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COMPUTER AIDED ENGINEERING AS A USEFUL TOOL IN HYDRALIC TURBINE DESIGN

This paper threats some aspects of Computer Aided Engineering in regards to Turbine design. Parametric modeling of the blades and impellers is central in the application of CAE, another aspect of CAE which is discussed is Computational Fluid Dynamics.

1. Introduction

The role of CAD-CAE in component production

The development of all mechanical products, proceed as a series of steps: planning, design, proto-typing, experimental evaluation and production. Figure 1 shows conventional procedure.

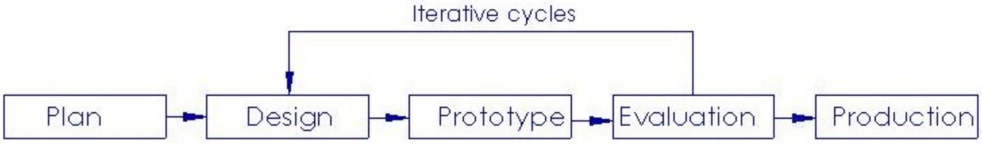

Figure 1. Conventional development procedure

That is to say, the basic sequence is that an idea is expressed in a drawing, and good product is made through repeated failures in experiments. It is obvious that development can be accelerated by repeating the cycle of design, prototyping and evaluation as little time as possible. But it cost money and time. Therefore if the design proposal prior to the prototyping stage can be sufficiently competed by CAE studies at an earlier stage, it should be possible to reduce the number of cycles of prototyping and evaluation, **Figure 2**.

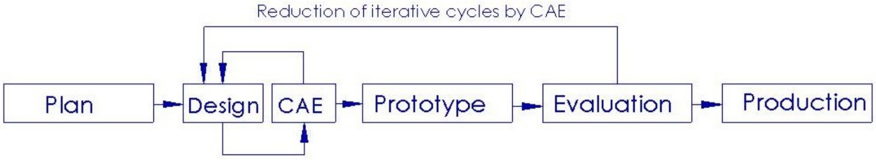

Figure 2. Development procedure with reduced iterative cycles by ACE

Finally, it should be possible to bring down the prototyping and evaluation process down to a single step, **Figure 3**.

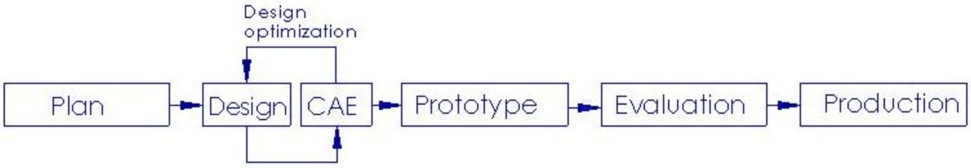

Figure 3. Development procedure with single prototype step

In case of water turbines, the importance of Computer Aide Engineering increases. One of the reasons is related to their component production. Moreover, the theoretical base to the calculations is often limited; it has to be completed by empirical values coming from existing solutions and model tests.

Although CAE alone delivers results of less accuracy than prototyping, CAE when used by experienced designers enables the most cost effective assessment of many design alternatives. CAE provides enough accuracy to understand the impact of design choices, and will contribute to the deeper understanding of product behavior and problems before the design is put into production.

2. The types and parameters of water turbines

A water turbine is a water engine which converts the energy of water into effective work in a rotating runner. In the runner the water changes its direction due to the shape of blades passage and creates a torque that can be transmitted to a generator.

Figure 4. Pelton Turbine Runner

There are two types of water turbines: impulse turbines and reaction turbines. The first type of water engine converts only the kinetic energy of the water (the kinetic energy, $c^2/2g$). It means that water with atmospheric pressure is directed onto a set of blades placed circumferential around a shaft. The traditional impulse turbine is the Pelton turbine, the construction of which will be described in the following part of the paper.

Reaction turbines convert both the potential energy of the water (pressure, p/ρ) and the kinetic energy (velocity, $c^2/2g$) into useful work. To this type of turbines we include Propeller Turbines, Kaplan Turbines, Deriaz Turbines and Francis Turbines.

The Pelton Turbine, Figure 4, works with the high heads that could be in the area of 500 to 2000m. The turbine is construed of a rotor disk with a hub and regularly located blades on its circumference (also known as buckets). Buckets are manufactured separately and then connected to the rotor disk. The controlling element in Pelton turbines are nozzles placed circumferential to the runner and directing water onto the buckets. The regulation of the flow can be made with the use of the needle which is located in the nozzle. Generally, turbines with vertical and horizontal shaft are used. The difference between those solutions is significant. The Pelton wheel with the vertical shaft occurs mainly with only one rotor and the water is directed onto the buckets with up to six nozzles. Turbines with horizontal shaft can work even with three runners on one shaft but then on the other hand the flow is directed by fewer numbers of nozzles.

The Propeller and Kaplan Turbines, Figure 5, are reaction turbines which work in the lower head range, from only a few meters up to around 75m. The difference between a Kaplan turbine and a Propeller turbine is that the angle of blades in the Kaplan Turbine can be regulated. The regulation of blades takes place by the use of an automatic operated adjusting mechanism located inside the hub of runner. The changes of the blade angle are made continuously during the operation of the machine, as a consequence the Kaplan turbine maintain a high efficiency over a wide range of flows. These types of turbines also occur in the vertical and horizontal design.

Figure 5. Kaplan turbine runner

Francis turbines, Figure 6, are commonly used in power plants where heads are below 600m. The rotor of turbine is made of curved blades joined by two rims. The water is directed to the turbine by a set of regulated guide vanes whose function is control the amount of water through the turbine. Francis turbines are probably the most commonly used of all the types of water turbines.

Figure 6. Francis turbine runner

Deriaz turbine, Figure 7, are used in the lower medium head range, typically with heads from 13 to 300 m. The water which flows through the runner has axial-radial direction and the blades of the runner are fixed to the hub. Such turbines are also often used in pumped-storage power station because in the lower head segment. The Deriaz turbines, like the Kaplan turbines have regulated runner blades and high efficiency can therefore be obtained with different flows. To some extent the Deriaz and Kaplan turbines can work at the same head, but from the experience we know that it’s better to apply the Deriaz turbine above 36 m compared to the fully axial Kaplan turbine.

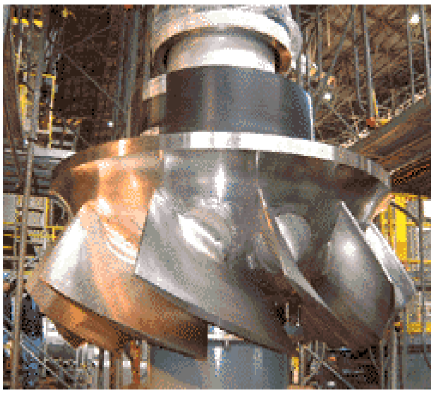

Figure 7. Deriaz turbine runner

The positive aspect of Deriaz turbine is a better cavitation performance. Because of the axial – radial design the rotational speed is less at the outlet then in the inlet, while the propeller and Kaplan turbines have the same rotational velocity along the blades passage. However the Deriaz turbines are more difficult to design.

3. Design outline

The fundamental design parameters for any turbine design are determined by the localization and topology of the power station in which the turbine is going to operate. Factors such as head and the amount of water give not only information of how much energy that can be produced but also determines the type of turbine and its basic design parameters.
The available energy can be calculated as follows

$$P = \rho \cdot Q \cdot g \cdot H \cdot \eta \qquad (1)$$

Where:
P – Power [W],
Q – Flow [m^3/s],
ρ – Water density [kg/m^3],
H – Head [m],
η – estimated efficiency.

Figure 8, shows the efficiency as a function of $(\frac{Q}{Q^*})$ for different types of water turbines. Where Q^* means the flow at the turbine's best efficiency point and Q means flow at the point of operation.

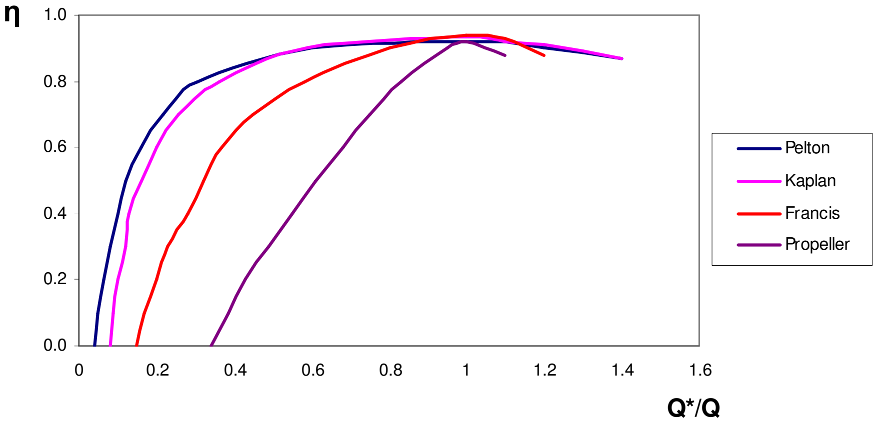

Figure 8. Efficiency of different types of turbines versus flow

It is desirable to obtain an efficiency curve as flat as it possible, because then turbine will operate with a high efficiency over a large flow area. This in turn will heavily influence the earnings from the power station.

a. Airfoil profile theory

The main elements in the design of propeller turbines are the runner blades, because they play major role in the power generation. Due to their irregular shape and the smoothness requirement, they are complex to manufacture. The design of the blades are based on aerofoil profiles, due to their ability to generate a big Lift force and a relatively low Drag force, see **Figure 9**.

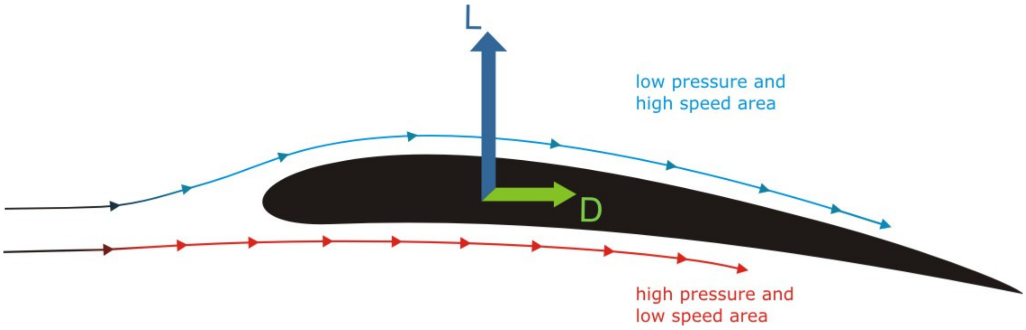

Figure 9. Airfoil cross-section

On the **Figure 9** it is shown how the flow pass the profile. Low velocity is marked by red, high by blue. The higher velocity on the upper surface makes that area a low pressure area. The opposite situation is on the lower surface which is high pressure area. That pressure difference creates an upward lift force. Its component in the direction of the impeller rotation is responsible for the generation of torque. The Lift force is defined as:

$$L = C_L \cdot \rho \cdot \frac{V_m^{\ 2}}{2} \cdot l \cdot dr \tag{2}$$

Where:

C_L – Lift force coefficient,
ρ – Density of water [kg/m^3],
V_m – Apparent velocity [m/s],
$l * dr$ – Area [m^2].

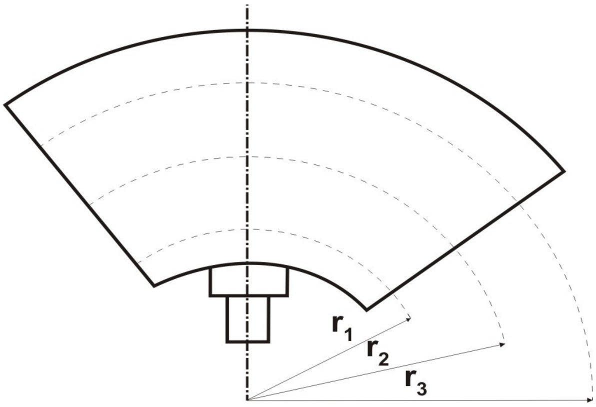

Figure 10. Blade view

The second force that exerts the blade is the Drag force. Its direction is always the opposite to the direction of flow **Figure 9**. The Drag force can be calculated as:

$$D = C_D \cdot \rho \cdot \frac{V_m^{\ 2}}{2} \cdot l \cdot dr \tag{3}$$

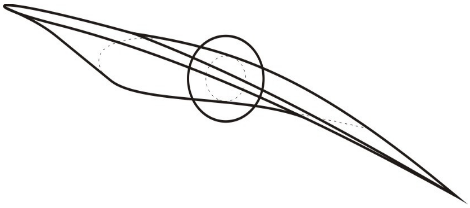

Figure 11. Runner blade, top view

The coefficients C_L and C_D are based on empiric data, carried out in wind tunnels. They are related to the type of the profile, angle of attack α (Angle between apparent velocity vector of the stream and chord line of the profile) and the Reynolds's number. A convenient way of describing aerodynamic characteristics of a profile is to plot the value of the coefficients against the angle of attack (functions: $C_L = f(\alpha)$**,** $C_D = f(\alpha)$ **).** The lift coefficient increases almost linearly with angle of attack until the critical value is reached (about α=15° for NACA 4412 profile, and $R_e = 3 \cdot 10^6$), then decreases rapidly. This is due to flow separation. The drag coefficient has a minimum value at low lift coefficient and the shape of the curve is approximately parabolic at angle of attack.

In turbine blade design it is very important to set the blades correctly with respect to the flow direction. A correct angle of attack gives desired C_L and C_D coefficients. To keep correct angle of attack on whole blade which means for each radius **Figure 10**, the shape of the blade has to be twisted it shown on **Figure 11**.

b. CAD in turbine blade design

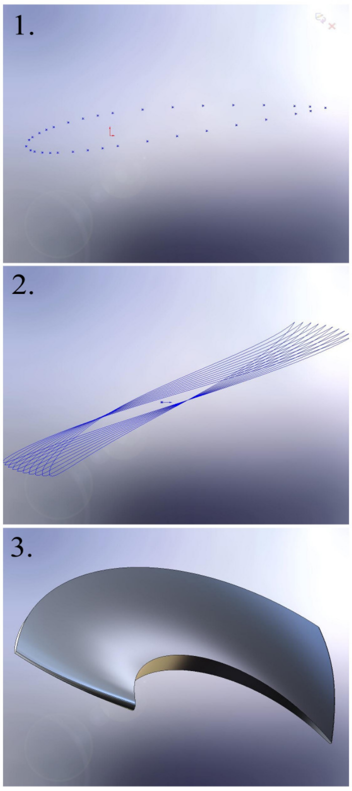

Figure 12. Steps in blade modelling

Computer Aided Design gives a possibility of 3D parametric modeling. Software such as Solid Works or Solid Edge are equipped with a tools which allow in easy way to model water turbine blade as a 3 dimensional solid. Many operations can be realized automatically thus creation of correct template is of help. The software executes all necessary operations. In the case of a water turbine, only the import of coordinates of the profiles **Figure 12** (upper) are required to build whole blade**Figure 12** (lower). The coordinates are generated in through a series of calculations performed in Excel or similar programs. In this template, the program builds curves based on clouds of singular points. Several profiles are required due to a few reasons. First, because it gives better sensitivity of the control on each part of the blade, secondly, because a blade usually has a variable thickness and thirdly, in order to keep the correct angle of attack on each section. After that, the surface's have to be created. This step can be done using advanced surface modeling. When initial shape is obtained, ending operations as filleting and bending should give a last shape.

When the correct template is prepared, almost all operations can be done automatically. Only two steps require the designer's attention, importing points and finishing operations. After that, the shape and geometry has to be analyzed.

An important factor in turbine blade design is to obtain smooth surfaces. Both the upper and lower surfaces have to have no sudden geometry change. The radius on the leading edge has to change continuously. CAD Software, such as Solid Works, gives the designer a possibility to check, whether the geometry is correct or has to be improved, **Figure 13**.

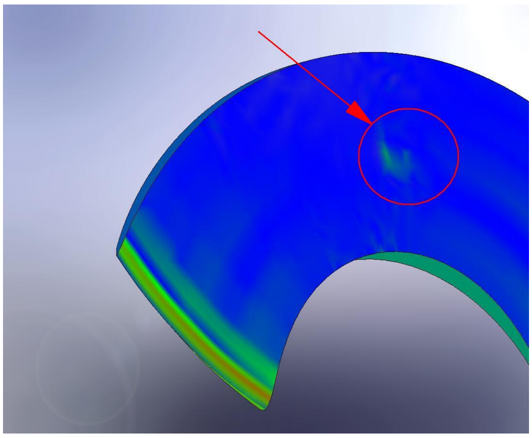

Figure 13. Defects in the surface

c. *Innovate solution*

As mentioned earlier, in Kaplan turbines, the runner blade angles are adjustable. It has to be done due to the requirement of constant rotational speed for synchronous generators. In this solution advanced mechanism, responsible for blade rotation is required. In typical Kaplan turbines torque is being moved to the generator through a shaft. All these things together make construction complicated. The Turbo set, which the CEDI and Turbinova companies works on, doesn't require either adjustable blades or a shaft.

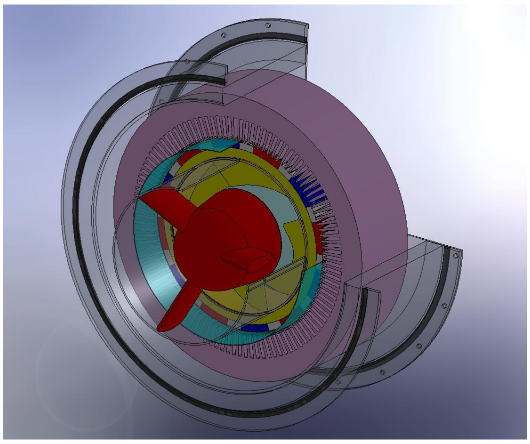

Figure 14. Turbine and generator, integrated

Moreover, the torque is being received by outer ring what means that shaft is unloaded. Synchronic generator, based on permanent magnets technology (PMSG) is integrated with the turbine what makes construction simple that is durable **Figure 14**. Functions which are realized by mechanical equipment in typical turbo sets, here have been moved to the electrical side. Stabilization of the voltage and frequency which are linearly related to a rotational speed, are being carried out by power electronic converters. Its task is to adjust all electrical parameters to the grid standards. This solution allows a turbine to work with a variable speed.

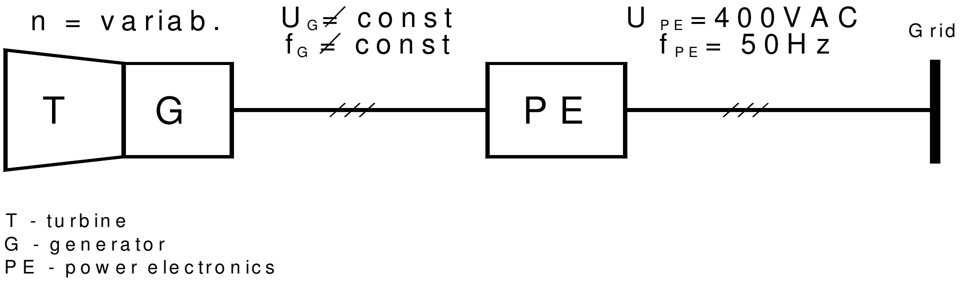

Figure 15. Block diagram

Application of Permanent Magnet Technology has many advantages. One of them is good energy density to machine overall dimensions and mass (good kW/kg relation). Losses in the magnets caused by the circulation of eddy currents in the PM volume are much lower. Fewer rotating components (such as exciters) and simple construction (without slip rings) reduce mechanical stress and increase life of the machine. Like in every solution, there are drawbacks to. One of them is high cost of permanent magnets, but it is successfully reduced by simplified mechanical part. Demagnetization under high temperature which is another disadvantage, is eliminated by water cooling (gap between rotor and stator is fulfilled by water flow), additionally control system monitors the temperature all the time.

4. Water turbine optimization supported by numerical method.

CFD – computer fluid dynamic are helpful to the verification of the design and give a graphic description of the water flow in the turbine channels. We can use CFD to find an approximate pressure on the surface of the blades and we can look at velocity vectors stepping in the turbine passage. Such information is helpful when design the water turbine, because we can eliminate the construction mistake, is completely change the shape of the blade passage and the inlet and outlet as well.

During the flow of water through the propeller of the reaction turbine, the kinetic energy (velocity) as well as potential energy (pressure) converts to mechanical energy. The ideal turbine should be designed to transform the whole energy only in the runner; however the flow through the inlet and outlet should be characterized with a minimum drag. In reality the inlet and outlet of the turbine generate hydraulic losses which has influence on the efficiency of the water turbine.

To describe the use of CFD method for optimizing turbines we can use a propeller turbine, which can show us how to eliminate constructional mistakes. The main parameter of water turbines is the head H which is measured in meters. The head is the difference between the level of water before and after the water power station.

$$H = \frac{\Delta p}{q \cdot g} \tag{4}$$

Δp – pressures difference p_1-p_2 [N/m^2],
q – fluid mass density [kg/m^3],
g – acceleration of gravity [m/s^2].

In **Figure 16**, the pressure distribution which occurs on the surfaces of a propeller turbine can be seen. When the pressure at the inlet and outlet of the turbine is checked, the head at which the turbine works can be calculated. This information is important because it helps us to eliminate design mistakes. Additionally, we can observe how the pressure on rotor blades changes. As it was mentioned before, to find the highest efficiency of turbines constructors are interested in converting the biggest possible pressure difference of on blades surfaces.

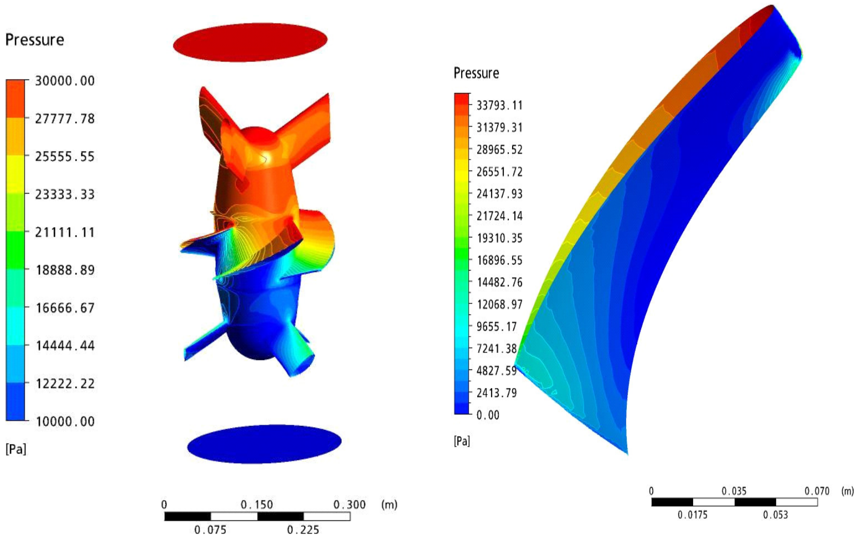

Figure 16. Pressure distribution on hub and along blade

The above **Figure 16** explains the working principle of water turbines and also inform us about the pressure distribution in a blades passage. On the surface of the upper blade we can observe the correct variation of pressure, which convert the potential energy. The visible pressures difference on both sides of the blade gives the rotor a rotary movement.

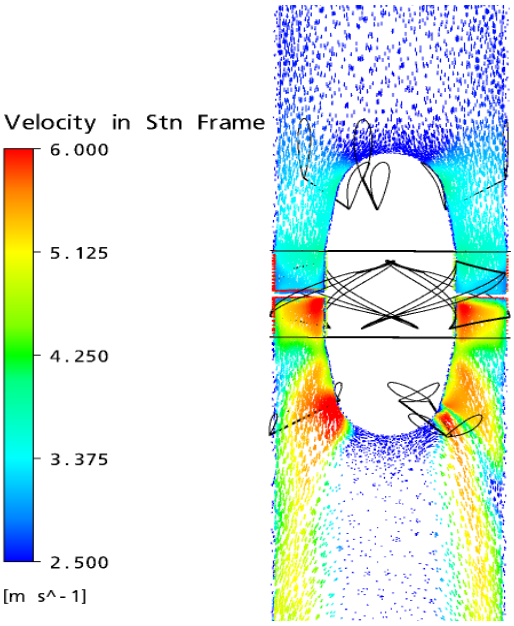

Figure 17. Velocity vectors on a plane through the turbine axis

Next step in the numeric analysis is the velocity distribution in the runner passage. It is of importance for the designer because it is possible to eliminate the undesirable whirls and disturbance of the flow. In **Figure 17** the flow through the whole machine can be seen. The vectors show the speed of the water from inlet, through propeller to the outlet. On the basis of this picture we can draw conclusions about the shape of the runner passage. **Figure 18** presents the velocity distribution inside the blade passage of the runner. This CFD picture informs us about the fact that the profile of blades was chosen properly, and that the angle of inclination is correct.

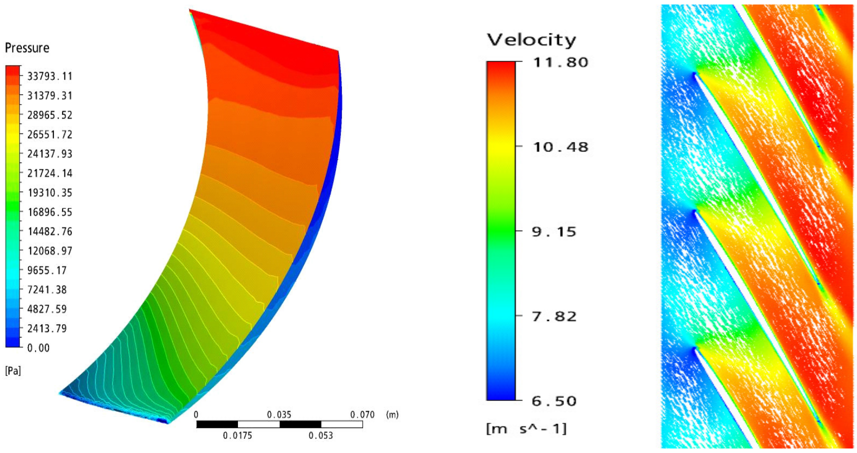

Figure 18. Results from CFD analysis

5. Conclusion

In this paper we have considered the role that Computer Aided Engineering plays in water turbine development. We have shown how parametric design allows designers to put improvements in a fast way, and receive refreshed solution almost immediately. It has been pointed out how CFD in a graphic way shows phenomena's which take place inside turbines. It is obvious that owing to CAE turbine models are better optimized before the model tests will begin which is important from an economic point of view. It has to be remembered, that regardless of its value, it remains a tool, all decisions about changes and improvements are being made by designers.

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