MODELLING OF SINGLE-PHASE FLOW IN THE STATOR CHANNELS OF SUBMERSIBLE AERATOR

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The paper deals with the design of stator channels of the aerator using CFD code ANSYS Fluent. The main problem is to design proper inclination of the channels corresponding with the direction of flow at the impeller outlet. The direction of flow is variable along the channel and represented by the absolute velocity angle. Therefore, this angle is computed first, and according to it, the inclination of stator channels is designed. Numerical simulations are made as single-phase flow for two different shapes of channels and for two different channel inclinations – for already computed ones and for ones used in older type of aerator which this work develops. Stator channels inclined by computed angle that corresponded with the direction of flow had the best results. On the other hand, the channels inclined by the same angle as the channels of older aerator had the worst efficiency. The decrease of aerator efficiency was caused by the large vortexes in the stator channels.

Keywords: *submersible aerator, stator channels, aerator impeller, numerical simulation, CFD, absolute velocity angle, single-phase flow, ejector*

1. Introduction

Aerators are devices used for supplying oxygen into the water. For this reason they have strong representation in wastewater treatment plants, ponds, lakes and so on. Aerators are widely used in a number of industries wherefore they have various principles they work on. Aerator mentioned in this work falls into the category of submersible aerators. Various constructions of these aerators are patented by Nigrelli [1], Arbisi [2] and Han [3].

Basic parameters (Tab. 1) of numerically analysed aerator were preliminary calculated or evaluated according to the design procedure described in a paper [4]. This procedure comes from the same theory as Stepanoff [5] which is also mentioned in the work of Cancino [6]. The blades of the aerator impeller were designed by software using Bézier surfaces [7].

The design of the numerically analysed aerator is based on an older type of aerator. The older type of aerator (Fig. 1) was experimentally tested in the laboratory of the Department of Fluid Engineering in Brno [8] and worked on the same principle as the aerator patented by Gross [9]. The main difference between older and newer type of aerator is in the way of sucking air and water. Older type of aerator sucks air via the lower part of impeller and water sucks via its upper part of impeller and the mixture of water and air flows through the channels to the diffuser. On the other hand, newer type of aerator (Fig. 2) sucks water via the lower part of the impeller and pumps the water through the channels to the jets. These jets are actually parts of ejectors which suck air into the mixing chambers. Similar

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submersible aerator which sucks air just via two jets was patented by Frankl [10]. Newer aerator should suck air via more jets equally spaced on circumference.

The aim of this work is to prove that the right inclination angle of the stator channels corresponds to the direction of flow and influences the value of efficiency. Last but not least, this work reveals which shape of stator channels is better from a hydraulic point of view and which shape of channels is better with regard to the attachment of a nozzle to the end of each channel. All numerical simulations were made for the best efficiency point of the aerator impeller which corresponds with the flow rate 6 l/s.

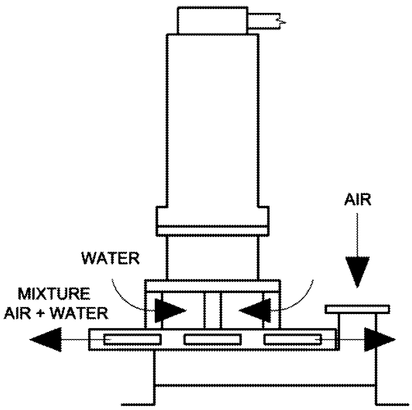

Fig.1: Old and experimentally tested aerator

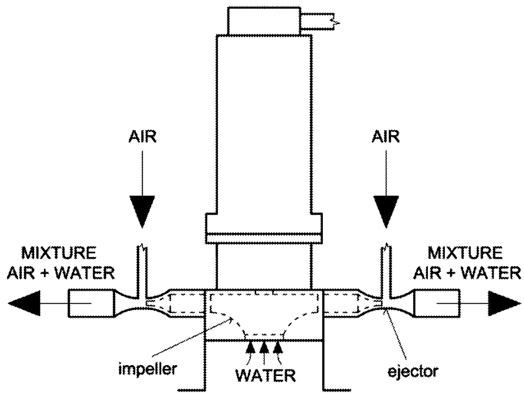

Fig.2: New and numerically tested aerator with ejectors

Power applied to the liquid by the impeller	P	500	[W]
Flow rate	Q	6	[$\mathrm{l\,s^{-1}}$]
Rotational speed	n	2700	[rpm]
Impeller outlet diameter	D_2	92	[mm]
Number of blades	z	6	[–]
Impeller outlet width	b_2	12.5	[mm]

Tab.1: Input parameters of the aerator impeller

2. Design and numerical simulation

2.1. Computing the absolute velocity angle

A direction of flow is represented by the absolute velocity vectors. It is necessary to know the angles of these vectors at the impeller outlet because then is possible to design the right inclination of the channels. The absolute velocity angle α_2 is computed from the velocity triangle at the impeller outlet (see Fig. 3) according to formula (1) or (2). Velocity components in these equations represent absolute velocity magnitude v_2 (m/s), meridional (radial) velocity magnitude and v_{m2} (m/s) and tangential velocity v_{u2}. These components are computed on the basis of the results from the CFD analysis.

$$\alpha = \arcsin\left(\frac{v_{\mathrm{m2}}}{v_2}\right) , \tag{1}$$

$$\alpha = \arcsin\left(\frac{v_{m2}}{v_{u2}}\right) . \tag{2}$$

Firstly, the numerical simulation of the aerator impeller was made with the stator ring placed behind the impeller outlet (Fig. 4) using Ansys Fluent software. Setting of the software was as follows (see [11] for more details):

- MRF (Multiple Reference Frame) approach was used which assumes that the flow field is steady.
- Two-equation realizable k-ε turbulence model was selected for near wall treatment.
- Non-equilibrium wall functions were set for near wall treatment.

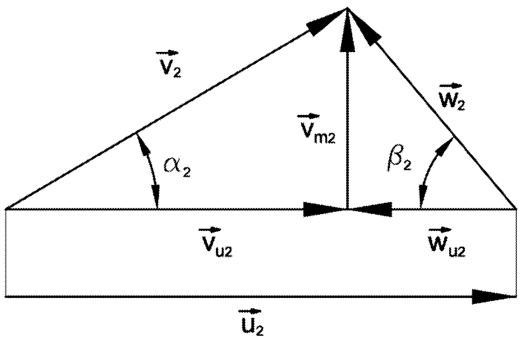

Fig.3: Velocity triangle at the impeller outlet

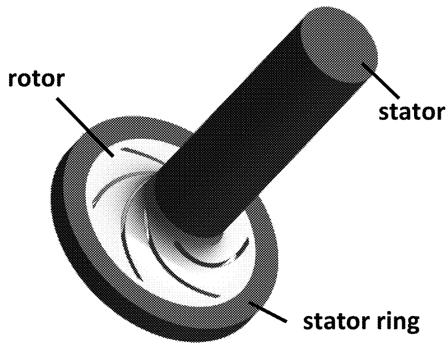

Fig.4: Computational domain of the aerator impeller with signed inlet stator and outlet stator ring

To compute the magnitudes of velocity components, a cylindrical surface was created. This surface has same axis of rotation as the aerator impeller and its radius is a little bit bigger than the impeller outlet radius R_2. On this radial surface the vectors of meridional velocities and absolutes velocities were displayed. After that the average magnitudes of these velocities were computed thanks to Vertex average function implemented in Ansys Fluent software. The computed value of absolute velocity angle α_2 was about 14° and it was rounded up to the value 15°. This is why the stator channels were designed with an angle of inclination corresponding to the absolute velocity angle 15°.

2.2. Design stator channels

Two conceptions of stator chambers which had different shapes of stator channels were design. Further, the channels of each chamber were numerically tested for two angles of inclination – for computed angle 15° and for angle 45°, which had the older conception of aerator. All four types of stator chambers were designed and numerically tested. All chambers had eight channels equally spaced around the circumference with the height of channels 14.5 mm. The width of channel decreases with the decrease of channel inclination therefore all channels inclined by 15° had width of channel 15 mm and all channels inclined by 45° had width of channel 25.8 mm.

The design of straight stator channels inclined by 15° and 45° shown in Fig. 6 and Fig. 8 seems to be the best solution from a hydraulic point of view. But newer kind of aerator is supposed to suck air via ejectors and the nozzles must be properly attached to the end of each channel. For better attachment of the nozzles to the stator chamber, another shape of channels with inclined inlets and radial outlets was designed. Channels which are inclined by 15° and 45° and which have radial outlets are shown in Fig. 5 and in Fig. 7. The lengths of all channels were extended just for computational reasons.

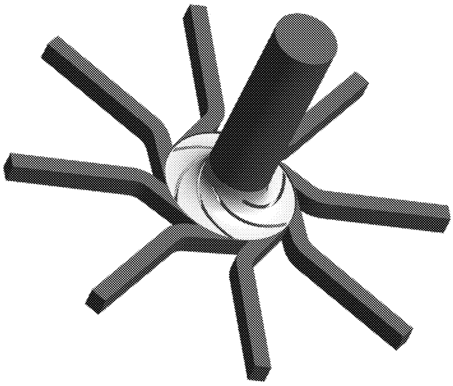

Fig.5: Computational domain of the aerator impeller and the channels with radial outlets and inclined inlets by 15°

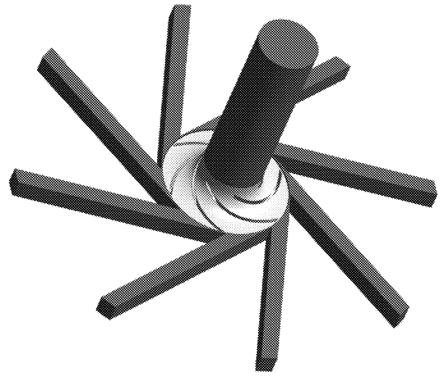

Fig.6: Computational domain of the aerator impeller and straight channels inclined by 15°

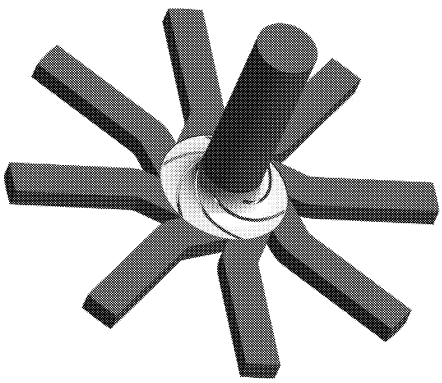

Fig.7: Computational domain of the aerator impeller and the channels with radial outlets and inclined inlets by 45°

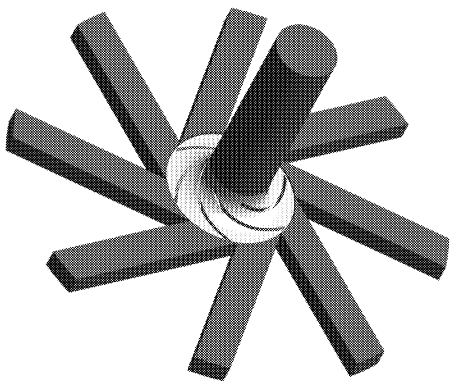

Fig.8: Computational domain of the aerator impeller and straight channels inclined by 45°

All numerical simulations of these stator chambers that were made had follow setting of the Ansys Fluent software [11] :

- Sliding Mesh approach was used for a time-accurate solution of rotor-stator interaction to compute the unsteady flow field (cell zones move relative to each other along the mesh interface)
- Two-equation realizable k-ε turbulence model was selected for near wall treatment.
- Non-equilibrium wall functions were set for near wall treatment.
- Second-Order Implicit-time stepping method was used for time-accurate calculations.
- Second-Order Upwind Scheme was used for achieving higher-order accuracy at cell faces.

To decide which shapes and angles of the channels are the best, it was necessary to compute the efficiency. For computing the efficiency, the below mentioned equations were used. Firstly, total pressure of the aerator at the inlet ptot1 and outlet ptot2 was computed according to formula (3), which is the sum of static and dynamic pressure. All these pressures were computed by the Ansys Fluent software using Data Sampling for Time statistic function.

$$p_{\mathrm{tot}} = p_{\mathrm{stat}} + p_{\mathrm{dyn}} = p_{\mathrm{stat}} + \frac{1}{2}\,\varrho\,v^2\ . \tag{3}$$

Then the specific energy Y defined in equation (4) was computed which is the ratio of total pressure difference to density ϱ.

$$Y = \frac{p_{\mathrm{tot1}} - p_{\mathrm{tot2}}}{\varrho}\ . \tag{4}$$

After calculating the mass flow rate Q_{m} according to equation (5) the input power P_{m} and output power P_{h} were computed on the basis of equation (6) and (7) where M_{k} is torque on the rotational walls of the impeller (computed by Ansys Fluent) and n is the rotational speed of the impeller.

$$Q_{\mathrm{m}} = Q\,\varrho\ , \tag{5}$$

$$P_{\mathrm{h}} = Q_{\mathrm{m}}\,Y\ , \tag{6}$$

$$P_{\mathrm{m}} = M_{\mathrm{k}}\,\omega = M_{\mathrm{k}}\,2\,\pi\,n\ . \tag{7}$$

Finally, the efficiency of the aerator by equation (8) was obtained.

$$\eta = \frac{P_{\mathrm{h}}}{P_{\mathrm{m}}}\ . \tag{8}$$

3. Results

3.1. Results of the numerical simulation of the impeller with stator ring

As already mentioned above, the computed value of the absolute velocity angle α_2 was rounded up to 15°. The values used for computing angle α_2 are shown in Tab. 2. These values were evaluated on the cylindrical surface with the radius 46.5 mm. In Fig. 9 directions of absolute velocity vectors are represented, which confirm an assumption that the absolute velocity angles are variable and decreasing from the pressure side to the suction side of the blade. This is why the implemented Ansys Fluent function (vertex average) had to be used for computing the required velocity components.

radial (meridional) velocity	v_{m2}	1.661	[m/s]
tangential velocity	v_{u2}	6.949	[m/s]
velocity magnitude	v_2	6.72	[m/s]

Tab.2: Values of velocity components gained from Ansys Fluent software

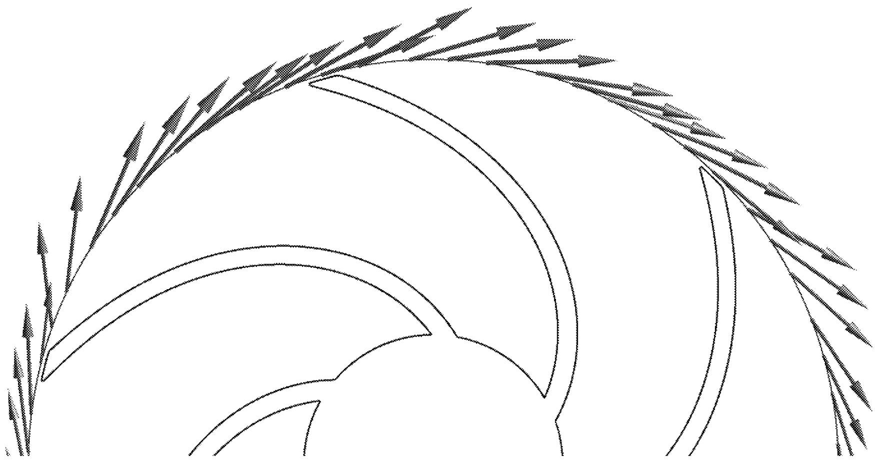

Fig.9: Absolute velocity vectors in a cross-section through the middle of outlet width and cylindrical surface

3.2. Results of the numerical simulation of the impeller with stator chambers

An important value which was evaluated on the basis of CFD simulations was the value of Wall Yplus (non-dimensional distance from the wall to the first mesh node). To obtain reliable results, it is recommended to keep the value of Wall Yplus for the k-ε 2-equation turbulence model between 30 and 300. It is suggested that the value of Wall Yplus should be as close to 30, as it is practical [12].

The contours of these values for one kind of stator chamber are shown in the Fig. 10. The critical values of Wall Yplus are represented by the darkest colours (the value of Wall Yplus is lower than 30) and the lightest ones (the value of Wall Yplus is higher than 300). The most critical places were on the leading edges and trailing edges (with the value of y^+ between 150 and 200). Other critical places are just behind the rotor where the stator channels converge (y^+ between 180 and 300). Nevertheless, these critical places represent negligible small surface compared to total surface with appropriate values of Wall Yplus.

The numerical results of CFD simulations for four different types of stator chambers are stated in Tab. 3. As expected, the best efficiency values had stator chambers with channels inclined by 15°. On the other hand, the stator chambers with channels inclined by 45° had the worse efficiency values. The efficiency differences between channels designed with the angle 15° and 45° are around 9 to 14 %. Another interesting finding comes from a comparison between stator chambers with the angles 15° where an efficiency difference is just around 0.54 %. This result comes to the conclusion that the bend of channel may not represent such big hydraulic losses as expected.

kind of channel: inlet/outlet	α_2 [°]	Y [J.kg^{-1}]	M_k [N.m^{-1}]	P_h [W]	P_m [W]	η [%]
inclined/inclined	15	81.5	1.874	489.01	865.195	56.52
inclined/radial	15	80.82	1.877	484.93	866.129	55.98
inclined/inclined	45	67.463	1.862	404.778	859.54	47.09
inclined/radial	45	57.602	1.782	345.613	822.783	42.01

Tab.3: Results of numerical simulations for different stator chambers

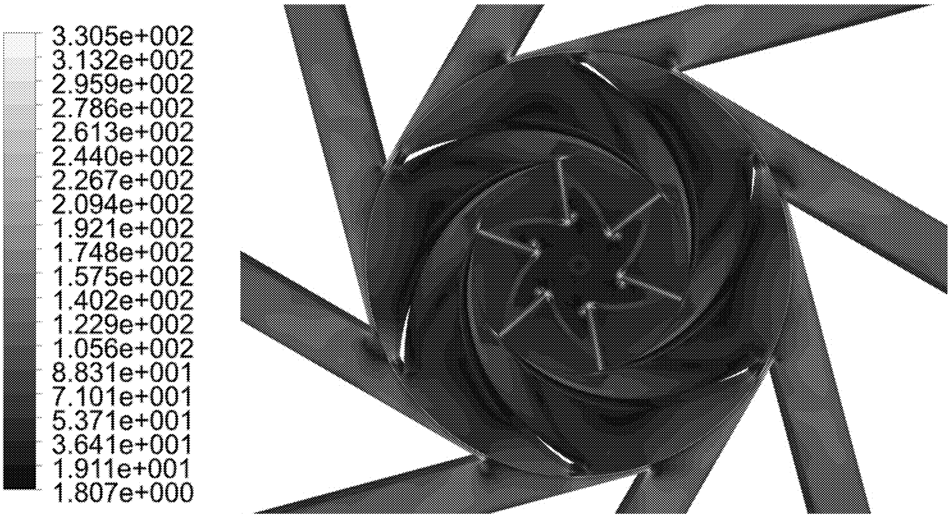

Fig.10: Contours of Wall Yplus values on the stator chamber and on the rotor of the aerator (stator chamber with straight channels inclined by 15°*)*

In Fig. 11, Fig. 12, Fig. 13 and Fig. 14 streamlines are shown in different kinds of stator chambers and the influence of channel inclination on the flow through the aerator channels. In Fig. 11 and Fig. 12 stator chambers for two different shapes of channels with the angle of inclination 45° are represented. Thanks to plotted streamlines it is possible to see big vortices in stator channels. These figures just proved that channels designed with the angle of inclination 45° are unsuitable and reveal the main cause of low efficiency. On the other hand, Fig. 13 and Fig. 14, which represent stator chambers with the computed angle of inclinations 15°, show no vortices in the stator chambers. This result proves that designed channels inclined by computed angle α_2 correspond with the direction of flow, which is favourably reflected on the efficiency of the aerator.

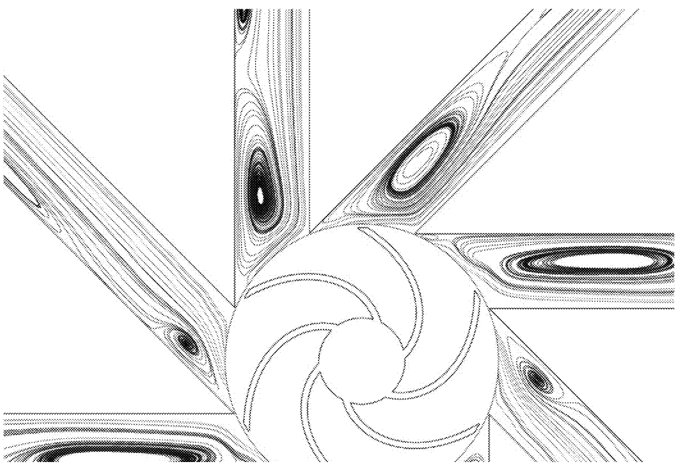

Fig.11: Streamlines in a cross-section of the middle of the stator chamber (stator channels with straight channels inclined by 45°*)*

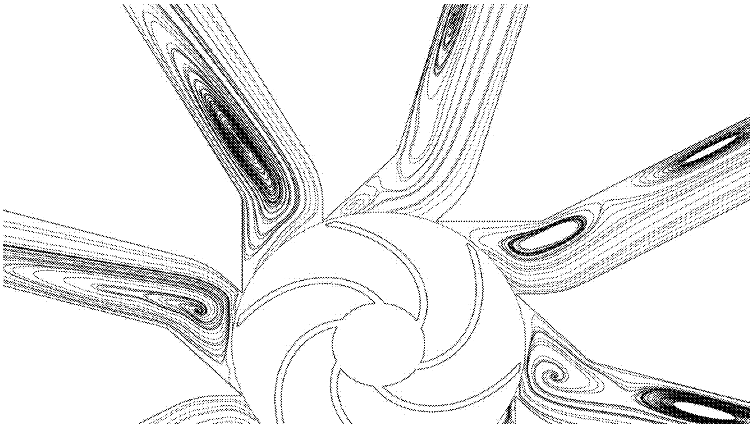

Fig.12: Streamlines in a cross-section of the middle of the stator chamber (stator channels with radial outlets and inclined inlets by 45°)

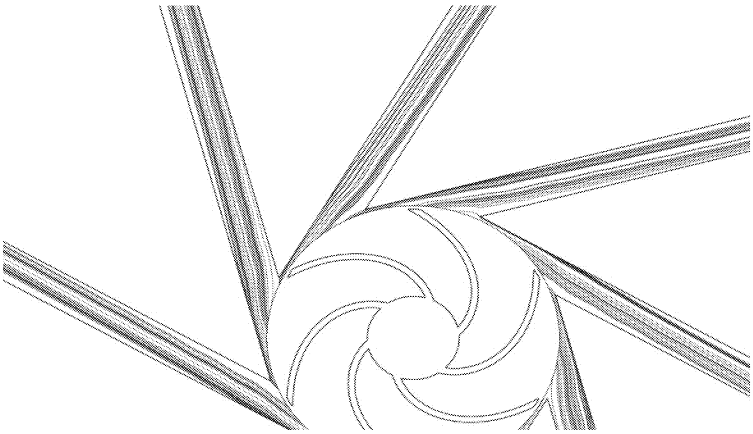

Fig.13: Streamlines in a cross-section of the middle of the stator chamber (stator channels with straight channels inclined by 15°)

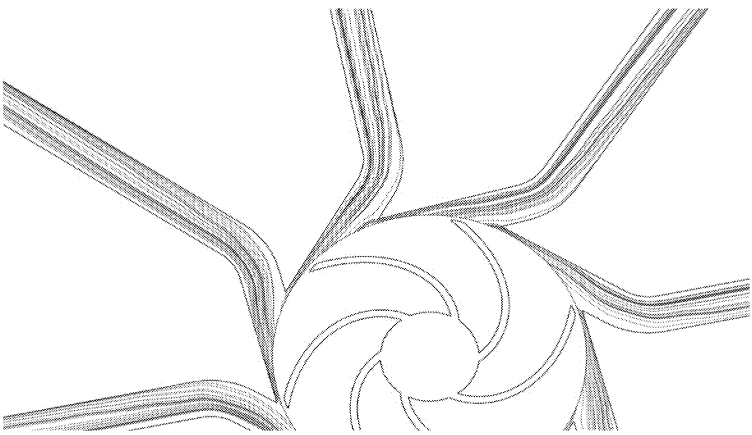

Fig.14: Streamlines in a cross-section of the middle of the stator chamber (stator channels with radial outlets and inclined inlets by 15°)

4. Conclusion

The modelling of single-phase flow in stator channels of aerator was investigated. First, a CFD analysis was made with the stator ring in order to compute the absolute velocity angle α_2. The computed value of α_2 was 15°. Then, numerical simulations for four different stator chambers were made. Two of them had straight stator channels with different angle of inclination (15° and 45°) and other ones had stator channels with radial outlets and inclined inlets by 15° and 45°.

Results from the CFD analysis showed that the worst efficiencies had aerators with stator channels inclined by 45° which the older type of aerator had. The figures with plotted streamlines revealed that in stator channels designed with the inclination angle of 45° big vortices appeared, causing a decreasing efficiency. On the other hand, the aerators designed with the channels inclined by 15° had the best efficiencies, regardless of the kind of outlet the channels had.

These results are very valuable for the next work. Following work will be focused on the shape design of the nozzles and mixing chambers. One of the possible problems with the design of nozzles might be a small width of channels by the stator chambers with the angle of inclination 15°. This problem could limit the design procedure of nozzles. In the next work, only chambers with the channel inclination of 15° will be used because aerators with these chambers had the best efficiencies. Although one of these chambers has bended channels which represent minor hydraulic losses and the chamber will be more difficult to manufacture, but the attachment of the nozzle to the stator chamber will be better.

After design procedure of the nozzles and the mixing chambers, another CFD analyse will be continued – this time it will be focused on the suction of air into the mixing chamber. All CFD simulations will be solved as two-phase problems.

Nomenclature

P	Power applied to the liquid by the impeller	[W]
Q	Flow rate	[l.s^{-1}]
n	Rotational speed	[rpm]
D_2	Impeller outlet diameter	[m]
z	Number of blades	[–]
b_2	Impeller outlet width	[m]
p_{tot2}	Total pressure at the impeller outlet	[Pa]
p_{tot1}	Total pressure at the impeller inlet	[Pa]
p_{stat}	Static pressure	[Pa]
p_{dyn}	Dynamic pressure	[Pa]
ϱ	Density	[kg.m^{-3}]
v	Absolute velocity	[m.s^{-1}]
α_2	Absolute velocity angle at the impeller outlet, angle of inclination of the channel	[°]
Y	Specific energy	[J.kg^{-1}]
Q_{m}	Mass flow rate	[kg.s^{-1}]
P_{m}	Output power	[W]
P_{h}	Input power	[W]
M_{k}	Torque	[N.m^{-1}]
ω	Angular velocity	[rad.s^{-1}]
η	Efficiency	[–]
y^+	Wall Yplus	[–]

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