Research Article

Janusz Skrzypacz* and Marcin Bieganowski

Investigations of drilled and multi-piped impellers cavitation performance

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Abstract: The industry needs the rotodynamic pumps operating with ultra-low specific speed and relatively low flow rate more often. Designing of such structures on acceptable efficiency level is extremely difficult and require non-standard approach to design as for example: drilled impeller or patented by author multi-piped impeller. Such pump elements are very easy to manufacture and operate with relatively high efficiency, but cavitation behavior is unknown.

This paper focuses on experimental research in order to determine the cavitation characteristics of the drilled impellers and multi-piped impellers. The test rig was presented. Impeller models were made by means of SLS Rapid Prototyping methods. Additionally, CFD calculations were presented in order to determine static pressure distribution in the inlet sections of the investigated impellers.

Keywords: drilled impeller, multi-piped impeller, cavitation, CFD

Symbols

c_s	fluid velocity at section pipeline, m/s
c_t	fluid velocity at discharge pipeline, m/s
g	gravity, m/s ²
H	pump head, m
n_q	kinematic specific speed, rpm
$NPSH_r$	net positive suction head (required), m
p_b	barometric pressure, Pa
p_{ms}	gauge pressure in the pump inlet, Pa

p_{mt}	gauge pressure in the pump outlet, Pa
P_u	hydraulic power, W
p_v	fluid vapor pressure, Pa
P_w	power on the pump shaft, W

Greek symbols

β_1	impeller inlet angle, deg
η	pump efficiency
ρ	density, kg/m ³

1 Introduction

Modern world industry, especially chemical one, requires pumps that will be able to operate in range of extremely low specific speed ($n_q < 10$) with acceptable level of efficiency. Designing rotodynamic pumps operating in mentioned range of parameters is extremely difficult because of low performance [1–3]. Such structures must be designed in non-standard way.

During the work over this problem, the idea of drilled impeller [4] was developed. The new solutions of the rotodynamic impellers were introduced as:

1. Drilled impeller with side holes [5].
2. Multi-piped impeller [6].

The numerous researches confirmed positive operation of such structures from energy consumption point of view [7, 8], but cavitation performance was unknown.

The main aim of this project was determining cavitation characteristics of the pump impellers listed above, designed in non-standard way. The special test rig was described and results of measurements were presented. Additionally, in order to interpret better the results of measurements, the CFD calculations were carried out and the static pressure at the impellers inlet passages were shown.

***Corresponding Author: Janusz Skrzypacz:** Wrocław University of Science and Technology, Department of Mechanical and Power Engineering, ul. Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland; Email: janusz.skrzypacz@pwr.edu.pl

Marcin Bieganowski: Wrocław University of Science and Technology, Department of Mechanical and Power Engineering, ul. Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland; Email: marcin.bieganowski@pwr.edu.pl

Figure 1: Geometry of the impeller 1 (I1)

Figure 2: Geometry of the impeller 2 (I2)

Table 1: Design parameters of the impellers

No	Parameter	Unit	Value
Operation parameters			
1	Flow rate	Q [m ³ /h]	4.5
2	Head	H [m]	27
3	Rotational speed	n [rpm]	2870

2 Research objects

The main objects of the research were four rotodynamic pump impellers, designed for working parameters presented in Table 1. All impellers were manufactured with SLS rapid prototyping method (Selective Laser Sintering), using DuraForm EX material described below:

- density (sintered part) 1.01 g/cm³;

- flexural modulus 1310 MPa;
- flexural strength 46 MPa;
- tensile strength 48 MPa;
- elongation at break 47 %;
- hardness 74 shore.

Impeller 1 (I1). The first one (I1) was a drilled impeller with additional side holes. Such a structure is a developing of the commonly known idea of drilled impeller presented in [4]. Basic parameters were shown in the Figure 1.

Impeller 2 (I2). The second one (I2) was multi-piped impeller, designed according to patent [6]. Such structure was described in detail in [9]. The shape and basic parameters were presented in Figure 2.

Impeller 3 (I3). Impeller 3 is a modification of Impeller 2 where the number of the channels (z) and external diameter (d_2) were decreased to $z=4$ and $d_2=130$ mm respectively. The model was shown in the Figure 3.

Table 2: Measuring instruments [9]

No	Measuring instrument	Range	Accuracy class
1	Electromagnetic flow meter Arkon MAGS1-ST DN25 PN 40	0.18 – 17.67 m ³ /h (0.1 – 10 m/s)	0.2%
2	Pressure Gauge (suction) FUJI FKP 01	–0.7 – 0.5 bar	0.1%
3	Pressure Gauge (discharge) FUJI FKP 03	0 – 30 bar	0.1%
4	Active Power Transducer METROL PP73	0 – 3000 W	0.3%
5	Temperature Transducer FLEXTOP 2202	0 – 50°C	± 0.9°C

Figure 3: Geometry of the impeller 3 (I3)

Impeller 4 (I4). Impeller 4 is a modification of Impeller 2 concept where the pipes that create impeller passages were bended in such way in order to obtain optimal values of the inlet and outlet angles. The number of passages is $z = 4$, inlet angle $\beta_1 = 50$ deg., outlet angle $\beta_2 = 30$ deg.

Figure 4: Geometry of the impeller 4 (I4)

3 Test rig

In order to conduct investigation, a specialized test rig - presented in Figure 5 - was designed and constructed [9]. The main element of the test rig is a pump (Figure 5b) with a special design allowing for the quick replacement of the tested impellers while maintaining the repeatability of the measurement results.

The pump is supplied from a closed tank where - depending upon the needs - one can generate overpressure or negative pressure and control the medium level and temperature.

The pump capacity can be adjusted with a ball control valve, namely MARS 88V with an IntrOM OM-1 electric drive. The measuring instruments which parameters are presented in Table 2 were used for measuring the specific values.

The characteristics of the tested impeller were measured in a fully automated way, according to the recommendations given in EN ISO 9906:2000. The measurement process is controlled by a computer and dedicated software. The test rig gives possibility of cavitation research by means of three methods:

- generation vacuum in the tank,
- decrease water level in the tank,
- throttling at the suction pipeline.

The third method (throttling at the suction pipeline) was selected as the fastest and which generated accuracy on the acceptable level.

4 Result of the measurements

The basic parameters were determined according to following formulas:

Pump head:

$$H = \frac{P_{mt} - P_{ms}}{\rho g} + \frac{c_t^2 - c_s^2}{2g}, \quad (1)$$

Figure 5: View of the test rig [9]

Hydraulic power:

$$P_U = \rho \cdot g \cdot Q \cdot H \quad (2)$$

Pump efficiency

$$\eta = \frac{P_U}{P_w} \quad (3)$$

Net Positive Suction Head

$$NPSH = \frac{p_b}{\rho g} + \frac{p_{ms}}{\rho g} + \Delta z_s + \frac{c_s^2}{2g} - \frac{p_v}{\rho g} \quad (4)$$

Required Net Positive Suction Head

$$NPSH_r = k \cdot NPSH \quad (5)$$

Based on data presented in Table 1 the average measurement uncertainty were determined as follows:

- for pump head $\Delta H = 4\%$,
- for hydraulic power $\Delta P = 8\%$,
- for $NPSH$ $\Delta NPSH = 3\%$.

The results of the measurements are presented in the Figures 6-13.

Based on the results presented above, we can formulate the following conclusions:

1. Only impeller 2 achieved the assumed operating parameters (Table 1).
2. The maximal efficiency was reached by impeller 1 and impeller 4, respectively.
3. For the flow rate $Q=4.5 \text{ m}^3/\text{h}$, the best cavitation performance achieved impeller 4 ($NPSH_r = 8\text{m}$), the worst – Impeller 1 ($NPSH_r=10.5 \text{ m}$).
4. The lowest value of $NPSH_r=8 \text{ m}$ (Impeller 4) is much higher than expected for classical centrifugal impeller ($NPSH_r=5.5 \text{ m}$ – value obtained from author's research).

Figure 6: Cavitation curves of the Impeller 1

Figure 7: Characteristics of the Impeller 1

5. The shapes of the cavitation curves are typical for classical centrifugal impellers and double elbows do not appear as for impellers with large inlet attack angle [10].

Figure 8: Cavitation curves of the Impeller 2

Figure 9: Characteristics of the Impeller 2

Figure 10: Cavitation curves of the Impeller 3

5 CFD modeling

In order to better understand cavitation behavior of the investigated impellers, the CFD calculations were performed for all impellers. The main aim of this calculations was to determine the static pressure distribution and to evaluate the pressure drop. Due to this fact, analysis were

Figure 11: Characteristics of the Impeller 3

Figure 12: Cavitation curves of the Impeller 4

Figure 13: Characteristics of the Impeller 4

done without multiphase model. General description of the numerical model, applied grid, boundary conditions and rules of CFD modeling in detail one can find in [9]. In the Figures 14-17 the static pressure distribution was presented.

Based on presented results, we can formulate following conclusions:

1. In case of Impeller 1 additional pressure drop is observed in the inlet to the first side hole. This is the reason of the worst cavitation performance.

2. The Impellers 3 and 4 have better cavitation performance than Impeller 2 (Figure 15). This confirms assumption that impellers with lower number of passages and larger area of the inlet cross-section work better (lower pressure drop at the inlet section – Figures 16-17).
3. The Impeller 4 has lower NPSH_r than Impeller 3. It means that there is optimal value of the inlet angle β_1 from cavitation performance point of view (Figure 17) [10].

Figure 14: Static pressure distribution [Pa] in Impeller 1

Figure 15: Static pressure distribution [Pa] in Impeller 2

Figure 16: Static pressure distribution [Pa] in Impeller 3

Figure 17: Static pressure distribution [Pa] in Impeller 4

6 Summary

Drilled impellers and multi-piped impellers are an interesting alternative for classical centrifugal impellers in the range of extremely low specific speed ($n_q < 10$). The values of the $NPSH_r$ for all investigated impellers are much higher than for classical centrifugal impellers. Among the researched impellers the best one was Impeller 4, that had 4 passages and the value of inlet angle β_1 within the optimal range [10].

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