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(54) **Title**: WIND TURBINE BLADE

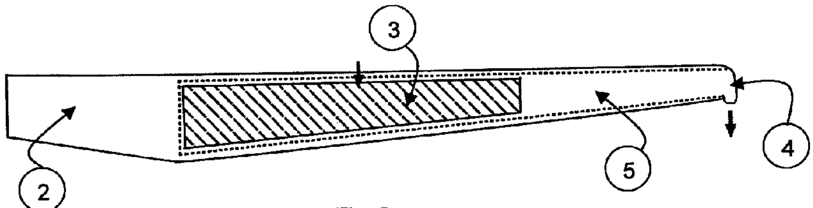

Fig. 2

(57) **Abstract**: A turbine blade (2) for a wind, turbine has an airfoil with a certain shape which determines during operation the airflow over the airfoil and thereby the energy production of the wind turbine. The shape of the airfoil is such that a sub-optimal airflow pattern is obtained by the shape with regard to said energy production. The turbine blade in its airfoil surface is provided with one or more first openings (3) in a radially inner region of the turbine blade as well as one or more second openings (4) in a radially outer region of the turbine blade. The first and second openings are interconnected by an air passage (5) arranged within the blade, whereby, during operation, air is sucked in through the first openings and air is blown out through the second opening. At least the first openings are arranged such that the airflow over the airfoil surface is enhanced with regard to said energy production.

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Wind turbine blade

BACKGROUND OF THE INVENTION

The present invention relates to a wind turbine comprising a rotor with turbine blades. In particular the present invention relates to the design of turbine blades for such a wind turbine.

The wind turbine industry is growing very rapidly. Due to the increasing prices of fossil fuels and due to environmental concerns, there is a growing demand for green energy. To ensure the lasting success of wind turbines and to meet the future requirements of wind turbines, lots of R&D is being carried out on all aspects of a wind turbine.

Considering modern horizontal-axis wind turbines, the goal of the R&D is maximizing the energy production of a wind turbine, divided by all production costs and operational costs of this wind turbine. As the energy produced by a wind turbine is a direct function of the rotor diameter, large diameters are favorable for the overall energy production of a wind turbine. However, large rotor diameters require a high stiffness of the blades. A sufficient stiffness is needed to avoid aerodynamic losses or even to avoid a tower strike due to high bending of the turbine blades. However, the design of increasingly larger wind turbines is limited as rotor power and mass output are proportional to the second and third power of the wind turbine diameter respectively. In other words, to guarantee the required stiffness of the blades with increasing length, more and more materials have to be added to the blade structure, which exponentially increases the weight and the costs of the blade. An alternative way to guarantee the required stiffness is to use stiffer materials (e.g. carbon fiber materials). However, because of the high price of these materials, this option also increases the costs of the blade significantly.

If manufacturers want to maintain the trend of increasing blade lengths, then one of the most important challenges in wind turbine blade design is to guarantee the stiffness of the blades in a cost and weight efficient manner.

SUMMARY OF THE INVENTION

The present invention has for an object to improve wind turbine blades such that the overall cost per kWh of wind energy is decreased.
This object is achieved with a wind turbine blade according to claim 1 and a method according to claim 35.

Wind turbine blades with a thicker cross section would have higher stiffness compared to blades with a thinner conventional cross section. In other words, if the thickness of the blade profiles used for defining the aerodynamic blade shape is increased, then also the stiffness of the blade increases. However, the disadvantage of blade profiles with increased thickness is that the aerodynamic performance of the thicker profiles is less than the aerodynamic performance of in this regard optimized blade profiles as mentioned above. This means that the energy production of a wind turbine with blades with increased thickness is lower than the energy production of a wind turbine with blades having optimized shape for optimal aerodynamic performance. An optimized profile is defined as a profile which is designed as a compromise between the aerodynamic performance and the stiffness of the blade such that – given the boundary condition that the stiffness of the turbine blade must be sufficient – only the fixed external shape of the profile guarantees an optimal airflow over the blade and consequently optimal aerodynamic performance, without needing any additional means for flow control.

The present invention proposes to solve this problem, by means of boundary layer control on wind turbine blades in order to avoid or postpone flow separation on the thicker airfoil surface. Thanks to the boundary layer control on a blade with increased thickness, the aerodynamic performance of this blade can be improved, so that it matches the aerodynamic performance of the thinner, optimized blade. This means that due to boundary layer control, thicker blades can be used without decreasing the performance of the wind turbine. The thicker blades have a higher stiffness, which makes it possible to use less material to have the same stiffness as an optimized wind turbine blade. Less material means less production costs and a lower weight. Thanks to the higher stiffness of the thicker blades, more flexible materials can be used for the production of the wind turbine blades. For example, the expensive carbon fibers used for the production of blades could be replaced by cheaper glass fibers. All these advantages improve the cost efficiency of wind energy in general.

As a preferred boundary layer control method, boundary layer suction is suggested.

Moreover, the invention has for an object to provide a system design in order to achieve the desired suction amounts.

As already explained, the goal of the suction technique presented here is the enhancement or "reparation" of the airflow over blade airfoils which have an increased thickness compared to airflow-optimized blade airfoils, in order to postpone and/or avoid flow separation on these airfoils. These thicker airfoils provide higher stiffness to the blade, so materials can be reduced in order to meet the structural requirements. Materials can be reduced directly by implementing the same structure as in conventional blades, but then with reduced material thicknesses, but it is also possible to change the structure or to spread out the original material in the flanges of the structural beam(s) in the blade, in order to have longer but thinner flanges, thereby reducing the usage of expensive foams or other expensive core materials. As an alternative for reducing materials and thereby reducing costs, the blade can also be made longer without inducing higher stresses in the blade structure compared to the stresses in the original blade structure, thanks to the thicker airfoil shapes used for the blade.

As the stiffness of the blade is mostly relevant for the inner part of a turbine blade (the part closest to the hub), most of the materials used in the blade are concentrated in this region, and so the suction technique should also be applied on this inner part of the blade, preferably between 0% and 75% of the blade span in order to reduce material costs and weight. The region between 0% and 75% of the blade represents more than 90% of the blade mass.

In this region underpressure inside the blade is available due to centrifugal forces. Due to the rotation of the blade and due to the opening(s) in the blade surface near the blade tip, centrifugal forces create an underpressure inside the blade, inside an air passage. This underpressure however is not constant along the blade span. The underpressure is very small at the opening(s) at the blade tip, and it increases gradually towards the blade root near the turbine hub. In order to postpone or avoid flow separation over an airfoil, a certain suction amount and thus a certain underpressure in the blade is required. On the last 25% of the blade span this underpressure is not available or at least not sufficiently. Therefore, it is preferred to apply suction somewhere between 0% and 75% of the blade span.

Not applying suction over the outer 25% of the blade also has a beneficial effect on the required lift for starting up the turbine. During start-up, the centrifugal forces are not enough to induce the suction. This means that the wind turbine blade should be able to generate enough lift without the suction effect for starting up. As the outer 25% of the blade creates relatively the most lift and torque, it is very important that this part of the blade performs optimal without the suction technique. Therefore it is preferred not to increase the blade airfoil thickness, thus to optimise the blade airfoil for an optimized aerodynamic performance. Therefore suction on the outer 25% of the blade span can be omitted.

Besides the effect of postponing and/or avoiding flow separation on relatively thick airfoils, the suction can have the following secondary advantages:

- The blade section close to the wind turbine hub is mostly circular to guarantee the required structural properties and to enable pitching of the blade. To avoid an abrupt transition in the blade profile, there is a large spanwise region where the blade profile changes from the ideal aerodynamic profile to the circular profile. In this region, the wind turbine blade does not have an optimal aerodynamic shape, which locally causes early flow separation without the application of suction. By applying boundary layer suction, the blade section close to the root can become more efficient by delivering a higher contribution to the energy production of the wind turbine.
- Postponing or avoiding flow separation by suction means that the maximum lift coefficient of the wind turbine blade can be increased. With a constant maximum acceptable load on the blade, a higher maximum lift coefficient means that the chord length of the blade can be reduced. A blade with a smaller chord length is less sensitive for heavy gusts during operation or even during standstill, which means that less fatigue damage will occur.
- For large high-tech wind turbines, trailing edge noise is the dominant factor in the noise emission. Trailing edge noise is directly dependant on the thickness of the boundary layer at the trailing edge of a wind turbine blade. As the boundary layer thickness can be decreased using suction, this technique leads to a lower noise emission. As the maximum tip speed of a wind turbine is limited due to a limit on the noise emission of the turbine, boundary layer suction enables the engineers to design for higher tip speeds. The energy produced by the wind turbine is directly related to the rotation speed. Thus, boundary layer suction enables higher tip speeds and as a consequence, a higher energy production.

- By applying boundary layer suction, flow separation can be postponed or avoided and the boundary layer thickness decreases. As a consequence, the pressure drag of the blade profile will decrease, and the lift coefficient will increase due to the higher effective curvature felt by the air flowing over the blade. Combining these advantages, the lift to drag ratio in a large range of angles of attack can be increased significantly. By increasing the lift to drag ratio, the overall performance of the wind turbine is increased.
- The aerodynamic performance of a wind turbine blade is highly dependant on the soiling of the blade surface due to environmental influences. Especially for stall controlled turbines this effect is important as the angle of attack at which flow separation occurs is highly dependant on the soiling of the blade. As a result of the soiling, a thicker boundary layer is created over the blade surface which will separate from the blade surface at a lower angle of attack than without the soiling. This sensitivity for soiling is significantly reduced by influencing the airflow over the wind turbine blade by a boundary layer suction system. The boundary layer suction system thus avoids fatigue loads due to uncontrolled or unforeseen flow separation.

The air sucked into the wind turbine blade is blown out again in a radially outer region of the turbine blade. The blowing part of the system presented in the invention may be used to reduce the blade tip vortex in such a way that the induced drag of the blade and/or the noise generation is decreased. Therefore, the air coming out of the air passage(s) in the blade is not ejected over the blade surface to enhance the aerodynamic lift, it is not ejected at the trailing edge to fill up the wake, but it is ejected at the blade tip in order to influence the tip vortex.

The presented system preferably works completely passively, which means that no actively operable valves or pumps are needed to generate the described advantages. Only the natural centrifugal forces are used. As a consequence, no extra complexity and/or costs are introduced. Due to the fact that the system works completely passively, the selection of the appropriate blade profiles and the generation of the right amount of suction is crucial but complex.

In order to guarantee the right suction rates by only using the passive centrifugal forces, different aspects should be taken into account. Namely, different profile shapes require different suction rates to avoid flow separation. Typical flow rates are expressed in the ratio between the suction velocity and the undisturbed flow velocity at the relevant blade profile.

Typical ratios are between 0,001 and 0,01, depending on the adverse pressure gradient on the profile. Generally, thicker profiles need more suction than thinner profiles. As the blade profiles close to the hub are thicker than the profiles further away from the hub, the closer to the hub, the higher the required suction ratios.

Suction is achieved by creating a pressure difference over openings and/or porous elements in the blade surface. In order to achieve the local suction ratios, different underpressures should be generated inside the turbine blade. To determine the required underpressures, the outside pressure distribution on the blade should be known. This outside pressure is highly variable depending on the rotational speed of the blade, and depending on the position on the blade. For example at the extrados (rear side or suction side) of the blade, the pressure over the blade at the tip is much lower compared to the pressure over the blade close to the hub. The reason for this difference is the relatively higher flow velocities at the tip than at the root.

When the outside pressures and the required suction ratios are known, the appropriate inside pressures should be generated. The inside pressures are dominated by centrifugal effects, by friction effects, and by the effects due to the addition of mass and momentum because of the suction. If only the centrifugal effect is considered, it always creates a pressure distribution inside the blade which shows a quadratic behaviour with increasing distance from the opening(s) at the blade tip. At the blade tip, the pressure is about equal to the ambient pressure. Towards the root of the blade, the pressure inside the blade decreases due to the rotation of the blade, and has its lowest value at the root. The underpressures inside the blade due to centrifugal forces are obviously not equal to the required underpressures in order to generate the appropriate suction ratios. Therefore, the effects on the inside pressures due to friction, addition of mass and addition of momentum in the blade should be tuned in order to guarantee the required underpressures and as such the required suction distribution over the blade.

Consequently, it is preferred to provide means to tune the effects of friction, addition of mass and addition of momentum inside the blade. There are several passive means to achieve this. Some of them are listed below:

- Change or vary the porosity of the porous elements and/or the dimensions of the openings over the blade surface;
- Change or vary the cross section of the air passage(s) inside the blade;

- Guide the airflow through openings and/or porous elements in the web of structural beams inside the blade;
- Separate the airflows coming from different parts of the porous area in the blade or coming from different parts of the area provided with openings, and guide the different airflows through different air passages;
- Create openings and/or porous elements to eject the airflow out of the blade not only at the tip, but at different locations along the span of the blade;
- Combining some of the means listed above;

These means can be translated into a system design and/or an internal blade design.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a front view in perspective of a wind turbine with 3 blades and a hub,
Fig. 2 schematically shows a top view of a wind turbine blade according to the invention,
Fig. 3a and Fig. 3b show a sectional view in perspective of two possible embodiments of a turbine blade tip with openings according to the invention,
Fig. 4a and Fig. 4b show a sectional view in perspective of a wind turbine blade equipped with a porous element and 3 slots in the outer blade surface respectively,
Fig. 5 shows a sectional view in perspective of a turbine blade getting its structural strength and stiffness from a shell construction,
Fig. 6a, Fig. 6b and Fig. 6c show a sectional view in perspective of a turbine blade comprising one, two and three structural beams respectively, all three equipped with porous material in the outer blade surface adjacent to a space inside the blade between the rearmost beam and the trailing edge,
Fig. 7 shows a sectional view in perspective of a turbine blade provided with a porous element in the outer blade surface with variable porosity, adjacent to an air passage formed by the available space between the rearmost beam and the trailing edge of the blade,
Fig. 8a and Fig. 8b show a sectional view in perspective of a turbine blade comprising a porous element in the blade outer surface adjacent to an air passage inside the blade formed by the available space between two structural beams and adjacent to an air passage inside the blade formed by the available space between a structural beam and the leading edge respectively,
Fig. 9a shows a sectional view in perspective of a turbine blade getting its structural strength and stiffness from 2 structural beams; one beam comprising a web and two flanges,

Fig. 9b shows a sectional view of the wind turbine blade in Fig. 9a,

Fig. 10 shows 3 sectional views in perspective of a turbine blade wherein a part of the surface of the blade is removed, all three of the blades having one air passage between both structural beams, and having a porous element incorporated in the outer blade surface adjacent to a space inside the blade next to the air passage, the air passage and the space next to the air passage being separated by an interjacent beam,

Fig. 10a shows an interjacent beam equipped with different openings with the same dimensions, but with variable interspacing,

Fig. 10b shows an interjacent beam equipped with different openings with different dimensions and constant interspacing,

Fig. 10c shows an interjacent beam equipped with different porous elements with different porosities,

Fig. 11 shows a sectional view in perspective of the turbine blade in Fig. 10a, wherein the space inside the blade adjacent to the porous element is divided into several spaces by ribs installed in chordwise direction,

Fig. 12 shows a sectional view in perspective of the turbine blade in Fig. 10a, wherein the space inside the blade adjacent to the porous element is used as a second air passage,

Fig. 13 shows a sectional view in perspective of the turbine blade in Fig. 10a, wherein the space inside the blade adjacent to the porous element is divided into two spaces by one rib installed in chordwise direction, the most outer space in spanwise direction forming a second air passage and the other space being in connection with the first air passage through openings in the web of the interjacent beam,

Fig. 14a shows a sectional view in perspective of a turbine blade equipped with two air passages and with one opening at the blade tip as also shown in Fig. 3a,

Fig. 14b shows a sectional view in perspective of the turbine blade in Fig. 14a, equipped with an extra air passage which guides air inside the blade to an opening in the outer blade surface located between 40% and 90% of the blade span,

Fig. 15 shows a sectional view in perspective of the turbine blade wherein the porous element through which air is sucked inside the blade is incorporated in an airfoil section with a partially flat outer surface,

Fig. 16 shows a sectional view in perspective of the turbine blade wherein a flat back airfoil shape is used for the blade,

Fig. 17 shows a sectional view in perspective of the turbine blade having different porous elements with different porosity incorporated in the outer blade surface,

Fig. 18 schematically shows a top view of a wind turbine blade according to the invention, equipped with a valve installed between the air passage inside the blade and the outside air close to the hub,

Fig. 19 schematically shows a top view of a wind turbine blade according to the invention, equipped with a valve installed between the air passage inside the blade and the opening incorporated in the outer surface of the blade near the blade tip,

Fig. 20 shows a sectional view in perspective of the turbine blade wherein a part of the surface of the blade is removed, and wherein an extra channel is formed by the available space between both structural beams, the pressure inside the channel controlled by a valve and used to control the airflow rate between a pressure chamber and an air passage.

DETAILED DESCRIPTION

The invention has for an object to improve wind turbine blades such that the overall cost per kWh of wind energy is decreased. This object is achieved by providing a wind turbine blade with an improved boundary layer control system which mainly uses the suction technique to enable the use of blade airfoils which are thicker compared to airflow-optimized blade airfoils. An airflow-optimized airfoil is defined here as an airfoil which is designed as a compromise between the aerodynamic performance and the stiffness of the blade such that – given the boundary condition that the stiffness of the turbine blade must be sufficient – only the fixed external shape of the profile guarantees an optimal airflow over the blade and consequently optimal aerodynamic performance, without needing any additional means for flow control.

A wind turbine is shown comprising a rotor with a hub – indicated by reference numeral 1 in Figure 1 – and turbine blades 2 (see Figures 1, 2, 18 and 19). The turbine blades comprise:

- one or more openings 3 (see Figures 2, 5, 6, 8, 10, 11, 12, 13, 15, 18, 19 and 20) incorporated in the outer surface of the blade 2 somewhere between 0% and 75% of the blade span;
- one or more openings 4 (see Figures 2, 14, 18 and 19) incorporated in the outer surface of the blade 2 near the blade tip;
- one or more air passages 5 (see Figures 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 18, 19, 20) connecting the one or more openings 3 somewhere between 0% and 75% of the blade span with the one or more openings 4 near the blade tip.

During rotation of the blade 2, centrifugal forces on the air in the internal passage(s) cause air to be sucked into said passage(s) through the one or more openings 3 in the outer blade surface somewhere between 0% and 75% of the blade span.The sucked in air is ejected downstream through the one or more openings 4 near the blade tip. The sucked in air locally postpones or avoids flow separation on the wind turbine blade 2 while the ejected air reduces the blade tip vortex in such a way that the induced drag of the blade 2 and/or the noise generation is decreased.

As the internal blade design is determining the suction distribution over the one or more openings 3 in the blade surface, several preferred internal blade designs are presented below. The presented blade designs serve as examples, but do not limit the application of this invention. When one or more openings 3 are mentioned in the presented blade designs below, it can mean that one or more holes, slots 6 (see Figure 4) and/or porous elements 7 (see Figures 4 and 17) are used. In the latter case, the openings 3 are then constituted by pores of the porous element 7. Also the one or more openings 4 in the blade 2 near the blade tip can be one or more holes 8 (see Figure 3), slots and/or porous elements 9 (see Figure 3).

A preferred system can be achieved using a single air passage 5 through the blade 2. If the blade 2 is made out of a shell construction 10 (see Figure 5) – a construction in three-dimensional form, having all strength in the skin, and/or in the immediate underlying frames and stringers, with no interior structure or bracing – then the air passage 5 can be formed by the available space next to the shell construction 10 inside the blade 2. If the blade 2 comprises one or more internal beams 11 (see Figures 6, 8 and 13) to provide the structural strength and stiffness of the blade 2, then the air passage 5 can be formed for example by the available space between the rearmost beam 12 (see Figures 6, 7, 13 and 20) in the blade 2 and the trailing edge. The suction can then be applied through one or more openings 3 incorporated in the blade surface, adjacent to the air passage 5. In order to achieve a variable suction over the one or more holes, slots 6 and/or porous elements 7 respectively, holes or slots 6 with variable dimensions can be used and/or one or more porous elements with variable porosity 13 (see Figure 7) can be used. In a preferred embodiment, the dimensions of the holes or slots 6 and/or the porosity of the porous element(s) 13 increase with increasing spanwise location.

Alternatively, in the case of the blade 2 with internal structural beams 11, the desired system can be achieved using a single air passage 5 through the blade 2, formed by the available space between two beams 11 inside the blade 2 or between the front beam 14 (see Figures 6, 7, 8, 10, 11, 12 and 20) and the leading edge of the blade 2. The suction can then be applied through one or more openings 3 incorporated in the blade surface adjacent to the air passage 5, according to the system described above, or the suction can be applied through the blade surface adjacent to a space inside the blade 2 next to the air passage 5, the air passage 5 and the space next to the air passage 5 being separated by one or more interjacent beams 15 (see Figures 10, 11 and 12) or by one or more interjacent ribs 16 (see Figures 11, 13 and 20). Considering the cross section of a beam 11, 12, 14 or 15 and rib 16, a beam 11, 12, 14 or 15 and a rib 16 are built up by a vertical element called the web 17 (see Figure 9) and by one or more horizontal elements, called the flanges 18 (see Figure 9).

E.g. in the case of an interjacent beam 15, one or more openings 19 (see Figures 11, 12 and 13) should be made in the web 17 of the beam 15 in order to create the desired underpressure in the region in the blade 2 adjacent to the opening(s) 3 incorporated in the outer blade surface. When one or more openings 19 are mentioned below, it can mean that one or more holes 20 (see Figure 10), slots and/or porous elements 21 (see Figure 10) are used. The openings 19 are then constituted by pores of the porous element 21.

If the opening(s) 19 in the web 17 have constant dimensions, then the hole(s), slot(s) 6 and/or porous elements 7 incorporated in the outer blade surface should have variable dimensions and/or porosities respectively in order to create the desired variable suction over the blade 2. However, the desired variable suction over the blade 2 can also be achieved by varying the dimensions of the opening(s) 19 in the web 17 of the interjacent beam 15. In order to control the underpressure even better in the region in the blade 2 adjacent to the opening(s) 3 incorporated in the outer blade surface, this region can be divided into several chambers by adding ribs 16 installed in chordwise direction inside the blade 2. Every chamber should then be in connection to the air passage 5 by one or more openings 19 per chamber in the web 17 of the interjacent beam 15.

The blade designs mentioned above can even be combined into a system with at least 2 air passages 5 and 22 (see Figures 12, 13, 14 and 20). If for example suction is applied through one or more openings 3 incorporated in the outer blade surface behind the rearmost beam 12 in chordwise direction, then the area between the rearmost beam 12 and the trailing edge forms the first air passage 5. Air flowing through the opening(s) 3 in the outer blade surface adjacent to this first air passage 5 can flow directly towards the blade tip. The second air passage 22 is formed by the area in the blade 2 between two beams, whereby the rearmost beam 12 is in this case actually the interjacent beam 15 between the two air passages 5 and 22. Through one or more openings 19 in the web 17 of the interjacent beam 15, air can flow from the first air passage 5 to the second air passage 22 or in the opposite direction. By creating two air passages 5 and 22, a larger cross section can be created for the airflow through the blade 2, inducing lower flow velocities and less friction losses inside the blade 2.

In the configuration with two air passages 5 and 22, it is also possible to divide the area behind the rearmost beam 12 in at least two regions by at least one rib 16 installed in chordwise direction. In this case, the most outer region in spanwise direction forms the first air passage 5. Air flowing through the opening(s) 3 in the outer blade surface adjacent to this air passage 5 directly enters the air passage 5 to be guided towards the blade tip. The one or more other regions (pressure chambers) behind the rearmost beam 12 created by the presence of the one or more ribs 16 are in connection with the second air passage 22 located between two beams 11 inside the blade 2, through one or more openings 19 in the web 17 of the rearmost beam 12. The air flowing through the opening(s) 3 in the blade surface adjacent to these pressure chambers flows into one of these pressure chambers, through an opening 19 in the web 17 of the rearmost beam 12 and finally through the air passage 22 to be ejected at the blade tip.

When more than one air passage is used, then an other way to design a wind turbine blade 2 in order to create the desired underpressures inside the blade 2 is to provide the blade 2 with more than one opening 4 to eject the air out of the blade 2; the 2 or more openings being positioned at different locations in the blade surface. E.g., consider the blade design described above incorporating one or more ribs 16 in chordwise direction. The air passage 22 guides the air from the one or more pressure chambers – created by the one or more ribs 16 and the rearmost beam 12 – towards an opening 4 in the blade surface close to the tip of the blade 2. The other air passage 5 can lead the air to an opening 23 (see Figure 14) in the blade outer surface at a different location, e.g. towards an opening 23 in the blade outer surface at 75% of the blade span. Because of the different locations of the outlets 4 and 23, the underpressures in the different air passages 5 and 22 will be different, and consequently also the underpressures below the one or more openings 3 in the outer blade surface.

In order to decrease complexity, it is possible to apply suction on airfoils with a perfectly flat outer surface section 24 (see Figure 15) somewhere between 50% and 100% of the airfoil chord, still achieving the same aerodynamic properties as with a conventional airfoil. This way, suction can be applied on a flat surface 24, which decreases production costs. Moreover, suction can also be applied on flat back airfoils 25 (see Figure 16), still achieving the same aerodynamic properties as with a conventional airfoil. Also this way, production costs can be decreased.

An other way to decrease complexity is by dividing the area of the blade surface equipped with holes, slots 6 and/or porous elements 7 in different regions of constant opening dimensions and/or constant porosity. The dimensions and position of these different regions is determined by the variation of the pressure inside and outside the blade 2.

The design of the internal blade layout, the materials and the design of the openings 3 in the outer blade surface will all be determined so that there will be no blowing of air out of the blade 2 at off design conditions. This is done by designing such that – at a certain spanwise location – the pressure inside the blade 2 will always be lower than the lowest pressure acting on the outside of the blade 2.

All presented blade layouts and/or system designs described above can achieve the desired airflow through the blade 2 and consequently also the desired underpressures, in a passive way, in order to minimize complexity. Alternatively, an active system can be designed in order to change the underpressures inside the blade 2 and consequently the suction distribution over the blade surface during operation of the turbine. Below, three system designs will be described which can be controlled with one single valve, in order to limit the added complexity.

In a first system embodiment, a valve 26 (see Figure 18) is installed in one of the systems described above, between at least one air passage 5 in the blade 2 and the space inside the hub 1 and/or the outside air close to the hub 1. When the valve 26 is closed, the pressure inside the air passage 5 is at its lowest, guaranteeing the highest suction. When the valve 26 is opened, air from the space inside the hub 1 and/or from outside the blade 2 can enter into the air passage 5, causing the pressure inside the air passage 5 to raise. Consequently, the suction rate will decrease. By tuning the setting of the valve 26, the underpressure inside the air passage 5 can be tuned, and as such also the suction rate.

In a second embodiment, a valve 27 (see Figure 19) is installed in one of the systems described above, between at least one air passage 5 in the blade 2 and an opening 4 incorporated in the outer surface of the blade 2 near the blade tip. When the valve 27 is open, the air coming from the air passage 5 can flow through the opening 4 at the tip, so the pressure inside the air passage 5 is at its lowest, guaranteeing the highest suction. When the valve 27 is closed, the air coming from the air passage 5 cannot leave the blade 2 any more, and consequently the pressure inside the air passage 5 will raise. Consequently, the suction will stop, or a combination of suction and blowing will occur on the suction area. By tuning the setting of the valve 27, the underpressure inside the air passage 5 can be tuned, and as such also the suction rate.

In an alternative embodiment, an extra channel is created inside the blade 2 which has an opening close to the blade root. Due to centrifugal effects, an overpressure will be created inside this channel. The overpressure can be controlled with one single valve 28 (see Figure 20) positioned inside the channel or at the opening of the channel close to the blade root. The overpressure in the channel can then be used for controlling and/or changing one of the following parameters:

- the porosity of the porous elements 7 and/or the dimensions of the holes and/or slots 6 in the blade surface;
- the cross section of at least one air passage 5 inside the blade 2;
- the dimensions of the holes 20 and/or slots and/or the porosity of the porous elements 21 in the web 17 of the structural beam(s) 11 inside the blade 2;
- the separation of the airflows coming from different parts of the porous area in the blade 2 or coming from different parts of the area provided with openings 3, and guide the different airflows through different air passages 5 and 22;
- A combination of some of the parameters listed above;

In particular, consider a blade 2 with two beams – one front beam 14 and one rearmost beam 12 – inside the blade 2 which are positioned in spanwise direction inside the blade 2. The two beams 12 and 14 divide the space inside the blade 2 in three areas. The blade 2 can have one or more air passages 5 and 22, but at least one air passage 22 is formed by the area between the leading edge and the front beam 14.

To guide the air from the suction region to the air passage 22, openings 29 (see Figure 20) and 30 (see Figure 20) are provided in the webs 17 of both beams 12 and 14 inside the blade 2. Furthermore, one or more pipes 31 (see Figure 20) made out of flexible material are provided which connect an opening 29 in the front beam 14 with a corresponding opening 30 in the rearmost beam 12. The air travelling through the opening(s) 3 in the outer blade surface flows in the area behind the rearmost beam 12, it can then flow through an opening 30 in the rearmost beam 12, then through the one or more pipes 31 to cross the area between both beams 12 and 14, then through an opening 29 in the front beam 14, and finally through the air passage 22 formed by the leading edge and the front beam 14 to be ejected out of the blade 2.

The area between both beams 12 and 14 forms a channel which has an opening close to the blade root and through which the flexible pipes 31 are installed. Due to centrifugal effects, an overpressure will be created inside the channel which determines the exact cross section of the flexible pipes 31. If the pressure inside the channel is high, the cross section of the flexible pipe(s) 31 will be small; if the pressure inside the channel is relatively low, then the cross section of the flexible pipe(s) 31 will be large. By regulating a valve 28 installed inside the channel or at the opening of the channel close to the root, the overpressure in the channel can be regulated, and consequently the cross section(s) of the pipe(s) 31 can be regulated. The cross section of the pipe(s) 31 determines the flow through the pipe(s) 31, and so the pressure distribution inside the blade 2, adjacent to the opening(s) 3 in the outer blade surface. By using this active system, the suction distribution over the suction area can be modified during operation of the wind turbine.

The active valves 26, 27 and/or 28 in the system can be controlled by an electronic unit. The electronic unit can have different input parameters, such as the output of a mathematical model, the rotational speed, the blade angle of attack, the instantaneous power production, the instantaneous torque and/or the local and instantaneous measurements of aerodynamic loads acting on the blade 2, of the deflections of the blade 2 due to aerodynamic loads, or of the strains in the blade material due to the aerodynamic loads.

CLAIMS

1. A turbine blade for a wind turbine, which turbine blade has an airfoil with a certain shape which determines during operation the airflow over the airfoil, and thereby the energy production of the wind turbine, wherein the shape of the airfoil is such that a sub-optimal airflow pattern is obtained by the shape with regard to said energy production, and wherein the turbine blade in its airfoil surface is provided with one or more first openings in a radially inner region of the turbine blade as well as one or more second openings in a radially outer region of the turbine blade, which first and second openings are interconnected by an air passage arranged within the blade, whereby, during operation, air is sucked in through the first openings and air is blown out through the second openings, wherein at least the first openings are arranged such that the airflow over the airfoil surface is enhanced with regard to said energy production.

2. A turbine blade according to claim 1, wherein the turbine blade has:

a) one or more first openings incorporated in the outer surface of the blade somewhere between 0% and 75% of the blade span;

b) one or more second openings incorporated in the outer surface of the blade near the blade tip.

3. Wind turbine blade according to claim 1 or 2, wherein the one or more openings in the outer blade surface are formed by one or more porous elements, such that the one or more openings are constituted by pores in the one or more porous elements.

4. Wind turbine blade according to any one of the preceding claims, wherein the blade comprises a shell construction to provide for the structural strength and stiffness of the blade.

5. Wind turbine blade according to claim 4, wherein one or more air passages are formed by the available space(s) next to the shell construction inside the blade.

6. Wind turbine blade according to claims 4 or 5, wherein one or more air passages are formed by the available space(s) inside the shell construction inside the blade.

7. Wind turbine blade according to any one of the preceding claims, wherein the blade comprises one or more internal beams installed in spanwise direction in the blade to provide the structural strength and stiffness of the blade.

8. Wind turbine blade according to claim 7, wherein an air passage is formed by the available space between the trailing edge and the beam inside the blade closest to the trailing edge and possibly one or more ribs installed in chordwise direction inside the blade.

9. Wind turbine blade according to claims 7 or 8, wherein an air passage is formed by the available space between two beams inside the blade and possibly one or more ribs installed in chordwise direction inside the blade.

10. Wind turbine blade according to any one of the claims 7 - 9, wherein an air passage is formed by the available space between the leading edge and the beam inside the blade closest to the leading edge and possibly one or more ribs installed in chordwise direction inside the blade.

11. Wind turbine blade according to any one of the preceding claims, wherein one or more air passages have a variable cross section.

12. Wind turbine blade according to any one of the preceding claims, wherein the one or more openings and/or the one or more porous elements are incorporated in the outer surface adjacent to one or more air passages.

13. Wind turbine blade according to any one of the claims 7 - 12, wherein the one or more openings and/or the one or more porous elements are incorporated in the outer blade surface adjacent to a space inside the blade next to at least one air passage, the air passage(s) and the space next to the air passage(s) being separated by one or more interjacent beams or by one or more interjacent ribs.

14. Wind turbine blade according to claim 13, wherein the space adjacent to the one or more openings and/or one or more porous elements incorporated in the outer blade surface and situated next to at least one air passage is divided into two or more spaces by ribs installed in chordwise direction.

15. Wind turbine blade according to claims 13 or 14, wherein the connection between the air passage(s) and the space(s) inside the blade next to the air passage(s) is made by one or more openings or one or more porous elements in the web of the interjacent beam(s) and/or rib(s).

16. Wind turbine blade according to any one of the preceding claims, wherein the desired variable suction distribution over the blade is realised by providing in the blade outer surface:

a. one opening stretched out in spanwise direction which has variable dimensions, and/or;
b. different openings with the same dimensions, but with variable interspacing, and/or;
c. different openings with different dimensions and constant interspacing, and/or;
d. different openings with different dimensions and different interspacing, and/or;
e. one or more porous elements with variable porosity, and/or;
f. at least two porous elements with different porosities.

17. Wind turbine blade according to claims 15 or 16, wherein the desired suction distribution over the blade is realised by providing in the web of the interjacent beam(s) and/or rib(s):

a. one opening stretched out in spanwise direction which has variable dimensions, and/or;
b. different openings with the same dimensions, but with variable interspacing, and/or;
c. different openings with different dimensions and constant interspacing, and/or;
d. different openings with different dimensions and different interspacing, and/or;
e. one or more porous elements with variable porosity, and/or;
f. at least two porous elements with different porosities.

18. Wind turbine blade according to any one of the preceding claims, wherein an extra air passage is incorporated which guides air inside the blade to an opening or porous element in the outer blade surface located between 40% and 90% of the blade span.

19. Wind turbine blade according to any one of the preceding claims, wherein the one or more openings and/or the one or more porous elements incorporated in the outer blade

surface are provided at the extrados (rear side or suction side) of the blade, located somewhere between 50% and 100% of the airfoil chord.

20. Wind turbine blade according to any one of the preceding claims, wherein the one or more openings and/or the one or more porous elements through which air is sucked inside the blade are incorporated in an airfoil section with a partially flat outer surface.

21. Wind turbine blade according to any one of the preceding claims, wherein flat back airfoil shapes are used for the blades.

22. Wind turbine blade according to any one of the preceding claims, wherein the one or more porous elements used in the design are made of sintered porous plastic materials.

23. Wind turbine blade according to claim 22, wherein the sintered porous plastic materials are reinforced with fibre material and/or with a metal grid and/or with perforated sheet material.

24. Wind turbine blade according to any one of the preceding claims, wherein the one or more openings and/or one or more porous elements incorporated in the outer surface of the blade near the blade tip is/are shaped such that the air ejected through these one or more openings and/or porous elements reduces the tip vortex of the blade.

25. Wind turbine blade according to any one of the preceding claims, wherein one or more actively operable flow regulating valves are incorporated in the one or more air passages.

26. Wind turbine blade according to any one of the preceding claims, wherein one or more passively operable flow regulating valves are incorporated in the one or more air passages.

27. Wind turbine blade according to claims 25 or 26, wherein at least one valve is installed between the one or more air passages in the blade and the space inside the hub and/or the outside air close to the hub.

28. Wind turbine blade according to any one of the claims 25 - 27, wherein at least one valve is installed between the one or more air passages in the blade and the one or more openings incorporated in the outer surface of the blade near the blade tip.

29. Wind turbine blade according to any one of the preceding claims, wherein the airflow rate from a pressure chamber to an air passage or from an air passage to another air passage is regulated by changing the pressure in an extra channel, located inside the blade between the pressure chamber and the air passage or between the two air passages, which is in connection with the outside air by an opening and/or a porous element in the outer blade surface.

30. Wind turbine blade according to claim 29, wherein the extra channel is formed by the space inside the blade between two structural beams in spanwise direction and possibly by one or more ribs in chordwise direction installed in the blade.

31. Wind turbine blade according to claim 29, wherein the extra channel is formed by the space inside the blade between the leading edge and the beam inside the blade closest to the leading edge and possibly by one or more ribs in chordwise direction installed in the blade.

32. Wind turbine blade according to one of the claims 29 - 31, wherein one or more valves are installed inside the extra channel and/or at the opening or porous element of the channel.

33. Wind turbine having a blade according to claims 25, 27, 28 or 32, in which the one or more valves are controlled by an electronic unit; the electronic unit having different possible inputs such as a mathematical model, the rotational speed of the blade, the blade local angle of attack, the instantaneous power production, the instantaneous torque and/or the instantaneous measurements of aerodynamic loads acting on the blade, of the deflections of the blade due to the aerodynamic loads or of the strains in the blade due to the aerodynamic loads.

34. Wind turbine having a blade according to any one of the preceding claims, wherein the boundary layer control system is combined with a pitch control system of the blades.

35. A method for designing/manufacturing a wind turbine blade, which turbine blade has an airfoil with a certain shape which, during operation, determines the airflow over the airfoil, and thereby the energy production of the wind turbine,

wherein in a first designing step the wind turbine blade is designed with a shape that provides a certain desired length and a certain desired stiffness to the blade, said shape in itself being sub-optimal with regard to the airflow pattern over the airfoil surface and the energy production, and

wherein in a subsequent designing step the sub-optimal flow pattern resulting from said sub-optimal blade shape is enhanced by designing the airfoil surface of the turbine blade to have one or more suction openings whereby, during operation, air is sucked in, wherein at least the position and shape of the suction openings are designed such that the airflow pattern over the airfoil surface is enhanced so as to achieve or at least approximate an optimal flow pattern with regard to energy production.

36. A wind turbine blade comprising:

a) one or more openings incorporated in the outer surface of the blade somewhere between 0% and 75% of the blade span;

b) one or more openings incorporated in the outer surface of the blade near the blade tip;

c) one or more air passages connecting the one or more openings somewhere between 0% and 75% of the blade span with the one or more openings near the blade tip;

whereby during rotation of the blade, centrifugal forces on the air in the internal passage(s) cause air to be sucked into said passage(s) through the one or more openings in the outer blade surface somewhere between 0% and 75% of the blade span, and then to be ejected through the one or more openings near the blade tip in order to, respectively, locally postpone or avoid flow separation on the wind turbine blade and to reduce the blade tip vortex.

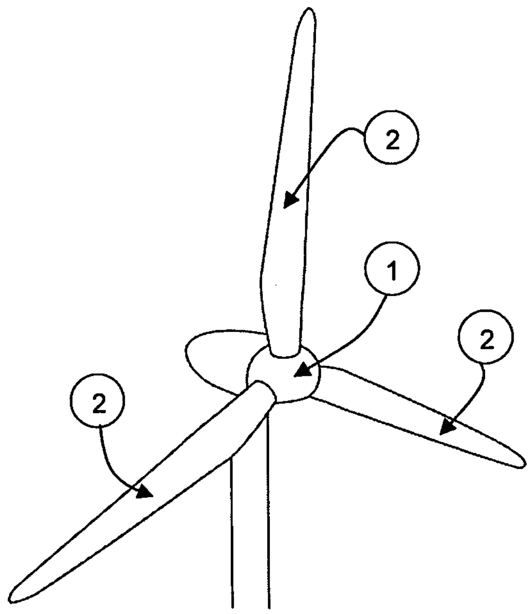

Fig. 1

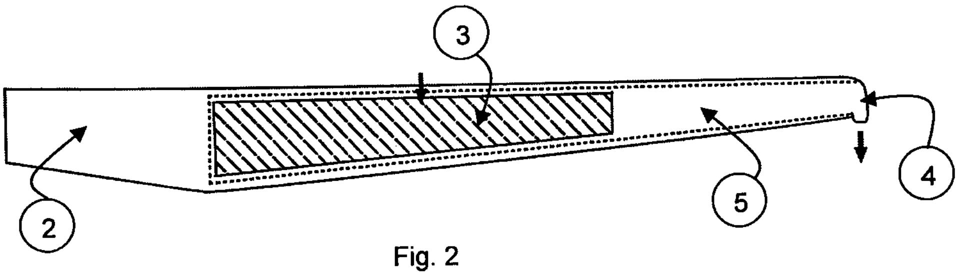

Fig. 2

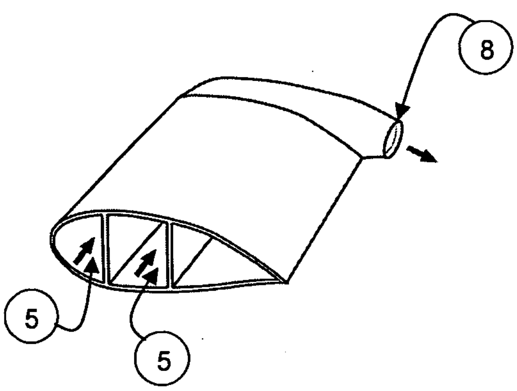

Fig. 3a

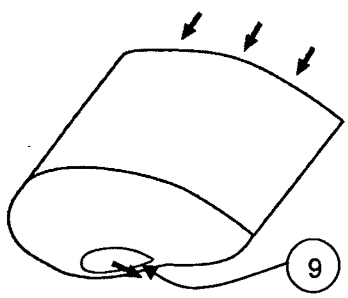

Fig. 3b

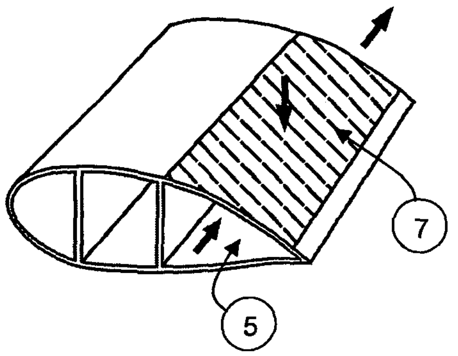

Fig. 4a

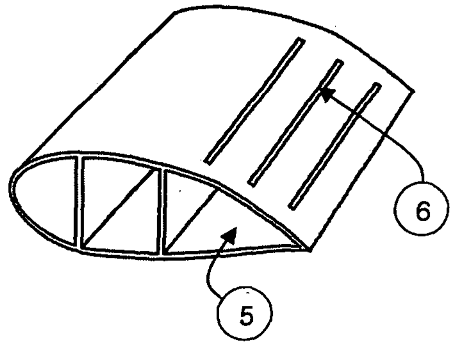

Fig. 4b

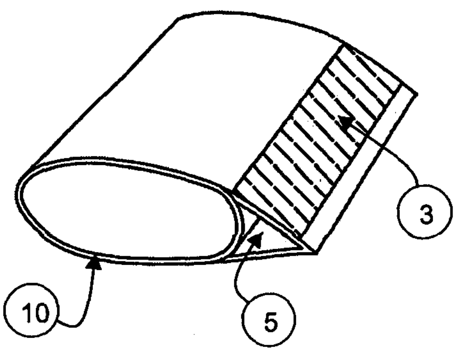

Fig. 5

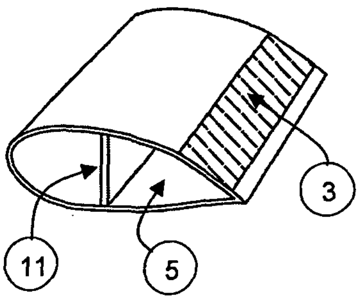

Fig. 6a

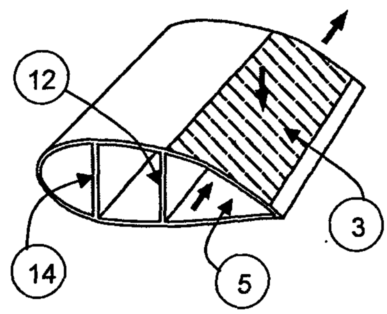

Fig. 6b

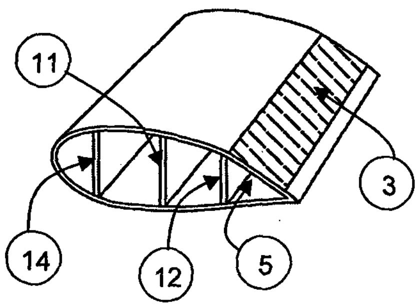

Fig. 6c

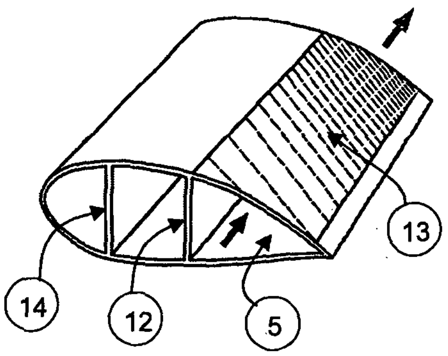

Fig. 7

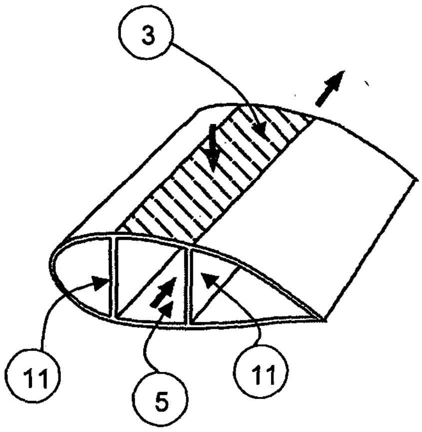

Fig. 8a

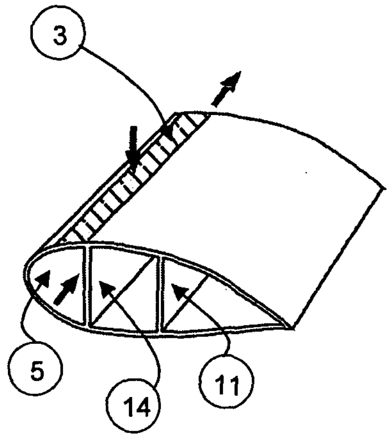

Fig. 8b

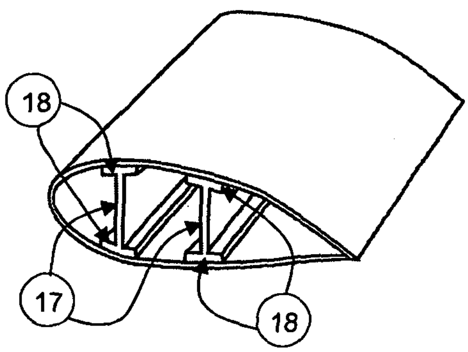

Fig. 9a

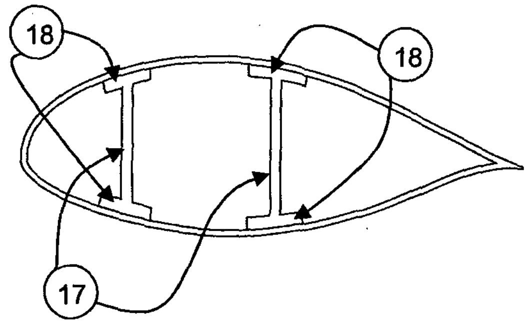

Fig. 9b

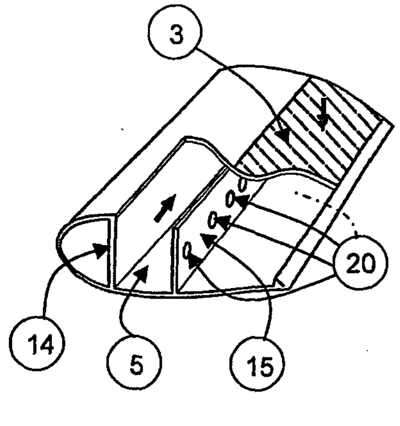

Fig. 10a

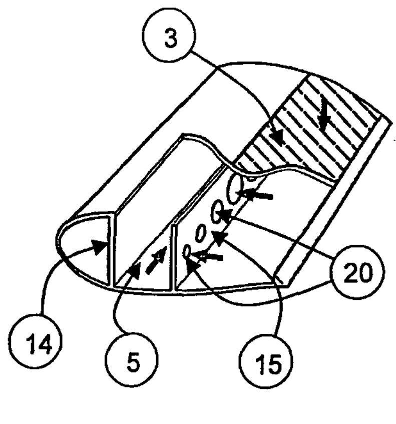

Fig. 10b

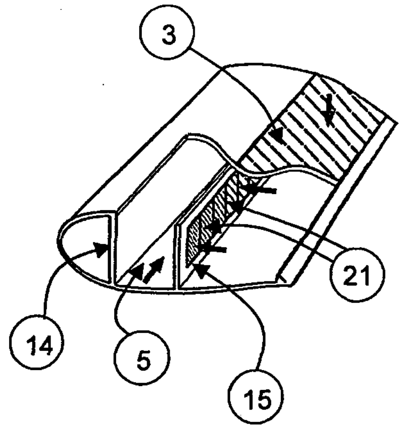

Fig. 10c

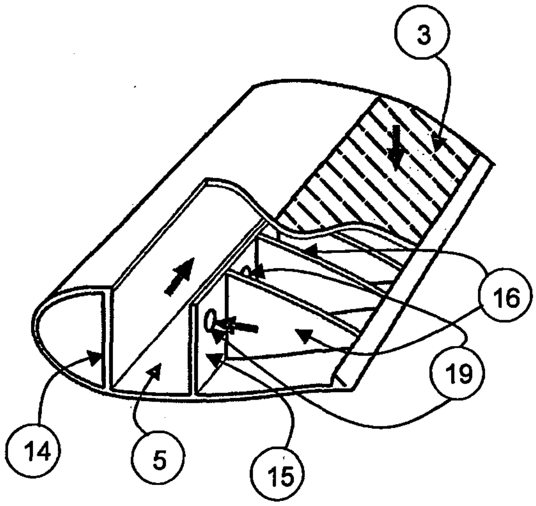

Fig. 11

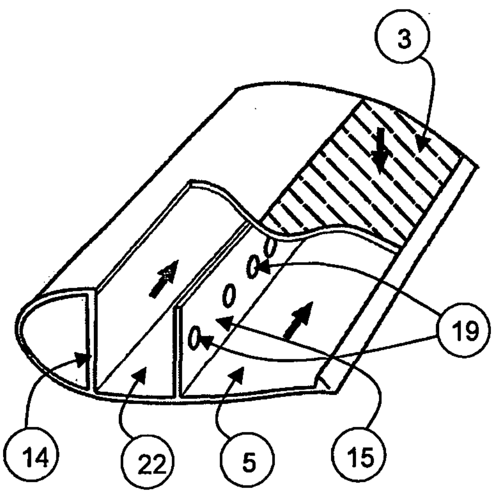

Fig. 12

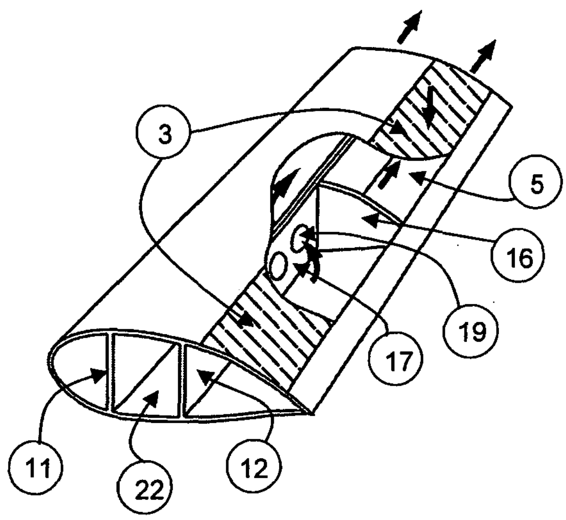

Fig. 13

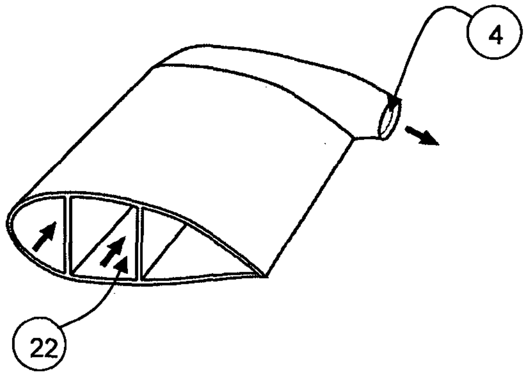

Fig. 14a

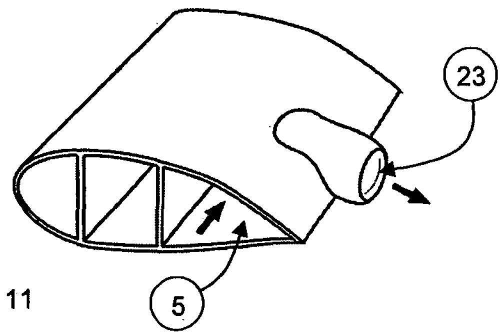

Fig. 14b

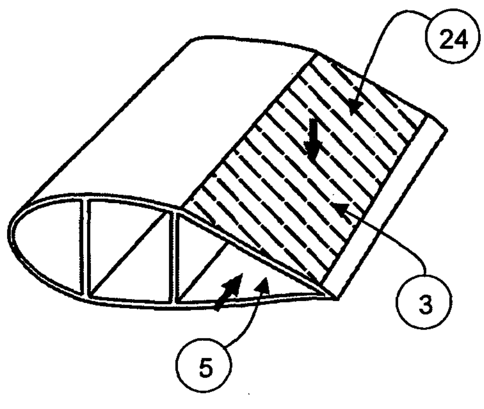

Fig. 15

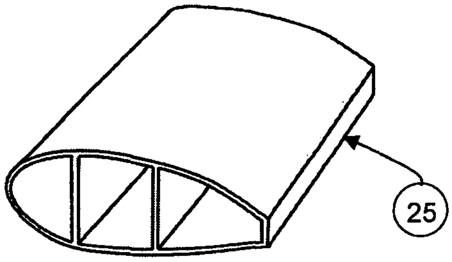

Fig. 16

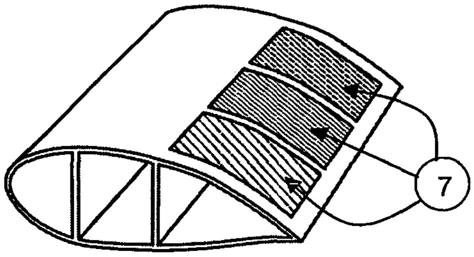

Fig. 17

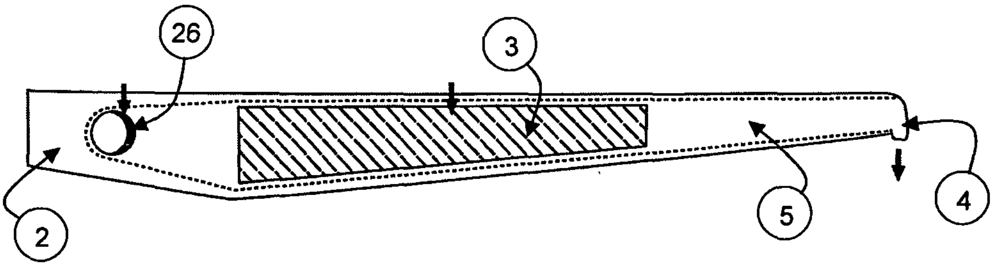

Fig. 18

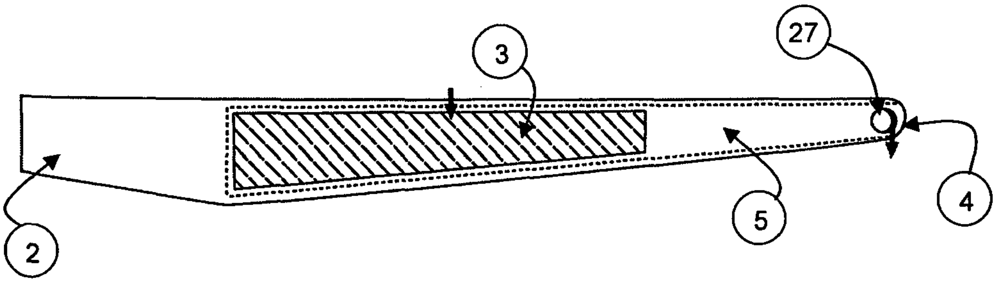

Fig. 19

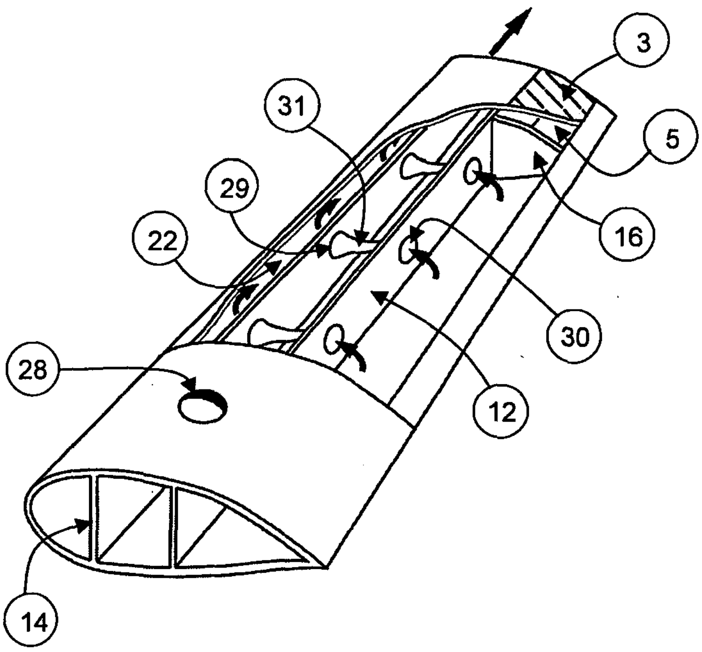

Fig. 20

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2009/000204

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03D1/06
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2 053 240 A1 (ACTIFLOW B V [NL]) 29 April 2009 (2009-04-29) paragraphs [0013], [0017] - [0025]; figures 1-16	1-10, 12-14, 16, 18-23, 25-36
X	GB 2 186 033 A (NEI INTERNATIONAL RESEARCH & D NORTHERN ENG IND [GB]) 5 August 1987 (1987-08-05) page 1, line 119 - page 3, line 13; figures 1-4,7	1,2,11, 12,18, 19, 24-28, 33-36

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
1 September 2010	14/09/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Jucker, Chava

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2009/000204

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 780 408 A1 (GEN ELECTRIC [US]) 2 May 2007 (2007-05-02) paragraphs [0006] - [0010], [0014] - [0021]; figures 1-5	1,2,11, 12,16, 18-20, 24,25, 27,28, 33,35,36
X	WO 2007/035758 A1 (UNIV FLORIDA [US]; SFORZA PASQUALE MICHAEL [US]) 29 March 2007 (2007-03-29) page 3, paragraph 1 - page 5, paragraph 3; figures 1-5,8	1-3,11, 12,16, 19,20,36

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/NL2009/000204

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 2053240	A1	29-04-2009	WO	2009054714	A1	30-04-2009
GB 2186033	A	05-08-1987	NONE			
EP 1780408	A1	02-05-2007	BR	PI0604707	A	28-08-2007
			CN	1955459	A	02-05-2007
			US	2007098552	A1	03-05-2007
WO 2007035758	A1	29-03-2007	NONE			