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- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.
Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 114, 2003, 3-4

Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

Dr Edward Śliwicki
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 114, 2003, 99-110

ROMUALD PUZYREWSKI[*] and RAFAŁ BIERNACKI

Volute scroll as an alternative to guide vanes at inlet to a turbine

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Abstract

This research was undertaken as a preliminary investigation into the possibility of feeding steam into a turbine by means of a flow-vectoring volute scroll, intended as a replacement for the conventional guide vane ring in the first (control) stage of the turbine. A volute-shaped inlet can serve to distribute flow evenly along the circumference of the blade ring. The volutes considered in this paper are also intended to generate correct angular momentum in the stream, so that correct rotor inlet angles can be obtained by means of the volute alone. A one-dimensional analytical model of compressible flow through a volute is proposed and evaluated. The empirical coefficients needed for its closure are derived, for a range of volute configurations, from 3-D numerical simulation. An ordered series of virtual volute models has been constructed and three-dimensional flow computations have been carried out for these models. The results obtained from 3-D computations have been confronted with the corresponding predictions yielded by the 1-D analytical model. The differences found are small, confirming the usefulness of the 1-D model for preliminary design. The data obtained from the 3-D numerical flow simulations for a number of volute configurations have been evaluated to extract information on flow uniformity and other key parameters of the stream. These results were subsequently interpolated over a range of volute configurations, systematized according to two key geometrical factors. Within this space, optimized volute shapes were selected, on the basis of flow angle and flow uniformity, for a system of two matched volutes of different throughputs. Flow through these paired volutes was then evaluated numerically at full design flow as well as at various levels of partial flow, to facilitate comparison with existing partial admission schemes.

Keywords: Turbomachinery; Steam turbine; Volute inlet; Volute duct; Scroll casing; Guide vanes

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1 The concept of angular-momentum generating volutes

Turbine admission by means of a volute or scroll casing is employed in some types of hydraulic turbines, as well as occasionally in steam turbines. In all such cases, however, the scroll inlet is seen only as a means of distributing inflow uniformly. It is followed by an independent ring of guide vanes which serves to vector the flow at a suitable angle before it enters the rotor.

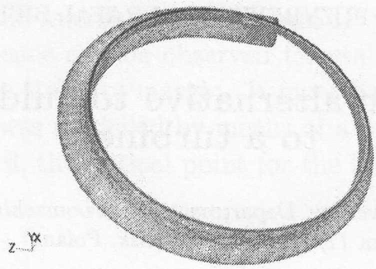


Figure 1. Example of a momentum-generating volute.

The significant innovation in volute scroll design, as discussed in this paper, is the concept of controlling the angle of flow entering the rotor blading by means of the volute duct alone, dispensing with guide vanes altogether. Through specific alterations of volute geometry it is possible to generate controlled amounts of angular momentum in the mass flow within the volute, causing the medium to exit the volute duct helically at the desired angle. The research undertaken by the authors aimed to demonstrate, on the basis of numerical simulations, that the volute scroll can be used to generate exit angles within the range required for direct feed onto rotor blading of existing turbines, while simultaneously fulfilling the conventional function of distributing the mass flow uniformly along the circumference of the blade ring.

2 One-dimensional model

Flow through the volute may be modeled as the 1-D process shown in the following process graph (Fig. 2), where state 1 corresponds to volute inlet, state 2 to its outlet, and state 2s represents the conditions at the outlet if the process is assumed to be isentropic.

On the basis of the above graph, one can formulate the following closed system

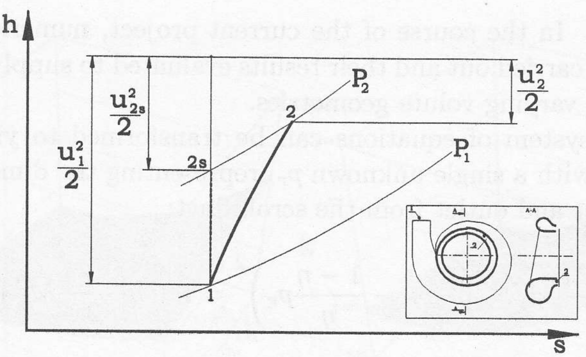


Figure 2. $h - s$ graph of flow through a volute.

of equations:

$$u_{z2} = \frac{\rho_1}{\rho_2} S_r u_1, \tag{1}$$

$$u_{\theta 2} = K_V r_r u_1, \tag{2}$$

$$h_2 = h_{01} - \frac{u_{z2}^2 + u_{\theta 2}^2}{2}, \tag{3}$$

$$\frac{p_1}{p_r \rho_2} = \frac{\kappa - 1}{\kappa} h_2, \tag{4}$$

$$\frac{p_1}{p_r \rho_{2s}} = \frac{\kappa - 1}{\kappa} h_{2s}, \tag{5}$$

$$\left(\frac{\rho_1}{\rho_{2s}}\right) = \frac{p_1}{p_2} = p_r, \tag{6}$$

$$h_1 - h - 2s = \eta(h_1 - h_2), \tag{7}$$

with seven unknown quantities: p_r, ρ_2, ρ_{2s}, u_{z2}, $u_{\theta 2}$, h_2 and h_{2s}.

These equations include inlet parameters (known quantities – subscript 1), outlet parameters (subscript 2), theoretical isentropic outlet parameters (subscript $2s$) and dimensionless ratios of inlet parameters to outlet parameters (subscript r). For example, the ratio $r_r = r_1/r_2$ is the ratio of inlet to outlet radius of gyration. The quantities u_{z2} and $u_{\theta 2}$ are the axial and circumferential components, respectively, of outlet velocity. In addition, two empirical coefficients make an appearance in the equations: K_V (angular momentum conservation coefficient) and η (process efficiency). These coefficients are dependent on three-dimensional geometry of the volute scroll; they cannot be obtained within the constraints of the one-dimensional model. In order to close the model, the empirical coefficients must be assumed, or supplied on the basis of either experimental or numerical simulation data. In the course of the current project, numerical simulations of volute flow were carried out and their results evaluated to supply tabulated values of K_V and η for varying volute geometries.

The above system of equations can be transformed to yield a single non-linear equation with a single unknown p_r, representing the dimensionless ratio of pressures at inlet and outlet from the scroll duct:

$$p_r^{\frac{1-\kappa}{\kappa}} + \eta\frac{\kappa-1}{\kappa}M_1^2 S_r^2\left(\frac{1}{\eta}p_r^{\frac{1}{\kappa}} - \frac{1-\eta}{\eta}p_r\right)^2 = 1 + \eta\frac{\kappa-1}{2}M_1^2\left(1 - K_V^2 r_r^2\right) \qquad (8)$$

With the flow parameters at inlet known, and the values of the empirical coefficients supplied, equation 8 may be used to obtain exit pressure and consequently the other parameters at volute outlet.

In this context it becomes desirable to predict the influence of changes in empirical coefficients K_V and η on the solution of Eq. 8. The equation can only be solved implicitly, the unknown p_r occurring in the form of several factors with fractional powers. Consequently, the coefficients K_V and η may be seen to influence the solution in a complex non-linear way which is not immediately evident from the form of the equation.

Results obtained from 3-D numerical simulations indicate that, for a broad range of volute duct configurations, the value of K_V falls into the $0.4 \div 0.8$ range, whereas efficiency η remains consistently above 0.5. Taking these ranges into account, a parametric analysis of equation 8 has been carried out by solving the equation iteratively for K_V varying from 0 to 1, and η from 0.5 to 1. The results (obtained in terms of p_r) were in turn used to derive the values of other relevant quantities at outlet. Some relationships obtained in this analysis are illustrated in the plots below.

3 Uniformity criteria

The one-dimensional model discussed above operates on the *mean* values of volute outlet parameters, and makes possible to calculate these mean values only. It provides no information on the distribution of parameters over the circumference of the outlet slit. However, volute admission scheme, as investigated in this project, is intended both to yield the flow angles required by first stage rotor blading directly at exit from the scroll, and to provide uniform distribution of this angle and of mass flow over the entire rotor ring. Thus for the 1-D model to be relevant, it must be supplemented by a definition of quantitative uniformity criteria for at least these two parameters. The values of uniformity factors characterize 3-D geometries of various volute configurations, rather than the 1-D model; they can be determined by analyzing data from simulation runs over a

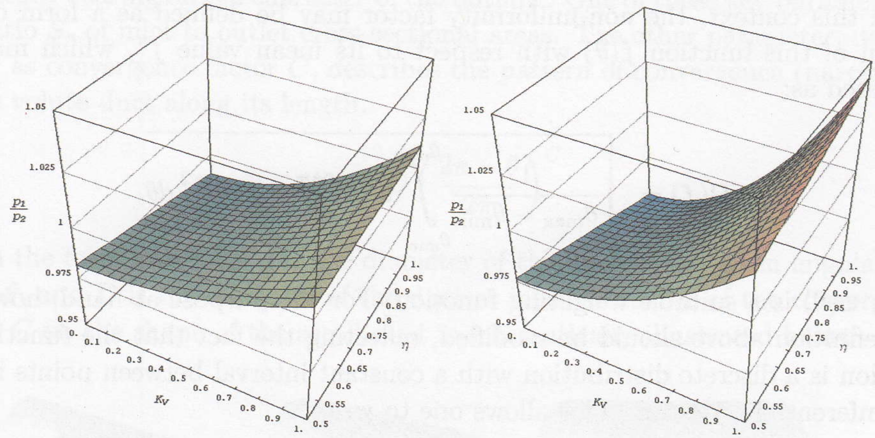


Figure 3. Ratio of inlet to outlet pressure p_r for large and small volute ducts, in terms of K_V and η.

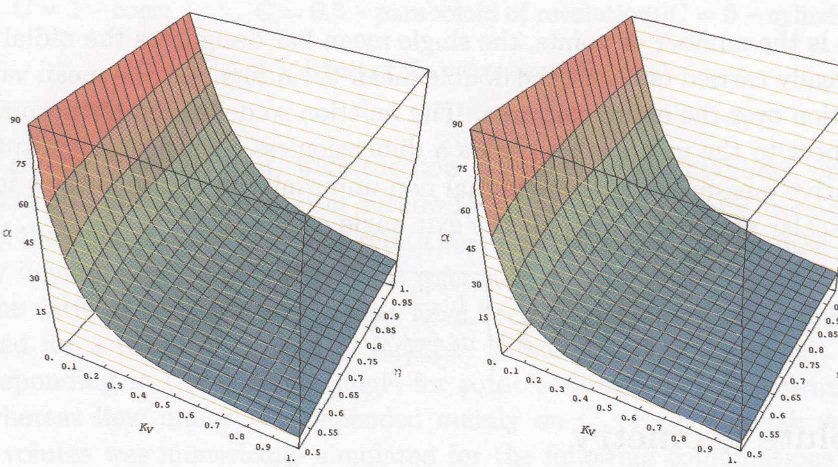


Figure 4. Exit angle α for large and small volute ducts, in terms of K_V and η.

3-D *numerical model of the volute.*

The exit plane from the volute scroll is a narrow circular ring, which in the numerical model is subdivided into small finite regions corresponding to the neighborhoods of computational grid nodes. Having performed weighted[1] averaging in the radial direction of the values at individual nodes, one obtains a discrete distribution of parameters as a discrete function in terms of angle θ, corresponding to arc distance along the exit ring.

[1]*The values at individual nodes have been assigned weight factors proportional to* mass flow rate through the neighborhood of the given node.

In this context, the non-uniformity factor may be defined as a form of deviation of this function $f(\theta)$ with respect to its mean value f'', which may be expressed as:

$$D(f) = \sqrt{\frac{1}{\theta_{\max} - \theta_{\min}} \int\limits_{\theta_{\min}}^{\theta_{\max}} w(\theta) \left[\bar{f} - f(\theta)\right]^2 d\theta} \tag{9}$$

where $w(\theta)$ is a suitable weighting function. For the purpose at hand, however, the definition above should be modified, reflecting the fact that the function in question is a discrete distribution with a constant interval between points in the circumferential direction. This allows one to write

$$D(\bar{f}) = \sqrt{\frac{1}{m} \sum_{j=1}^{m} \left[\bar{\bar{f}} - \bar{f}(\theta_j)\right]^2} \tag{10}$$

where m is the number of points, the single mean bar designates the radial averaging already carried out, and the double mean bar designates the mean value of the function over the entire exit area. The function so defined, after normalizing with respect to the mean value, yields a dimensionless coefficient constituting a quantitative measure of circumferential non-uniformity in volute outflow for any desired scalar parameter, e.g. for the exit angle α:

$$N_\alpha = \frac{1}{\bar{\bar{\alpha}}} \sqrt{\frac{1}{m} \sum_{j=1}^{m} \left[\bar{\bar{\alpha}} - \bar{\alpha}(\theta)\right]^2} \tag{11}$$

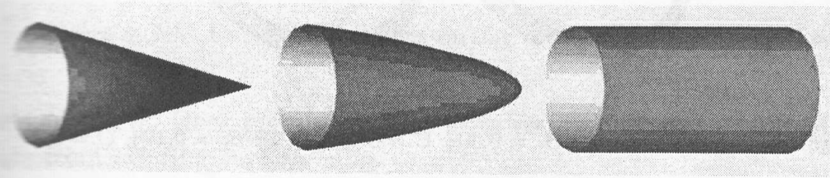
4 Volute geometry

The dimensions of the turbine to which the volute inlet is to be fitted, including in particular the dimensions of the inlet plane to the first rotor blade ring, fix some of the dimensions of the volute scroll – its outlet slit dimensions in particular. The shape of the scroll duct, on the other hand, may within some constraints be varied so as to obtain a geometry which optimizes flow exit angle and uniformity of flow distribution, and minimizes losses. Topologically the volute duct has the form of a gradually narrowing tube with its inlet at the wide end and its outlet taking the form of a longitudinal slit along the tube. This tube is wound around the axis of the turbine, forming a closed ring.

A series of preliminary numerical computations, made for a number of geometrically diverse volute variants, has shown that description of volute shape may be simplified to include just two key quantitative parameters, which have the most significant bearing on the character of the outflow. One of these key parameters is the ratio S_r of inlet to outlet cross-sectional areas. The other parameter, defined below as convergence factor C, describes the pattern of convergence (narrowing) of the volute duct along its length.

$$d(\theta) = D\left(\frac{2\pi - \theta}{2\pi}\right)^C . \tag{12}$$

In the formula above, d is the diameter of the duct at the given angular distance θ, and D is the diameter of the duct at inlet. Influence of the convergence factor C on the shape of the scroll duct is schematically illustrated below.



$C = 1$ – cone; $C = 0.5$ – paraboloid of revolution; $C = 0$ – cylinder

Figure 5. Effect of the convergence factor C.

It should be noted that, were the flow is lossless and frictionless, one would expect to obtain the most uniform outflow for a linearly decreasing cross-sectional area of the duct (i.e. for $C = 0.5$). For a real flow, however, the optimal value of C may deviate considerably from that reference.

The variants of volute scrolls that have been investigated in detail were constructed for a range of S_r and C factors. It was found that the exit angle α (corresponding to the entrance angle for rotor blading) depended primarily on S_r, whereas flow uniformity depended mainly on C. Flow through small and large volutes was numerically simulated for the following combinations of these two parameters:

Table 1. Investigated volute shape variants.

	Large volute			Small volute		
$C \backslash S_r$	0.302[2]	0.236	0.194	0.310	0.244	0.201
0.3		√			√	√
0.5	√	√	√	√	√	
0.67	√	√		√	√	

Flow through the volutes was modeled at the design point corresponding to full loading of the turbine. The operating medium was superheated steam at [illegible] K, exiting from the volute at 8.63 MPa. Inlet velocities were set at different values for volute variants of different inlet areas, so as to obtain total mass flow rate through both volutes of 58 kg/s (the large volute carried $\frac{2}{3}$, and the small $\frac{1}{3}$ of this total throughput).

Figures 6 and 7 below show the actual shape of some of the investigated volute variants, illustrating the influence of the S_r and C factors on volute geometry.

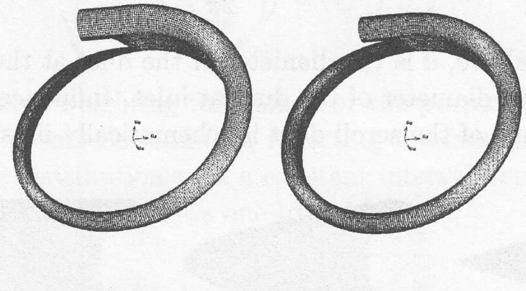


Figure 6. Large volutes for $S_r = 0.302$, $C = 0.67$ and for $S_r = 0.194$, $C = 0.3$.

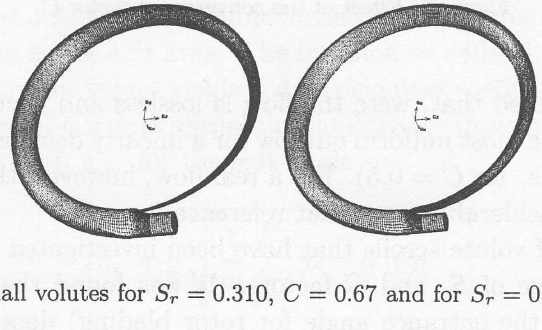


Figure 7. Small volutes for $S_r = 0.310$, $C = 0.67$ and for $S_r = 0.201$, $C = 0.3$.

5 Flow parameters and boundary conditions

The fluid modeled was superheated steam at 790 K (517°C) inlet temperature and outlet pressure of 8.634 MPa. Inlet velocities varied between the different configurations, so as to yield a combined mass flow rate of 58 kg/s through both volutes (This flow was split $\frac{2}{3} - \frac{1}{3}$ between the large and small volutes; the resulting velocities are listed in Fig. 8.). Uniform velocities were specified as boundary conditions at inlet, and a tubular introductory section was added to the model for the velocity profile to develop in before reaching actual inlet to the volute.

Quantities k and ε, needed for modeling turbulence within the flow, were estimated on the basis of inlet dimensions and an assumed value of turbulent

	Large volute			Small volute		
$S_r \rightarrow$	0.302	0.236	0.194	0.31	0.244	0.201
avg. inlet velocity [m/s]	159.17	203.64	248.12	149.21	189.95	230.64
inlet k	186.21	304.8	452.49	163.64	265.2	390.98
inlet ε	54100	128147	255860	61024	142055	281282

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Gibbs: KJ/Kg       -1886.0
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Other fluid parameters at inlet.

Figure 8. Inlet boundary conditions varying between volute configurations.

intensity I of 7%. Back pressure at exit from volute was set at 8.634 MPa, based on data from existing turbine inlet.

6 Flow parameters at outlet from volute

The values of key parameters at computational grid nodes at the outlet plane have been obtained from numerical data for all the simulation runs. These data were then processed to obtain the distribution of radially-averaged values along the length of the outlet slit. The distributions were plotted as a function of angular distance along the volute outlet. Sample plots of exit angle distributions for all the investigated variants are shown in Fig. 9 below, separately for the large and the small volutes. Note that the entrance to the small volute is offset by 180° with respect to the large volute; hence the different position of inlet/tip disturbances on the two sets of plots.

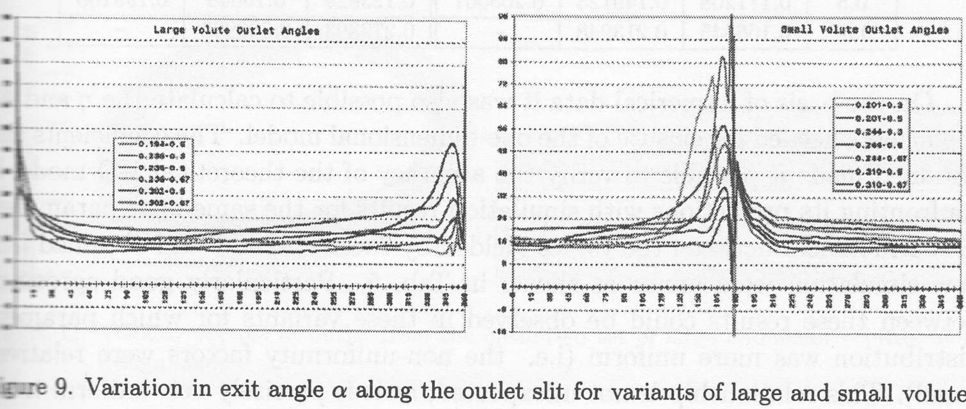

Figure 9. Variation in exit angle α along the outlet slit for variants of large and small volutes.

The mean values of exit angles for all the variants were also obtained, and the non-uniformity factors were subsequently calculated in accordance with the scheme discussed above. These are tabulated in tables 2 through 4. The same method was used with respect to other parameters at volute outlet. The values for non-uniformity factors, along with other relevant results, were interpolated as functions of shape parameters S_r i C to determine the optimal configuration of the large/small volute assembly.

Table 2. Comparison of ideal to actually obtained exit angles.

	Large volute			Small volute		
$C\backslash\alpha_{id}$	15°	12°	10°	15°	12°	10°
0.3	–	18.155°	–	–	20.480°	16.978°
0.5	22.135°	18.441°	14.598°	22.472°	18.776°	16.011°
0.67	20.016°	16.265°	–	25.080°	23.402°	–

Table 3. Non-uniformity factors obtained for exit angle α.

	Large volute			Small volute		
$C\backslash S_r$	0.302	0.236	0.194	0.31	0.244	0.201
0.3	–	0.492313	–	–	0.464845	0.447019
0.5	0.267072	0.236018	0.254974	0.14219	0.180102	0.199168
0.67	0.127263	0.218926	–	0.429203	0.508009	–

Table 4. Non-uniformity factors obtained for mass outflow.

	Large volute			Small volute		
$C\backslash S_r$	0.302	0.236	0.194	0.31	0.244	0.201
0.3	–	0.468882	–	–	0.40417	0.447019
0.5	0.171208	0.149125	0.205567	0.123829	0.16648	0.199168
0.67	0.166845	0.213948	–	0.279803	0.330903	–

On the basis of numerical data it was also possible to calculate the η and K_V coefficients needed for closure of the one-dimensional model. The coefficients thus obtained made it possible to verify the accuracy of the theoretical 1-D model by confronting its predictions with simulation results for the same inlet parameters.

Differences between the values yielded by the 1-D model and obtained from flow simulation were minor as shown in Tab. 5. Particularly good agreement between these results could be observed in these variants for which parameter distribution was more uniform (i.e. the non-uniformity factors were relatively small). This relationship is not unexpected, as it is precisely non-uniform transverse distributions that the 1-D model cannot account for. For relatively uniform

Table 5. Mean exit angles predicted by the 1-D model and obtained from 3-D simulations.

	Large volute			Small volute			
$C\backslash S_r$	0.302	0.236	0.194	0.31	0.244	0.201	
0.3	–	17.307°	–	–	19.730°	16.280°	⇐1-D calc.
	–	18.155°	–	–	20.480°	16.978°	⇐ 3-D data
0.5	21.464°	17.333°	18.832°	22.155°	18.244°	15.318°	⇐1-D calc.
	22.135°	18.441°	14.598°	22.472°	18.776°	16.011°	⇐ 3-D data
0.67	19.778°	15.891°	–	22.848°	19.835°	–	⇐1-D calc.
	20.016°	16.265°	–	25.080°	23.402°	–	⇐ 3-D data

distributions, the values of exit angles predicted by the 1-D model are consistently lower than the obtained 3-D values by about one degree. This is a systematic discrepancy that can easily be rectified by including an appropriate "fudge" correction factor in the 1-D model.

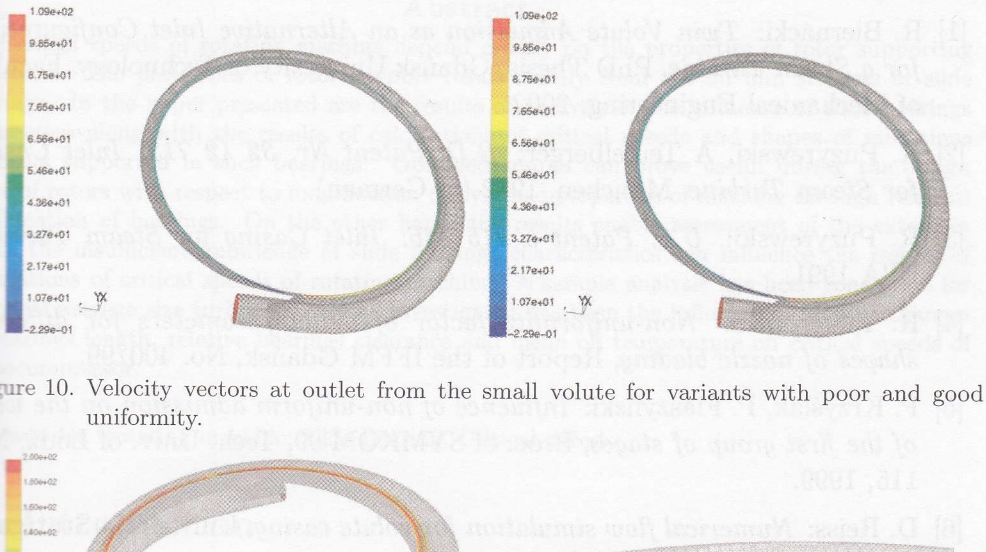

Figure 10. Velocity vectors at outlet from the small volute for variants with poor and good uniformity.

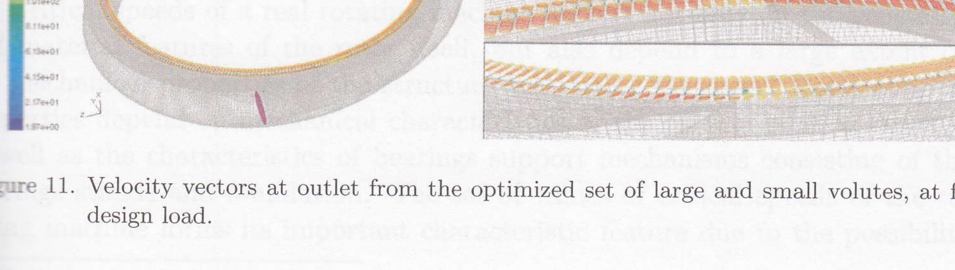

Figure 11. Velocity vectors at outlet from the optimized set of large and small volutes, at full design load.

7 Conclusions

Flow parameters obtained in the numerical simulation runs fell into the range required for proper operation of the turbine. Evaluation of the data indicates that the admission volute is capable of generating flow angles suitable for direct feeding into first stage rotor blading, obviating the need for guide blading. Furthermore, the flow angle can be precisely calibrated to match the rotor by making systematic adjustments to the geometry of the volute duct. The proposed one-dimensional model of volute flow yields results consistent with the results of a more complex three-dimensional computation, raising the possibility of utilizing this simple model for preliminary design of angular momentum generating volutes.

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