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Distribution of flow velocity in a shaft intake structure

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ORIGINAL RESEARCH PAPER

ABSTRACT

Recently, the construction of shaft intake structures in Slovakia has increased. The shaft intake structures overcome significant vertical depth over short horizontal distance. The flow of water in these shaft intake structures is therefore very complicated. The velocity field at a shaft intake of a small hydropower plant was investigated on a physical model in a hydraulic laboratory using the particle image velocimetry method. The particle image velocimetry measurements were realized for different shaft depths and the results of this study can increase negative effects of not suitable the design of construction on the flow homogeneity in the turbine intake.

KEYWORDS

shaft intake structure, physical model, particle image velocimetry measurements, flow homogeneity

1. INTRODUCTION

Intake structures are the most important parts of Small HydroPower Plants (SHPPs) and are directly related to the entire function of the power plant. Many authors have dealt with the flow in the inlet objects [1–4]. Intake structures connect hydropower plants with reservoirs and lead water to the turbine units. Proper construction of intake structures ensures sufficient water flow and should ensure minimum pressure losses of the flow [3, 5] and also prevents the formation of vortices in this area [6–8]. Uneven inflow in the intake structures causes irregular load of the turbine impeller [9].

The homogeneity of the flow velocity fields at the intakes to the turbines has a great influence on the flow conditions, while the inhomogeneous distribution of the flow velocities has a negative effect on the power and efficiency of the turbine [10].

Special type of intake structures is the shaft intake structure. They are named after their shape, by which they overcome significant vertical depth over short horizontal distance. In the first section of the structure, the shape is horizontal and the flow can be both pressurized and free flow here. Before entering the turbines, the flowing water overcomes the slope in the "shaft" and changes the flow to pressurize. The flow is therefore very complex and the hydraulic design of these objects should be subjected to hydraulic research. For this reason, it is necessary to examine these structures and examine the velocity field at the intake to the turbine. Various branches of research can be observed in laboratories. Physical models are used to investigate hydraulic phenomena on a scale model [11, 12]. Shaft intakes (Fig. 1) are usually built with additional use of hydropower potential on already built water structures. Despite their construction, many of them were in Slovakia built without research, only on the basis of a design proposal [13]. This has led to many operational problems of the SHPPs connected to hydraulic issues of the design. One of the main hydraulic problems in the shaft intakes is the inhomogeneous flow velocity distribution, which has negative effects on the performance of the turbines leading to the reduction in their efficiency and uneven mechanical load on the turbine parts, which results in a

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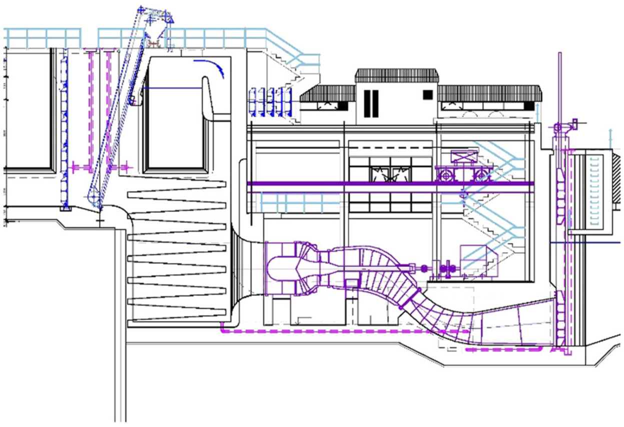

Fig. 1. Longitudinal section of the intake structure of SHPP Dobrohošt' [14]

reduction in their lifetime. Therefore, a hydraulic research of the effects of the shaft intake shape on the flow was realized.

2. MATERIALS AND METHODS

To investigate the effects of the shaft shape on the flow velocity distribution a physical model of the SHPP

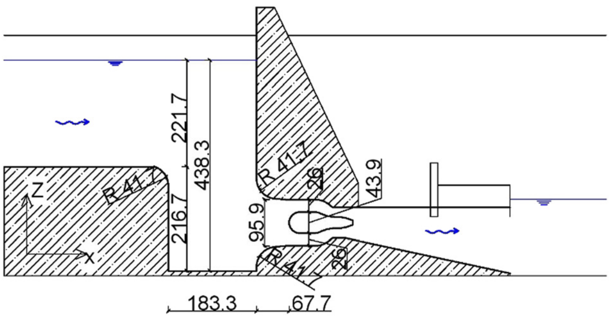

Fig. 2. Physical model of SHPP Dobrohošt'

Table 1. Scales of the physical model

Length scale	M_l	1:	30
Area scale	M_S	1:	900
Speed scale	M_v	1:	5.477
Flow scale	MQ	1:	4 929.503
Specific flow rate	Mq	1:	164.317

Table 2. Basic modeling parameters

		Reality	Model	
h	m	6.65	0.222	depth of water at the intake to the buffer chamber
b	m	6	0.200	width of the canal at the inlet to the buffer chamber
S	m^2	39.9	0.044	flow area
Q	$m^3.s^{-1}$	25	0.005	flow through SHPP
q	m^2s^{-1}	4.167	0.025	specific flow at the intake to the buffer chamber
v	$m.s^{-1}$	0.627	0.114	mean cross-sectional velocity at the intake to the chamber

Dobrohošt' shaft intake structure (Fig. 2) was created in the flow channel of the hydraulic laboratory. The model was built as a 2D model of the axial cross section of the shaft intake in a scale of 1:30. Tables 1–3 show the calculations of scale, parameters, and shaft flow in the flume. The model was designed to investigate the effects of the shaft height on the flow velocity distribution in the turbine intake. The transverse flow was neglected and the research was focused only on longitudinal flow distribution.

Various methods are currently used to measure the velocity field. In the past, mainly mechanical devices were used and it was not possible to measure the speed sufficiently precisely with them. Today's modern devices like the Ultrasound Velocity Profile (UVP), Particle Image Velocimetry (PIV), Laser Doppler Anemometry (LDA) are able to measure speed both precisely and areally (spatially) [15].

For the velocity measurements on the model of the shaft intake, the PIV method was used, as a very effective method. It is an optical method that allows to measure the instantaneous values of sizes and direction of velocity vectors in a given flow cross section. The so-called reflective particles are introduced into the liquid, which reflect the laser beam. The narrow light beam is guided directly from the laser. It is modified by a cylindrical lens in the shape of a light knife, by means of which the selected plane of the measuring space is illuminated. The illuminated area is bounded by the field of view of the camera and reflections from reflective particles are recorded by it. The PIV system records images in two pulses. The laser sends the first beam, which irradiates the particle. The particles shift in time between the transmission of the second laser pulse, but do not leave the pixel. The new location is also captured by the camera. It uses a Charge-Coupled Device (CCD) camera or Complementary Metal Oxide Semiconductor (CMOS) camera for processing, which is connected to a computer via a digital card. Information about the change of position and time is evaluated then the speed is calculated [16].

The measuring cross-section was located in the axis of the 2D model of the shaft intake. To observe the velocity field in the shaft intake structure, 5 scenarios of different shaft heights were proposed (Fig. 3).

Table 3. Parameters of the physical model

B	m	0.409	gutter width
B_m	m	0.380	chamber model width (shaft)
Q_t	$m^3.s^{-1}$	0.00964	flow in the trough
Q_t	$l.s^{-1}$	9.6	

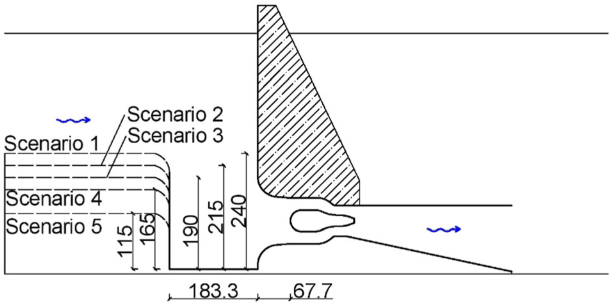

Fig. 3. Scheme of the modeled scenarios

The PIV system was installed on a physical model of a shaft intake structure (Fig. 4). Subsequently, the basic settings of the PIV system took place: camera settings, laser pulse power settings, laser flash frequencies and basic system calibration. The shooting time for the observed measurements was set to 6000 µs, pulses of 3 Hz and the number of measurements (frames) was set to 500. For each scenario, the flow velocity field in the shaft in axial cross section of the model was measured by the PIV method.

3. RESULTS AND DISCUSSION

The results of PIV measurements were processed in DynamicStudio software. Figures 5–9 show velocity maps with flow vectors for all scenarios. These maps show the area of the shaft and the intake of the turbine. The areas with high and low flow velocities can be observed. A significant flow and no-flow area in the shaft can be observed. At the bottom of the shaft intake, the smallest flow velocities occur. The assessment of the measured flow maps also shows an uneven vertical flow distribution in the turbine intake, where the most of the flow and the highest velocities are in the upper part of the turbine intake cross section.

Figure 10 shows the distribution of flow velocity in the observed profile for each selected scenario and is compared to the average cross-sectional velocity. The average cross-sectional velocity was 0.24 $m\,s^{-1}$. The most significant deviations from the average cross-sectional velocity are obtained in scenario 1, while in scenario 5 these deviations are the smallest. By decreasing the height of the shaft, the

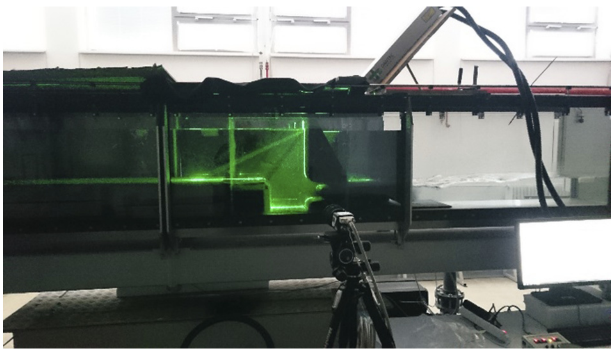

Fig. 4. Physical model of a shaft intake structure

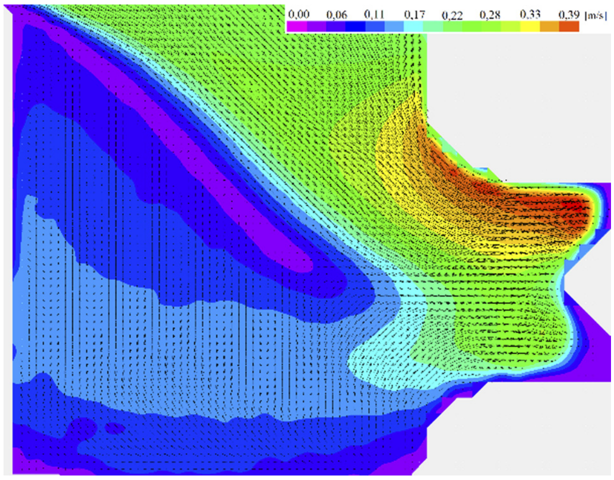

Fig. 5. Scenario 1 - shaft height 240 mm, Scalar velocity map with flow vectors

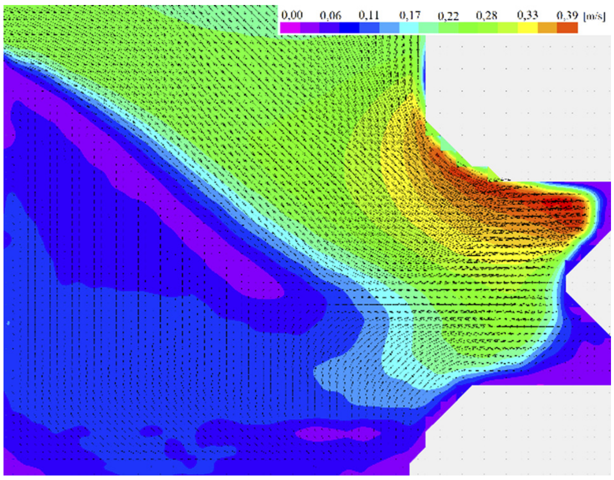

Fig. 6. Scenario 2 - shaft height 215 mm, Scalar velocity map with flow vectors

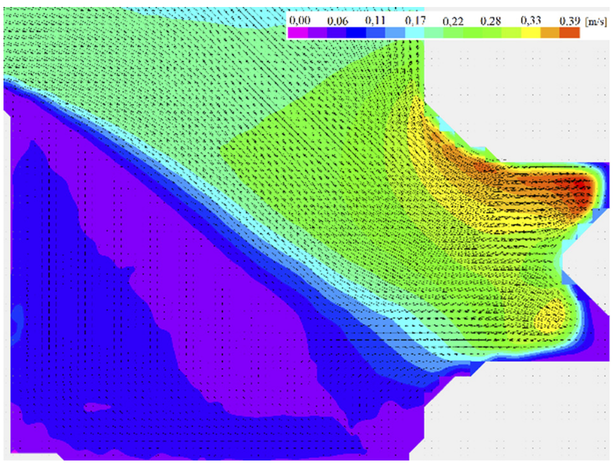

Fig. 7. Scenario 3 - shaft height 190 mm, Scalar velocity map with flow vectors

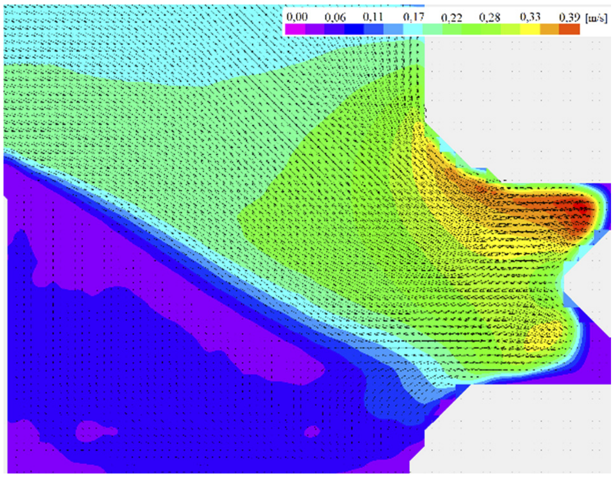

Fig. 8. Scenario 4 - shaft height 165 mm, Scalar velocity map with flow vectors

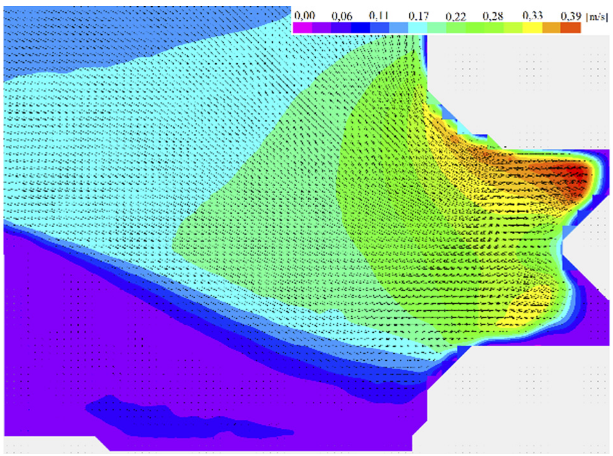

Fig. 9. Scenario 5 - shaft height 115 mm, Scalar velocity map with flow vectors

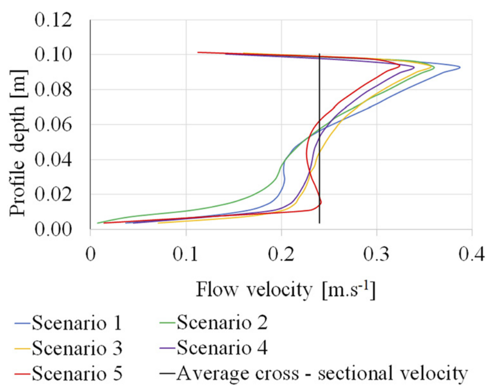

Fig. 10. Distribution of flow velocities in the observed profile

deviations of the flow velocities are reduced. It is also possible to observe the distribution of the flow between the turbines on the graph, where most of them are concentrated in the upper half of the observed profile.

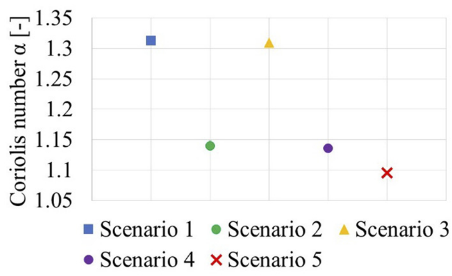

Fig. 11. Coriolis number for the selected scenarios

The uneven distribution of the flow velocities was subsequently evaluated by the Coriolis number. The Coriolis number is a dimensionless parameter that expresses the ratio of the actual kinetic energy height to the energy height expressed from the mean cross-sectional velocity. Figure 11 shows the calculated Coriolis numbers. The ideal Coriolis number $\alpha = 1$ means an evenly distributed flow velocity. In scenario 5, the Coriolis number came closest to a value of 1.

The results show that the shaft height has a significant effect on the flow velocity distribution in a shaft intake. The increase in the shaft height increases the size of the ineffective flow area in the shaft intake and leads to significant uneven flow velocity distribution in the turbine intake. The decreasing shaft height increases the effective flow area and helps to distribute the flow velocities more evenly in the turbine intake.

4. CONCLUSION

Research of the shaft height effects on the flow velocity distribution in the turbine intake was realized on a 2D physical model for 5 different shaft heights.

The research helped to identify the problems and tools for assessing the homogeneity of the velocity field. Uneven distributions of flow velocities were observed in the observed shaft intake structure. The performed measurements proved the negative effect of the shaft intakes especially the shaft height, on the distribution of flow and the flow velocities in the turbine intakes. Increase of the shaft height leads also to the increase of ineffective flow area in the shaft, which can be avoided or minimize by modifications to the design of the intake structure itself.

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