Strojniški vestnik - Journal of Mechanical Engineering 51(2005)3, 146-159
UDK - UDC 621.311.245:519.6
Kratki znanstveni prispevek - Short scientific paper (1.03)

Dvostopenjska vetrna turbina

A Double-Stage Wind Turbine

Vlado Schweiger - Brane Širok - Matija Tuma - Niko Mihelič

V prispevku je predstavljen postopek za povečanje izrabe energije vetra z uvedbo dvostopenjske nasproti se vrteče vetrne turbine. Teoretični aerodinamični izkoristek, poznan kot Betzova meja, se pri tem poveča iz 0,593 na 0,640. V nadaljevanju je predstavljen numerični model, s katerim je bila izdelana analiza tokovnih in energetskih lastnosti za eno- in dvostopenjsko vetrno turbino. Rezultati kažejo na dejansko povečanje izkoristka z vpeljavo druge stopnje, kar potrjuje smotrnost nadaljevanja študije.

(Ključne besede: turbine vetrne, turbine dvostopenjske, izkoristek aerodinamični, analize numerične)

In this paper we present an approach to increasing the wind-energy efficiency of a turbine by using a double-stage counter-rotating wind-turbine installation. The theoretical, aerodynamic efficiency, known as the Betz limit, is increased from 0.593 up to 0.640. A numerical analysis was made to establish the power and kinematic characteristics of single- and double-stage models. The results of the analysis show a significant increase in the aerodynamic efficiency with a second-stage installation. These results point toward the need for a further investigation of the double-stage model.

(Keywords: wind turbines, double-stage turbines, aerodynamic efficiency, numerical analysis)

0 UVOD

Izkoriščanje vetrne energije sega približno 3000 let v zgodovino. Do začetka sodobne industrializacije je bila kinetična energija vetra, poleg potencialne energije vode, pomemben vir mehanskega dela. S pričetkom izrabljanja fosilnih goriv, ki pomenijo stalnejši vir energije, je začel veter izgubljati pomen. Ob izbruhu energijske krize v sedemdesetih letih prejšnjega stoletja pa se je začel ponoven vzpon izkoriščanja te vrste energije. Proizvodnja električne energije iz kinetične energije vetra se je v zadnjem desetletju podvojila vsaka tri leta.

Problem kinetične energije vetra je njena nestalnost ter njena majhna gostota. Znano je, da je moč sorazmerna tretji potenci hitrosti vetra: podvojitev hitrosti vetra pomeni osemkratno povečanje moči, obenem pa se 10% nihanja hitrosti vetra kaže v 30% nihanju energije [1].

Znano je, da lahko kinetično energijo vetra, ki prehaja skozi vetrno turbino, izkoristimo le z 59,3% izkoristkom. Ta izkoristek, imenovan tudi

0 INTRODUCTION

The exploitation of wind energy goes back at least 3000 years. Until the beginning of modern industrialization, wind and water power represented the most important sources of mechanical energy. The exploitation of fossil fuels, which enabled a more steady source of energy, caused a decline in the use of wind energy. However, the energy crisis of the 1970s caused a renewed interest in using wind energy, and electricity production from wind energy has doubled every three years in the past decade.

The main problem with wind energy proved to be its unsteadiness and its low density. Wind power is proportional to the third power of the wind speed: a doubling of the wind speed results in eight times more power, while at the same time a fluctuation of 10% in the wind speed results in a 30% power fluctuation [1].

It is known that theoretically only 59.3% of the available wind energy that passes through a wind turbine can be used. That efficiency, known as the aerodinamični izkoristek vetrne turbine ali Betzova meja, je teoretična zgornja meja. Dejanski izkoristki so manjši, vendar se pri sodobnih izvedbah vetrnih turbin približujejo 50%. V obratovanju so vetrne turbine majhnih moči do 20 kW, ki so namenjene posameznim porabnikom, ter vetrne turbine do 4 MW moči, ki so povezane z javnim električnim omrežjem.

Z uvedbo druge stopnje vetrne turbine želimo izkoristiti preostalo kinetično energijo vetra, ki jo prva stopnja turbine ne predela. Izračun dvostopenjske vetrne turbine je predstavljen v [2], pri tem se teoretični aerodinamični izkoristek poveča na 64%. Z nadaljnjim povečevanjem števila stopenj se približujemo mejni vrednosti. Pri neskončnem številu stopenj znaša teoretični izkoristek 66% [3].

1 ENORAZSEŽNI MODEL ENO- IN DVOSTOPENJSKE VETRNE TURBINE

Model enostopenjske vodoravne vetrne turbine propelerskega tipa je bil izdelan na začetku 20. stoletja [5], dvostopenjska vetrna turbina pa je bila matematično obdelana šele v osemdesetih letih prejšnjega stoletja ([2] in [3]).

Oba modela sta enorazsežna in temeljita na naslednjih predpostavkah:

- tok je idealen in nestisljiv,
- hitrost vetra je ustaljena in homogena,
- hitrostno polje je v ravnini prereza vetrne turbine enakomerno,
- ni tokovnih motenj pred vetrno turbino in za njo,
- ni vrtenja toka zaradi vrtenja vetrne turbine,
- vrtenje same vetrne turbine ni upoštevano,
- pri dvostopenjski vetrni turbini ni upoštevan vpliv medsebojne oddaljenosti obeh stopenj.

1.1 Enostopenjska vetrna turbina

Model enostopenjske vetrne turbine prikazuje slika 1. Vetrna turbina je postavljena v "namišljeno tokovno cev", prek katere ni pretoka zraka. Ker je model poznan, so v nadaljevanju napisane le najpomembnejše enačbe, ki so potrebne za razumevanje in so namenjene kot izhodišče za dvostopenjsko vetrno turbino.

Namišljena tokovna cev se razširi od vstopa proti izstopu. Ta razširitev je posledica ohranjanja masnega toka skozi vetrno turbino. Zakon o ohranitvi mase:

Betz limit, represents the theoretical upper limit of the kinetic energy that can be extracted from the wind. Currently, the aerodynamic efficiency of wind turbines in operation is close to 50%. Nowadays, there are wind turbines up to 20 kW, which are intended for individual users, and large wind turbines, 30 kW up to 4 MW, which are connected to the electricity grid.

With the installation of a second stage we want to make use of the energy remaining after stage one. The theoretical approach to a double-stage wind turbine is presented in [2]. With a second stage installation the theoretical aerodynamic efficiency increases up to 64%. In theory, the aerodynamic efficiency of a wind turbine with an infinite number of stages reaches 66% [3].

1 ONE-DIMENSIONAL MODEL OF SINGLE- AND DOUBLE-STAGE WIND TURBINES

The well-known actuator-disc theory for an axial wind turbine was presented at the beginning of the 20th century [5]. The double-stage wind turbine was reported in the 1980s, ([2] and [3]).

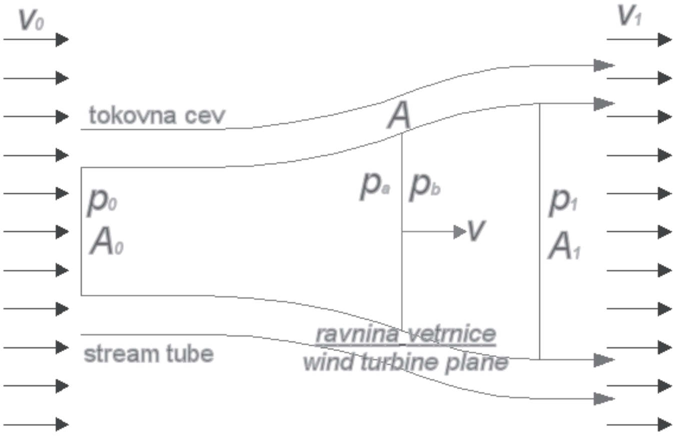
Both models are one-dimensional and are based on the following assumptions:

- the flow is ideal and incompressible,
- the wind speed is uniform and stationary,
- the flow field in the plane of the wind turbine is uniform,
- there is no flow disturbance upstream and downstream of the wind turbine,
- there is flow, with no rotation
- the wind-turbine rotation is neglected,
- the distance between the stages is not considered for a double-stage wind turbine.

1.1 Single-stage wind turbine

The one-dimensional model is presented in Fig.1. The wind turbine is placed in an imaginary stream tube, and there is no airflow over the stream-tube boundaries. The theory of the single-stage wind turbine has been known for 100 years; therefore, only the basic relations of the single-stage model that are needed for a further understanding of the double-stage wind turbine model are presented.

The stream-tube cross-section increased from the inlet towards the outlet region, the extension of the stream tube is a consequence of the mass conservation over the wind turbine. The equation of continuity can be written as follows:



Sl. 1. *Model enostopenjske vetrne turbine*
Fig. 1. *Single-stage wind-turbine model*

$$\rho A_0 v_0 = \rho A v = \rho A_1 v_1 \quad (1).$$

V lopaticah vetrne turbine se kinetična energija zraka spremeni v mehansko delo, hitrost zraka se pri tem zmanjša od v_0 na v. Sprememba hitrosti je podana s količnikom hitrosti a:

On the blades of the wind turbine the kinetic energy is transformed to mechanical energy. This transformation is caused by a velocity reduction from the inflow velocity v_0 to the velocity v. The reduction of the velocity is expressed by the retardation factor a:

$$a = \frac{v_0 - v}{v_0} \quad (2)$$

ali v urejeni obliki:

or in a settled form:

$$v = v_0(1-a) \quad (3).$$

Sila zaradi razlike hitrosti od začetne pred vetrno turbino v_0 do končne za vetrno turbino v_1 je:

The velocity reduction from the inlet velocity v_0 to the outlet velocity $v_1$results in a force:

$$F = \dot{m}(v_0 - v_1) = \rho A v (v_0 - v_1) \quad (4).$$

Ta sila nastane zaradi razlike tlakov pred ravnino vetrne turbine (indeks a) in za njo (indeks b). Ob predpostavki, da je tokovna cev v celoti obdana z atmosferskim tlakom, zaradi česar je rezultanta sil pred vetrno turbino in za njo enaka nič, dobimo:

The acting force is also a consequence of the pressure difference present on the wind turbine's plane. The stream tube is surrounded with atmospheric pressure; therefore, there is no resulting force on the stream tube. From this we have the following:

$$F = (p_a - p_b)A = \rho A v_0 (v_0 - v_1)(1-a) \quad (5),$$

$$F = (p_a - p_b)A = \frac{1}{2}\rho A (v_0^2 - v_1^2) \quad (6).$$

Povezava enačb (5) in (6) da hitrost za vetrno turbino:

Combining Equations (5) and (6) gives the downstream velocity:

$$v_1 = v_0(1 - 2a) \quad (7).$$

Teoretična moč vetrne turbine je enaka zmnožku sile F in hitrosti zraka v skozi vetrno turbino:

The wind turbine's theoretical power is the product of the force F and the velocity v of the air over the wind turbine's plane:

$$P = Fv = \rho A v^2 (v_0 - v_1) \qquad (8).$$

Povezava enačb (3), (7) in (8) da končni izraz teoretične moči vetrne turbine:

Combining Equations (3), (7) and (8) gives the final expression for the wind turbine's theoretical power:

$$P = 2\rho A {v_0}^3 a(1-a)^2 \qquad (9).$$

Teoretična moč vetrne turbine je enaka tudi razliki kinetičnih energij vetra pred vetrno turbino in za njo:

The theoretical power is also equal to the difference between the upstream and downstream kinetic energy:

$$P = \frac{1}{2}\rho A v (v_0^2 - v_1^2) \qquad (10)$$

pri tem je največja teoretična moč vetrne turbine dosežena pri pogoju: $v_0 = v$ in $v_1 = 0$:

The maximum theoretical power is achieved with $v_0 = v$ and $v_1 = 0$:

$$P_0 = \frac{1}{2}\rho A v_0^3 \qquad (11).$$

Aerodinamični izkoristek vetrne turbine je definiran kot razmerje med teoretično močjo in največjo teoretično močjo. Podan je s funkcijo:

The aerodynamic efficiency of a wind turbine is defined as the relation between the theoretical power and the maximum theoretical power:

$$\eta_V(a) = \frac{P}{P_0} = \frac{2\rho A v_0^3 a(1-a)^2}{\frac{1}{2}\rho A v_0^3} = 4a(1-a)^2 \qquad (12).$$

Z odvajanjem funkcije, enačba (12), po spremenljivki a ter izenačenjem odvoda z nič, dobimo:

The differential of function, Equation (12), with respect to a and setting the derivative equal to zero gives:

$$\frac{d\eta_V(a)}{da} = 4(1-a)^2 - 8a(1-a) = 4(1-a)(1-3a) = 0 \qquad (13).$$

Če vstavimo izračunano vrednost za hitrostni količnik a v enačbo (12), dobimo največji mogoči aerodinamični izkoristek vetrne turbine, imenovan tudi Betzova meja:

By inserting the obtained value for a into Equation (12), we obtain the maximum aerodynamic efficiency of the wind turbine, known as the Betz limit:

$$\eta_{V\max}\left(\frac{1}{3}\right) = 0{,}593 \qquad (14).$$

Vrednost a je omejena na območje:

a is limited on the next interval:

$$0 < a < 0{,}5 \qquad (15),$$

saj je pri $a = 0{,}5$ hitrost za ravnino vetrne turbine enaka nič, kar je v nasprotju z zakonom o ohranitvi mase.

With $a = 0.5$ the downstream velocity is equal 0, which is inconsistent with the continuity equation.

1.2 Dvostopenjska vetrna turbina

Pri enostopenjski vetrni turbini je optimalna hitrost za turbino enaka tretjini hitrosti pred njo. To pomeni, da je na voljo še nekaj kinetične energije vetra, ki bi jo bilo mogoče izkoristiti v naslednji stopnji. Druga turbinska stopnja je postavljena v osi za prvo, vendar oddaljena toliko, da je tok zraka v drugo stopnjo nemoten, kakor je prikazano na sliki 2. To omogoča ponovitev izračuna kakor je bil izveden za prvo stopnjo. Velikost druge stopnje vetrne turbine je enaka prvi stopnji, kar v splošnem ni nujno.

Analizo dvostopenjske vetrne turbine lahko obravnavamo z metodo superpozicije. Model razbijemo na dva dela in ju obravnavamo ločeno, na koncu pa zopet združimo. Pri dovolj veliki oddaljenosti med stopnjama je izstopna hitrost zraka iz prve stopnje enaka vstopni hitrosti v drugo stopnjo:

2.1 Double-stage wind turbine

For a single-stage wind turbine the downstream velocity is equal to 1/3 of the upstream velocity, which means that some of the remaining energy could be used in the next stage. The second stage is placed in the flow field behind the first stage, where the flow field is undisturbed, as shown in Fig. 2. This allows us to reuse the relations of the single-stage model. This is not consistent with the real conditions; in reality, both stages are close together. The second stage's cross-section is equal to the first stage's cross-section, but in general this is not necessarily the case.

In an analysis of a double-stage turbine it is assumed that every stage is analyzed separately and at the end both parts are merged together. With the distance between the stages large enough, the inflow velocity of the second stage is equal to the outflow velocity of the first stage:

$$v_1 = v_{02} = v_0(1-2a) \quad (16).$$

Hitrost v ravnini druge stopnje vetrne turbine se zmanjša za hitrostni količnik b, ki v splošnem ni enak hitrostnemu količniku a prve stopnje:

The velocity over the second stage's plane is reduced by a retardation factor b, which is not necessarily equal to the first stage's retardation factor a:

$$b = \frac{v_{02} - v_2}{v_{02}} \quad (17)$$

ali v urejeni obliki:

Or in a settled form:

$$v_2 = v_{02}(1-b) \quad (18).$$

Hitrost za drugo stopnjo vetrne turbine je:

The second-stage downstream velocity is:

$$v_{12} = v_{02}(1-2b) \quad (19).$$

Teoretična moč druge stopnje je enaka zmnožku sile F_2 in hitrosti pretoka zraka skozi drugo stopnjo v_2:

The second stage's theoretical power is a product of the force F_2 and the velocity v_2 over the second stage's plane:

$$P_2 = F_2 v_2 = \rho A_2 v_2^2 \left(v_{02} - v_{12}\right) \quad (20).$$

Povezava enačb (16), (19) in (20) da:

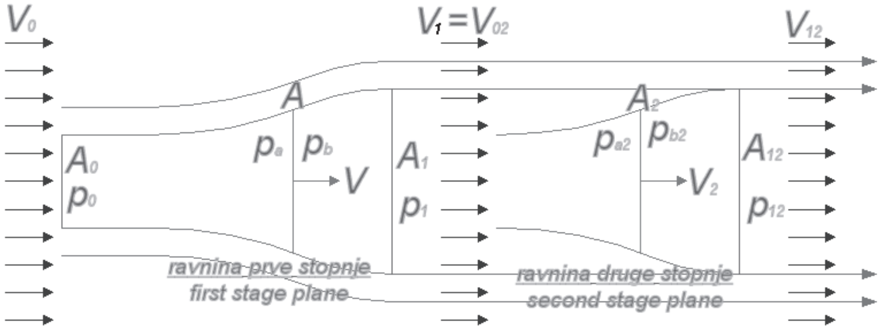
Combining Equations (16), (19) and (20) gives:

$$P_2 = 2\rho A_2 v_{02}^3 b(1-b)^2 = 2\rho A_2 v_0^3 (1-2a)^3 b(1-b)^2 \quad (21).$$

Tudi za drugo stopnjo velja, da je teoretična moč enaka razliki kinetičnih energij vetra pred vetrno turbino in za njo:

The second stage's theoretical power can be expressed as a kinetic energy difference:

$$P_2 = \frac{1}{2}\rho A_2 v_2 (v_{02}^2 - v_{12}^2) \quad (22),$$



Sl. 2. *Model dvostopenjske vetrne turbine*
Fig. 2. *Double-stage wind-turbine model*

pri tem je največja teoretična moč druge stopnje dosežena pri pogoju: $v_{02} = v_2$ in $v_{12} = 0$:

The theoretical maximum second-stage power assumes $v_{02} = v_2$ and $v_{12} = 0$:

$$P_{02} = 2\rho A_2 v_{02}^3 \qquad (23).$$

Aerodinamični izkoristek druge stopnje je definiran enako kakor izkoristek prve stopnje:

The second-stage aerodynamic efficiency is defined as follows:

$$\eta_{V2}(b) = \frac{P_2}{P_{02}} = \frac{\frac{1}{2}\rho A v_{02}^3 4b(1-b)^2}{\frac{1}{2}A_2 \rho v_{02}^3} = 4b(1-b)^2 \qquad (24).$$

Z odvajanjem funkcije, enačba (24) po spremenljivki *b*, ter izenačenjem odvoda z nič dobimo enačbo, ki je podobna enačbi (13). Tudi za drugo stopnjo velja Betzova meja:

Differentiating the of function, Equation (24), with respect to *b* and setting the derivative equal to zero gives an equation similar to Equation (12). The Betz limit is also valid for the second stage:

$$\eta_{V2\max}(b) = 0{,}593 \qquad (25)$$

in omejitev

And the limitation

$$0 < b < 0{,}5 \qquad (26).$$

Površina dvostopenjske vetrne turbine je enaka največji skupni površini obeh stopenj. Glede na to lahko zapišemo največjo teoretično moč:

The cross-section of the double-stage wind turbine is equal to the largest area of both stages. The maximum theoretical power can be written as follows:

$$P_0 = \frac{1}{2}\rho(A, A_2)_{\max} v_0^3 \qquad (27).$$

Skupni aerodinamični izkoristek dvostopenjske vetrne turbine, enačbe (9), (21) in (27), je podan z enačbo:

The double-stage wind turbine's total aerodynamic efficiency, Equations (9), (21) and (27), is as follows:

$$\eta_{Vtot}(a,b) = \frac{P + P_2}{P_0} = \frac{\frac{1}{2}\rho A v_0^3 4a(1-a)^2 + \frac{1}{2}A_2 v_0^3 (1-2a)^3 4b(1-b)^2}{\frac{1}{2}\rho(A, A_2)_{\max} v_0^3} \qquad (28).$$

S preureditvijo dobi enačba (28) končno obliko:

By manipulating Equation (28) we get:

$$\eta_{Vtot}(a,b)=\frac{1}{(A,A_2)_{\max}}=\left[4Aa(1-a)^2+4A_2(1-2a)^3b(1-b)^3\right] \qquad (29).$$

Aerodinamični izkoristek η_{Vtot} je odvisen od obeh hitrostnih količnikov (a, b) ter premera posamezne stopnje.

Za nadaljevanje je treba analizirati vpliv velikosti vetrne turbine na izkoristek η_{Vtot}.

$A_2 > A$ izraz $(A, A_2)_{\mathrm{maks}}$ je enak A_2. To ima za posledico povečanje P_0 in P_2. Povečanje P_0 pa je večje od prispevka drugega člena enačb (29) k skupni moči. Tako je skupni izkoristek manjši.

$A > A_2$ izraz $(A, A_2)_{\mathrm{maks}}$ je enak A. V tem primeru se povečata P_0 in P. Povečuje se prvi člen enačbe (29), ki prispeva največ k skupni moči, drugi pa se zmanjšuje. Tako je skupni izkoristek zopet manjši.

$A = A_2$, v tem primeru je aerodinamični izkoristek dvostopenjske vetrne turbine največji.

Enačba (29) je zvezna dvoparametrična funkcija. Za izračun optimuma funkcije je treba izračunati odvod funkcije po obeh spremenljivkah, tako po hitrostnem količniku a kakor hitrostnem količniku b:

The total aerodynamic efficiency η_{Vtot} is dependent on both the retardation factors (a, b) and the stage diameters.

For a further analysis the effect of the stage diameter on the total aerodynamic efficiency η_{Vtot} has to be determined.

$A_2 > A$, the expression $(A, A_2)_{\max}$ is equal to A_2. Consequently, the maximum theoretical power P_0 and the second-stage power P_2 both increase. The increase of P_0 is greater than the second-stage contribution and hence the efficiency is smaller.

$A > A_2$, The expression $(A, A_2)_{\max}$ is equal to A. The available power P_0 increases again, but consistently the power in the first stage also increases, which contributes most to the total power. The extracted power in the second stage falls, so the efficiency drops again.

$A = A_2$, The double-stage wind turbine's total aerodynamic efficiency reaches its maximum value.

Equation (29) is a function of the two variables. To obtain an optimum, a partial derivative with respect to both variables, the retardation factors a and b, has to be performed:

$$\frac{\partial\eta_{Vtot}(a,b)}{\partial a}=\frac{4A}{(A,A_2)_{\max}}\left[(1-a)^2-2a(1-a)^2\right]-\frac{24A_2(1-b)^2}{(A,A_2)_{\max}}(1-2a)^3 \qquad (30)$$

ter

and

$$\frac{\partial\eta_{Vtot}(a,b)}{\partial b}=\frac{4A_2}{(A,A_2)_{\max}}(1-2a)^3\left[(1-b)^2-2b(1-b)\right] \qquad (31).$$

Ob upoštevanju $A = A_2$ ter z izenačitvijo odvodov z nič, preideta enačbi (30) in (31) v obliko:

Considering $A = A_2$ and setting both derivatives equal to zero, the final form of Equations (30) and (31) is obtained:

$$\frac{\partial\eta_{Vtot}(a,b)}{\partial a}=4(1-a)^2-8a(1-a)^2-24(1-b)^2(1-2a)^3=0 \qquad (32)$$

ter

and

$$\frac{\partial\eta_{Vtot}(a,b)}{\partial b}=4(1-2a)^3\left[(1-b)^2-2b(1-b)\right]=0 \qquad (33).$$

Rešitev enačb (32) in (33) da optimalni vrednosti hitrostnih količnikov:

By solving the Equations (32) and (33) the optimum values for both retardation factors are obtained:

$$a_{opt}=\frac{1}{5} \quad \text{ter/and} \quad b_{opt}=\frac{1}{3} \qquad (34).$$

Pri optimalnih vrednostih obeh količnikov doseže izkoristek po enačbi (29) največjo vrednost:

The two values give the maximum of Equation (31), which is:

$$\eta_{Vopt}\left(\frac{1}{5},\frac{1}{3}\right)=\frac{16}{25}=0{,}64 \qquad (35).$$

Enak rezultat za teoretični aerodinamični izkoristek so predstavili tu drugi avtorji v [2] in [3], vendar z drugačnim postopkom.

Enorazsežna modela za eno- in dvostopenjsko vetrno turbino dasta informacijo o hitrosti za vetrno turbino, v_1, v delu, kjer se namišljena tokovna cev razširi. V primeru enostopenjske turbine znaša hitrost za vetrno turbino po enačbi (7) v optimalni točki tretjino vstopne hitrosti v_0. V primeru dvostopenjske vetrne turbine, pri kateri je dobljena večja teoretična moč vetrne turbine ter s tem večji aerodinamični izkoristek, mora biti hitrost v delu za drugo stopnjo še nekoliko manjša. S kombinacijo enačb (16), (19), ter (34) dobimo hitrost za drugo stopnjo dvostopenjske vetrne turbine v optimalni točki in znaša petino vstopne hitrosti v_0.

The result obtained is the same as in [2] and [3], but uses a different approach.

One-dimensional models of single- and double-stage wind turbines provide information about the velocity behind the wind turbine, v_1, in the part where the imaginary stream-tube cross-section increases. In the case of a single-stage wind turbine the downstream velocity at the optimum point is equal to 1/3 of the upstream velocity v_0. In the case of a double-stage wind turbine, which has a higher theoretical power and consequently a higher aerodynamic efficiency, an even lower downstream velocity is expected. Combining Equations (16), (19) and (34) gives the downstream velocity at the optimum operating point of the double-stage wind turbine, which is 1/5 of the upstream velocity v_0.

2 NUMERIČNA ANALIZA ENO IN DVOSTOPENJSKE VETRNE TURBINE

2 NUMERICAL ANALYSIS OF SINGLE- AND DOUBLE-STAGE WIND TURBINES

Za izračun je uporabljen paket za numerično modeliranje tokov CFX 5.6. Tehnični podatki o vetrni turbini so zbrani v preglednici 1 in 2.

The numerical analysis was made with CFX 5.6 software. The technical model data are given in Table 1 and Table 2.

Preglednica 1. *Tehnični podatki modela*
Table 1. *Model technical data*

R	400	*mm*
N	5	-
λ	6	-

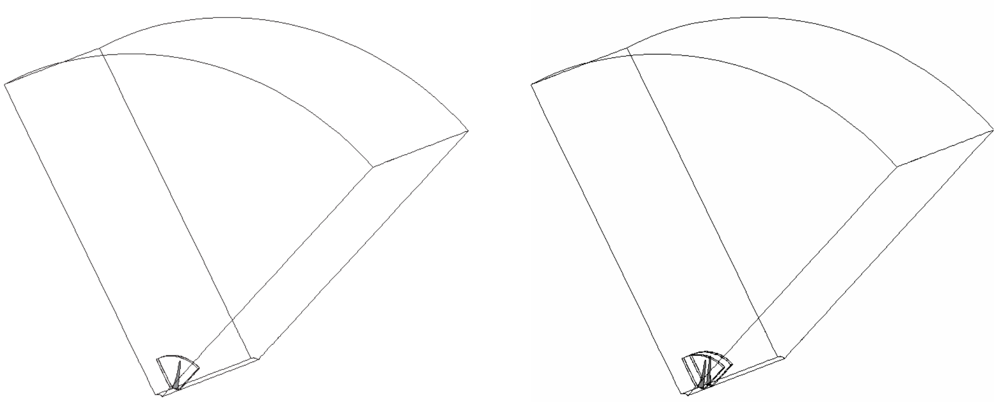
Premer R vetrne turbine in število lopat N sta enaka za enostopenjsko in dvostopenjsko izvedbo. Geometrijska oblika lopate vetrne turbine pa je določena s hitrostnim številom λ, ki je podano z enačbo:

Rotor radius and the number of rotor blades were equal in both cases. The tip speed ratio λ is a dimensionless number that defines the geometry of the wind-turbine blades:

$$\lambda = \frac{R\omega}{v_0} \qquad (36).$$

Preglednica 2. *Robni pogoji modela*
Table 2. *Model boundary conditions*

v_0	6	m/s
ρ	1,164	kg/m^3
ν	$1{,}824 \times 10^{-5}$	Ns/m^2



Sl. 3. *Geometrijsko topološki model eno- (levo) in dvostopenjske (desno) vetrne turbine*
Fig. 3. *Geometrical and topological models of single- (left) and double-stage (right) wind turbines*

Preglednica 3. *Število elementov ter vozlišč računske mreže*
Table3. *Number of mesh nodes and elements*

n	Okolica – Surrounding Elementov – Elements / Vozlišč – Nodes	Rotor – Rotor Elementov Elements / Vozlišč Nodes
1	120959/112140	121848/113370
2	137228/126756	121848/113370

Delovna snov je zrak pri 20°C in atmosferskem tlaku z nespremenljivo hitrostjo v_0. Spreminjajoč parameter je predstavljala kotna hitrost vetrne turbine ω.

Za modeliranje turbulence je bil uporabljen turbulentni model TSN (transport strižnih napetosti). Konvergenčni kriterij, ki mora zadostovati za zaključek izračuna, je podan z največjo dopustno napako 10^{-4}.

Geometrijsko topološki model enojne in dvojne izvedbe vetrne turbine je prikazan na sliki 3.

V obeh primerih je bila modelirana po ena lopata, torej krožni izsek 72°. Pri tem zajema okolica desetkratni polmer vetrne turbine. Pri eno- in dvostopenjski vetrni turbini je za vse dele opazovane prostornine uporabljena nestrukturirana šesterokotna mreža. Število vozlišč in elementov v posameznem delu računske mreže je podano v preglednici 3. V obeh primerih imata rotorja enako število vozlišč in elementov. V primeru okolice pa je število vozlišč ter elementov zaradi modeliranja razdalje med stopnjama nekoliko večje pri dvostopenjski vetrni turbini.

Slika 4 prikazuje porazdelitev tlakov pri eno- in dvostopenjski vetrni turbini. Iz porazdelitve je

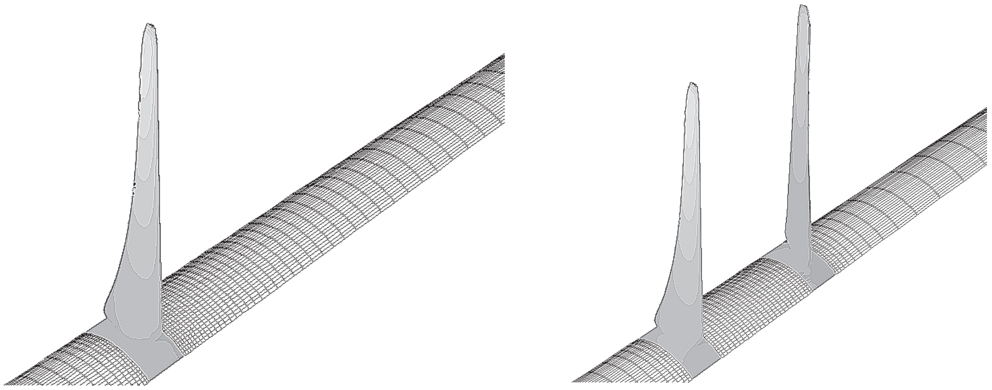
The working fluid is air at 20°C and atmospheric pressure with a constant inflow velocity v_0. The varying parameter was the wind turbine's angular velocity ω.

The turbulence was modeled with the turbulent model SST (Shear Stress Transport). The convergence criterion was set to 10^{-4} for maximum error.

The geometrical and topological models of the single- and the double-stage wind turbines are shown in Fig. 3.

Only one blade was modeled in both examples, representing 72° of the whole turbine. The turbine surrounding was ten times the rotor radius. An unstructured hexagonal mesh was used in both cases. The number of nodes and elements are given in Table 3. The rotor had the same number of nodes and elements in both examples. The surroundings had more nodes and elements in the case of the double-stage model due to the space between the stages.

Fig. 4 shows the pressure distribution on the turbine blades. There is almost no second-stage



Sl. 4. *Razporeditev tlakov na lopatici eno- in dvostopenjske vetrne turbine v optimalni obratovalni točki*
Fig. 4. *Static pressure distribution on the wing of the single- (left) and double-stage (right) wind turbine at the optimal operating point*

Preglednica 4. *Kotne hitrosti pri dvostopenjski vetrni turbini*
Table 4. *Double-stage angular velocities*

ω (s^{-1})	75				90				105			
ω_2 (s^{-1})	50	60	70	80	50	60	70	80	40	50	60	70

razvidno, da je medsebojni vpliv stopenj na tlačno porazdelitev na lopaticah najmanjši, saj se tako pri enojni kakor pri dvojni izvedbi porazdelitev statičnega tlaka na prvi stopnji skoraj ne razlikujeta.

Numerični izračun aerodinamičnega izkoristka je bil najprej izveden za enostopenjsko vetrno turbino, pri tem je bila kotna hitrost rotorja spreminjana od 60 do 120 s^{-1}. Izračun dvostopenjske vetrne turbine pa je izveden tako, da se prva stopnja vrti s stalno kotno hitrostjo ω, kotna hitrost druge stopnje ω_2 pa se spreminja, tako da je tudi v drugi stopnji dosežen optimum. Kombinacije kotnih hitrosti so zbrane v preglednici 4.

Rezultati simulacije so predstavljeni na sliki 5, na kateri je predstavljen tudi skupni aerodinamični izkoristek. Izračunani optimalni izkoristek enostopenjske vetrne turbine je 0,453. Z vgradnjo druge stopnje vetrne turbine, ki se vrti v obratni smeri, se ta izkoristek poveča na 0,517. Povečanje izkoristka gre na račun izrabe preostale kinetične energije vetra ter vpliva interakcije med obema rotorjema. Poleg navedenega povečuje vgradnja druge stopnje tudi relativno kotno hitrost med stopnjama.

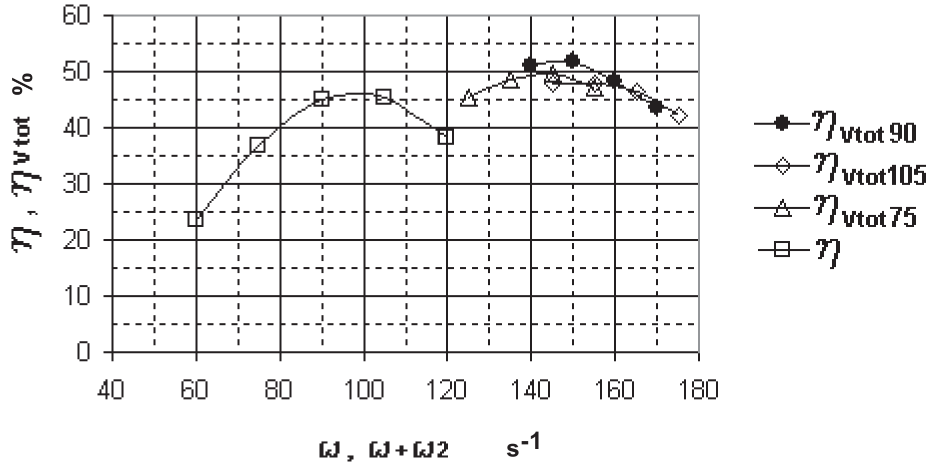
Na sliki 6 so prikazani vektorji vzdolžnih hitrosti za obema izvedbama vetrne turbine. Razvidno je, da so hitrosti v primeru dvostopenjske izvedbe manjše, kar kaže na dodatno spremembo energije

feedback influence on the first stage. This can be concluded from the almost identical static pressure distribution on the first-stage blade in both models.

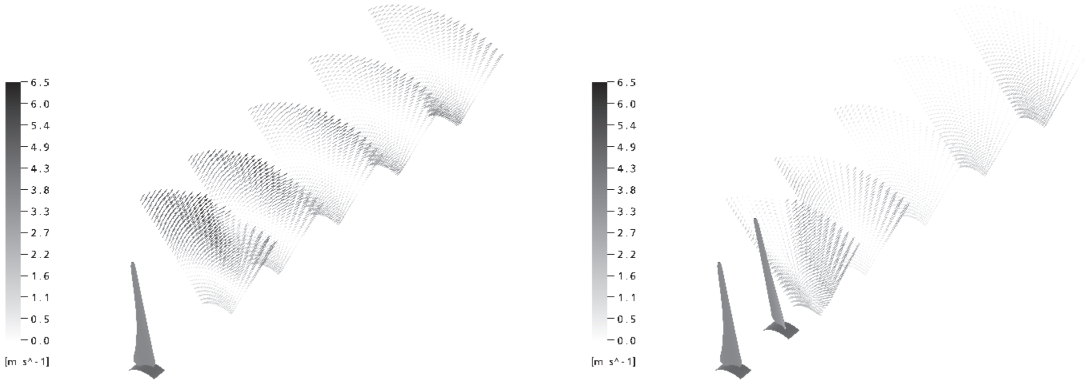
The aerodynamic efficiency was first calculated for the single-stage model. The varying parameter was the angular velocity, in the range from 60 to 120 s^{-1}. The simulation of the double-stage model was made with a constant first-stage angular velocity ω, while varying the second ω_2 until the second-stage optimum operating point was obtained.

The simulation results are presented in Fig. 5. The aerodynamic efficiency characteristic is presented for single- and double-stage models. The maximum calculated aerodynamic efficiency for a single-stage model is 0.453. With the installation of a second counter-rotating stage the maximum aerodynamic efficiency rises to 0.517. The second stage uses some of the kinetic energy left over from the first stage and so the total aerodynamic efficiency is increased. The installation of a second counter-rotating stage has the additional benefit of increasing the wind turbine's relative angular velocity (Fig. 5).

Fig. 6 shows the axial velocity vectors behind both wind turbines. It is evident that the axial velocity behind the double-stage wind turbine is smaller than the axial velocity behind the single-stage model, which indicates an additional energy



Sl. 5. *Aerodinamični izkoristek eno- in dvostopenjske vetrne turbine*
Fig. 5. *Aerodynamic efficiency characteristics of single- and double-stage wind turbines*



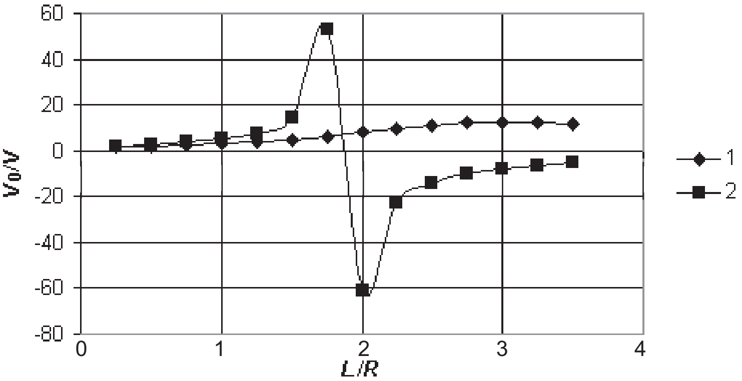
Sl. 6. *Vzdolžna hitrost za enostopenjsko (levo) in dvostopenjsko (desno) vetrno turbino.*
Fig. 6. *Axial velocity behind a one-stage (left) and two-stage (right) wind turbine*

vetra v drugi stopnji vetrne turbine. Ocena zmanjšanja hitrosti za obema izvedbama vetrne turbine v optimalni točki je prikazana na sliki 7.

Prikazana je odvisnost površinsko povprečene vzdolžne hitrosti (normirane na v_0), na enakih prerezih vzdolž okolice, od oddaljenosti od stopnje za vetrno turbino (normirane na polmer vetrne turbine R). Prerezi so pri obeh izvedbah vetrne turbine enaki, in sicer zajemajo površino krožnega izseka s polmerom vetrne turbine (R = 400 mm). Iz analize tokovnega polja z obema izvedbama vetrne turbine, slika 6 in 7, izhaja, da pride v primeru dvostopenjske vetrne turbine do občutnega zmanjšanja vzdolžnih hitrosti, kar kaže na večjo izrabo kinetične energije vetra in s tem na večji aerodinamični izkoristek

transformation in the second stage. Quantitative results of the velocity reduction behind both wind turbine models at the optimum operating point are shown in Fig 7.

Fig. 7 shows the area-averaged axial velocity (normalised to v_0) depending on the distance behind the wind-turbine stage (normalised to the wind-turbine radius R). The average cross-sectional areas are equal in both models, they capture an area equal to the circular section area with the wind-turbine radius (R = 400 mm). The velocity field analysis behind both models shows, Fig. 6 and Fig. 7, a significant axial velocity reduction that occurs in the case of the double-stage model, which points to greater usage of the wind's kinetic energy and



Sl. 7. *Zmanjšanja hitrosti za vetrno turbino*
Fig. 7. *Velocity reduction behind a wind turbine*

dvostopenjske vetrne turbine. V primeru dvostopenjske vetrne turbine je zmanjšanje hitrosti tolikšno, da pride do povratnih tokov, vrtinčenja, za vetrno turbino, kar je razvidno s slike 7, razmerje v_0/v na določenem mestu spremeni predznak.

3 SKLEPI

Raziskana je bila eno- in dvostopenjska vetrna turbina z nasprotno vrtečima se rotorjema.

Enostopenjska izvedba doseže teoretično največji aerodinamični izkoristek 16/27 = 0,593 (Betzova meja), medtem ko doseže dvostopenjska izvedba v teoriji največji skupni izkoristek 16/25 = 0,64.

Izvedena je bila numerična analiza eno- in dvostopenjske vetrne turbine, pri čemer je bila razdalja med obema stopnjama manjša od zahteve pri teoretičnem izračunu, pri katerem je predpostavljen nemoten tok zraka iz prve v drugo stopnjo.

Izračunan je bil aerodinamični izkoristek 0,453 pri enostopenjski izvedbi in 0,517 pri dvostopenjski. Povečanje skupnega izkoristka dvostopenjske vetrne turbine gre na račun izrabe preostale kinetične energije vetra za prvo stopnjo.

Nadaljnje raziskovalno delo bo usmerjeno v eksperimentalno preverjanje dobljenih rezultatov numeričnega modela in eksperimentalno-parametrično analizo geometrijskih in kinematskih parametrov dvostopenjske vetrne turbine.

consequently to a higher aerodynamic efficiency. In the case of a double-stage wind turbine the velocity reduction is so high that back flow occurs, as shown in Fig. 7, where the relation v_0/v at a certain point changes from a positive to a negative value.

3 CONCLUSIONS

Single- and double-stage counter-rotating wind turbines were investigated.

In theory a single-stage wind turbine has a maximum aerodynamic efficiency of 16/27 = 0.593 (the Betz limit). A double-stage wind turbine has a maximum aerodynamic efficiency of 16/25 = 0.64.

A numerical analysis of both modes was performed. In the theoretical model an undisturbed flow between the stages was assumed. In the numerical double stage the model distance between the stages was smaller than theoretically demanded.

Numerical results show an aerodynamic efficiency of 0.453 in the single-stage model and 0.517 in the double-stage model. The increase in the aerodynamic efficiency in the double-stage model is a consequence of the additional power extraction from the wind's kinetic energy behind the first stage.

Further investigations will include an experimental confirmation of the numerical results and an experimental-parametric analysis of the geometric and kinematic parameters of a double-stage counter-rotating wind-turbine model.

4 OZNAKE
4 SYMBOLS

prerez vetrne turbine	A	m^2	wind-turbine cross-section
hitrostni količnik prve stopnje	a	-	first-stage retardation factor
hitrostni količnik druge stopnje	b	-	second-stage retardation factor
sila	F	N	force
razdalja, oddaljenost	L	m	distance
število lopat	N	-	number of blades
število stopenj	n		number of stages
moč	P	W	power
tlak	p	Pa	pressure
polmer vetrne turbine	R	m	wind-turbine radius
hitrost	v	m/s	velocity
izkoristek	η	-	efficiency
hitrostno število	λ	-	tip-speed ratio
gostota zraka	ρ	kg/m^3	air density
kinematična viskoznost	ν	Ns/m^2	kinematic viscosity
kotna hitrost	ω	1/s	angular velocity

Indeksi		**Indexes**
tik pred vetrne turbino	a	just in front of the wind turbine
tik za vetrno turbino	b	just behind the wind turbine
največji	max	maximum
med stopnjama	s	between stages
skupni	tot	total
pred vetrno turbino	0	in front of the wind turbine
za vetrno turbino	1	behind the wind turbine
druga stopnja	2	stage two

5 LITERATURA
5 REFERENCES

[1] Ackerman, T., L. Soder (2002) An overview of wind energy status 2002, *Renewable & Sustainable Energy Reviews*, 67-128, June 2002.

[2] Neman, B.G. (1983) Actuator-disc theory for vertical-axis wind turbine, *Journal of Wind Energy And Industrial Aerodynamics,* Volume 15, Issue 1-3, 347-355, December 1983.

[3] Neman,B.G. (1986) Multiple actuator-disc theory for wind turbines, *Journal of Wind Energy And Industrial Aerodynamics*, Volume 24, Issue 3, 347-355, October 1986.

[4] Izumi Ushiyama,Toshihiko Shimota, YukihiroMiura (1996) An experimetal study of the two staged wind turbines, *Renewable Energy*, Volume 9, Issue 1-4, 909-912, September-December 1996.

[5] Burton, T., D. Sharpe, N. Jenkins, E. Bossanyi (2001) Wind energy (handbook), *John Willey & Sons Ltd*, England.

Naslova avtorjev: Vlado Schweiger
Turboinštitut
Rovšnikova 6
1000 Ljubljana
vlado.schweiger@turboinstitut.si

prof.dr. Brane Širok
prof.dr. Matija Tuma
Niko Mihelič
Fakulteta za strojništvo
Univerze v Ljubljani
Aškerčeva 6
1000 Ljubljana
brane.sirok@fs.uni-lj.si
matija.tuma@fs.uni-lj.si

Authors' Addresses: Vlado Schweiger
Turboinštitut
Rovšnikova 6
1000 Ljubljana, Slovenia
vlado.schweiger@turboinstitut.si

Prof.Dr. Brane Širok
Prof.Dr. Matija Tuma
Niko Mihelič
Faculty of Mech. Eng.
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia
brane.sirok@fs.uni-lj.si
matija.tuma@fs.uni-lj.si

Prejeto:
Received: 24.5.2004

Sprejeto:
Accepted: 2.12.2004

Odprto za diskusijo: 1 leto
Open for discussion: 1 year