OVERVIEW OF A NEW METHOD FOR DESIGNING HIGH EFFICIENCY SMALL HYDRO POWER PLANTS

by

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Significant number of research projects in the area of renewable energy sources (especially for small hydro power plants) has been made within the Department for Energy and Process Engineering and Regional Euro Energy Efficiency Center at Faculty of Mechanical Engineering (University of Kragujevac, Serbia) since early eighties. The results are various; numerous domestic and international recognition and technical performance tell about the success of the research. Research projects have been following the technical and technological development of research equipment and economy growth. This has led to the development of software for designing turbines of small hydro power plants. In order to notify the public about possibilities of our software, in this paper is briefly described a mathematical model and procedures for calculating and designing of small hydro power for known conditions. As an argument for assessing the validity and potential of our research results is shown constructed small hydro power plant "Bosnia 1", 2 x 100 kW power.

Key words: *SHP, optimal shape, meridional plane, cross section, turbine, impeller, CAD, CATIA*

Introduction

For years, with more or less success, the problem of energy use of both listed and uninvestigated hydro potentials have been trying to be put in first plan at the local scene in order to obtain the status of development priorities. Insisting on small hydro power (SHP) plants and putting extra attention on their significance is justified, because the energy that can be obtained from it is not negligible.

For some time, many international and domestic companies and entrepreneurs without the media exposure, almost stealthily are investigating the most cost-effective

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locations for the construction of SHP plants, buying land, preparing the terrain and building SHP plants. Since 2002th until today about twenty SHP plants of unknown power and performance were built. The SHPP made in the process are mainly individually built or purchased abroad and generally are not designed and developed in the energy optimal manner to use all available hydro energy of the source. The reasons for this situation are: the insufficient presence of inspection authorities on site, lack of expertise of designers, primitive construction of SHP plants and inadequate logic – these are low power sources, so why insist on a high performance efficiency and increasing investment. This way of thinking would be tolerable if a number of SHP plants we consider are small. Not insisting on the high performance of SHP plants (in terms of the massive use of available SHPP potential) means losing precious energy in long term. That is why we insist on the introduction of special regulations to investors interested in the construction of SHP plants (along with already prescribed conditions) so that they would achieve optimal use of available hydro potential on each specific location, as well as the minimum allowed efficiency of SHP plants [1].

In order to arrange the construction of SHP plants, raise their energy performance and to reduce total investment costs related to the design of SHP plants, the authors of this paper have developed sophisticated and relatively inexpensive process of designing SHP plants for each specific location which guarantees high-energy and other technical and technological quality of SHP plants. This software will be described in the following text.

Brief review of the methodology designing turbine of SHP plant

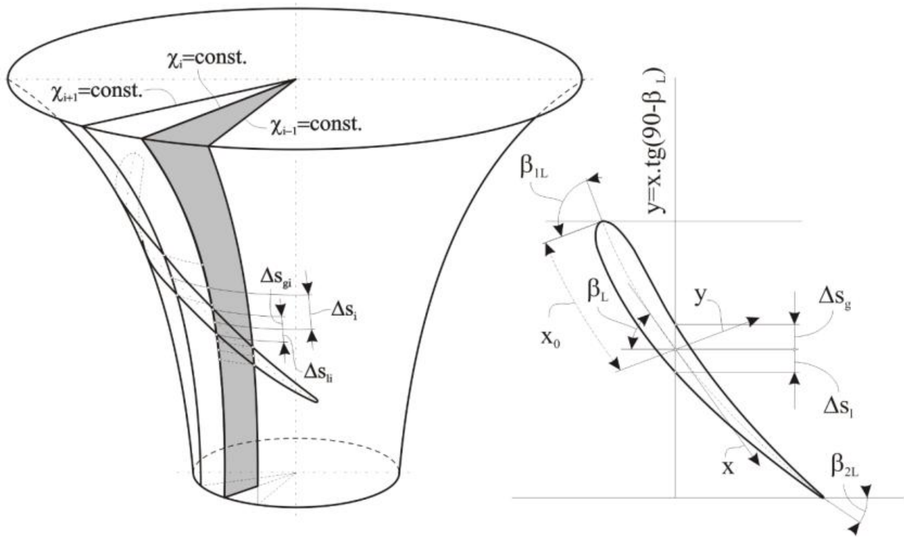

Figure 1. Random axisymmetric stream surface of Francis turbine impeller (left) and penetration of a blade through axisymmetric stream surface (right)

Adjusting the location for the construction of SHPP to the cheapest or easily available design of SHP plant is neither economically nor from the energy aspect justified in the longer term. If we want to produce the optimal amount of energy and also to protect the interest of the government, we have to consider the fact that each site for the SHP plant construction is corresponding to a nominal power, one and only one type of turbine, generator, equipment and other infrastructure systems [2].

Due to limited space, in this paper will be discussed only designing turbine for SHP plant and, again, for the same reason – only one type of turbine. It will be explained the designing of Francis type turbine since the methodology of calculation and design is the most complex (but also for all other types methodology is developed and tested several times).

The methodology for calculating and determining the optimal shape cross section area of the blades and volute casing of SHPP turbine

Because on the several years of experience we know that every detail and substructure of turbines is important for final performance quality. Regardless, we think that the two most responsible parts of turbine for the quality of the energy transformations are [3, 4]:

- impeller – as a "user" of available water potential, and
- the volute casing – as a "distributor" which steers and evenly distributes water power towards impellers' periphery.

It is well known that even the best designed impeller will not work on the optimal way if it's not properly tuned with the volute casing and *vice versa*.

The following text is about basics of the original method, which allows computer calculation and 3-D design of impeller and volute casing of Francis SHPP turbine. This method was checked in the practice several times.

Before we applied this methodology it is necessary to chose the optimal location for the SHPP building, and then to define the number and type of SHPP turbines.

Calculation is based on the so-called semi three dimensional approaches and is divided into four coupled phases.

The *first phase* involves the preparation and definition of the optimal meridional cross section area of impeller. Realization of the first phase is made using software for flow modeling in meridional plane using infinite elements method. The software is used to determine distribution of meridional velocity and optimal number of impeller axisymmetric segments (figure 4). When we are looking the boundaries of these axisymmetric segments in the meridional plane they are consistent with the intersection of appropriate cross section of radial cascade with meridional plane (figure 1).

In the *second phase* the calculation is made to look for the energy optimal cascade within impeller axisymmetric segments defined in the first phase. In order to make impeller with the best energy and cavitations characteristic we shape impeller axisymmetric segments according to curve presented in figure 2 [4-14]. Mathematical model of the curve is:

$$Y_{th} = Y_{th0} \cdot \left(1 - \frac{s}{s_0}\right)^{\left(\frac{s}{s_0}\right)^k \cdot x} \tag{1}$$

where ε and $c_{u\infty}$ from exit till entrance of the new impeller are calculating according to expression:

$$c_{u\infty} = \frac{1}{r \cdot \omega}\left(Y_{th0} - \frac{\Delta Y_{th}}{\varepsilon}\right) \tag{2}$$

$$\varepsilon = \frac{1}{1 + 0{,}8 \cdot (1 + \cos\beta_L) \cdot \left(1 - \frac{60}{n_{sp} + 30}\right) \cdot \frac{r^2}{z \cdot S}} \tag{3}$$

$$S = \int_{r_1}^{r_2} r \cdot dS \tag{4}$$

$$\beta_L = arctan \frac{c_m}{u - c_{u\infty}} \tag{5}$$

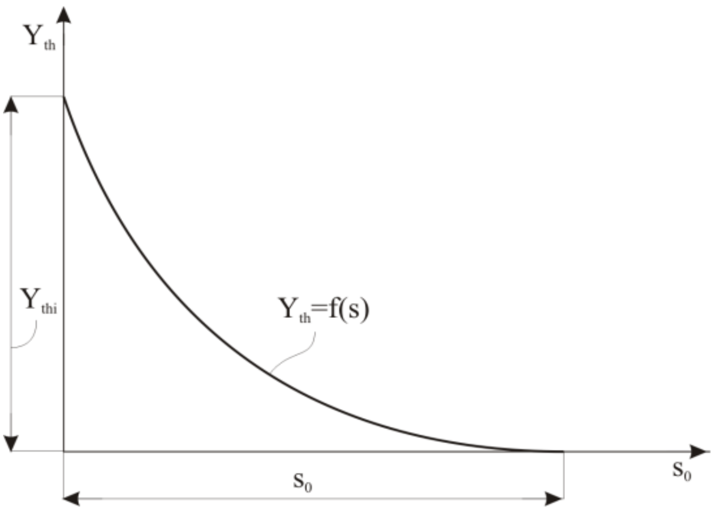

Figure 2. The most eligible curve shape of the available energy for energy transfer in the impeller axisymmetric segments

$$\mathrm{c_m} = \frac{\mathrm{c_m^\infty}}{1 - \frac{\mathrm{z} \cdot \delta}{2 \cdot \pi \cdot \mathrm{r} \cdot \sin\beta_L}} \tag{6}$$

$$\delta = \delta_{\max} \cdot \left[A \cdot \left(\frac{l}{l_{\max}}\right)^3 + B \cdot \left(\frac{l}{l_{\max}}\right)^2 + C \cdot \left(\frac{l}{l_{\max}}\right) + D\right] \tag{7}$$

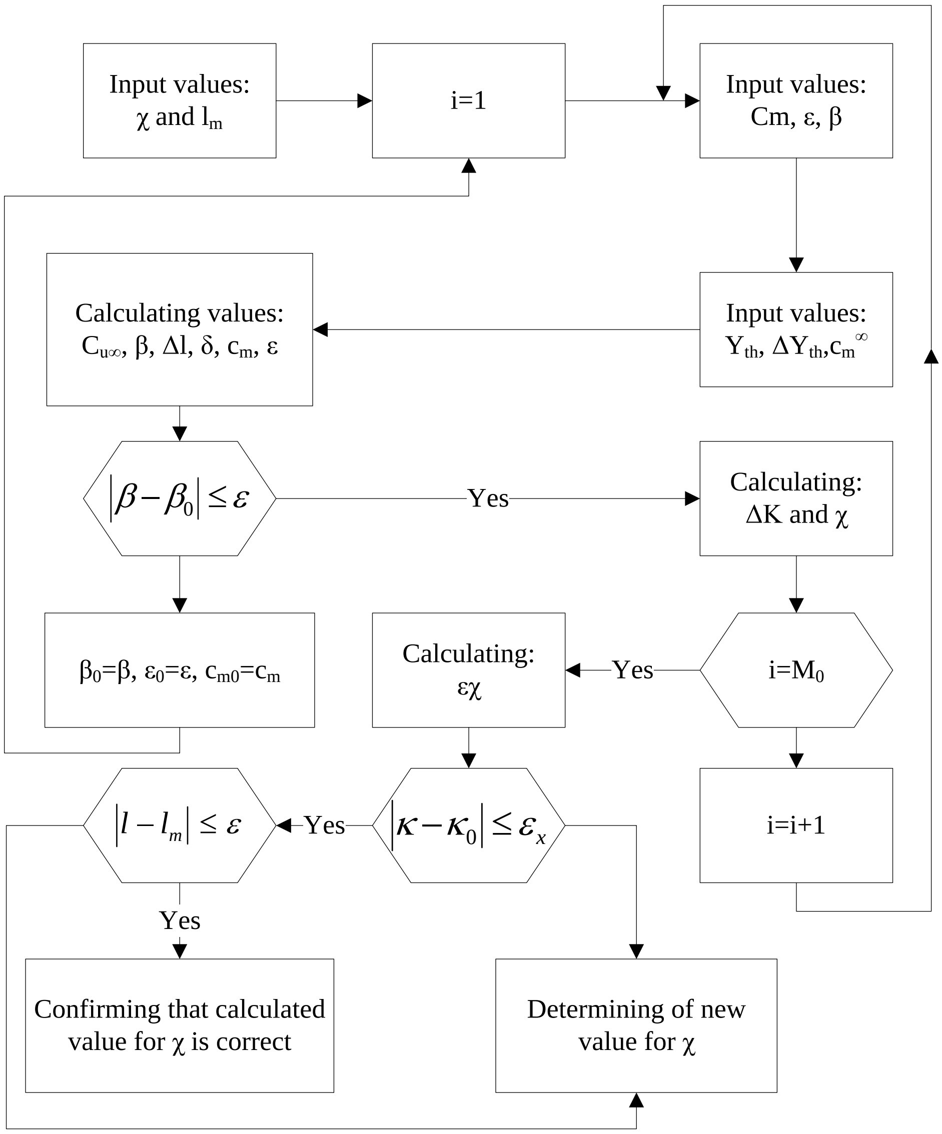

Figure 3. Algorithm for calculating blade angle in circular plane of the impeller

$$l = \sum_{k=1}^{i} \frac{\Delta s}{\sin \beta_L} \tag{8}$$

Due to the mutual interdependence of factors in terms (1) – (8), the calculation is made according to iterative algorithms shown in figure 3.

In the iterative procedure shown in figure 3 the angle of blades in the circular plane of impeller (figures 4 and 5) is determined using the relation (9) and (10):

$$\Delta\chi = \frac{r \cdot \omega - c_u}{r \cdot c_m} \cdot \Delta s \tag{9}$$

$$\Delta\chi = \sum_{k=1}^{n} \Delta\chi \tag{10}$$

The *third phase* includes the calculation and obtaining the radial section coordinates of the impeller (figures 4 and 5). These radial sections are starting points for impeller blades production or impeller in whole using CNC machines, casting or press tools. The process of obtaining the r and z-coordinates of the radial sections (shown in figures 4 and 5) is based on the postulates of geometry, and it is an integral part of program modules for calculation and designing of impellers.

The *fourth phase* includes the calculation and obtaining of the coordinates of volute casing sections. The method is also easily shown as algorithm and it's based on the theoretical and experimental results. Application of this method in practice provides the highest quality turbine volute casing. Program module, made on the basis of this algorithm, allows obtaining the coordinates of volute casing suitable for turning mathematical model into physical model using CNC machines, casting molds or for preparation of an appropriate structure for welding.

For the calculation of optimal impeller, intake guide device and guide vanes, in accordance with the previously stated procedure, we have developed a module in the FORTRAN programming environment, and for the development of CAD models we used the CATIA programming environment.

Forming CAD model of the volute casing and impeller in CATIA and benefits

Impeller and volute casing of SHPP are characterized by very complex geometry so 3-D modeling is a prerequisite for a successful and quick design and production of high efficient SHPP. Please note that this approach, due to relatively high costs of production of these parts, is cost-effective even for production of individual cases of SHPP and also provides the following benefits:

- quality assessment of the impeller in the design stage (the possibility of "measuring" of distance, area, *etc*., which is very difficult to consider in the 2-D model);
- quality assessment of assembly SHPP, especially the relations among the impeller, volute casing and other SHPP subassemblies, and in particular, and
- the possibilities to use similitude which allow us to make simple constructive changes of the key parameters in order to achieve very quickly design of a new SHPP.

In the following text is shown the approach used which is interesting because of the rational engagement of 3-D design in single or small serial production.

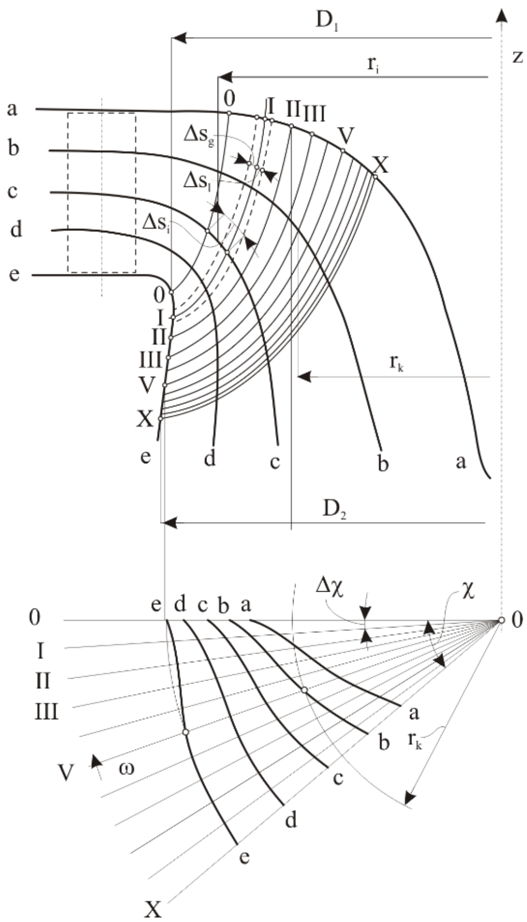

Figure 4. Impeller axisymmetric segments of small turbine (top) and radial cross section of the blades in meridional and circular plane (bottom)

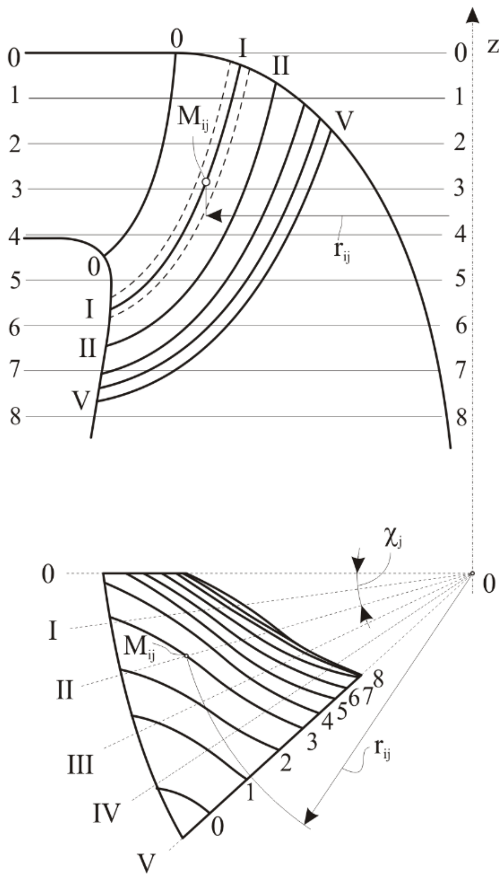

Figure 5. Cross section of the blades in meridional and circular plane suitable for molding

Development of CAD impeller model

The impeller which will serve to illustrate possibilities of the proposed procedure for calculating and 3-D modeling after the agreement with the manufacturer was decided be cast. The dimensions of calculation model were automatically increased for subsequent machine processing but for the impeller blades dimensions' increasing is minimum, almost negligible.

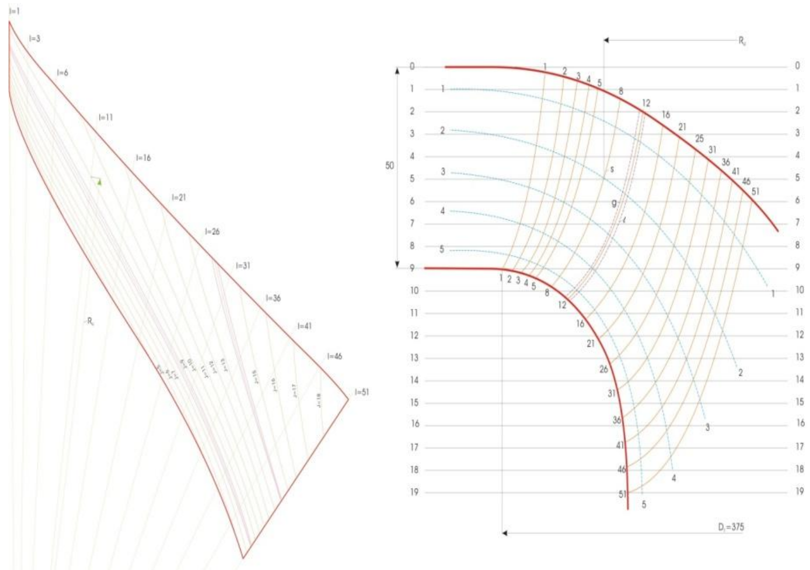

Figure 6. Cross section of the blades in meridional and circular plane suitable for molding retrieved from original methodology. Together with additional coordinates these cross sections represent starting points for impeller 3-D model development (circular projection – left, meridional projection – right).

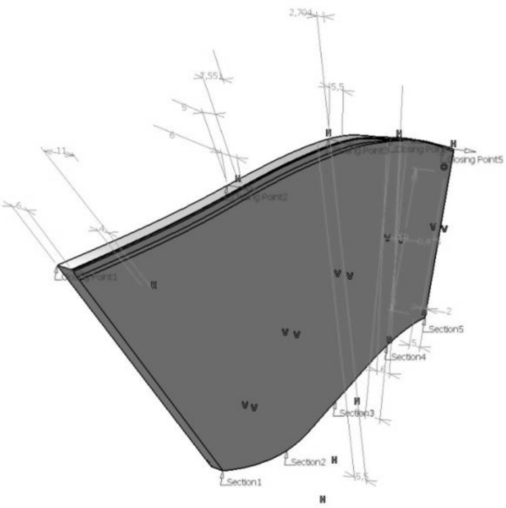

Figure 7. Impeller blade of SHPP turbine "Bosna 1" defined by calculated values

For illustrations of the possibilities and the quality of the procedure described for calculating and designing SHPP turbine we have selected a few steps that are in our opinion, the most eligible for this paper and show them in figures 6, 7, 8, 9, 10, 11, 12, 13 and 14. These figures represent the axisymmetric segments of project documentation created for the job request of designing SHP plant "Bosna 1" which has been erected and has a nominal power of 2 x 100 kW.

A full potential of using CAD design would be expressed if the CAD model of impeller would be printed on the 3-D printer and the result of printing would be used as a cast kernel. During the design of impeller for SHPP “Bosna 1” 3-D printer wasn’t used because of the high cost of printing.

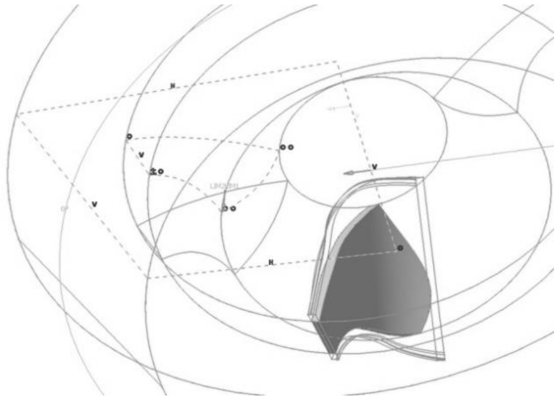

Figure 8. Defining profiles for “cutting” and forming entrance and exit blade curve

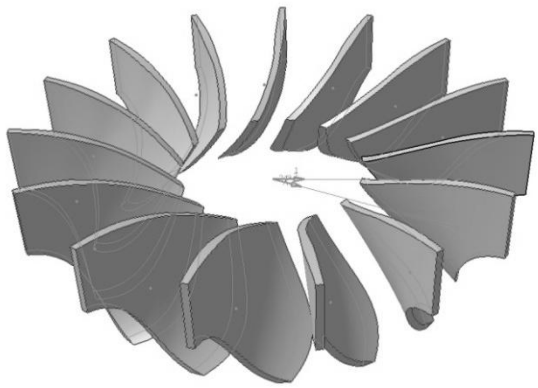

Figure 9. Impeller with 15 blades formed using command “Circular pattern”

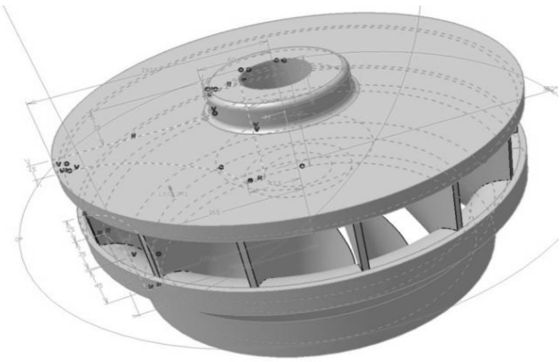

Figure 10. Adding impeller’s “body”

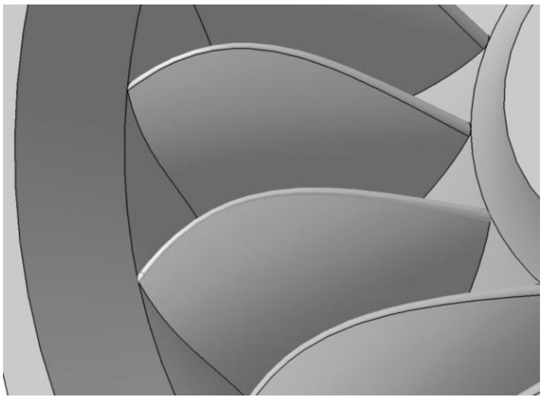

Figure 11. Using command "Tritangent fillet" (marked surface) for final shaping of impeller's blades entrance, exit and interblade space

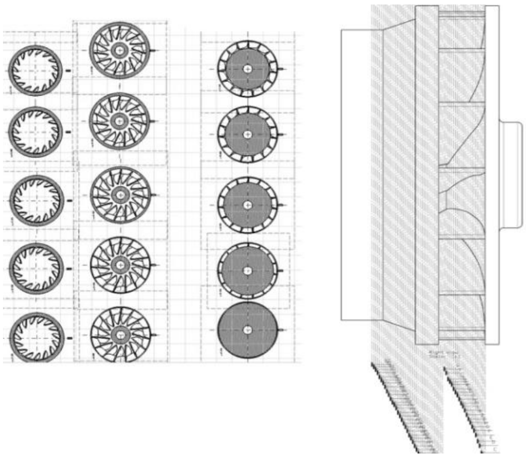

Figure 12. Positioning cutting surfaces on 2 mm distance and sections generation

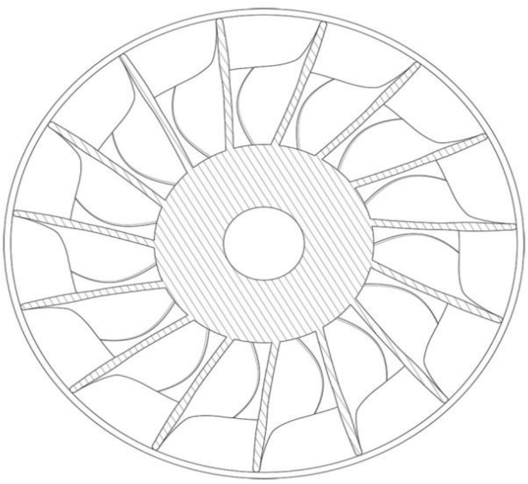

Figure 13. Example of the sections of the impeller suitable for molding

Figure 14. Impeller CAD model (left) and photography of casted impeller (right) of SHPP "Bosna 1"

Development of CAD volute casing model

In agreement with the manufacturer of SHP plant "Bosna 1", it was decided that the volute casing will be made by casting and welding. Casting was used for parts of casing that needs to have a larger mass and the bending and welding of the metal sheet was used for volute casing itself.

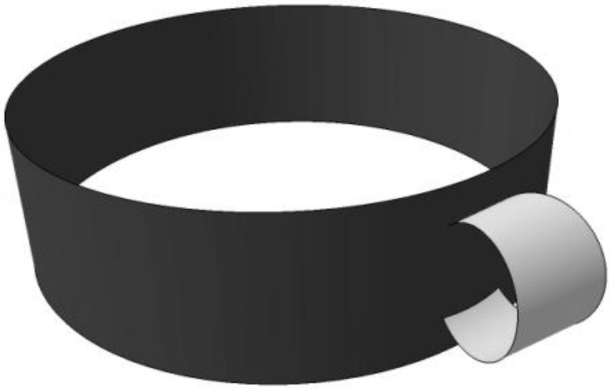

Figure 15. Example of a volute casing axisymmetric segment (120°-135°) in folded state

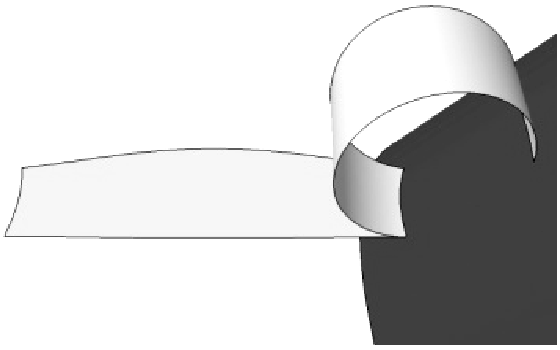

Figure 16. Axisymmetric segment (120°-135°) in unfolded state

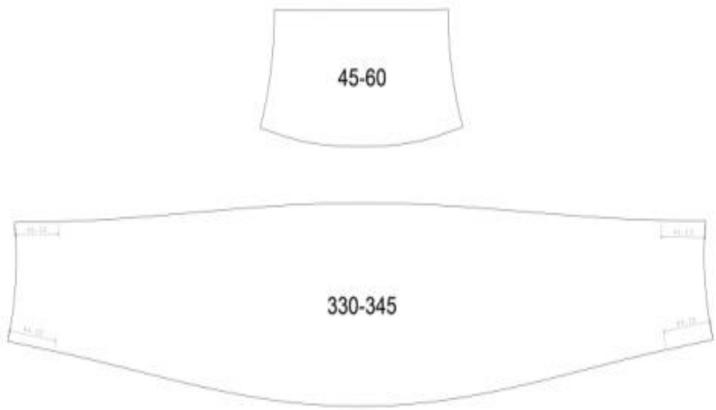

Figure 17. Examples of unfolded state (top – 45° – 60° – elliptic flow area; bottom – 330° – 345° – circular flow area)

"Tailoring" from the metal sheets for the volute casing and obtaining their unfolded state is done in the CATIA environment (figures 15 and 16). Therefore, it was possible to divide casing in 24 axisymmetric segments with a step of 15^{o}.

Unfolded states are printed (figure 17) and according to them are made metal plates axisymmetric segments. The first 13 axisymmetric segments have a cross section in shape of circle and the other 9 in the shape of ellipse. Ellipses are defined by semi-axis and distance of the ellipse center from impeller axis. Circular axisymmetric segments are defined by the radius and distance of the circle center from impeller axis.

It should be noted that the entire process is done for the "average" area (half of the sheet thickness should be added on actual dimensions) in order to fit casing proper after bending.

In figure 18 is shown the photo of volute casing of SHPP turbine “Bosna 1”, which is produced using described technology design.

Figure 18. Photography of produced volute casing of SHPP turbine “Bosna 1”

Brief description of SHP plant “Bosna 1”

SHP plant “Bosna 1” consists of two aggregates shown at figure 19 and located in a building which is specially redesigned for this purpose. Both aggregates are equipped with an automatic control of pre-runner for the regulation of the basic parameters. Applied executive actuators are electric-mechanical type with the processors for managing the entire process and managing the performance of automated substructure that provide: the stability of work, the frequency and voltage of produced electricity, connection to grid, measuring, balancing and billing of produced electricity, *etc.* Generators and transformer are domestic products, and SHP plant is powered through the intake pipeline that has two branches to bring water to the "mouth" of each of the aggregates. The processors in the command cabinet monitor the flow to the SHP plant and decide when it is optimal to put in the function only one, and when both aggregates.

Figure 19. Photography of actual state SHPP turbine “Bosna 1” 2 x 100 kW

Figure 20. Photography of actual state of control panel of SHP plant “Bosna 1”

The number of import components involved in the SHP plant is minimal, as a curiosity, we would like to stress that all parts of both aggregate turbines made of stainless steel and producer and supplier of whole SHP plant is company "Kragujelektrane", Ltd. from Kragujevac.

Conclusions

Original SHPP conceptual design presented in this paper is in compliance with new energy efficiency approach. This design allows achievement of highly efficient SHPP with low investments and which would be able to utilize complete hydro potential at each location considered.

Conducted research on site where power plants are erected according to presented methodology completely confirmed our assumptions about highly efficient characteristics of these SHPP.

Nomenclature

b – impeller axisymmetric segment width
c_m – meridional component of absolute velocity of calculated impeller axisymmetric segments
c_m^∞ – meridional component of absolute velocity of calculated axisymmetric segments of the impeller with infinite number of blades
$c_{u\infty}$ – velocity component in circumferential direction of the impeller with infinite number of blades
i – current cross section of the impeller axisymmetric segment
k – exponent which determines curve type $Y_{th} = f(s)$
l – blade profile length
l_{max} – total blade profile length of the impeller axisymmetric segment
M_0 – number of calculated sections of the impeller
n_{sp} – specific rotational speed of turbine impeller according to the turbine power
r – radius of calculated impeller axisymmetric segments
r – axis of cylindrical coordinate system
S – static momentum of the average meridional line in impeller axisymmetric segment
s – distance of current cross section from impeller axisymmetric segment entrance measured in average meridional stream line
s_0 – total length of average meridional stream line at impeller axisymmetric segment cross section
Δs – length of average stream line in meridional cross section of impeller axisymmetric segment between two adjacent calculated cross section areas
u – peripheral velocity of the impeller in calculated cross section
$\Delta \dot{V}_k$ – flow through impeller axisymmetric segment
x – exponent which is determined by iteration method during the calculation
Y_{th} – impeller axisymmetric segment head of the turbine exchanged from impeller entrance till current calculated cross section
Y_{th0} – impeller head that should be achieved in every impeller axisymmetric segment
ΔY_{th} – impeller head exchanged between two adjacent cross section areas of the impeller axisymmetric segments
z – blade number of the impeller
z – axis of the cylindrical coordinate system

Greek letters

β_L – blade angel of calculated impeller axisymmetric segments
δ – width of the profile blade in calculated axisymmetric segment of the impeller
δ_{max} – maximum width of the profile blade in calculated axisymmetric segment of the impeller
ε – head decrease in axisymmetric segment of the impeller

χ – angle that in circular plane of the impeller defines the mutual position of entrance and exit blade curves

$\Delta\chi$ – angle that in circular plane of the impeller defines the mutual position between two adjacent cross section areas of the impeller

ω – angular velocity of the impeller

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