow state was named bi-stable.

A clear explanation of the phenomenon was given by Schewe in 1983. He wrote: “The explanation lies in the behaviour of the boundary layer. A laminar separation bubble is formed as follows: after laminar separation, the transition from laminar to turbulent flow occurs in the detached boundary layer (shear layer) just downstream from the separation point. Turbulent flow gets more energy and is able to reattach. After reattachment of the boundary layer on the back of the cylinder, the separation is turbulent.” All of that occurs on an only one side of the cylinder. On the other side there is laminar separation. At higher Re, the pressure distribution becomes symmetric again, it means that the transition is completed also on the other side of the cylinder. In these conditions the drag coefficient reaches the minimum value at the critical Re.

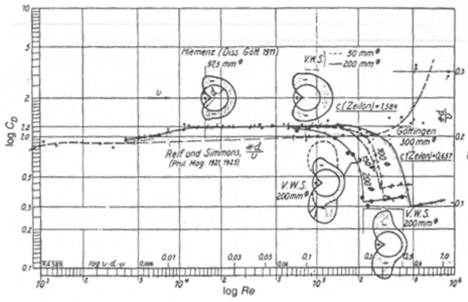


Figure 1: Asymmetric mean pressure distribution (Eisner, 1925).

This fluid dynamic phenomenon around isolated cylinders occurs in specific conditions, to which it is extremely sensitive. The phenomenon has a stochastic character. The process leading to the transition in the detached boundary layer (free shear layer) is initiated by perturbations or fluctuations in the boundary layer and the free stream. The occurrence of these perturbations is stochastic in space and time. The sign of the mean lift (created by the asymmetric pressure distribution) depends on the side where a perturbation sufficient to initiate the boundary layer transition first occurs (Schewe, 1983).

The asymmetric flow is only possible if there is a very low probability for simultaneous occurrence of perturbations on both sides of the cylinder, which would be able to initiate simultaneous formation of both bubbles, producing a symmetric condition. The asymmetric state is stable for a small range of Reynolds number immediately before Re_{crit}.

The width of the range of Reynolds where the asymmetric flow state is stable approaches zero if additional parameters, such as turbulence intensity of the free stream and surface roughness, are increased. In fact, on rough circular cylinders in turbulent flow, the extension of the critical range is reduced and mainly consists of a shift downstream of the separation point.

3 CASE STUDY

The investigation of the flow around a slender vertical circular cylinder of finite length was performed within a research on Solar Updraft Towers. These are huge and extremely thin shells, which produce renewable energy on the basis of solar radiation and the natural updraft of heated air. At the tower foot there is a big collector made of glass. Solar radiation heats the collector ground and consequently warms up the air inside the collector. The warm air rises up in the chimney and turns the turbines at the chimney foot. In the power conversion unit the kinetic energy of the flow is transformed into electric power. The working principle is sketched in Figure 2. Further information can be found in (Lupi, 2011).

Best locations for Solar Updraft Towers are the great deserts where the solar radiation input is high. The efficiency of the power plant depends on the height of the tower and the diameter of the collector (Schlaich, 2005). For example, the power of a plant with 1 km tower and 5 km collector is up to 200 MW. Higher values, even doubled, can be reached with 1.5 km tower and 7 km in collector diameter.

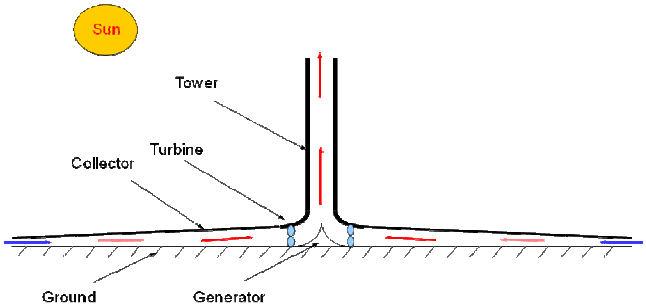


Figure 2: Working principle of Solar Updraft Towers.

Two design proposal are reported in Figure 3. In both cases the tower - which height is 1 km - is a cylindrical structure, eventually turning into a hyperboloid at lower levels like a huge cooling tower. The aspect ratio is around 1:7 or 1:8. Moreover, in both cases stiffening rings are applied along the height in order to reduce ovalling deformations of the shell and guarantee a beam-like behaviour.

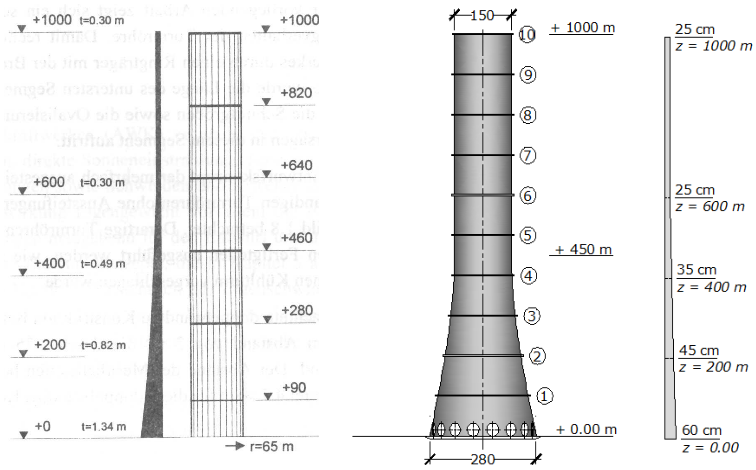


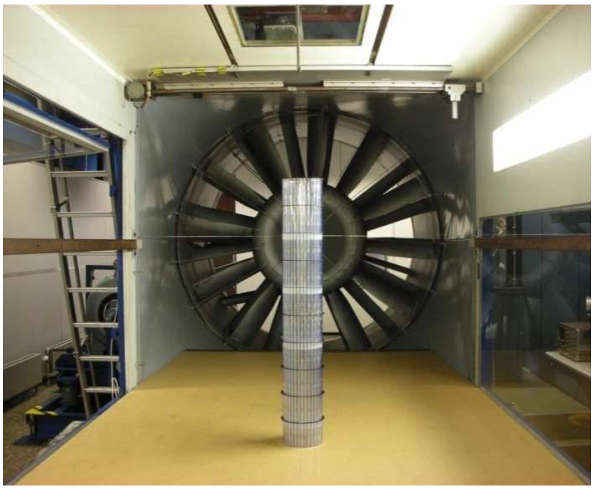
Figure 3: Design proposals of Solar Updraft Towers (a. Goldack, 2004; b. Kraetzig, 2008)

4 EXPERIMENTAL SET-UP FOR WIND TUNNEL TESTS

An extensive wind tunnel investigation has been recently performed at WiSt laboratory at Ruhr-University Bochum (Germany) and at Criaciv laboratory at University of Florence (Italy).

The model for wind tunnel tests represents a Solar Tower prototype of 1 km in height and 150 m in diameter in scale 1:1000. Although the real shape of the tower may turn into a hyperboloid at lower levels, the wind tunnel model is a circular cylinder. This shape, which makes the manufacturing much easier, allows the evaluation of the aerodynamic effects without any loss in generality.

The collector roof is modelled at WiSt as a very smooth panel. Its function in the wind tunnel is only the creation of a two-phase wind profile. The efflux inside the tower is not reproduced by means of the collector, but artificially by using the pressure difference outside-inside the wind tunnel. Tests are performed both with and without efflux in boundary layer flow. The no-efflux condition (out-of-use of the power plant) resulted to be the most representative for the following results and discussions about the bistable flow.



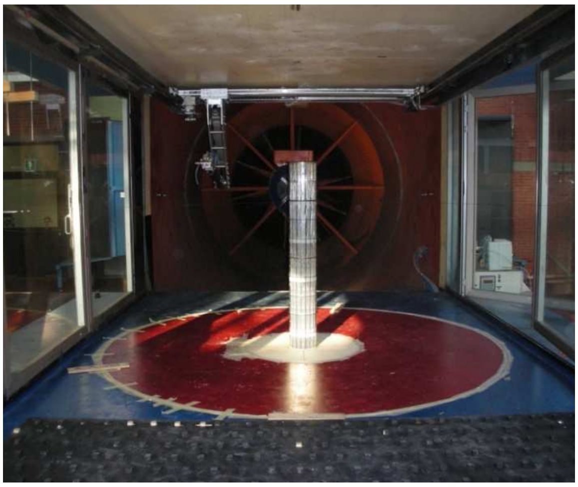


Figure 4: Wind tunnel tests on Solar Updraft Tower. a) WiSt boundary layer wind tunnel, Ruhr-University Bochum, Germany; b) Criaciv boundary layer wind tunnel, Florence, Italy

The tower model is a rigid body equipped with 342 pressure taps, placed at several levels along the height and at a spacing of 20° in the circumferential direction, in order to investigate vertical and horizontal cross-correlations. Both external and internal pressures are measured at each level.

The wind tunnel scale of the model and of the boundary layer properties reduces of around three orders of magnitude the Reynolds number from full-scale to wind tunnel conditions ($Re = UD/\nu$; $Re_{FS} = 50*150/1.5*10^{-5} = 5*10^{8}$; $Re_{WT} = 30*0.15/1.5*10^{-5} = 3*10^{5}$). Because of that, surface roughness (ribs) is applied along the model (Figure 5 a), in order to reproduce the same state of the flow as in full-scale. The target condition is described in the VGB guideline for cooling towers (curve K1.5-1.6). The final choice for the surface roughness is k/D = 0.25/150, being k (mm) the thickness of the ribs. The ribs are at an angular distance of 20°, i.e. in between two pressure taps. In any case, ribs are only applied in the scaled wind tunnel model because of Re effects, while the surface of the tower in full-scale conditions must be smooth in order to reduce the drag (Niemann, 2009).

Figure 5 a) b): Model of Solar Updraft Tower: application of surface roughness and stiffening rings.

Circular ring beams are applied along the height of the tower (Figure 5 b). Tests are performed both without and with rings. The size and the number of the rings resulted to be influencing parameters of the flow around the tower. Being w the width of the rings in mm (jutting out of the shell surface) and D the diameter of the tower, the following conditions were tested:

- w/D = 7/150 = $4.67*10^{-2}$; n. 10, 7, 5 rings along the height; with and without efflux;
- w/D = 3.5/150 = $2.33*10^{-2}$; n. 10, 7, 5 rings along the height; with and without efflux;
- no rings; with and without efflux;

Only results with 10 rings and w/D = 4.67*10-2 will be discussed in this paper.

5 RESULTS AND DISCUSSIONS

The presence of ten rings along the tower creates a bistable flow with jumps in the time-histories between two situations. These jumps occur in the pressures, as well as in the lift coefficient (Figure 6). Their occurrence is stochastic, as turbulence is.

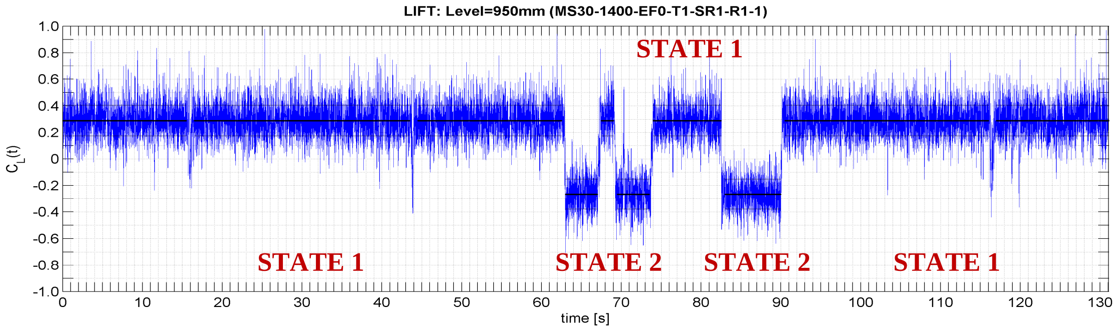


Figure 6: Bistable flow condition: lift coefficient in the tip region (z/H = 0.95)

The flow is not only bistable, but there is also an inversion of mean lift along the height, as shown in

Figure 7, which refers to the compartment below the ring placed at z/H = 0.9.

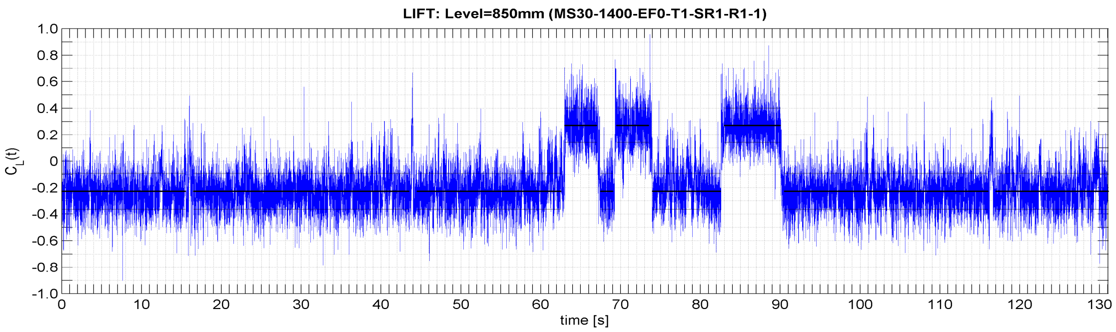


Figure 7: Bistable flow condition: lift coefficient in the tip region (z/H = 0.85)

An interesting feature is that the two states of the bistable flow are identical, just mirrored. The blue line in Figure 8 represents the mean pressure distribution during the state 1, while the pink line during the state 2. Such distributions are asymmetric. If state 2, for example, is mirrored, it perfectly superimposes the state 1 (Figure 9).

The asymmetry is presumably due to the formation, on an only one side of the cylinder, of a separation bubble. The effect on the pressures is the same as the case described in literature around Re_{crit}, but the conditions of occurrence are completely different. In this case the separation bubble cannot be in the classical sense, i.e. a laminar separation bubble. In fact, it is apparent that on a rough cylinder in turbulent flow the separation cannot be laminar.

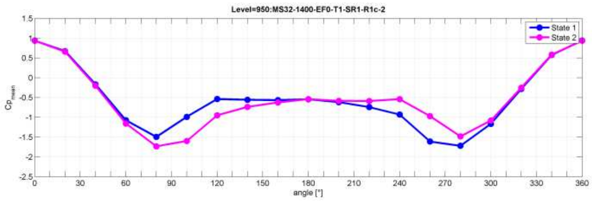


Figure 8: Asymmetric and bistable flow condition, 10 rings: state 1 (blue) and state 2 (pink). Cp,mean z/H = 0.95

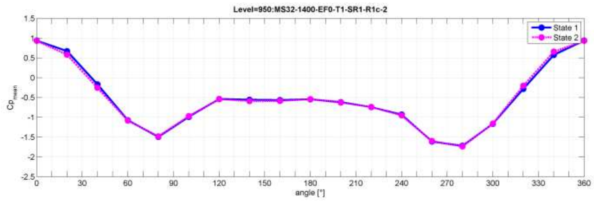


Figure 9: State 2 (pink) is mirrored and it superimposes the state 1: two mirrored, identical states.

A fundamental characteristic is that there is not a significant dependence on the Reynolds number, as it is, instead, in the well known case reported in literature. This is shown in Figure 10. Although trans-critical conditions of Re are only achieved by surface roughness on the circular cylinder, the data in the available range of Re have not suggested, so far, any reason for which the bistable flow should disappear at higher Re.

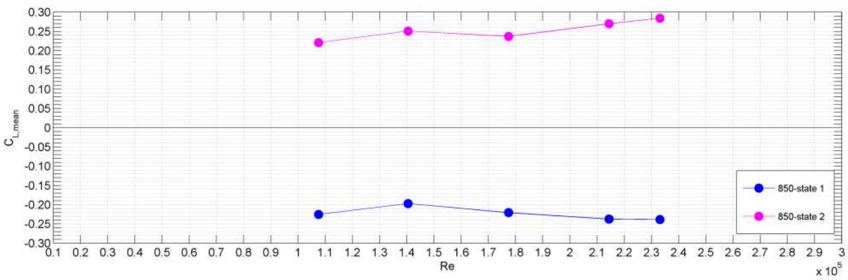


Figure 10: Mean lift coefficient in the two states as a function of Re (z/H = 0.85)

All the graphs shown up to now are referred to results measured in Bochum. The cross-check of results at CRIACIV wind tunnel has also excluded that the phenomenon could be induced by local conditions of a certain laboratory. The bistable flow occurs in the same manner, with jumps in the time histories, in the two wind tunnels. The differences in the standard deviations which can be detected by comparing Figure 6 and Figure 11 are related to the turbulence intensity.

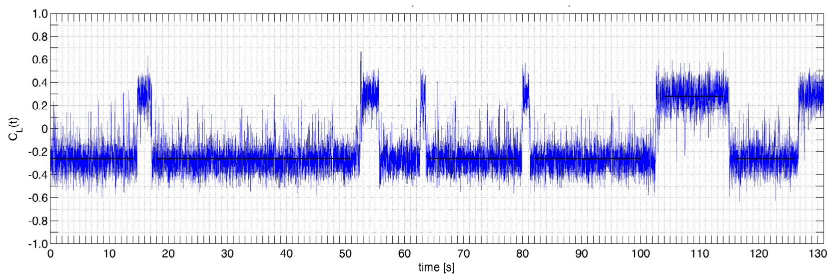


Figure 11: Bistable flow condition at Criaciv: lift coefficient in the tip region (z/H = 0.95)

6 CONCLUDING REMARKS

A bistable asymmetric flow condition around an isolated circular cylinder has been presented. The cylinder has a rough surface and it is immersed in boundary layer flow. 10 ring beams are placed along the height of the cylinder, equally spaced at a distance of 2/3 of the diameter. The effect does not disappear in the range of the Reynolds numbers which has been tested. The result is confirmed in two wind tunnels (WiSt and Criaciv).

7 REFERENCES

[1] F. Eisner, "Pressure measurements on cylinder surrounded by flowing fluid" (in German). *Zeitschrift fuer angewandte Mathematik und Mechanik*, **5**, 486-489, (1925).
[2] A. Goldack, "Tragverhalten und Aussteifung hoher Stahlbetonrohren fuer Aufwindkraftwerke" (Load-bearing behaviour and stiffening of high-rise RC-tubes for updraft power plants). Dissertation, University of Stuttgart, (2004).
[3] R. Harte, G.P.A.G. van Zijl, "Structural stability of concrete wind turbines and solar chimney towers exposed to dynamic wind action". *Journal of Wind Engineering and Industrial Aerodynamics*, **95**, 1079-1096, (2007).
[4] R. Harte, M. Graffmann, R. Wörmann, "Progress in the structural design of solar chimneys", SCPT2010, *Proc. 2nd Int. Conf. Solar Chimney Power Tech.*, Bochum, Germany, (2010).
[5] W.B. Krätzig, R. Harte, R. Wörmann, "Large shell structures for power generation technologies". *Proc. of the 6th Int. Conf. IASS-IACM*, Cornell University, Ithaca, NY, USA, (2008).
[6] W.B. Krätzig, R. Harte, U. Montag, M. Graffmann, "On structural engineering problems of solar updraft chimneys". *Proceedings of the 4th Int. Conf. Structural Engineering, Mechanics and Computation*, Cape Town, South Africa, (2010).
[7] F. Lupi, "Structural behaviour, optimization and design of a solar chimney prototype under wind loading and other actions". Master Thesis, University of Florence (within a cooperation with Ruhr University Bochum), (2009).
[8] F. Lupi, C. Borri, W.B. Krätzig, H.-J. Niemann, "Solar Updraft Power Plant technology: basic concepts and structural design". In *Encyclopedia Online of Life Support Systems* (EOLSS) developed under the auspices of the UNESCO, Eolss Publishers, Oxford, UK, (2011).
[9] F. Lupi, C. Borri, H.-J. Niemann, U. Peil, "Non-conventional wind loading on ultra-high Towers in Solar Updraft Power Plants", *Int. Journal of shell and space structures*, **52** (4), 257-264, (2011).
[10] H.-J. Niemann, R. Höffer, "Wind loading for the design of the solar tower". *Proceedings of the 3rd Int. Conf. Structural Eng., Mechanics and Computation*, Cape Town, South Africa, (2007).
[11] H.-J. Niemann, "A Refined Approach to Wind Loading for the Design of the Solar Tower", *CICIND Report*, **25** (2), (2009).
[12] H.-J. Niemann, F. Lupi, R. Höffer, W. Hubert, C. Borri. „The solar updraft power plant: design and optimization of the tower for wind effects". *Proceedings of the 5th European and African Conference on Wind Engineering* EACWE5, Florence, Italy, (2009).
[13] G. Schewe, "On the forces acting on a circular cylinder in cross-flow from subcritical up to transcritical Reynolds numbers", *Journal Fluid Mechanics*, **133**, 265-285.
[14] J. Schlaich, *The Solar Chimney, Electricity from the Sun*, Edition Axel Menges, Stuttgart, (1995).
[15] J. Schlaich, R. Bergermann, W. Schiel, G. Weinrebe, "Design of Commercial Solar Updraft Tower Systems - Utilization of Solar Induced Convective Flows for Power Generation", *Journal of Solar Energy Engineering*, **127**, 117-124 (2005)