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Experimental and Mathematical Modelling of the Flow at the Intake Part of the Hydropower Plant Libčice at Vltava River

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1 Summary

The paper deals with the results of experimental laboratory research and the mathematical modelling of turbulent flow at the intake part of the small hydropower plant, which was designed and is recently additionally built at the log sluice of the weir Libčice - Dolany at the Vltava river. The special attention was given to the evaluation of velocity field distribution just behind the turbine inlets. The comprehensive experimental laboratory research was performed at the Water Structures Institute at the Technical University in Brno to determine the most appropriate shape of intake part, especially the shape and location of guide vanes at the approach canal. The mathematical model was used additionally to prove results of experimental modelling and to verify available CFD software ANSYS-FLOTRAN for similar water structures computations.

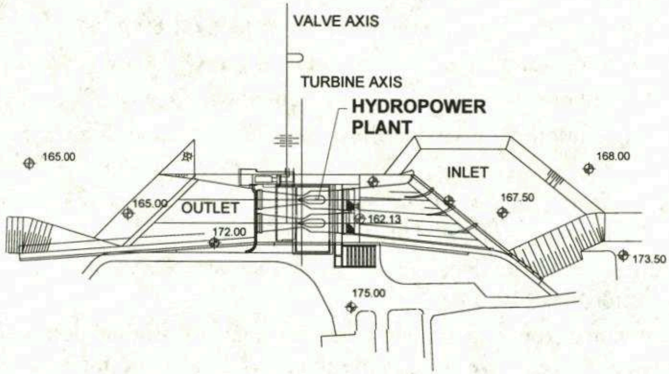


Fig. 1 The ground plan of the hydropower plant

2 Introduction

Water structure Libčice - Dolany is located at the km 218.55 of the Vltava river approximately 20 km to the north of Prague. It consists from the movable flap gate weir with three spans and two lock chambers located at the right bank navigable canal. The left bank log sluice was liquidated and at its extended space the hydropower structure was designed and is recently under construction. At the machine hall two straight-flow Kaplan turbine sets are installed - the runner diameter is

D = 3350 mm, maximal turbine discharge is 2 x 80 m^3/s, the hydraulic head is varying from 4.25 to 2.5 m, installed output is more than 5 MW. The chief designer of the scheme is Aquatis Brno, a.s., building owner is Vltava river basin agency Prague (Povodí Vltavy a.s.), general contractor of the structural part is Metrostav, a.s. Prague, the contractor of the technological equipment is Voest-Alpine, MCE, GmbH Linz, Austria.

An extended space at the left bank of the Vltava river, where the hydropower plant was located, was quite narrow (the land owner demands), so the inlet part had to be designed relatively narrow. Therefore the axis span had to be quite small. To avoid high velocities at the inlet sill, the inclined inlet sill was designed (see Fig. 1). The left boundary of the inlet sill is two times farther from the turbine inlets than the right one; therefore the inlet bed is created by the skew surface, so the flow (velocity field) is predominantly three-dimensional. This solution called up the question of the irregular velocity field at the turbine inlets and of the origin of the inlet vortexes close to the water level just in front of turbine inlets. To avoid and to minimize these effects, the comprehensive experimental research was carried out at the laboratory of Water Structures Institute at the Technical University of Brno.

The original goal of the research was to verify designed shapes of the inlet part and to measure the velocity field at the cross section just behind the turbine inlets (14 m in front of the turbine axis). Following operating conditions were assumed:

a) two machines in operation, the discharge studied was Q = 2 x 80 m^3/s;

b) one (left) machine in operation, the discharge studied was Q = 1 x 80 m^3/s;

c) one (right) machine in operation, the discharge studied was Q = 1 x 80 m^3/s;

d) two machines in operation, 90 m^3/s overflow over the weir, total discharge was Q = 250 m^3/s;

e) two machines in operation 2 x 80 m^3/s, one weir span opened - overflow 290 m^3/s, total discharge was Q = 450 m^3/s.

The permissible difference of the local velocity at particular observation points of measuring cross section was ±10%.

Based on results obtained from experimental measurements of original design, the research was extended to optimize the turbine inlet and to arrange the upstream nosing of the division wall between the weir and the hydropower plant to avoid inlets vortexes in front of the turbine inlet and to improve the velocity field distribution. The ±10% condition mentioned above had to be fulfilled and moreover the sum of discharge differences at all four quadrants of measuring profile from the regular discharge distribution had to be less than 5%.

3 Experimental research

3.1 Physical model

The physical model of the hydropower plant consists of two direct-flow Kaplan turbine sets, the left flap-gated weir span and the 225 m long river Vltava reach upstream from the weir and the 138 m long river reach downstream from the weir. The model was built at the river observation flume at the Laboratory of Water Structures Institute. With respect to the hydropower plant layout and to the size of the flume (16,5 x 3,5 m), the 1:25 scale was selected.

3.2 Hydraulic similitude

The free surface flow regime at the inlet part is corresponding with the Froude similarity law respecting prevailing gravity forces:

$$Fr = \frac{v^2}{g \cdot l} = idem \qquad (1)$$

The complete geometrical similarity was assumed together with gravitational dynamic similarity:

The similitude scale ratio for model dimensions 1 : 25,

scale ratio of lengths	$M_L = 25$,			
- for undistorted model	$M_H = M_B$	$= M_L$	$= 25$,	
scale ratio of velocity	$M_V = M_L^{1/2}$	$= 25^{1/2}$	$= 5$,	
scale ratio of discharge	$M_Q = M_L^{5/2}$	$= 25^{5/2}$	$= 3125$	
scale ratio of the time	$M_T = M_L^{1/2}$	$= 25^{1/2}$	$= 5$.	

As the liquid used was the same as the prototype liquid, $M_\rho = 1$.

Fig. 2 shows the scheme of the undistorted model of the Vltava river reach with the weir and hydropower plant. The model size is 14.5 x 3.5 m.

3.3 The equipment

The hydraulical observations were performed using following equipment:

The discharge adjustment was carried out using Poncelet rectangular weir. The water level position was read using the metal gauge mounted to the float.

The water levels were observed using mechanical point gauge with accuracy of 0.1 mm and with gauges mounted at the walls of the flume.

The flow direction was observed using textile fibre, dye and paper floats.

Velocity field was observed using micro-current meter Delft WSM01 connected to the integrator DISA TYPE 52 B30, which was averaging the values observed. Direct link with personal computer by means of multimeter M1T380 enabled the recording and computer processing of velocities observed.

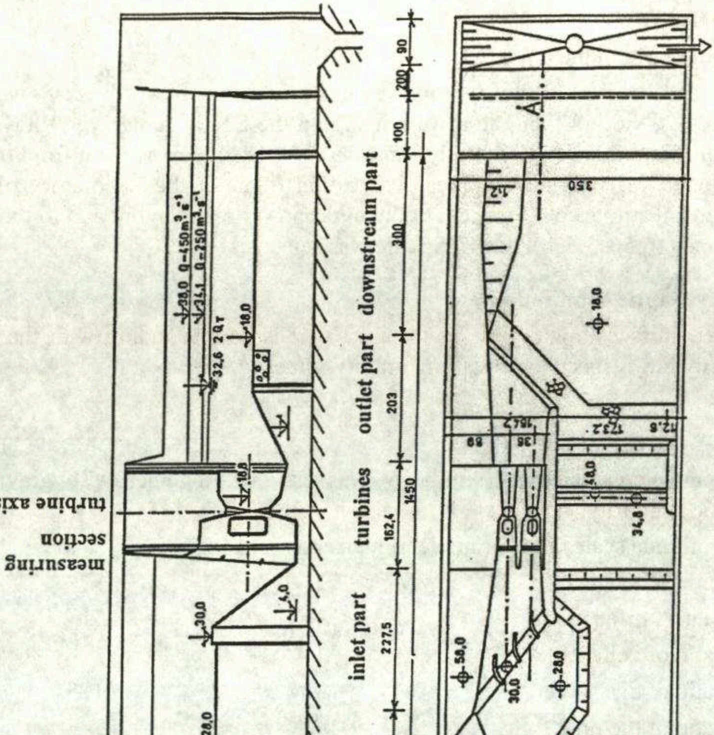


Fig. 2 The scheme of undistorted scale model of the hydropower plant Libčice (dimensions in cm) : a) longitudinal section A-A'; b) ground plan

3.4 Results of the research

The results of velocity measurements for originally designed variant of the input part showed that the difference between local velocities and mean velocity at the right turbine is significantly higher than ±10% and the velocity distribution is irregular and therefore some arrangements have to be necessary. Regarding the limited space for the hydropower plant construction, the only measure to improve the flow field was an arrangement of the upstream nosing of the partition wall and the number and the shape of guiding vanes at the intake sill.

Based on the results of experimental flow observations and measurements in front of and behind the turbine inlets, 9 variants of the arrangements mentioned above were gradually investigated. Variants 1 to 4 and 9 used the original length and shape of the inclined inlet sill. The arrangements were dealing with number, shape and the length of guiding vanes and with upstream nosing of division pillar. Variants 5 to 8 used the shortened partition wall between hydropower plant and the weir, the inlet sill was elongated and rounded and the fourth guiding vane was added. The original design and four following variants can be seen at Fig. 3.

For the original and all the other variants solved, three basic operational stages were selected:

a) maximum discharge through both turbines - 2 x 80 m^3/s ;

b) flow only through the left turbine - 80 m^3/s;

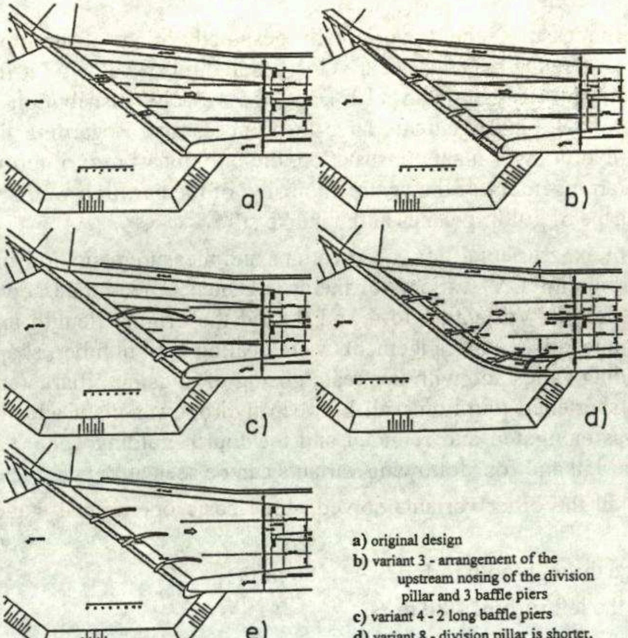
c) flow only through the right turbine - 80 m^3/s.

At all the mentioned stages, following parameters were observed:

- flow direction at the inlet sill, close to the upstream edge of the partition pillar, guiding vanes, at the space between inlet sill and the turbine inlet;
- forming of the vortexes at the free water level upstream from the turbine inlets;
- flow velocities at selected measuring section downstream of the turbine inlets at the 5 x 5 = 25 points observation net .

At the final ninth variant of the turbine inlet arrangement, following additional flow parameters were observed for all operational stages a) to e):

- flow direction at the turbine inlet;
- forming of the vortexes at the inlet part and just upstream of the turbine inlets;
- velocity field at the selected measuring section downstream of the turbine inlets at the denser network of 9 x 9 = 81 observation points.



a) original design
b) variant 3 - arrangement of the upstream nosing of the division pillar and 3 baffle piers
c) variant 4 - 2 long baffle piers
d) variant 8 - division pillar is shorter, longer inlet sill and 4 baffle piers
e) variant 9 - final proposal - arranged upstream nosing of the division pillar, 3 extended baffle piers

Fig. 3
Arrangemets of inlet part of hydropower plant Libčice

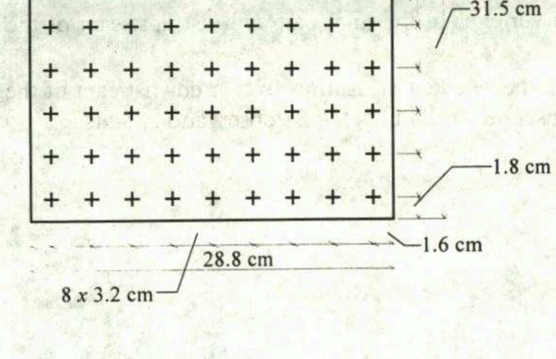


Fig. 4.
Observation network for the velocity measurements at ninth variant

y\x	1.60	4.80	8.00	11.20	14.40	17.60	20.80	24.00	27.20
1.80	30.67	32.29	31.05	29.50	28.98	29.02	32.07	31.92	31.29
5.30	27.82	32.85	31.05	29.97	29.75	29.62	31.04	30.95	30.32
8.80	28.54	30.30	29.14	29.68	29.22	29.90	29.68	29.69	27.35
12.30	31.07	30.19	29.19	28.56	28.29	28.16	28.05	28.67	29.07
15.80	30.80	30.28	29.27	28.84	29.05	28.53	28.08	27.79	27.72
19.30	29.08	29.51	28.97	29.70	29.03	28.35	27.99	27.27	26.60
22.80	28.20	27.65	27.47	27.35	27.61	27.21	26.94	27.70	28.28
26.30	29.54	30.03	29.93	29.09	29.93	29.57	28.99	28.38	28.63
29.80	27.60	29.61	29.44	28.20	28.37	29.62	29.45	29.18	27.35

the first quadrant	the fourth quadrant
the second quadrant	the third quadrant

Results of statistic	
Sum of all velocities	2363.09
Average velocity at intake	29.174 cm/s
The first quadrant	25.680 %
The second quadrant	24.785 %
The third quadrant	24.218 %
The fourth quadrant	25.316 %

Tab.1: Final evaluation of the velocity field measurement at the measuring profile behind the left turbine inlet for the 9th variant. Both turbines in operation, the total discharge $Q = 2 \times 80\ m^3/s$.

The 81 observation nodes network for the velocity measurement at ninth - final variant at the measuring section located 56 cm (at reality 14 m) in front of the turbine axis can be seen at Fig. 4.

For the separate performance of both turbines, two additional stages were observed according the agreement with the turbine contractor, $Q = 1 \times 60\ m^3/s$.

Final evaluation of results of the observations is shown at the Tab.1 and Fig. 5 and Fig. 6. The table shows observed values of flow velocity at 81 observation points. The percentage flow at particular quadrants is mentioned as well.

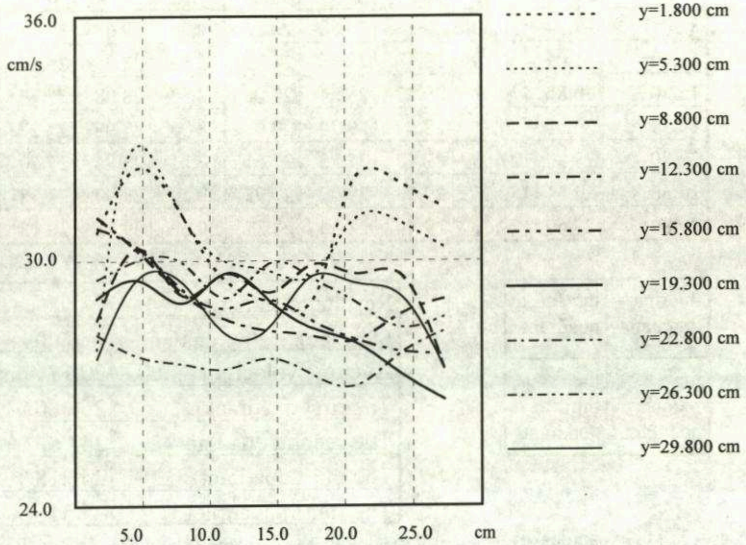
Fig. 5 shows the course of observed velocities (in cm/s) at both horizontal and vertical sections of the measuring profile of the left turbine for the discharge $Q = 2 \times 80\ m^3/s$ at the final variant.

Fig. 6 shows the isolinies of percentage differences between local velocities and calculated average velocity (arithmetical mean of observed values).

At all the variants solved, the forming of vortexes was observed at the free water surface in front of the turbine inlets. Even the vortexes were observed at all the previous variants, the final design eliminated their occurrence at the model. The possibility of vortexes forming was verified by computation along the five empirical formulas (compiled by 5 various authors), the occurrence of vortexes was confirmed only in one case.

Variant 9, both turbines opened, the left turbine, Q = 2 x 80 m^3/s

Horizontal sections



Vertical sections

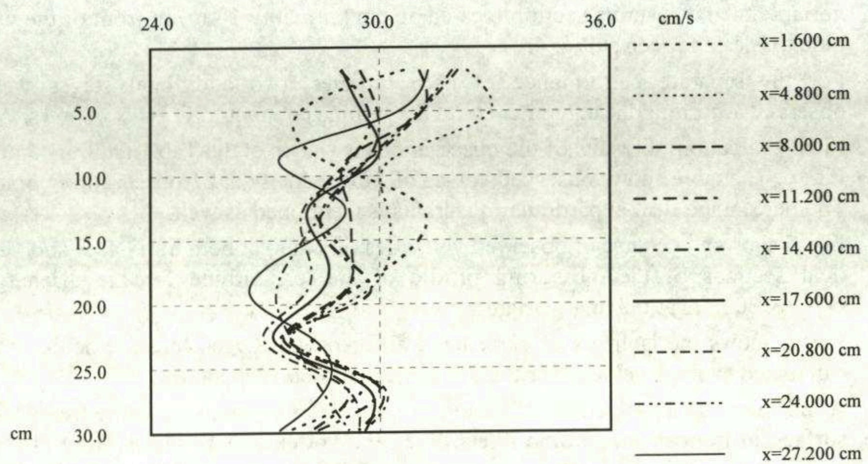


Fig. 5: Graphical processing of velocity measurements at measuring profile

Variant 9, both turbines opened, the left turbine, Q = 2 x 80 m³/s

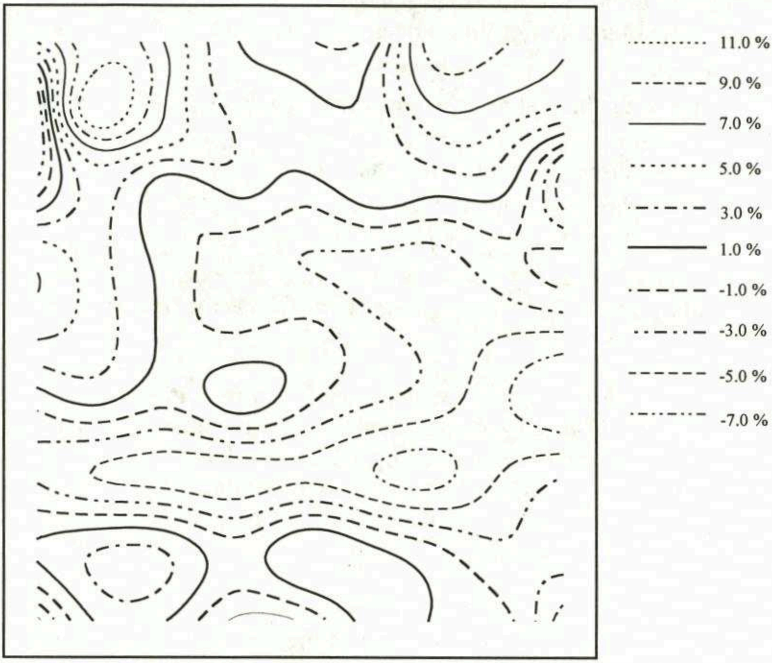


Fig. 6: The flow field evaluation in the form of isolinies of percentage differences between local velocities and calculated mean velocity

The experimental research showed, that the final (ninth) variant minimize the unevenness of the flow field at the turbine inlet. Nevertheless the ±10 % condition can hardly be reached in the case of some operational conditions. For these stages the decrease bigger than -10 % of the mean velocity can be observed within very small area close to the vertical partition turbine wall at the place of horizontal trash-racks beam. At the final variant, the sum of discharge differences at particular quadrants was less than prescribed limit of 5 %, only in the case of total discharge of 450 m^3/s the difference was 7 %. However this stage is exceptional with the quite wavy water level. No inlet vortexes were observed at variant 9 for any operational stage.

4 Mathematical and numerical model

The CFD software ANSYS-FLOTRAN was used for mathematical and numerical modelling of the described fluid flow problem. As the possibilities of the „university version" code are limited (number of elements, computational time), basically only two-dimensional (ground plan) steady state analysis of the problem was performed.

Following factors were assumed during the model compilation:

- dimensions of the structure and adjacent part of Vltava river;
- character of the flow at Vltava river upstream of the Libčice weir;
- hardware and software possibilities.

In accordance with the results of experimental modelling, three variants were studied:

- maximum discharge through both turbines - 2 x 80 m^3/s ;
- flow only through the left turbine - 60 m^3/s;
- flow only through the right turbine - 60 m^3/s;

The most inconvenient case from the point of view of velocity distribution at the intake part of hydropower plant was assumed - no flow across the weir flap.

4.1 Basic input data

The shape and dimensions of the structure were taken from the project of Libčice hydropower plant. The detailed shape and dimensions of guide vanes and the piers were taken from results of experimental modelling [Hynková et.al 1995]. All these data were available as an ACAD files and were transformed to the CFD software. The ground plan of the hydropower plant can be seen at Fig. 1.

4.2 Mathematical model

The equations governing turbulent are the time-averaged Navier-Stokes equations. The model presented uses the presumption of the steady-state flow, water is assumed to be incompressible and Newtonian. The equations can be expressed as follows [Rodi 1980]:

$$\frac{\partial \overline{v}_i}{\partial x_i} = 0, \tag{1}$$

$$\rho \overline{v}_j \frac{\partial \overline{v}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{v}_i}{\partial x_j} + \frac{\partial \overline{v}_j}{\partial x_i}\right) - \rho \overline{v'_i v'_j}\right], \tag{2}$$

where $\bar{v}$, $\bar{p}$, ρ and μ are the mean velocity, mean pressure, fluid density and dynamic viscosity. The last term at the right side of the equation (2) is the contribution of the turbulent motion to the mean flow and is called the Reynolds stress. In the presented paper, the Reynolds stress is approximated using the assumption of Boussinesq's eddy viscosity (μ_t), i.e.

$$\tau^t_{ij} = -\rho \overline{v'_i v'_j} = \mu_t \left(\frac{\partial \overline{v}_i}{\partial x_j} + \frac{\partial \overline{v}_j}{\partial x_i}\right) - \frac{2}{3} k \rho \delta_{ij}, \tag{3}$$

where k is the turbulent energy, ε is energy dissipation and δ_{ij} Kronecker delta. Variable μ_t is expressed using k-ε model [Wilcox 1994]:

$$\mu_t = c_\mu \rho \frac{k^2}{\varepsilon}, \tag{4}$$

$$\rho\frac{\partial k}{\partial t}+\rho\bar{v}_j\frac{\partial k}{\partial x_j}=\tau^t_{ij}\frac{\partial \bar{v}_i}{\partial x_j}-\rho\varepsilon+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]; \qquad (5)$$

$$\rho\frac{\partial \varepsilon}{\partial t}+\rho\bar{v}_j\frac{\partial \varepsilon}{\partial x_j}=c_{\varepsilon 1}\frac{\varepsilon}{k}\tau^t_{ij}\frac{\partial \bar{v}_i}{\partial x_j}-c_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right], \qquad (6)$$

c_m	c_{e1}	c_{e2}	σ_k	σ_e
0.09	1.44	1.92	1.0	1.3

Tab. 2 Coefficients of k - ε model

Coefficients - c_m, c_{e1}, c_{e2}, σ_k, σ_e - are assumed as constant [Launder, Spalding 1974].

4.3 Numerical solution

4.3.1 The discretization of the flow domain

The shape and dimensions of the flow domain are derived from the ground plan of the hydropower plant (see Fig. 1). The upstream boundary was determined sufficiently far from the hydropower plant, so that the velocity field at the Vltava river will be not influenced by the intake object. The simplified flow domain for 2D model is shown at Fig. 7. The flow domain was discretised by cca 15000 isoparametric quadrilateral FLOTRAN ET 141 finite elements.

4.3.2 Boundary conditions

The banks of the Vltava river, the weir flap, partition walls, land piers and guide vanes are assumed to be zero-velocity boundaries. At the inlet cross section on the right side of the flow domain, the known velocity field was introduced. The open turbine inlets are assumed as outlet with zero pressure boundary condition.

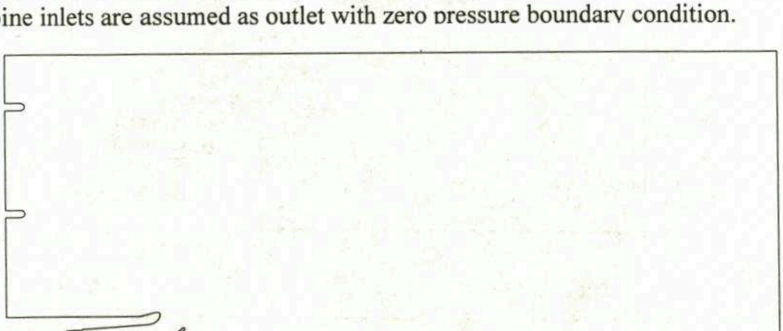


Fig. 7: The flow domain with baffle piers

Applying the finite element method (ANSYS - FLOTRAN), the above equations are transformed into a set of algebraic equations.

4.3.3 Model calibration and verification

The model calibration was carried out using the set of velocities measured during the experimental modelling. It can be stated that the sufficient agreement between results of numerical modelling and the values obtained from the experiment was reached. The results for the „Variant 9“ (see Fig. 7) and three subvariants mentioned above can be seen at Fig. 8 to 11.

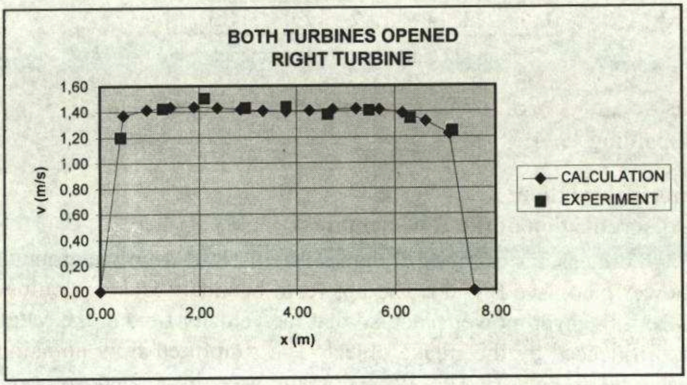


Fig. 8: Comparison of observed and calculated values of total velocities at the inlet of the right turbine when the both turbines are opened, total discharge is 160 m^3/s

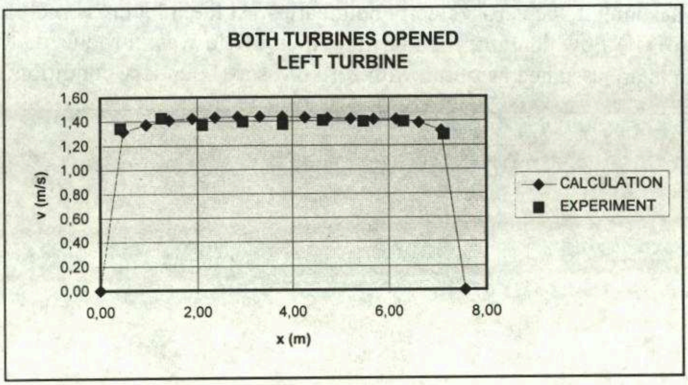


Fig. 9: Comparison of observed and calculated values of total velocities at the inlet of the left turbine when the both turbines are opened, total discharge is 160 m^3/s.

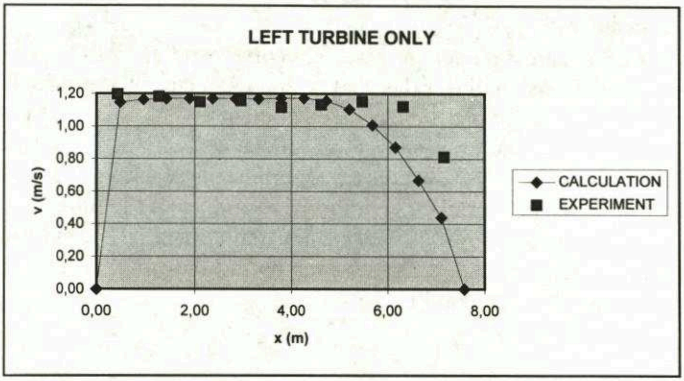


Fig. 10: Comparison of observed and calculated values of total velocities at the inlet of the left turbine when the only left turbine is opened, total discharge is 60 m^3/s.

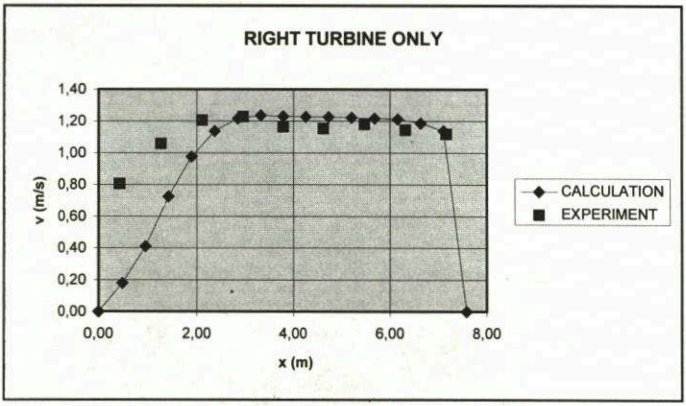


Fig. 11: Comparison of observed and calculated values of total velocities at the inlet of the right turbine when the only right turbine is opened, total discharge is 60 m^3/s.

Some differences between observed and calculated values of velocity vectors can be explained by the following facts:

- the numerical solution uses two-dimensional (2D) approximation while experiment was performed using the 3D scaled physical model.
- the numerical solution at the vicinity of division wall between the two turbine inlets is influenced by the presumption of sharp edges of the upstream face of the wall, while the experiment used rounded face. These differences are visible especially at the right side of Fig. 10 and on the left side of Fig. 11.

5 Conclusions

Results of mathematical model are generally corresponding with results of the experimental model, especially in the quality and character of the flow field. Some differences between solutions are discussed at the previous chapter. Moreover, the mathematical model enables visualisation of the velocity and flow fields at all critical regions of the entire flow domain for arbitrarily chosen variant of the shape of the flow domain and boundary conditions. Examples of the model output in the form of flow traces and velocity vectors are shown at Fig. 12, 13 and 14. The velocities at the turbine inlet cross sections during the flow without baffle piers and with them are compared at Fig. 15.

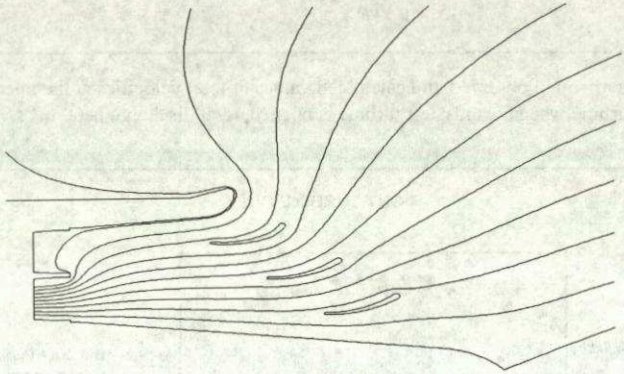


Fig. 12: Flow traces through the inlet part of the left turbine when the only left turbine is opened, total discharge is 60 m^3/s - variant 9 with baffle piers.

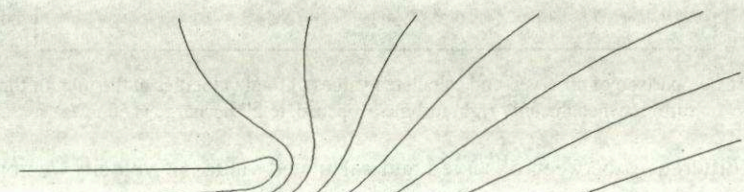


Fig. 13: Flow traces through the inlet part of the left turbine when the only left turbine is opened, total discharge is 60 m^3/s - variant without baffle piers.

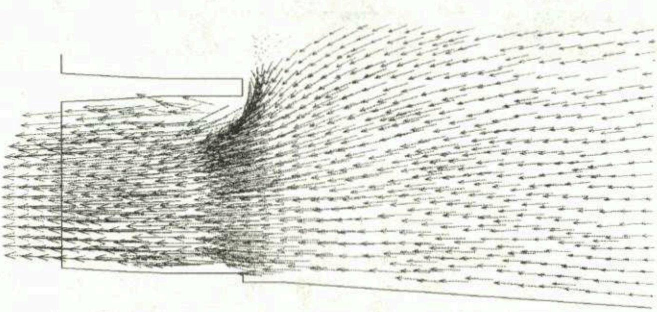


Fig. 14: Velocity field at the inlet part of the left turbine when the only left turbine is opened, total discharge is 60 m^3/s - variant without baffle piers.

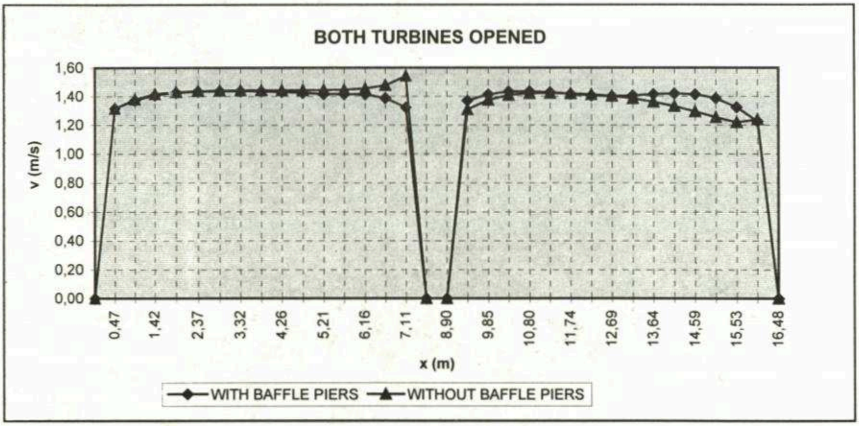


Fig. 15: Comparison of calculated values of total velocities at the inlets of the turbines during the flow without baffle piers and with them, total discharge is 160 m^3/s.

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