Numerical simulation and experimental investigation of submersible sewage mixer performance

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Abstract. This work focuses on methods of submersible sewage mixer performance evaluation comparison. In the paper an experiment with a submersible mixer with a published and known geometry has been presented. The authors measured thrust, torque rotation speed and electric power. Experiment was compared with results obtained with a steady state numerical simulation. Next CFD results were checked with a theoretical approach for the mixing range. Both theoretical and numerical methods showed good applicability for the industry.

1. Introduction

Submersible mixers are important sewage treatment machinery that is widely utilized in urban and rural sewage treatment farms. They play the most important role biochemical reactions such as anaerobic digestion, sedimentation, wastewater aeration and more [1–2].

Fluid mixing is a very complicated process and a theory of mixing machines has not fully been developed. In some theories a submersible mixer is treated as a jet nozzle [3]. However, this theory is very limited. At the moment, the authors of this paper did not meet any algorithms for high efficiency submersible mixer design. Therefore, there is a strong desire for creating a methodology for designing and validation of machine flowpath.

Since these machines are usually working round the clock they should be characterized by the highest efficiency of the mixing process. The cost of electrical energy consumption is the main operating cost of wastewater treatment plants. It can be assumed that the cost of energy consumed during entire life cycle of the mixer exceeds its buying cost. Trying to minimize overall operational cost, one can put forward a thesis that using more advanced blade design will result in energy consumption reduction that can overcome its higher purchase price.

In this paper the authors focused on presenting results from experimental, numerical and theoretical evaluation of sewage mixer performance. The authors extensively studied development and design methods of the submersible mixer and wastewater. Unfortunately, no or limited proofs, comparisons and records of a good design with validation were found. In order to support the community of scientists working in this field we decided to publish performance data from experiment and CFD simulation, so that other researchers can compare their results with a known and validated solution. The paper is divided into three sections. First part concerns about experimental setup and results. Next, numerical simulation is discussed. Finally comparison of experimental, numerical and theoretical performance evaluation is done.
2. Experiment

2.1. Test rig
Thrust and power on the shaft are main variables to evaluate machine efficiency. According to [4] the efficiency of the mixer can be calculated with equation:

$$\eta = \frac{9.55 F_T \pi}{40 d M n}$$

The efficiency of the mixer is proportional to the 3/2 power of water thrust $F_T$, inversely proportional to the blade diameter $d$, and inversely proportional to the shaft power of the submersible mixer. Shaft power $P_{sh}$ can be calculated from torque and rotational speed:

$$P_{sh} = \frac{Mn}{9.55}$$

Interestingly, T. Fei et. al proposed their own efficiency equation which has slightly different constants in comparison to the international standard [5]. Following approach of T. Fei et al. calculated efficiency will always give higher numbers that ISO. According to ISO21630:2007(E) permissible systematic uncertainty for thrust is ±2% and for electric power it is equal ±2%.

Thrust is the most important performance parameter of the mixer. It is essential for correct equipment selection. Required thrust is compared with the available thrust of the commercially available mixers and provides the number, size and arrangement that is needed to be used. Once the mixers type is known a power requirement can be determined with use of data delivered from factory. Factory testing is done in accordance with the relatively new ISO 21630 standard released in 2007. Thrust is considered as a rate of axial momentum imposed on water. It can be evaluated by measured velocity field integration or by measuring reaction force of the mixer. The second one is a simpler way to proceed and is used in our test rig (Fig. 1).

![Figure 1. Schematic of the test rig: 1 – submersible mixer, 2 – test rig frame, 3 – pivot bearings for torque measurement, 4 – pivot bearings for thrust measurement, 5 – thrust load cell, 6 – network meter, 7 – data acquisition system, 8 – torque load cell.](image)

The measurement of reaction force bases on the lever principal. The mixer (1) is suspended on a pivot (4) and connected to the frame (2) with a force transducer (5). Axis of pivot is perpendicular to
axis of mixer rotation. In order to calculate the thrust force a simple proportion equation can be used. The same approach has been utilized for torque measurement. Here, the cage is suspended on bearing (3) that are parallel to axis of mixer rotation. The torque is measured with another load cell (8). All data is collected with data acquisition module (7). Measurement of electrical power is done with network meter (6) and then transferred to computer. Additionally, by loosing frame screws it is possible to raise the submersible mixer with a chain hoist. Mixer is located about 1 m under the water surface. Photography of a test rig located on the marina platform can be found in Figure 2.

![Figure 2. Test rig placed on marina platform.](image)

When the data from experiment is collected, they need to be transformed into thrust and rotational force. In order to calculate thrust $F_T$ and rotational force $F_R$ following formulas were used:

$$F_T = F_{\text{load}_\text{cell}_T} \frac{R_1}{R_2},$$

$$F_R = F_{\text{load}_\text{cell}_R} \frac{R_2}{R_4},$$

where: $F_T, F_R$ – reaction forces of thrust and rotation, $F_{\text{ten}_o}, F_{\text{ten}_p}$ – forces on load cells, $R_1, R_2, R_3, R_4$ – lever arms distances.

2.2. Detailed experimental setup and procedure

For thrust measurement an S–type strain gauge consisting of 4 strain gauges connected in a full bridge configuration. Keli AMI model DEE–SS has C3 accuracy class according to OIML standards (Organisation Internationale de Métrologie Légale). In this load cell 2 strain gauges are compressed and two are stretched. The electrical resistance in compressed strain gauges decreases, while in stretched strain gauges it increases. By using this property, it is possible to measure the voltage imbalance across the diagonal of the bridge. The measuring system is excited with 4.2 VDC.

The load cell readings are amplified with 128 gain and then converted into a digital value using the HX711 24–bit analog–to–digital converter. The high resolution ADC allows for accurate signal processing. With a measuring range of $\pm$ 100 kg giving a $\pm 8,4$ mV at the output with 16777216 permissible values (2^24) for $\pm 20$mV ADC input, a measuring resolution of 0.028 g is achieved. The digital value is processed and sent to the computer using the Atmel ATmega328P microcontroller. Sample rate was set to 10 samples per second.

Strain gauge was calibrated with a set of known weights. Calibration weights were measured with PS 6000/C/2 laboratory scale with a linearity of $\pm 0.02$ g and repeatability of $\pm 0.015$ g. For testing the linearity an overhanging load cell was stretched with 15 trial weights that were added one by one.
Then this mass was removed to test hysteresis. A total trial mass was approximately 100 kg. The maximum difference between the scale weight value and one shown by load cell ADC was equal to 17 g. This is less than 0.02% for summed linearity and hysteresis error.

Submersible Mixer revolution speed was measured with XS112B3PAL2 inductive sensor in waterproof version (IP69K). The sensor is located near the hub. In the hub a retrieving pin was mounted. When ferromagnetic pin was passing sensor an impulse was created. The detection range is 4 mm, while the maximum sensor switching frequency is 2500 Hz.

Motor electrical power was measured with power network analyser Lumel ND10. It’s active power measurement accuracy is equal to ±0.5%. Current was measured through current transformers of ±0.5% basic accuracy. Lumel ND10 was communicating to PC through RS485 modbus protocol.

The measurements were taken in 5 minutes time interval. After that, all collected points were averaged.

2.3. Experimental results

For the experiment the authors have chosen the geometry of the impeller that is easy to be recreated by other researchers. A three blade mixer geometrical and operation data was placed in Table 1. A draft of the rotor was placed at the end of this paper. The rotor itself was fabricated from cast iron and then covered with black paint. The impeller can be seen in Figure 2.

| Table 1. Geometrical and operation data. |
|------------------------------------------|
| Number of blades | 3 |
| Impeller diameter | 339 mm |
| Hub diameter | 80 mm |
| Forward lean angle | 8° |
| Blade angle | 64° |
| Revolutions per minute | 740 1/min |
| Motor rated power | 4 kW |
| Power factor | 0.75 |
| Rated voltage | 400V L–L |
| Rated current | 9.7 A |
| Electric motor efficiency | 79° |
| Mechanical and sealing losses | 1.14 kW |

Figure 3. Tested impeller.
Collected data revealed that both thrust and rotation force are strongly fluctuating. For thrust the fluctuations equal approximately ±2%. For the rotation force fluctuations are approximately ±10%. These fluctuations are generated due to non–optimized impeller geometry which causes high turbulence at outlet. Also it should be noted that the stiffness of the test rig is limited. Transverse stiffness (in respect to axis of mixer rotation) which is responsible for transferring thrust forces is higher than longitudinal stiffness. This explains the difference in fluctuation differences. First minute of collected data has been presented in Figures 4 and 5.

![Thrust force measurement](image1)

**Figure 4.** Thrust force measurement.

![Shaft torque measurement](image2)

**Figure 5.** Shaft torque measurement.

**Table 2.** Experimental results.

| Parameter                        | Value  |
|---------------------------------|--------|
| Mean thrust force               | 460.7 N|
| Mean shaft torque               | 29.7 Nm|
| Mean electric motor power       | 3.7 kW |
| Mean revolutions per minute     | 738.5 l/min|

3. **Numerical simulation**

The CFD Ansys FLUENT software was used for analysing the operation of submersible mixer. The geometrical model reflected the real geometry of the experimental impeller. It was reverse engineered with use of 3D scanner. The main purpose of this simulation was to compare the experimental results with one obtained from simulation. Pressure and velocity fields are also an interesting source of
information about the impeller performance. By analysing the fields we can check the range of the mixer. Numerical simulation was conducted as steady RANS for the determined boundary conditions. SIMPLE solver was utilized. The medium was defined as clear water of viscosity \( \mu_{\text{H2O}} = 0.001003 \text{ Pa} \) and density \( \rho_{\text{H2O}} = 998.2 \text{ kg/m}^3 \). For the turbulence SST model was selected. Convergence criterion was assumed to be 0.00001 for all equations. The unstructured tetrahedral mesh was generated with Ansys Meshing software. It consisted of 44 million elements. Boundary layer on the blades has been resolved to keep \( y^+<1 \). The region behind the impeller was also refined in order to improve the resolution of numerical results.

The numerical model consisted of two fluid domains: impeller and surrounding. The boundary conditions were defined as the pressure at the inlet and at the outlet. Since the mass flow rate was not explicitly determined, problems with solving and convergence of continuity equation occurs. In order to prevent this a first order upwind approximation for momentum was used. For other approximation methods convergence for continuity could not get below 0.005. For turbulence second order upwind approximations were utilized. Pressure was also second order. Gradients were calculated with least square based method. Rotation speed of the impeller remained the same as in the experiment. Entire domain length is equal to 20 m. Diameter of the domain is 6.4 m (rotor diameter is 0.339 m). The computational mesh and 3D model were presented in Figure 6.

![Figure 6. Computational domain and mixer geometry.](image)

At post processing stage thrust force, torque and range was measured (Table 2). From Table 3, we can see that achieved results are close to those obtained from the experiment. The error is equal 1.6% and 5.2% for thrust and torque respectively. It should be noticed that the downgrade in approximation order did not affect the overall accuracy for mixer performance evaluation. From this comparison it can be assumed that proposed numerical simulation approach is sufficient for most industrial cases concerning design of new units. As for the shaft torque measurement a more sophisticated method could be used.

### Table 3. Comparison of simulation and experimental results.

|                      | CFD  | Experiment. | Error |
|----------------------|------|-------------|-------|
| Thrust force         | 453.2 N | 460.7 N    | 1.6%  |
| Mean shaft torque    | 28.2 Nm | 29.7 Nm    | 5.2%  |
| Revolutions per minute | 738.5 1/min | 738.5 1/min | 0%    |

Simulation showed that the volume of fluid is highly affected by the presence of the submerged mixer. It turns out that at the outlet of the domain there is no portion of fluid with zero velocity. Shortly after the impeller a contraction zone can be observed. This zone is called the core zone. This fact is confirmed by general model of a free stream of liquid immersed in an unlimited volume filled with the same liquid [6]. It changes into a transient zone where intensive mixing occurs. Finally, a diffusion zone can be designated. Here loss of momentum takes place and velocity field is being unified. The velocity distribution has been shown in figure 7. In order to match the number of blades two 120–degree planes were sliced.
4. Theory vs. numerical simulation

The velocity distribution in the space behind the mixer corresponds to the model of a free stream of liquid immersed in an unlimited space filled with the same liquid (Fig. 8).

As mentioned in section 3 we can designate 3 zones. First one is a core zone. In this zone streamlines resemble the shape of a cone with a base diameter of $d$ equal to the diameter of the impelled. The length of this zone is equal to $(4–5)d$. In this zone, the average velocity is equal to the average flow velocity directly after the mixer. Second zone is responsible for intensive mixing. In a structured flow zone, the cone angle is equal to approximately $2\pi/15$ radians. For zone 3 the velocity on the axis of rotation can be evaluated with following equation:

$$v(x,0) = C \frac{v(0,0)\sqrt{A}}{x\sqrt{\varepsilon}},$$
where: \( C \) – turbulence constant \((C = 5.7 - 7)\), \( v(0.0) \) – average outlet velocity, \( A \) – outlet surface area, \( \chi \) – contraction coefficient \((\chi = 0.61 - 1)\), \( \varepsilon \) – cross–sectional coverage factor \((\varepsilon \approx 1)\), \( x \) – distance from mixer.

The calculation of outlet mixer velocity is based on the thrust force and the impeller diameter:

\[
v(0,0) = \frac{1}{d} \sqrt{\frac{2F_T}{\rho \pi}},
\]

where: \( d \) – impeller diameter, \( F_T \) – mixer thrust, \( \rho \) – fluid density.

For the sake of simplicity in our theoretical performance evaluation basic set of coefficients were used: \( C = 5.7 \), \( \chi = 1 \), \( \varepsilon = 1 \). The value of thrust was taken from the experiment. For practical reasons it is important to know the velocity distribution perpendicular to the axis of mixer rotation. The velocity in diffusion zone can be approximated by describing the Gaussian curve and it’s based on a relative stream width \( \eta \):

\[
f = e^{-\left(\frac{x}{\eta}\right)^2}.
\]

**Figure 9.** Theoretical velocity field based on immersed free stream model.

Comparison of theoretical and numerical approach shows that both methods are not consistent (Table 4). In respect to simulation results the values for high velocity flow are overestimated. The value of low velocity is underestimated. Unfortunately, the technical possibilities of realization of such experiment widely exceed the conditions of the laboratory, thus the measure of precise value is difficult. Nevertheless, theoretical approach can be an excellent way for initial guess during the design of submersible mixers.

| \( v=0.2 \text{ m/s} \) | CFD | Theory | Difference |
|------------------------|-----|--------|------------|
| \( \text{m/s} \)       | 16m | 14.08 m | 12%        |
| \( v=0.3 \text{ m/s} \) | 9.01m | 9.12m | 1.2%       |
| \( v=0.4 \text{ m/s} \) | 5.24m | 6.84m | 30.5%      |
5. Conclusions
In this paper and experiment, numerical simulation and theoretical performance evaluation of submersible mixer has been conducted. With use of load cells, both thrust and torque of impeller was measured. The comparison between experiment and numerical simulation showed that a downgrade of order of accuracy for momentum equation did not affected consistency of the results. Calculated torque and thrust values were showed good agreement with experiment. Comparison between theoretical and numerical values of submersible mixer revealed that there obtained results vary, but a theoretical approach can be useful for initial parameters guess.

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References
[1] Weixing X U 2006 Design Theory of Submersible Mixer Impeller and Numerical Simulation of Agitated Flow Field 4
[2] Wei-Giang WU 2008 Introduction How to Select Mixer in Sewage Treatment Plant China Science and Technology Information 116
[3] Tian F, Shi WD, Jiang H 2014 Matching criterion of submersible mixer and pool Advances in Mechanical Engineering 4 1
[4] ISO 21630:2007 Standard Pumps – Testing – Submersible mixers for wastewater and similiar applications
[5] Fei T, Wei-Dong S, Xining L et al 2012 Theoretical calculation and simulation analysis of submersible mixer efficiency for wastewater treatment Transactions of the Chinese Society of Agricultural Engineering 28(12) 50
[6] Szewczyk H 1989 Fluid Mechanics, Laboratory Script (Wroclaw: Wydawnictwo Politechniki Wroclawskiej)
[7] Skrzypacz J, Skowroński M 2004 Methods for determination of mixer operating parameters Chemical and process engineering 24 20
