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Basic Solar Chimney Flow Improvements

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Preliminary note

This paper deals with the numerical analysis procedure and results of flow simulation through solar chimney. Because of relatively low Reynolds numbers, some aerodynamic improvements could be obtained. The paper links input heat energy with geometry or air flow parameters. Basic solar chimney geometry is carried out and analyzed with CFD application in three dimensional domain. The main assumption is to reach the optimal fractional pressure drop across turbines and maximal electric energy production by solar chimney geometry adaptation. Results are numerically tested by known parameters and improvements are applied and tested. Various shapes of internal solar chimney geometry are applied and the best for given input parameters are extracted. Also, some external geometry shape solutions are investigated. Test includes comparison with the known measured air flow results in similar solar chimney (Manzanares, Spain). Results provided validate the assumptions and could be a base for further experimental investigations.

Osnovna unapređenja solarne dimnjačne elektrane

Prethodno priopćenje

U radu se opisuju numerički postupci i rezultati simulacije strujanja kroz solarnu dimnjačnu elektranu. Zbog relativno malih Reynoldsovih brojeva moguće je izvesti određena aerodinamička unapređenja. Rad povezuje vanjsku dovedenu toplinu s parametrima unutarnjeg strujanja. Osnovna geometrija solarnog dimnjaka izvedena je i analizirana pomoću CFD aplikacije u trodimenzijskoj domeni. Osnovna pretpostavka rada je povećanje efikasnosti postizanjem optimalnog pada tlaka kroz turbinu i najveće produkcije električne energije promjenom geometrije. Rezultati su numerički testirani i uspoređeni s poznatim parametrima uz primjenjena unapređenja. Izdvojeno je i analizirano više geometrijskih oblika unutrašnjosti solarnog dimnjaka. Isto tako mijenjani su i neki vanjski oblici. Testiranje dobivenog obavljeno je usporedbom s poznatim mjerenim vrijednostima sličnog izvedenog postrojenja (Manzanares, Španjolska). Usporedbe ukazuju na ostvarenje predviđenog poboljšanja efikasnosti i mogu biti baza za daljni eksperimentalni rad.

1. Introduction

There is a growth trend in the implementation of renewable energy sources in the whole world today. There are also significant investments into research and development of new concepts that are related to the production of electricity and also thermal energy. New concepts that produce electricity through the utilization of natural resources (solar and wind energy) are of special interest. One of these, also a relatively new concept of electricity production which transforms available solar insolation into useful turbine work is Solar Chimney power plant (SC). A group of German scientists, led by professor Schlaich, successfully developed the prototype at the SC plant in Manzanares (Spain) [1] of 50 kW nominal power, and also tested it in real conditions [2-4]. With gained experience from the prototype plant, there are plans to build the first commercial SC plant in the world with nominal power of 200 MW, [5] in the desert area of Australia (Mildura).

Until today a considerable number of papers that deal with the research in the field of SC plants have been written. A summary overview of the research in this field till 2003 was given in the Bernardes in [6]. Analysis of the theoretical and real cycle in the SC plants is especially interesting from the thermodynamical aspect. This kind of analysis can be found in papers [7, 8]. The analysis of flow conditions in SC power plants (especially the pressure drop factor over the turbines), depending

Symbols/Oznake

d_{ch}	- chimney diameter, m - promjer dimnjaka
D_{CO}	- collector diameter, m - promjer kolektora
$\mathbf{f}_b^{\mathbf{B}}$	- buoyancy force, N - sila uzgona
$\mathbf{f}_g^{\mathbf{B}}$	- gravitational force, N - sila teže
$\mathbf{g}$	- gravitational constant, m/s^2 - gravitacijska konstanta
h_{ch}	- overall chimney height, m - ukupna visina dimnjaka
h_{co}	- collector height (average), m - visina kolektora (srednja)
p	- absolute pressure, N/m^2 - apsolutni tlak
p_k	- kinetic pressure, N/m^2 - kinetički tlak
p_s	- hydrostatic pressure, N/m^2 - hidrostatički tlak
p_0	- pressure in x_0, N/m^2 - tlak u x_0
O_{sd}	- volume flow rate through standard diffuser, m^3/s - volumni protok kroz standardni difuzor
O_{sd}	- volume flow rate through reverse nozzle, m^3/s - volumni protok kroz reverznu sapnicu
v	- average air velocity, m/s - srednja brzina zraka
v_a	- axial air velocity, m/s - aksijalna brzina zraka
v_r	- radial air velocity, m/s - radijalna brzina zraka
∇p_s	- hydrostatic pressure change, N/m^2 - promjena hidrostatskog tlaka
η_T	- theoretical efficiency for turbomachines (Betz limit) - teoretska iskoristivost turbostrojeva (Betzov limit)
ρ	- density, kg/m^3 - gustoća

from the intensity of the solar insolation and also from the other influential parameters is given in papers [9, 10]. Possibility of the SC power plant implementation in other geographical regions (except the desert areas, where from the economic aspect the utilization of the SC plants is desirable) is given in papers [11-13]. There is also research which is related to the modification of the SC power plant concept in order to achieve higher overall efficiency (respectively higher electric power output) [14]. Investigations of blade number effect for a ducted wind turbine is given in [15].

The objective of this paper is to analyze the flow conditions in the SC power plants depending on the characteristic input parameters (plant geometry, material, solar insolation etc.) through the implementation of the CFD analysis. Derived conclusions will be useful for detection of weak points in SC plants from the aspect of the fluid flow.

2. The basic assumptions of flow through solar chimney

This paper gives the basic parameters that describe the flow through the solar chimney, as a first step of the analysis. There are two key parameters identified that affect efficiency, the pressure drop and air mass flow rate. Both are described in ref.[7].

Additional pressure drop is to be achieved without a significant increase in height of a chimney by flow through a nozzle. The nozzle is performed as diffuser and this improvement is described in [16]. Transformation of kinetic energy should be obtained through simple turbomachine. In this case, turbomachine – axial wind turbine - is located in the chimney pipe, in the same way as mounted in experimental plant. Thus solar chimney power plants with and without the proposed improvement can be compared. If this comparison certificates mentioned assumptions, it is possible to propose further investigations or experimental verification of such system.

The only thermodynamic parameter considered is the buoyancy of hot air as the dominant physical phenomena in this type of power converters. Other parameters are not directly taken into account (radiation, convection, conduction, etc.). This is possible because of the assumption that temperature differences through chimney sections are relatively small. The next simplification of constant air temperature inside the chimney is also a very rough assumption. Pressure difference from the entrance of the collector on the ground to exit from the chimney was taken as the standard atmospheric pressure drop for the observed height. Aerodynamical pressure drop within a sufficiently wide chimney should be ignored, according to Nizetic, ref. [9].

3. Assumptions for CFD analysis

As mentioned before, temperature differences through chimney sections are relatively small. Energy loss depends of fluid properties and flow. Therefore, comparison of some parameters in the energy equation can assess the importance of energy loss.

$$\frac{\text{losses}}{\text{convection}} \approx \frac{\mu V^*}{C_v D^* T^* L^*} = \frac{\text{Ec}}{\text{Re}},$$
$$\frac{\text{losses}}{\text{diffusion}} \approx \frac{\mu V^*}{kT^*} = \text{Pr} \cdot \text{Ec}, \tag{1}$$

where L^* length, T^* temperature, D^* density and V^* - velocity. Effect of losses can be ignored if both expressions have a very small value. For air **Pr** ≈ 0,7 i **Ec** ≈ **Ma** and if Mach is small (because **Re** is small in chimneys) losses can be ignored. Prandtl number can be 10^4 and ignoring it depends of Eckert and Reynolds numbers. Finally, when loss is ignored, then Eckert number is low and temperature is not connected with flow field. In the solar chimney stationary flow is assumed. At stationery flow, pressure becomes hydrostatic, balanced with gravitational force.

$$p = p_s = pg \cdot (x\text{-}x_0) + p_0, \tag{2}$$

where p_0 is pressure in $\mathbf{x}_0$. General, hydrostatic pressure p_s is always part of the absolute pressure p. Hydrostatic pressure is not associated with the velocity field and therefore hidden in the process of solving. In many flows, hydrostatic pressure is much higher than the kinetic pressure:

$$p_k = p\text{-}p_s, \tag{3}$$

In this case, the existence of hydrostatic pressure may cause instability in the numerical analysis. Therefore, it is recommended to take the kinetic pressure in the analysis instead of absolute pressure as a variable in the process of solving. This can be simple to implement, by removing the term hydrostatic pressure from the expression for gravitational force:

$$\mathbf{f}_b^{\,B} = \mathbf{f}_g^{B} - \nabla p_s = -\rho g \beta (\theta - \theta_0). \tag{4}$$

The term is called the buoyancy force. Kinetic pressure replaces the absolute pressure and the buoyancy force replaces the gravitational force. From above it can be concluded that numerical analysis should deal with air flow only, with temperature included in the material definition.

4. Steps of analysis

Basic analysis in this work is done with CFD application ADINA®. This application has an integrated preprocessor, processor and postprocessor with structure, thermal, CFD and FSI modules driven by user-friendly interface. The processor core has a Navier-Stokes solver. Therefore ADINA® is convenient for simple or preliminary CFD analysis of this kind. For this analysis, steady-state flow is assumed. Because of low **Re** number, flow regime is assumed as laminar. Fluid velocity gives us small Mach number (below 1/3 **Ma**) and incompressibility of the fluid is assumed, also.

A complex thermal transport has not been considered in this work, because the main analysis is based on the flow behavior. Therefore, flow is achieved with simple hot air heated in a solar chimney collector on average collector temperature (as well as in Manzanares).

There are several main steps in preprocessing of CFD analysis:

1. Model geometry,
2. Material definition,
3. Boundary conditions,
4. Load definition (velocity),
5. Discretization and mesh generation.

The geometry of a solar chimney is derived from two simple cylinders: collector cylinder and chimney cylinder, Figure 1. Both cylinders (chimney and collector) are rotational bodies and flow can be simplified as symmetric – first there is a radial flow in the collector, then axial flow in vertical chimney.

Because of the flow in three axis, the problem should be described as three dimensional. In CFD applications, this means 3D discretization and use of a considerable amount of computer memory and computing time. Therefore, some further simplification can be achieved by dividing the collector and chimney into quarters. At the quarter sides, slip flow conditions should be applied for velocities at the boundaries.

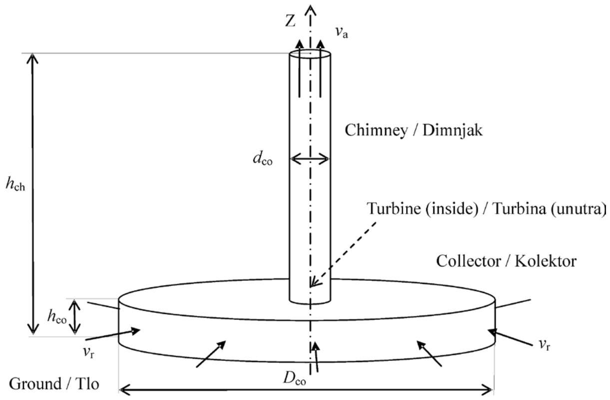

Figure 1. Basic types of flow through solar chimney: v_r radial air velocity and v_a axial air velocity.

Slika 1. Osnovna strujanja kroz solarni dimnjak: vr radijalna brzina zraka i va aksijalna brzina zraka.

Dimensions are taken from Manzanares real geometry:

Overall chimney height: h_{ch}=195 m,
Chimney diameter: d_{ch}=10 m,

Collector height: h_{co}=2 m,
Collector diameter: D_{co}=240 m.

Thus, a denser discretization grid should be achieved with the same computer performances as well as better results. The next step for denser grid gain is virtual shortening of the collector cylinder by radius and shortening of chimney by length (height). This can be possible by calculating velocity and pressure at corresponding radius for origin dimensions and then transferring them as boundary conditions on shorter model (quarter), ref.[10].

Figure 2. shows discretized one quarter of shortened SC, in which all computer power is concentrated around SC core – chimney inlet after collector, wind turbine closure.

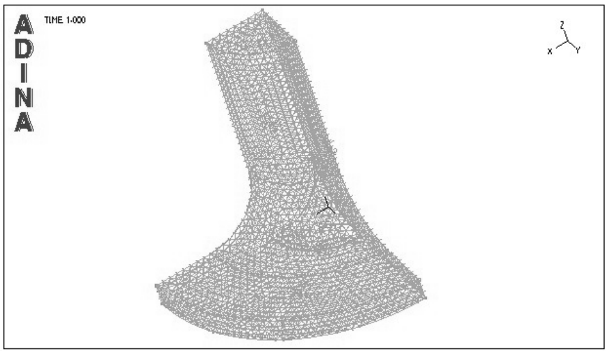

Figure 2. Discretized one quarter of shortened SC, 3D wind turbine closure.

Slika 2. Diskretizirana četvrtina solarnog dimnjaka, 3D okruženje vjetroturbine.

At the chimney bottom as in the Manzanares prototype plant, a basic aerodynamic improvement takes place: a simple coned transition from the radial flow through the collector to axial flow through the chimney. Thus some vortex generations should be prevented and a place for the generator set acquired (vertical axes). At the tip of the cone a wind turbine is set (the axial flow wind turbine). The cone is visible at the next Figure 3., where also calculated velocities are shown. At the top of the cone, in the vertical chimney inlet, the wind turbine is to be set. Wind turbine rotor is settled in horizontal X-Y plane.

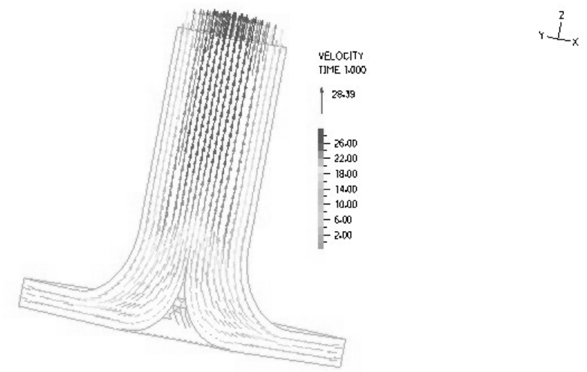

Figure 3. Calculated velocities in SC core (vortex prevented cone is visible).

Slika 3. Proračunate brzine u jezgri solarnog dimnjaka (vidljiv je stožac za sprječavanje vrtloženja).

Next Figure 4. shows velocity magnitudes in the whole wind turbine area. It can be seen that the boundary layer at the outer chimney boundaries grows constantly, dragging its origin from the collector inlet. On the wind turbine position, just over the cone in the middle of the SC, average air velocity is v=12 m/s. This value is close to velocity in real solar chimney. Figure 5. shows relative pressure field in the wind turbine area.

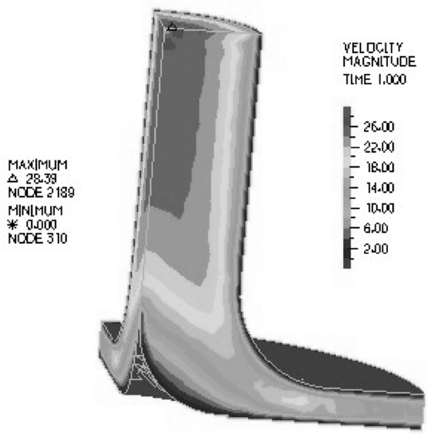

Figure 4. Velocity magnitudes in the wind turbine area.

Slika 4. Magnitude brzina u blizini vjetroturbine.

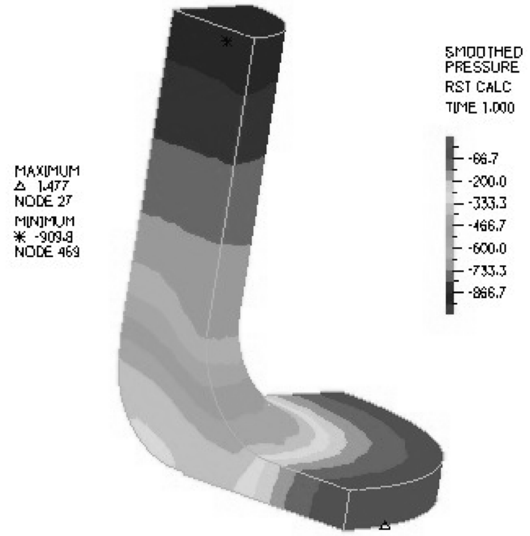

Figure 5. Relative pressure in the wind turbine area.

Slika 5. Relativni tlak u blizini vjetroturbine.

On the wind turbine the position field is not homogenous regarding horizontal X-Y plane (plane of the wind turbine rotor). Therefore some radial component of air flow on wind turbine blades can be expected. Thus more energy losses in turbomachine could occur, additionally reducing theoretical limit for turbomachines according to Alfred Betz (1920.), η_T=16/27.

5. Reversed nozzle in solar chimney

Differences of velocity in simple solar chimney in wind turbine plane are significant. Therefore some improvements should be made. Figure 6. shows nozzle or turbine diffuser in solar chimney according to Von Backström and Gannon, ref.[17], and proposed reverse nozzle concept [16].

The concept is based on contraction of air stream. Due to continuity law, velocity is higher in the narrow pipe than in the wide pipe for the same flow rate. The effect is the same in both nozzles, standard and bulb based diffuser, but difference occurs at turbomachine rotor blades. The main effect of reverse nozzle is to compress boundary layer and to provide as homogenous velocity and pressure field as possible, particularly in turbine plane, Figure 7.

For the same volume flow rate Q_{sd}=Q_{rd}, wind turbine rotor in standard diffuser has smaller dimensions than wind turbine in bulb based, reverse diffuser. Therefore, wind turbine blades are exposed to velocities with lower differences from the maximal to the minimal rotor radius. A simple chimney, without diffuser in wind turbine closure, as in Manzanares, has higher differences of velocities in the same plane.

Next Figure 8. shows basic velocity differences between three SC: simple pipe, diffuser and reverse nozzle (diffuser) type. The first two rotors have low rotational speed in the blade root, and the blade should be twisted more than at the third rotor. Lower velocities cause higher local pressure differences on blades as a consequence of aerodynamic forces.

Because of higher pressure differences, increased radial velocities along the blades should be expected. Therefore, for the second and third type of turbines, semi-cascade and cascade type rotors should be applied. These rotors have lower rotational speeds but higher torque than the first type. Because the flow through SC wind turbine is more uniform and constant than free area wind turbine, cascade rotors are a better solution.

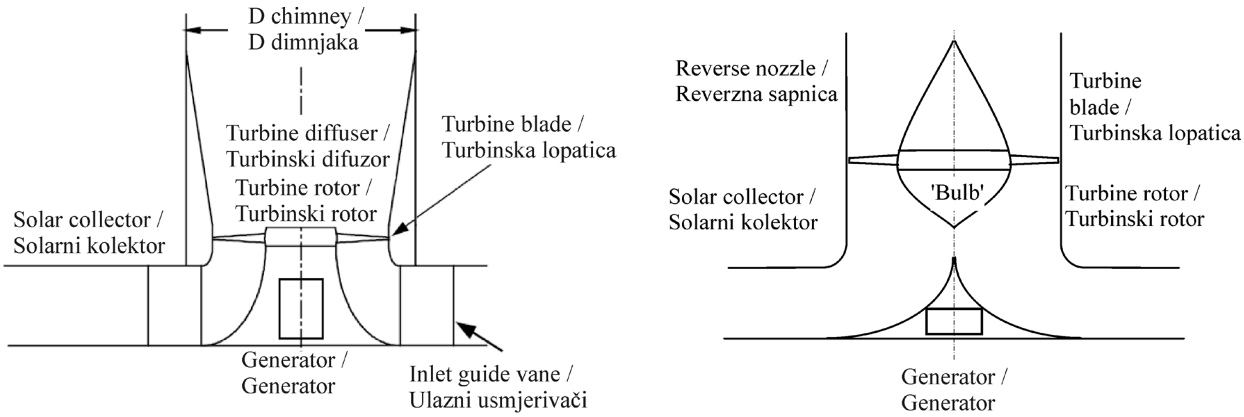

Figure 6. Nozzle (turbine diffuser) in chimney according to Von Backström and Gannon, ref.[17], and proposed reverse nozzle concept, ref.[16].

Slika 6. Sapnica (difuzor turbine) u dimnjaku prema Von Backström i Gannon, ref.[17] i predloženi koncept reverzne sapnice, ref.[16].

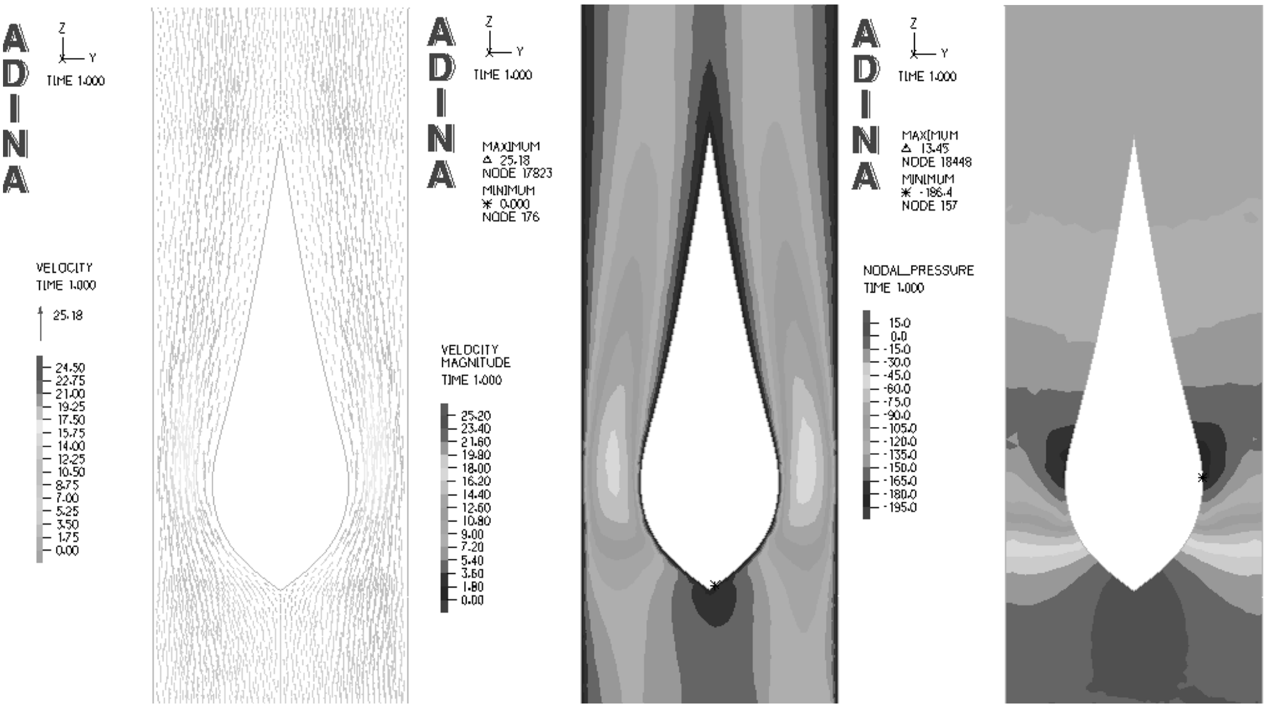

Figure 7. Velocity vectors around 'bulb', velocity magnitude and pressure field in 'bulb' closure.
Slika 7. Vektori brzina oko 'bulba', magnitude brzina i polje tlaka oko 'bulba'.

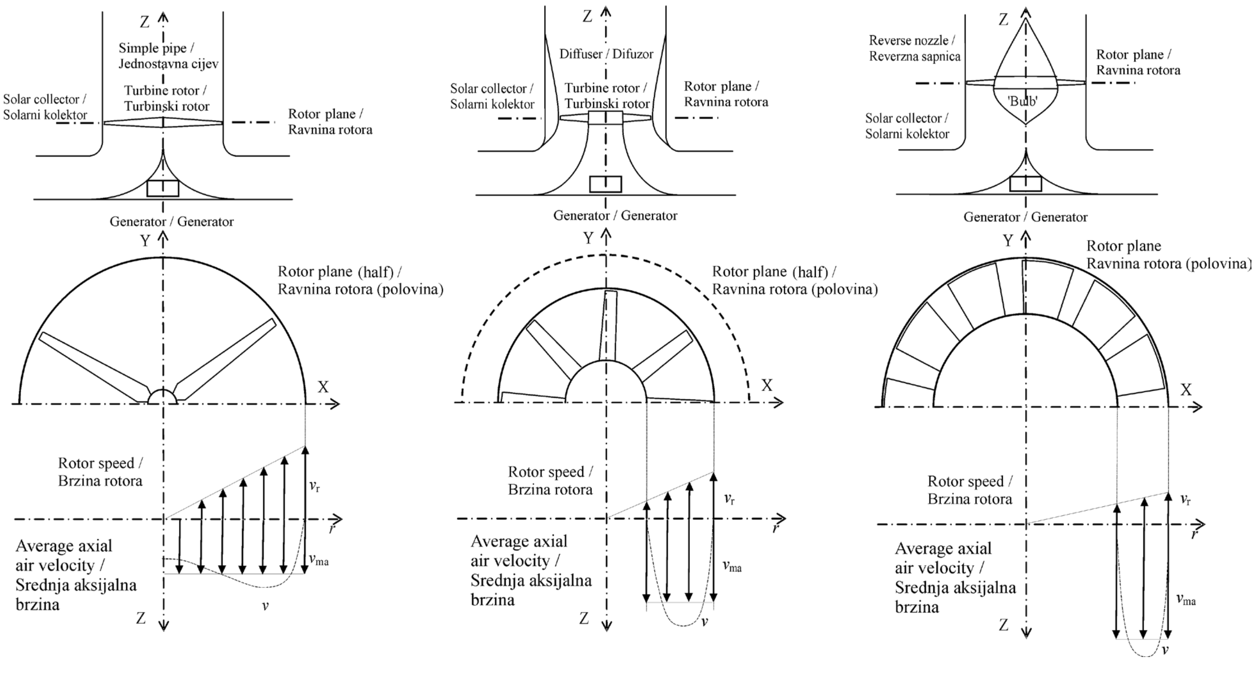

Figure 8. Basic velocity differences between simple pipe, diffuser and reverse nozzle/diffuser type SC.
Slika 8. Osnovne razlike brzina u jednostavnoj cijevi, difuzoru i reverznoj sapnici.

6. Analysis of the results

Results are provided with standard numerical accuracy of the N-S solver, relative 0,001 by default, with less than 30 iterations for attempt. From Figure 8 it is obvious that resultant wind speed at rotor blade inlet should vary along the radius causing twisting of the blades for this purpose. Most twisted blades belong to first type SC and less twisted to the third type as well as radial speed losses. Average axial velocity helps us in basic analysis but real velocity distribution along the blade is more complex as seen on interrupted line of real velocity distribution inside the chimney or flow area (qualitative assumption based on numerical results). Most uniform distributions of real velocities belong to third SC type. The next Figure 9 shows basic and relative axial and tangential velocities in wind turbine plane for a similar flow rate and power, from the chimney center (10-th position) to the chimney boundary (position 0).

Axial velocities belong to hot air in two chimneys: simple piped and with reversed nozzle. Reverse nozzle radial width is half of simple pipe radius.

Because of possible semi-cascade and cascade blades, with covered root and tip radius, shorter radial width and wide chord length, it is expected that wind turbine rotor in reversed nozzle should be less sensitive on radial losses of air than rotor blade of wind turbine in simple pipe.

As iswell known in turbomachinery, for internal flows cascade turbines are usually applied, while on open flows several blades are more often used. Even without thermal expansion, semi-cascade and cascade turbines are more efficient than turbines with several blades. Considering wind turbines, more blades provides higher power coefficient and torque coefficient at lower tip speed ratio than fewer blades and vice versa in closed flow, ref.[15]. Therefore, some optimization procedure should be developed for proposed improvements in future development.

7. Conclusions

With simplified CFD analysis several results are achieved. Cascade rotor provides more torque for the same power than axial wind turbine. This type of rotor is a better solution for flows with near constant flow as a solar chimney. On the other side, wind turbine is a better solution for open flows. Because solar chimneys are not widely used, more experience should be carried out in time as well as theoretical base. This paper is another step to further investigations. These investigations should take reversed nozzle into account as well as cascade wind turbine rather than simple pipe and wind turbine for open flows. Basic assumptions are analyzed and carried out with satisfactory results.

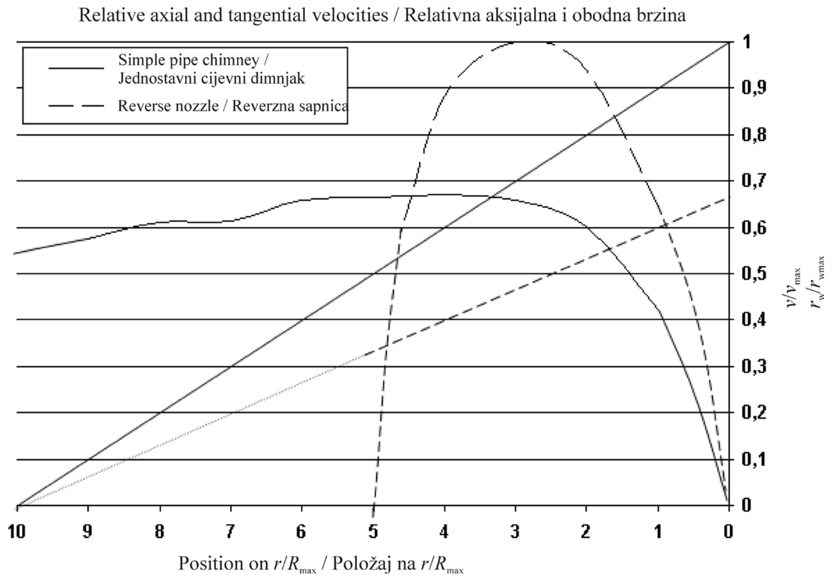

Figure 9. Relative axial velocities of hot air in chimney (lines) and tangential velocities of wind turbine rotors in wind turbine plane (curves).

Slika 9. Relativne aksijalne brzine vrućeg zraka u dimnjaku (pravci) i tangencijalne brzine vjetroturbinskog rotora u ravnini vjetroturbine (krivulje).

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