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Evaluation of the DWF

Aerodynamics
Review

Aerodynamic evaluation of the principle of the DWF

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1 Introduction

In this report the evaluation and review of the presented report of the Dynamic Wind Fence (DWF) is presented. This is done on the contractual agreement AMBL 122-18 Rev. A between aerodyn Energiesysteme GmbH and the DWF lab. Objective of this report is the review and verification of the presented aerodynamic calculations "DWF Aerodynamic Calculations2.pdf" of the Dynamic Wind Fence. The Input, additional information and calculations can be found in the data file "Evaluation of the DWF-data file" (Doc. No. see page two). The general principle was checked and some discussion points are presented.

As no page numbers were provided, it was decided to define the page after the cover sheet as page number one.

2 General principle functionality

Looking at the one row turbine with the optimal stagnation according to Betz (a=1/3) we fairly agree with the calculations, observations as well as assumptions done in the report. The procedure is similar to the BEM method used for modern horizontal wind turbines. However, adding the second row of the fence to the turbine the calculations get more complex. The proposed procedure and concept is outstanding and innovative, aiming to reduce the losses of the modern horizontal axis wind turbines. As the DWF concept is a new and so far not well known concept, not much theory and research exists. The second row, and especially the distance between the two rows, makes the verification more difficult. However, so far only a simplified approach has been considered, taking losses due to downwash and blade efficiency into consideration, but neglecting the losses in the downwash due to vortices produced by the first row.

3 Agreements and Clarifications

To prevent misunderstanding, some terms are defined and the general theories are presented.

3.1 Definition of Terms

3.1.1 Lift to drag ratio

For aerodyn, the lift to drag ratio is defined as the ratio of the lift coefficient to the drag coefficient of a two dimensional cross section of an airfoil. It assumes an infinite aspect ratio and does not take into account any losses at the tip or the root of the blades. The lift to drag ratio is depending on the Reynolds number, with typically favourable lift to drag ratios at higher Reynolds numbers.

3.1.2 Aspect Ratio

The aspect ratio is a purely geometric parameter. It describes the ratio of the span wise length of blade or wing to the chord length. It can have an influence on the forces acting on a blade or wing, as losses at the tip or root can be relatively decreased for an increasing aspect ratio.

3.1.3 Blade efficiency

The blade efficiency is defined as the ratio of the forces at the wing acting in the direction of the lift to the forces at the wing acting in the direction of the drag. The blade efficiency includes the losses at the tip and the root and should not be mixed up with the lift to drag ratio of a two dimensional cross section. The blade efficiency might be influenced by the aspect ratio, as described before. The DWF lab defined the blade efficiency as the "wing lift to drag ratio". As we understood, a blade efficiency of 10 was used to take into account the losses at the tip. This might be low but seems to be a good value for first rough calculations and estimations. The blade efficiency is described by the parameter k in this report.

3.1.4 Global and local axial induction factor

In this report the terms "local" and "global" (axial) induction factor are used. The "global" induction factor is used in the report of the DWF lab and describes the relative amount of the stagnation of the global wind speed V_∞ far in front of and far behind the rotor. Another way to define the stagnation is the "local" induction factor which describes the relative amount of the stagnation of the inflow wind of each actuator. The differences of the wind speeds can be seen in Table 3-1. The subscript are defining, whether the induction is defined global "g" or local "l". For the first row the local induction factor is the same as the global induction factor, because the inflow wind speed is the same as the global wind speed V_∞. For the second row however the local induction factor refers to the outflow of the first row $V_{1_{out}}$ not the global wind speed V_∞.

	Far in front of the turbine	Stagnation of 1st row	Stagnation of 2nd row
global, $a_{1_g} = \frac{1}{6}, a_{2_g} = \frac{1}{6}$	V_∞	$V_\infty * a_{1_g}$	$V_\infty * a_{2_g}$
local, $a_{1_l} = \frac{1}{6}, a_{2_l} = \frac{1}{5}$	V_∞	$V_{1_{stag}} = V_\infty * a_{1_l}$ $V_{1_{out}} = V_\infty * (1 - a_{1_l})$ $= V_\infty - V_{1_{stag}}$	$V_{2_{stag}} = V_{1_{out}} * a_{2_l}$

Table 3-1 Wind speeds for the DWF concept with local and global inductions

To prevent confusion and mistakes, the previously defined terms will be used in this report.

3.2 Theories

Some theories will be presented in the following, which are needed for the further discussion of the results.

The basic theory is the Betz theory, which states a maximal power coefficient of 16/27 for a single row wind energy converter. This power coefficient is achieved for an induction of a=1/3. The wind speed in the wake behind the turbine is then decreased by the factor $(1 - 2a)$. If a second wind turbine is put far behind the first turbine, so that the wind speed has recovered completely to the free stream velocity, one can theoretically extract a maximum of two times the maximal power coefficient of Betz. In Figure 3-1 one can find a graphical representation of the maximal power coefficient that is possible for the different theories and the corresponding wind speed of a one row turbine. The Betz limit is marked by the "B1", while the concept of two turbines with a far distance between them is named "B2". As it can be seen in Figure 3-1, the wind is decreased to $V_0(1 - 2a)$ in the wake and then recovers to the freestream wind speed far behind the first turbine, which makes it possible to extract twice the maximal possible power according to Betz.

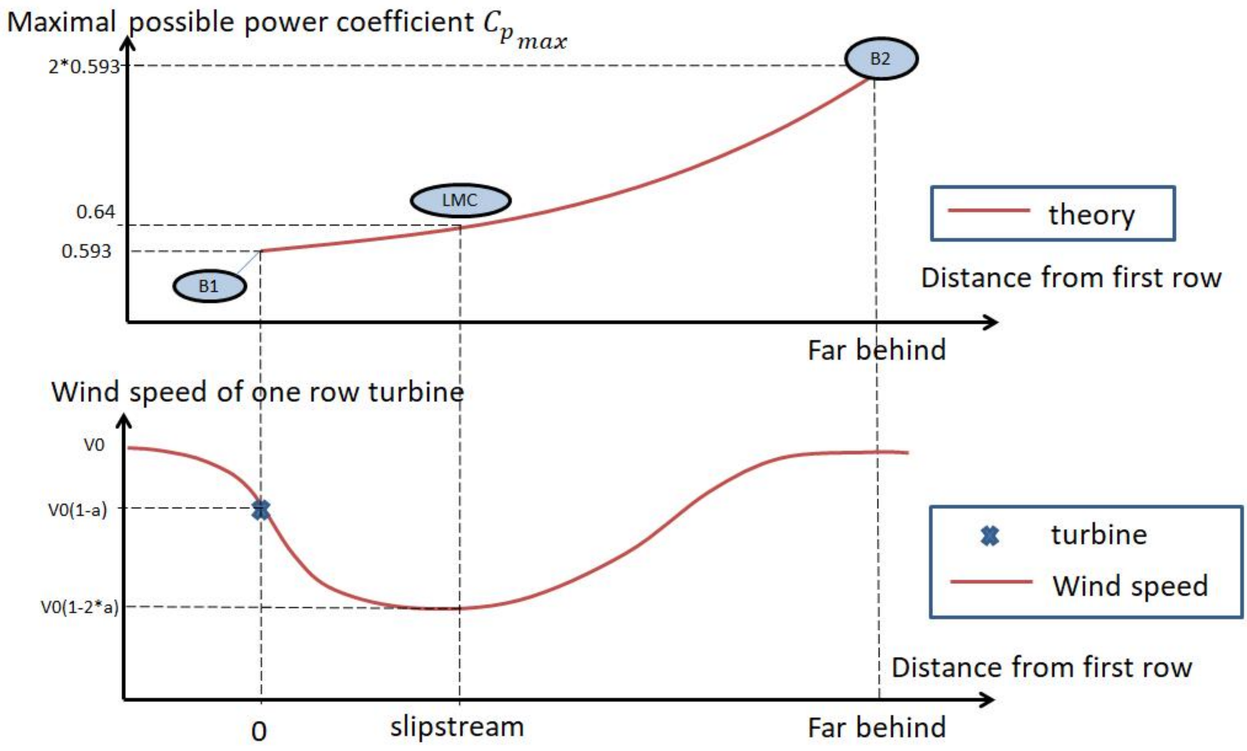

Figure 3-1 Maximal C_P for different theories and the wind speed for a single row turbine

Another theory to extract power from the wind using two converters behind each other is from Loth and McCoy. The scientific research paper describing the theory can be found in the file "Evaluation of the DWF-data file" (Doc. No. see page two).

In the report the maximal possible power coefficient of a two row wind energy converter is discussed and calculated. As a result the authors' say, that a maximum power coefficient of 0.64 is possible for two rows with minimized distance. This is the case, when the outflow of the first row, which is $V_0(1-2a)$, is the inflow of the second row. As a consequence there has to be a certain distance between the rows, to fully decrease the wind speed and to ensure, that the second row has no influence to the first row. This theory is marked by "LMC" in the Figure 3-1. The theory unfortunately makes no comment about the distance between the two rows, which makes it difficult to compare to the DWF. However they are referring to vertical axis wind turbines, which are similar to the concept of the DWF.

4 Discussion points

Reviewing the provided report some questions and discussable issues rose, which will be explained in the following.

4.1 Efficiencies

Some discrepancies have been observed for the calculation of the efficiency of the Dynamic Wind Fence, which is why the calculation of the single row and the double row DWF will be discussed in the following.

4.1.1 Single row DWF

The proposed calculation of the efficiency for a single row of the dynamic wind fence is applicable and we agree with it. The derivation is clearly and understandable. The efficiency is defined in the report as:

$$C_p = 0.59 * h/f \tag{4.1}$$

Where the factor "0.59" describes the maximal possible power coefficient and the factor h/f the losses due to downwash and blade efficiency. Using own calculations, the same values are calculated as shown in the design report for the single row. An induction factor of 1/3 was used to extract the maximal possible power from the wind.

Nevertheless, the proposed formula for the power coefficient or efficiency does not include the influence of variable stagnation. It is correct for the condition, that the local induction is 1/3. Furthermore it is valid for one row only. Adding a second row or changing the axial induction, one cannot keep the same formula with the fixed value of 0.59. This is due to the fact that the maximal possible power coefficient is depending on the stagnation. The theoretical maximal power coefficient is defined as:

$$C_{p_{max}} = 4 * a(1-a)^2 \tag{4.2}$$

It does not include the losses due to downwash, profile efficiency and tip losses; this is done by the term h/f as proposed by the DWF. However as can be seen in Figure 4-1 the maximal power coefficient that is possible decreases for other stagnations than 1/3. Using a stagnation of 1/6, one can extract not more than 46.3 % of the power in the wind.

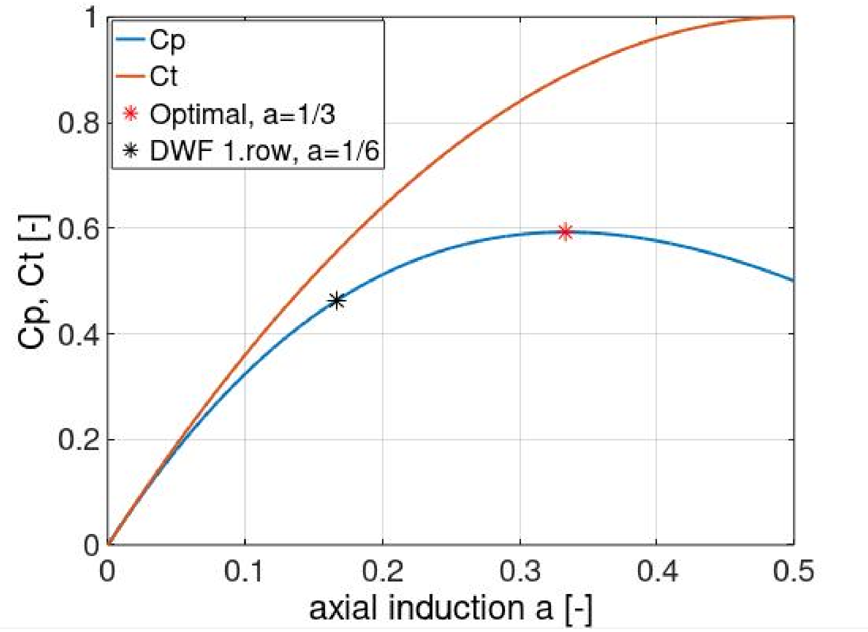

Figure 4-1 Power coefficient and thrust coefficient over axial induction for the 1D momentum theory

So the dependency of the stagnation could be included in the calculation of the power coefficient.

Therewith one gets for the power coefficient of the wind fence, if the variable stagnation is included:

$$C_p = 4a(1-a)^2 * \frac{h}{f} \tag{4.3}$$

The same applies for the calculation of the thrust coefficient C_t and therewith R_y. This however is valid for the first row only. For the second row, the calculation becomes more difficult.

4.1.2 Double row

Looking at Table 4-1 the reader can see the different maximal possible power coefficients for the different theories in this report and the calculated power coefficients for a blade efficiency k of 10.

Method	Abb.	$C_{P_{max}}$(no drag and downwash)	$C_{p_{max}}$ with k = 10 and downwash
Betz, one row	B1	0.593	-
Betz, two row, far distance[1]	B2	1.1852	-
Loth & Mc Coy[1]	LMC	0.64	0.467
DWF, one row	D1	0.593	0.409
DWF, two row[2]	D2	0.593	0.46
DWF, two row, method 2	D2.1	0.593	0.48
Formula (4.3), two row[1]	D2.2	0.82	0.58

Table 4-1 Efficiencies of the different calculation methods, the superscripts indicate whether the efficiencies of the rows are added[1] or averaged[2]. See further descriptions below.

1. ***B1: Betz, one row***

   This is the power coefficient from Betz with the global induction of 1/3.

2. ***B2: Betz, two row, far distance***

   This is the power coefficient for two turbines, with a far distance in-between, so that the wind speed can recover completely. The inflow of the second turbine is the freestream velocity.

3. ***LMC: Loth & Mc Coy, two row***

   This is the power coefficient according to the theory of Loth and Mc Coy. The maximal possible power coefficient is calculated using 0.2 as local induction factor for the first and 1/3 as local induction for the second row, which are the induction factors for the maximal power coefficient, neglecting all losses. The power coefficient in the last column of Table 4-1 is calculated with the global inductions of 1/6 for the first and second row, which have been the assumptions of the DWF. The efficiencies are added.

4. ***D1: DWF, one row***

   This is the power coefficient calculated using formula (4.1) for a single row with the global induction of 1/3, which is the proposed calculation of the DWF.

5. ***D2: DWF, two row***

   This is the power coefficient of the two row turbine calculated using formula (4.1) for a double row as proposed in the design report, using a global induction of 1/6 for the first and second row. The efficiencies of the first and second row then have been averaged, which is the proposed method by the DWF.

6. ***D2.1: DWF, method 2, two row***

   This is the power coefficient of the two row turbine using the additional method for the efficiency proposed in the additional word document that was submitted. It neglects the downwash of flow and assumes one row with an induction of 1/3.

7. ***D2.2: Formula (4.3), two row***

   This is the calculated power coefficient of the two row turbine using the proposed formula (4.3) for the first row and the formula (4.10) for the second row. The maximal possible power coefficient neglecting all losses was calculated using a local induction of 0.217 for the first and 1/3 for the second row. The power coefficient with losses due to downwash and a blade efficiency of 10 was calculated using a global axial induction of 1/6 in the first and the second row. The calculation of the power coefficient will be explained in more detail in section 4.1.2.1. The efficiencies have been added.

A graphical representation of the table is shown in Figure 4-2. It shows the maximal power coefficient that is possible for the different methods and the wind speed of the DWF. As it can be seen the maximal possible power coefficient increases sharply directly behind the first turbine and reaches its theoretical maximum of ca. 0.82 at the position of the second row.

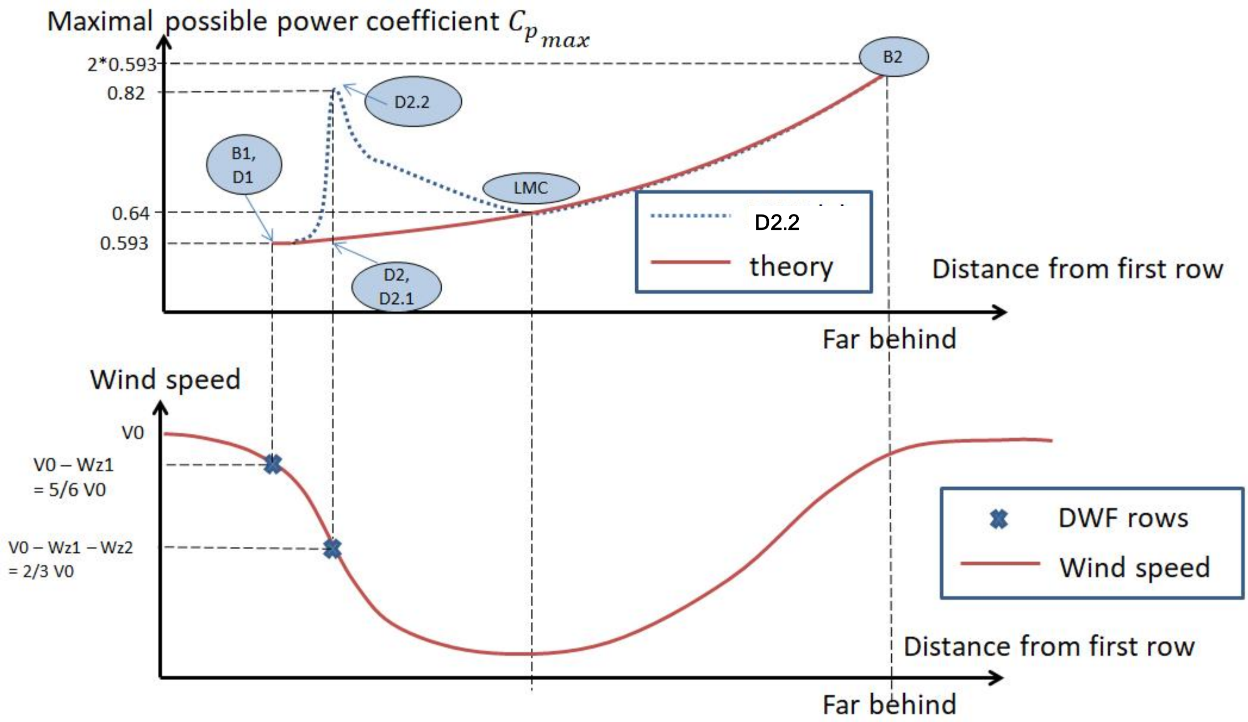

Figure 4-2 maximal C_P and wind speeds for the DWF(schematic)

Using an additional second row one has to take several things into consideration. Most important is the distance between the two rows, which in combination with the axial induction influences the wind speeds in the plane of the turbines and therewith the possible power output.

As no distances were given in the report, only estimations could be done concerning the influence of the first row on the second row and vice versa.

For the two theories explained in section 3.2 (B2 and LMC), there is only an influence of the first row on the second row. Looking at the necessary distance of the two times Betz theory (second row far behind, wind has recovered), one recognizes that this is too far for the concept of the DWF. The theory of Loth & Mc Coy however might work.

Nevertheless, moving the second row closer to the first row might cause, that the second row will also influence the first row due to the stagnation of the second row. The theoretical calculations proposed in the design report are however neglecting this influence, which can have a big impact on the physics.

4.1.2.1 Deviating definition of the efficiency/power coefficient

An alternative formula for the calculation of the efficiency was defined, as the proposed formula of the DWF lab did not take into account the influence of stagnation of the wind behind the first row as well as the influence of the decreased power in the inflow of the second row due to the decreased wind speed. In Figure 4-3 one can find a graphical representation of the following definition of the efficiency.

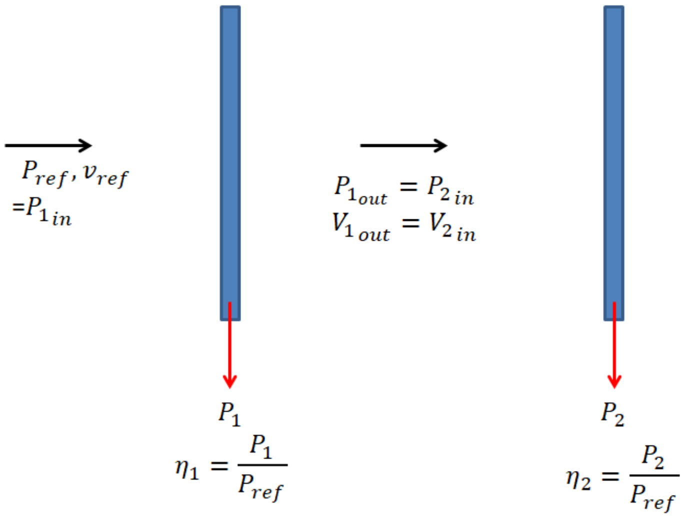

Figure 4-3 Graphical explanation of the efficiency calculation

The power coefficient for the whole turbine is defined as:

$$C_p = \frac{P}{P_{ref}} \tag{4.4}$$

It is the ratio of the amount of power extracted P to the amount of power that was put into the system, P_{ref}. As there are two rows in the system of the wind turbine, two different powers are extracted, P_1 and P_2, each having the global efficiency η_1 and η_2. They are defined as:

$$\eta_1 = \frac{P_1}{P_{ref}} \tag{4.5}$$

$$\eta_2 = \frac{P_2}{P_{ref}} \tag{4.6}$$

They refer to the reference power P_{ref} far in front of the turbine. Therewith the efficiencies can be added for the total power coefficient:

$$C_p = \frac{P_1 + P_2}{P_{ref}} = \eta_1 + \eta_2 \tag{4.7}$$

However, the mentioned efficiencies are "global" efficiencies. Global means, they refer to the reference power P_{ref}, not the input power of their own row. As the input power of the first row is already the reference power, we do not have to make any corrections to the formula (4.3) here. However the second row has the ingoing power $P_{2_{in}}$ which is the same as the output power of the first row P_1. The second row has only the wind speed $V_{1_{out}} = V_{2_{in}}$ as ingoing wind speed, which is then decreased by the stagnation of the second row. This follows, that the input power of the second row is reduced by $\left(\frac{V_{2\,in}}{v_{ref}}\right)^3$, as the wind speed is cubed in the formula of the power. Therewith the power coefficient can be calculated using the formula (4.3) and the mentioned power correction:

$$\left(\frac{V_{2\,in}}{v_{ref}}\right)^3 = \left(1 - a_{1_l}\right)^3 \tag{4.8}$$

$$\eta_2 = 4 * a_{2_l}\left(1 - a_{2_l}\right)^2 * \left(1 - a_{1_l}\right)^3 \tag{4.9}$$

With a_{2_l} being the local induction factor of the second row. Adding the proposed losses due to downwash and profile efficiency we get for the efficiency of the second row:

$$\eta_2 = 4 * a_{2_l}\left(1 - a_{2_l}\right)^2 * \left(1 - a_{1_l}\right)^3 * \frac{h}{f} \tag{4.10}$$

However, the DWF lab defined their inductions globally, which makes a conversion between local and global induction factor necessary. For the proposed distances between the rows by the DWF and the resulting wind speeds in-between, the conversion can be calculated as following:

$$a_{2_l} = \frac{a_{2_g}}{1 - a_{1_l}} \tag{4.11}$$

$$a_{1_l} = a_{1_g} \tag{4.12}$$

With a_{2_l} as the local induction factor of the second row, a_{2_g} the global induction factor of the second row, a_{1_l} as the local induction factor of the first row and a_{1_g} as the global induction factor of the first row. Therewith one can calculate the efficiency of the DWF according to the definition of the efficiency in formula (4.7).

4.1.2.2 Limits due to distances

However using the proposed definition of the efficiency, high values for the power coefficient are calculated. This is caused by the definition of the wind flow between the two rows by the DWF report. Not much information was given concerning this issue; however it was tried to extract as much information out of the submitted calculations and polygons as possible. A graphical representation of the wind speeds is shown in Figure 4-4.

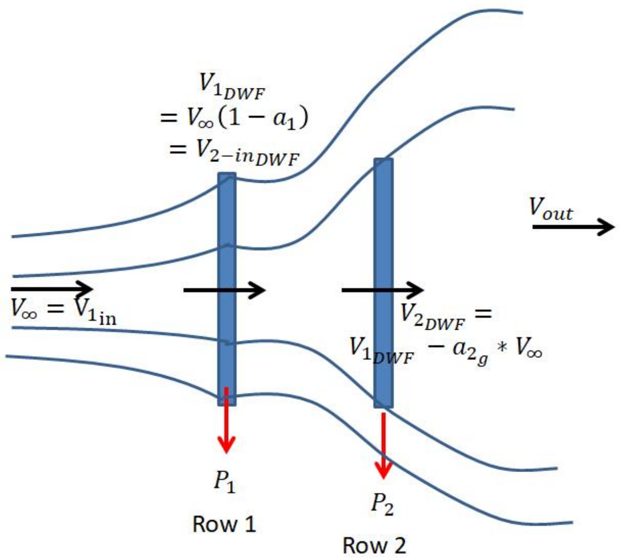

Figure 4-4 Actuator principle of the DWF lab (own figure)

The velocity polygons showed, that the wind speed that is within the plane of the first row $V_{1_{DWF}}$, is the ingoing wind speed for the second row $V_{2-in_{DWF}}$, which then is stagnated by the second row. This means, that the free stream velocity V_∞ is only decreased by the factor $(1 - a_1)$ in the first row, and then decreased by $(a_{2_g} * V_\infty)$ as stagnation of the second row. However, looking at a one row turbine, you will find that the wind is further decreased also behind the wind turbine (see Figure 3-1). This effect however is neglected in the calculation of the DWF. Moving the rows closer to each other will also have the consequence that the second row influences the first row, as well as higher influence of the vorticity created by the first row will be seen.

Comparing the arrangement of the DWF to the arrangement of the theory of Loth & Mc Coy(see Figure 4-5), one sees that the theory of Loth and Mc Coy takes into account the effect of the decreased wind speed. The second row is placed in the wake of the first turbine, when the wind speed is fully decreased. Without the second turbine, the wind speed would now increase again.

Additionally, one can see that the wind speed within the second row of the DWF $V_{2_{DWF}}$ is calculated to be higher than the value within the second row of the Loth and Mc Coy theory V_2, as shown in Figure 4-5.

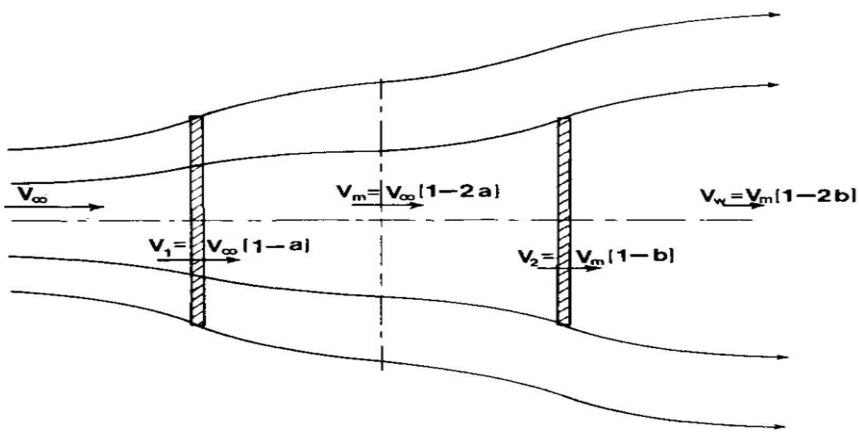

Figure 4-5 Double Actuator Disc (Loth & McCoy)

Consequently the power that is possible to be extracted is also higher. Using the theory of Loth and Mc Coy, the formula (4.10) then would have to be changed to:

$$\eta_2 = 4 * a_{2_l}\left(1 - a_{2_l}\right)^2\left(1 - 2 * a_{1_l}\right)^3 * \frac{h}{f} \tag{4.13}$$

Which includes the decrease of the wind by **two** times the local axial induction factor a_{1_l} of the first row. Consequently the maximal theoretical possible power coefficient decreases for the theory of Loth and Mc Coy to 0.64. That is why there is a peak of the possible power coefficient of 0.82 for the two row turbine in Figure 4-2.

However we guess that this peak of the theoretical power coefficient is not possible or similar behaviour can be found in reality.

4.1.3 Method 2 DWF

The proposed Method 2 from the DWF(D2.1) in the submitted Word document "Addition_DWF-2 ENG.docx" assumes that the downwash of the whole turbine is equal to zero and the total stagnation of the wind is optimal (1/3). This is a simple approach for a rough estimation of the power coefficient, however as we think not sufficient enough for more detailed investigations. Due to the flow complexity of the DWF design and the influence of the two rows on each other, the proposed method might be too simplified.

4.2 Minor issues

4.2.1 Relative Area of the wings

Written in the report it says that the specific wing area per square meter stays the same as for the one row turbine because the total extent of the stagnation of the flow stays the same. This is for the first estimation acceptable. However this assumes that the two rows act as one turbine with two rows having **no** distance between them and consequently also no influence on each other. The aerodynamic calculations proposed for the two line turbine show that there are different relative wind speeds V_r in the individual rows, as well as different values for the non-dimensional parameters i and g. This also causes differences in the calculated values for the specific wing area per square meter s, which of course could be compensated by the angle of attack and therewith the lift coefficient of the wing. The assumptions made within the submitted paper might be explained in more detail if the same relative wing area is chosen for both rows of the DWF.

4.2.2 Reynolds number

The influence of the Reynolds number has not been considered in the report. An assumption has been made on page one. However increasing the wing speed ratio may also increases the Reynolds number on the profile. This can lead to the fact that a higher lift to drag ratio is achieved for the same profiles, which increases the blade efficiency. On page 14 (above Fig. 10) in the report you are saying, that the influence of the blade efficiency on the power coefficient rises with the increasing wing speed ratio. This is true for a constant Reynolds number. However, as you are not decreasing the chord, but the distance between the wings, the Reynolds number also increases, which can lead to a lower drag coefficient of the wing, causing higher profile lift to drag ratios.

For a more detailed investigation the Reynolds number should be considered in order to get a more realistic representation of the blade efficiency, as the blade efficiency and the wing velocity V_C has a big influence on the efficiency of the whole turbine.

4.2.3 Lift, Drag and Resulting

In some pictures provided within the report it is not clear how the three forces relate to each other. In Fig.2 in the provided report for example it looks like the drag force is perpendicular to the resulting force R. However lift and drag are always perpendicular to each other. This might also cause a difference of the calculated angle between the lift and resulting force R. In the provided report in Fig.3 the angle is calculated to be 5.75° for a blade efficiency of 10, while the $\tan^{-1}(\frac{1}{10})$ is 5.71°.

4.2.4 Graphs and calculations

The graphical determination of the values using polygons is a nice possibility to present the calculated values. An alternative analytic calculation of the tables was done by aerodyn using the matlab based program GNU Octave. The same results were achieved, also for low wing speed ratios.

These calculations can be found within the O-file provided with this report, which might be helpful for the DWF.

4.2.5 Symbols

For our understanding on page 6 a wrong symbol is used for the swept out area. The corrected formula might be $A = b\ x\ d$ as used in the formula for the relative wing area.

Furthermore, using the same symbol for different parameters might be misleading; this is the case for example the angle α which is defined as the angle between the resulting force R and its projection on the y plane R_Y in the " DWF_additional_explanations.pdf" file, while it is shown as the angle between resulting and ideal resulting force i in the Additional fig 1. of the provided word document " Addition_DWF-2 ENG.docx". ´

5 Conclusion

The general aerodynamic design concept of the Dynamic Wind Fence was checked by aerodyn Energiesysteme GmbH. Due to the novelty of the proposed concept only few theory and scientific research exists which makes the evaluation and verification difficult. However the design was checked as far as possible and considered to be innovative and outstanding. For the simple first approach of a one line linear converter the aerodynamic concept was found to be realistic and feasible. However the second row, which aims to reduce the losses due to the downwash of the flow, makes the investigations more difficult. The assumptions made in the report of the aerodynamic calculations were checked and we would agree with most of them. However, some of them might be revised or explained in more detail. The distance between the two rows will have a big influence on the overall efficiency, which has not been considered in the aerodynamic calculations yet. To find theories or assumptions for a smart and simple evaluation of the proposed approach is quite challenging. Also, only the theory was checked. In reality one will find other effects, as e.g. a high vorticity caused by the first row, which will strongly influence the efficiency of the second row and the overall efficiency. Especially the interaction between the rows is difficult to evaluate and assess. Computational Fluid Dynamics (CFD) or reduced model tests could answer the questions of feasible distances of the rows and the relating energy extraction from the intransient inflow of the second row. To reduce these challenges it could be favourable to design the DWF with more distance between the rows by the consideration of the theory of Loth and Mc Coy.

Nevertheless the proposed innovative concept with two rows was found to be theoretical able to reduce the losses caused by the downwash and thereby increase the power coefficient compared to the one row linear wind-driven power plant.