

Constructive Optimisation of the Propeller Type Mixing Devices Using the Virtual and Rapid Prototyping

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The paper points out the advantages of rapid prototyping for improving the performances/constructive optimization of mixing devices used in process industries, here exemplified to propeller types ones. The multidisciplinary optimization of the propeller profile affords its design using parametric CAD methods. Starting from the mathematical curve equations proposed for the blade profile, it was determined its three-dimensional virtual model. The challenge has been focused on the variation of propeller pitch and external diameter. Three dimensional ranges were manufactured using the additive manufacturing process with Marker Boot 3D printer. The mixing performances were tested on the mixing equipment measuring the minimum rotational speed and the correspondent shaft torque for complete suspension achieved for each of the three models. The virtual and rapid prototyping method is newly proposed by the authors to obtain the basic data for scale up of the mixing systems, in the case of flexible production (of low quantities), in which both the nature and concentration of the constituents in the final product varies often. It is an efficient and low cost method for the rapid identification of the optimal mixing device configuration, which contributes to the costs reduction and to the growing of the output.

Keywords: constructive optimisation, virtual and rapid prototyping, propeller CAD design, mixing devices performances

One of the most important challenges of modern engineering design is to improve the design accuracy as main result of product technical performances. The virtual and rapid prototyping involves the modern multidisciplinary optimization as well as robust design. Both of them imply the study of shape design variation in order to achieve some required parameters and all the process is done as an automatic loop.

The geometry optimization as result of shape variation was analyzed and it was a stage of this complex design, taking in mind the optimization of all functional demanding. Consequently, the task could be achieved if we took into account the parametric three dimensional models, which is supported by a range of values with close influence.

The paper [1] presents the study of multidisciplinary optimization and robust design of gas turbine component design, by using the parametric CAD modelling and the methodology for the gas turbine disk. The result demonstrates that the CAD centric approach enables significant advantages over the manufacturing process. Some authors [2] have studied the robust design with minimizing the effect of uncertainty or variation in the design parameters without eliminating the source of the uncertainty factors. The important roles of modelling and calculation of robustness in a multidisciplinary design is discussed in Marczyk [3].

This paper concerned with the method of propeller-type mixer design following the multidisciplinary optimization and rapid prototyping manufacturing in order to analyze the shape variation over the mixer performances.

The propeller is generally used for mixing processes in low viscosity (2000 – 5000 cP) liquid medium (for example: solid suspensions; liquid-liquid dispersions; dissolving etc.). The generated flow pattern is primarily axial. Propellers are characterized by high discharge capacity (pumping action); the shearing action is significant at high rotational speeds.

Mixing in liquid medium is a frequent operation in the process industries [4-9]. The mechanical mixing devices optimization is based on the study of the correlation between the mixer constructive features, specific hydrodynamic phenomena produced and liquids mixing quality [7]. In case of propeller, the geometrical configuration of the blade (shape, curvature and angle of attack) affects the flow pattern in the vessel.

In order to achieve an optimum mixing (low energy consumption, good mixing quality, short mixing needed time) and taking into account the above mentioned aspects, it is important to study the mixing device optimization. At first, it was elaborate the mathematical model of the blade profile, so the set of equations afford the study of optimizing the theoretical approach. Next we have made the three dimensional model by using Catia V5R19 software, with Knowledge Advisor workbench for parametric modelling of the shape. Finally, the propeller was manufactured on the 3D printer, so that we have noticed a set of functional performances of the mixing device. The overall objective was to attend the optimal design with some uncertainties caused by hydrodynamic forces during the mixing.

The parametric design of the propeller

The propeller takes the most important functionality of the mixing devices, due to the flow generated during its movement. The relative velocity of the fluid along the blade will be influenced by the rotational speed as well as the blade three dimensional shape.

The propeller shape theory points out the mathematical model based on its geometry as it is shown in the figure 1.

The angle of attack α , is computed as function of the helix angle θ and the angle of the blade pitch Φ :

$$\alpha = \Phi - \theta \quad (1)$$

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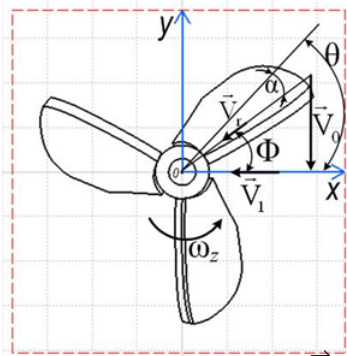


Fig. 1. The blade geometry

The liquid relative velocity \vec{V}_r as section local flow velocity vector, is acting along the direction imposed by Φ , as it is shown in figure 1, so it has to be compute as summation of the axial flow velocity at propeller disk \vec{V}_0 and the section local flow velocity vector \vec{V}_1 .

Due to the flow generated along the blade geometry, the angle of attack α will be computed following the eq. (1), where θ is the helix angle of the profile for each section of the blade. We aim to improve the mixing process by increasing or decreasing the value of this angle of attack, so that we may change the value of θ by changing the propeller geometry.

Consequently, the first important parameter value we have to analyze will be the helix angle θ .

The second parameter will be the angular pitch of the blade, so that a small pitch and helix angle too will provide very good performances against fluid resistance.

On the other side, the propeller diameter is a parameter used for computing the aspect ratio, meaning that a long and narrow blade will provide a high aspect ratio and a short and stubby blade will provide a low aspect ratio. From this point of view, we may take the assumption that a liquid cylinder having the propeller diameter will be generated around the propeller during its motion and the relative velocity \vec{V}_r (fig. 1) will characterize the flow. Regarding the mixing process, we conclude that a large blade diameter is working on a large theoretical cylinder, so that it is a wondering process characteristic. According the theory presented above, the third parameter will be the propeller external diameter.

We have used the method of parametric three - dimensional design starting with the law given by the algebraic equation of Archimedes helix, in order to define the helix angle. The values of polar coordinates computed for a point which is defined following this geometry are:

$$R = A \cdot \beta \quad (2)$$

where R - the radius of the helix considering the polar coordinates; β - the angle of the helix; A - the parameter of the helix.

Meantime we have to impose the pitch p of the helix:

$$p = A \cdot \beta \cdot \frac{\pi}{180} \quad (3)$$

For a point on the helix curve we may compute the curvature radius R_c :

$$\frac{1}{R_c} = \frac{R^2 + 2 \cdot R'^2 - R \cdot R''}{(R^2 + R'^2)^{\frac{3}{2}}} \quad (4)$$

Following the XOY plane, the Cartesian coordinates (x_c , y_c) for the curvature center point are given by the following equations:

$$x_c = R \cdot \cos(\beta) - \frac{(R' \cdot \sin(\beta) + R \cdot \cos(\beta)) \cdot (R^2 + R'^2)}{R^2 + 2 \cdot R'^2 + R \cdot R''} \quad (5)$$

$$y_c = R \cdot \sin(\beta) - \frac{(R' \cdot \cos(\beta) + R \cdot \sin(\beta)) \cdot (R^2 + R'^2)}{R^2 + 2 \cdot R'^2 + R \cdot R''} \quad (6)$$

We have analyzed the blade profile using eq. (1) - (6) and the final shape of proposed profile was computed using Matlab software, so the results are presented in figure 2 and figure 3.

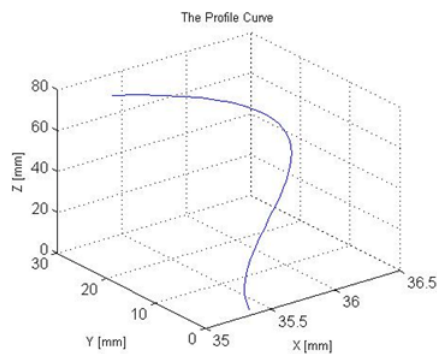


Fig. 2. The profile curve used for the blade shape

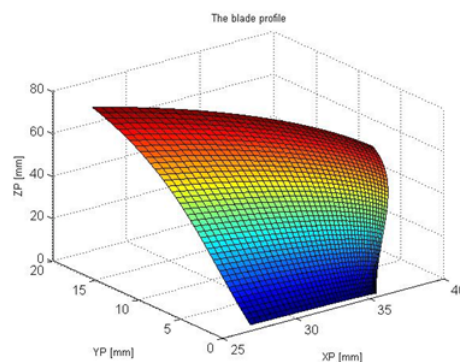


Fig. 3. The computed spatial blade profile

From figure 2 we may infer the orthogonal coordinates (X, Y, Z) of a point which describes the spatial curve, the Archimedes helix for instance, of the blade profile. The aim of mathematical modelling was to compute and to represent the three - dimensional shape of the blade, as it is shown in figure 3, by varying the helix angle and the angle for each normal section as well. We have taken in mind that the helix angle is one of the three main parameters of CAD design.

The parametric three dimensional design of the propeller

The parametric design was created as a better method of three - dimensional design by using CAD software, due to its main advantage of time saving. We have used the Catia V5 R19 software, Knowledge Advisor workbench, for the parametric shape design of one blade.

At first we have designed three new parameters of type length, so each one should have the values computed for the each Cartesian coordinates of the points on the three dimensional shape. For instance, for the first point P1 ($XP1, YP1, ZP1$), we have made the associations $length1 = XP1$, $length2 = YP1$ and $length3 = ZP1$. The values for all these points are written using three columns of an Excel file.

It was used the same method of association for the second point P2 ($XP2, YP2, ZP2$) for instance, characterized by new parameters of type length, named Length.4, Length.5, Length.6. From the Design table command of the workbench, the values are assigned (fig. 5).

The next step was to use the construction of points by using Catia functions of Point Constructors module. We have chosen the function that requires the three values of length, meaning the coordinates for each of three axes (fig. 6).

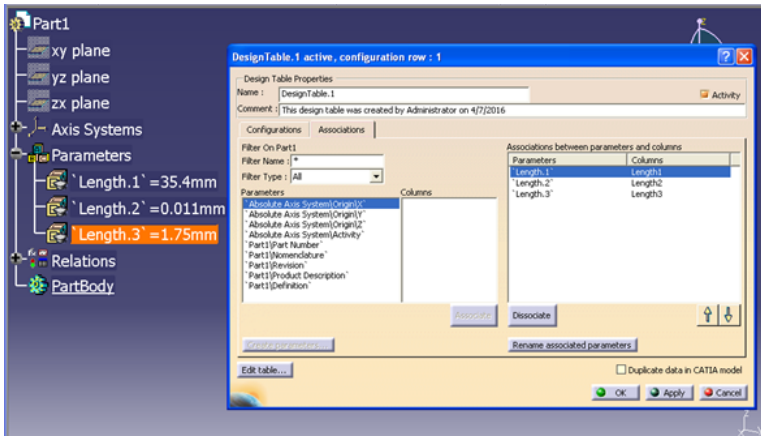


Fig. 4. The association function for length parameters

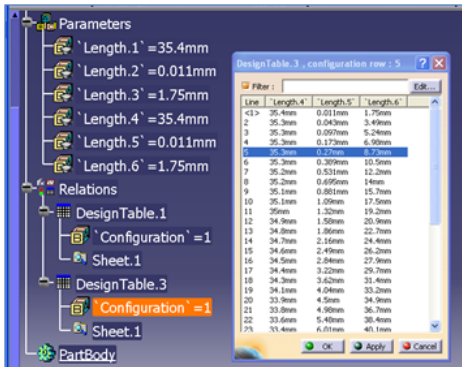


Fig. 5. The values assigned for the second point

We have to verify that the relationship is working, so the Active Tab was automatically set to Yes as we may see in figure 7.

All the points were designed in the three dimensional working space, following the stages explained before. Finally, by using the Catia functions of wireframe constructors, we have designed a spline curve passing through these points (fig. 8).

The final result is displayed in figure 9, so that the curve for the blade profile generation was computed using the mathematical model of its geometry.

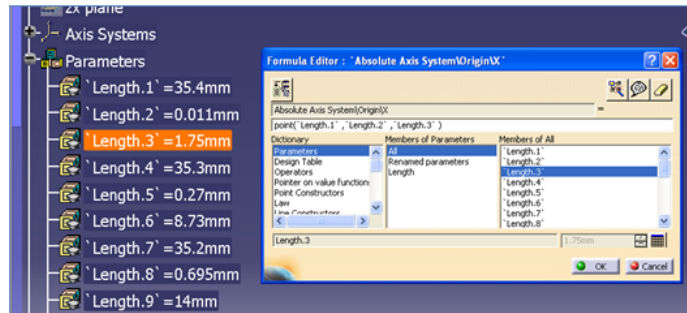


Fig. 6. The points designed by using the Catia functions

Finally, by using the Knowledge Advisor and Generative Shape Design workbenches, it has been made the propeller three - dimensional models, following the variation of three parameters presented above: the blade profile, which infers the pitch and the curve changing as well as the external diameter of the propeller. One of the three models is presented in figure 10.

Following the research steps presented above, we have made the three dimensional models for three propellers, using as parameters the variation of the pitch and angle of the profile as well as for their external diameters.

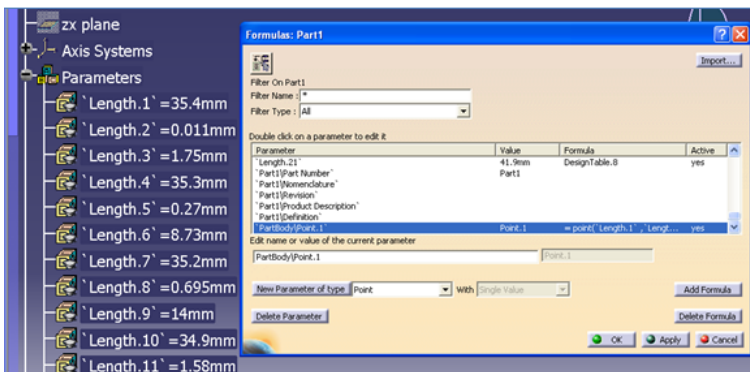


Fig. 7. The tab Active is set to Yes automatically

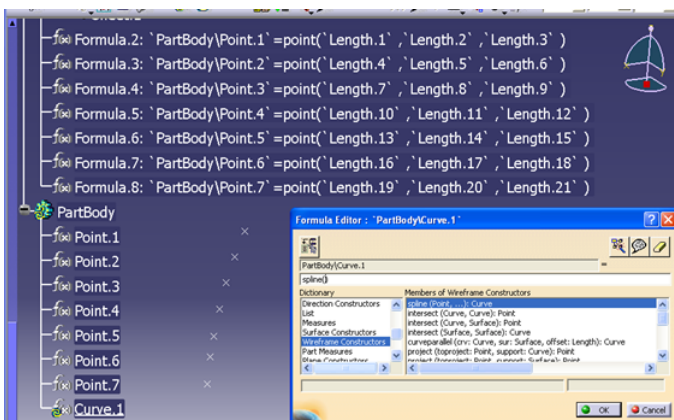


Fig. 8. The function for designing the spline curve

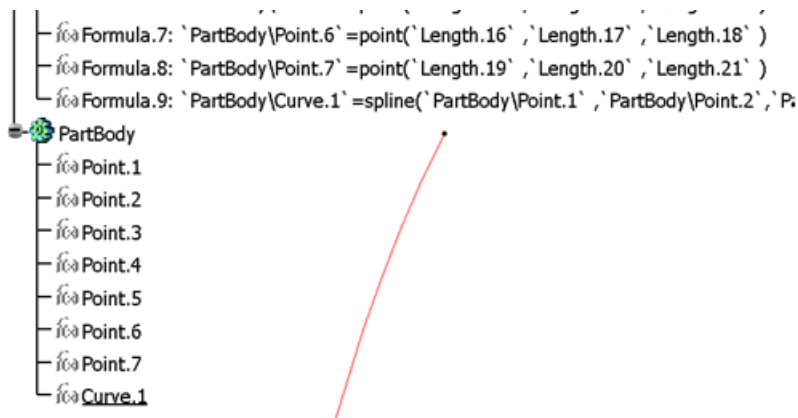


Fig. 9. The spline curve of the blade profile

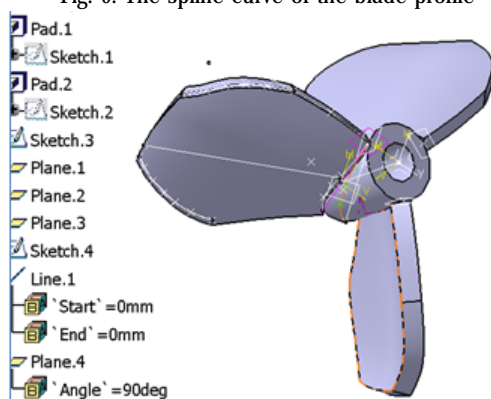


Fig. 10. The three - dimensional propeller model

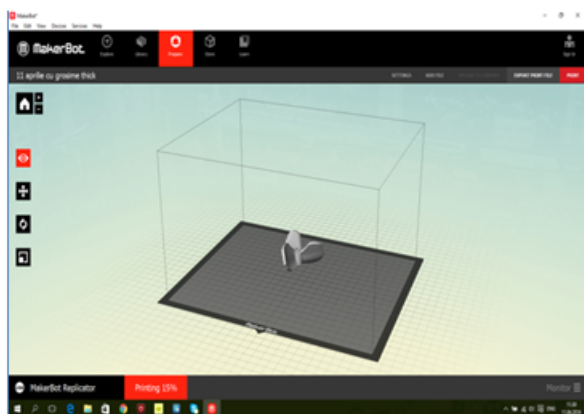


Fig. 11. The software used for the 3D printer

The rapid prototyping of the propeller

The new scientific field of manufacturing researches, known as Rapid Prototyping or Additive Manufacturing, are very modern technological ways of product set-up that are able to work with very complex shapes of the product involving time reducing and minimum costs. Meantime, other devices or machines are used, so the CAD model made with specific software is the only initial requirement.

The main word of all these technologies is the *section*, meaning that the part is made of series of sections added repetitively to materialize the final product shapes. The characteristic of the process is that the spatial shape was reduced to a planar one. If we use the Additive Manufacturing we may improve the complex and functional shapes because of the communication between the working teams of the same company or the abroad companies too. The main disadvantages are the accuracy and surface quality decreasing due to the scale effect.

The material we have used for propeller manufacturing is PLA (polylactic acid) warmed at 215°C, with 1°C above its melting temperature. We have to pay attention on the material properties, because of the heating process as



Fig. 12. The propeller at the beginning of the printing process

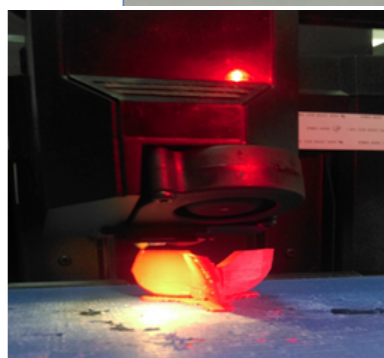


Fig. 13. The working table of the 3D printer

source of uncertainty. For instances, PLA has the density 1.1 g/cm³, elasticity module 560 MPa, 3% drop elongation, the heating resistance 13 J/m. Some other materials, such as ABS (acrylonitrile butadiene styrene), polyethylene HDPE, polypropylene, elastomer, Polyphenylsulfone (PPSF) and polyamide could be used. The extruded material has the active section of 0.12 – 0.15 mm and it is put along OZ axis of the spatial Cartesian system during the deposition process. The axial displacement is high accuracy computer controlled.

At first we have made the file needed for system interchange between Catia software and the working software of Marker Boot 3D printer, so the *stl* file was automatically provided. The 3D model is sliced vertically by the 3D print dedicated software, so the entire surface will be divided in layers. When we have started the process we have done this as we infer from figure 11.

All the propellers have been put on the working plane of the 3D printer horizontally working table as it is shown in the figure 12. During the printing process, the head with fused material is moving along Z axis, a pressured material passing through the pump will flow, so a new layer is put and glued on the previous layer. There are some other types of 3D printers whose printing heads are working inside a warmed room, preventing uncontrolled solidification phenomena generating the errors.

The propeller is materialized by using the Additive Manufacturing process as we have described.

The final product realized following the proposed method is presented in figure 14.

We have done each step described above for printing the three propellers modelled before. Their functionality performances depend on their surface quality, curve used for blade border and their curvature radius.

As future work we aim to improve the propeller spatial shape by modifying the propeller parameters with dynamic influence on the liquid flowing, such as hydraulic forces and couples. Meantime, the vertical movement of the

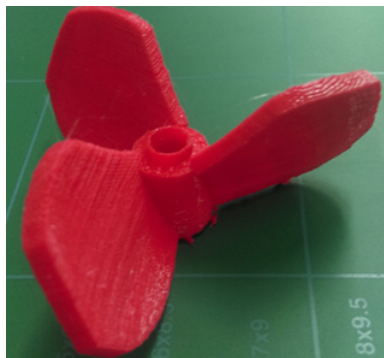


Fig. 14. The final shape of the propeller

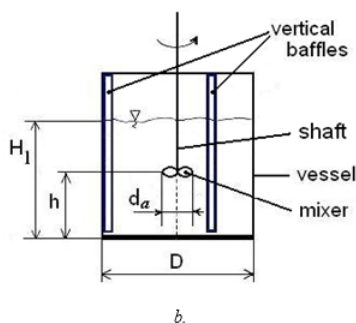
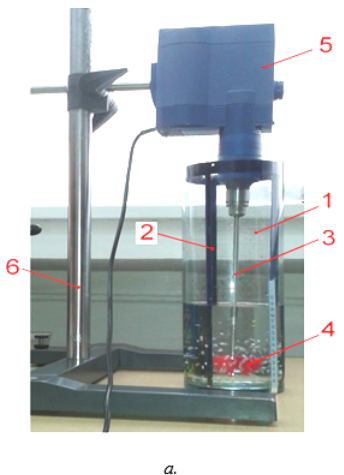


Fig.15. a. The mixing equipment used for dispersing solids into liquid.

- 1 - cylindrical vessel; 2 - vertical baffles; 3 - shaft equipped with propeller-type mixers; 4; 5 - driving device; 6 - support;
b. Schematic representation of mixing system configuration.

propeller along Z - axis during the mixing process should be studied and the list of some other parameters have to be completed. The new prototype should be tested and the technical performances should be analyzed.

Experimental measurements

We have tested the mixing performances of all three printed propeller-type mixers in the case of suspending of solid particles in water (low viscosity liquid). Polymeric particles ranging in size from 0.1 to 0.3 mm, and denser than water were used. Solids concentration was 10% by weight.

The mixing equipment is presented in figure 15a. Experiments were performed in a glass cylindrical vessel fitted with 3 vertical baffles, using a rotating mixing device with variable rotational speed (8 - 290 rot/min). In all cases the mixing device was centrally positioned in the vessel (fig 15b). The liquid height, H_l was equal to the vessel diameter, D ($D = 135$ mm).

On the mixing device shaft were mounted, in turn, the three printed impellers (fig. 16). The produced flow pattern was axial descendent.

The mixers have the same diameter - d_a - approximately 50% of the vessel diameter, D .

In order to compare the mixers functional performances, the following parameters were measured in the case of each tested impeller: the minimum rotational speed and the correspondent shaft torque for complete suspension (ascertained visually). The condition for complete solids suspension is that no solid particles rests stationary on the vessel base for more than one to two seconds. At this value of rotational speed, mixing time was set for 5 min.

The uniform distribution of particles throughout the whole vessel was not especially examined.



Mixer 1



Mixer 2



Mixer 3

Fig.16. The three printed propeller-type mixers

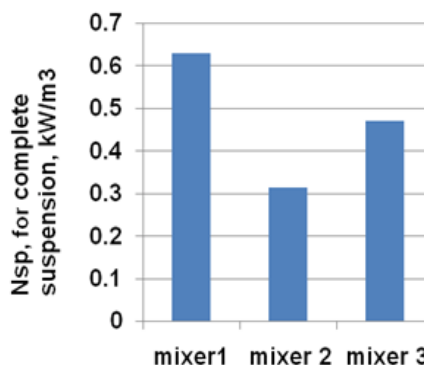


Fig.17. Mixer geometry influence on the suspension efficiency

Experimental results. Interpretation

The optimal impeller distance from the vessel bottom, denoted h (fig. 15,b), was determined experimentally for each mixer: $h \approx D/4$. This mixer position allows maximizing the effect of the pumping capacity of the impeller.

The chosen criterion to assess the suspension efficiency of each impeller was the specific mixing power, N_{sp} , required to ensure the complete solids suspension, and calculated with relationship:

$$N_{sp} = \frac{\pi \cdot n_{min} \cdot M_t}{30 \cdot V_l} \quad (7)$$

where:

n_{min} - minimum rotational speed of the mixing device, corresponding to the complete suspension;

M_t - measured shaft torque, corresponding to the n_{min} ;

V_l - liquid volume.

Figure 17 presents the results obtained.

Comparing the experimental results, maximum efficiency was obtained in the case of mixer 2.

Conclusions

The virtual and rapid prototyping are based on the three dimensional model of the part, made by using specialized CAD software, i.e. Catia, Pro-Engineering or Solid Works. In order to increase the technical performances of the product, the multidisciplinary optimization allows the parametric design as automatic loop. We have applied these ideas for the propeller design, working in mixing equipment establishing the mathematical model of the blade profile at first. Taking into account the propeller functionality, three parameters were identified - the pitch and angle of the curve profile for the blade, taken as Archimedes helix for instance, and the external diameter. The spatial curve of the profile has been modelled according to the

mathematical equations. The Catia software with Knowledge Advisor Workbench allows the parametric design, providing a set of three virtual propellers. All of them have been set up by using the rapid prototyping technique with 3D printer Marker Boot.

Experiments showed that the propeller mixing efficiency depends on the mixer geometry, rotational speed and impeller position related to the bottom of the vessel.

The experimental results obtained, presented in the paper, can be utilized in the scale-up process for the industrial mixing equipment for suspensions with similar properties of the ones obtained in the laboratory.

The virtual and rapid prototyping method is newly proposed by the authors to obtain the basic data for scale up of the mixing systems, in the case of flexible production (of low quantities), in which both the nature and concentration of the constituents in the final product varies often. It is an efficient and low cost method for the rapid identification of the optimal mixing device configuration, in each case, contributes to the costs reduction and to the growing of the output. Here there were demonstrated both the rapid prototyping method and the application in mixing optimization based on experimental procedure.

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