An experimental study of the flow in a sharp-heel draft tube

Urban Andersson
AN EXPERIMENTAL STUDY OF THE FLOW IN
A SHARP-HEEL DRAFT TUBE

Urban Andersson

Vattenfall Utveckling AB
SE-814 26 Älvkarleby
Sweden
E-mail: urban.andersson@utveckling.vattenfall.se
March, 2000

ABSTRACT

The goal of the Turbine 99 Draft Tube experiments is to provide extensive experimental data on a well-defined sharp-heel draft-tube flow. The data bank has served as calibration data for the simulation challenge presented by the Turbine 99 workshop in Porjus in June 1999.

This thesis gives some background on draft-tube flows in general and discusses in some detail the parameters and flow conditions relevant to the Turbine 99 draft tube. Some comments on the research and development conducted so far in the project and future plans are given at the end.

In the three accompanying papers, details of the developments and the scientific results are presented:

Paper 1. Presents the scope of the work and some initial results from the measurements

Paper 2. Discusses the quality of the measurements

Paper 3. Presents some of the results from the measurements
ACKNOWLEDGMENTS

This project has been funded from a research programme jointly financed by STEM (Swedish National Energy Administration; originally NUTEK, Swedish National Board for Industrial and Technical Development), ELFORSK (Joint organisation of Swedish Utilities) and KVAERNER TURBIN AB, Sweden (today: GE Sweden AB).

I would like to thank our co-workers at Vattenfall Utveckling and especially Klas-Göran Helzenius, for his professional skills in the turbine rig.

The cooperation with the division of Fluid Mechanics at Luleå University of Technology has been a great source of inspiration and I would like to thank Fredrik Engström for his help with the visualisations and John Bergström for his help with Cad and CFD.

Bengt Nauclér, KVAERNER TURBIN AB, has contributed to the understanding of the fundamentals of draft tubes.
LIST OF PAPERS

This Thesis summarises the work behind the following papers:

**Paper 1:**

**Paper 2:**

**Paper 3:**
Draft tubes

The purpose of hydropower is to convert potential energy into electric energy. In a reaction turbine, water leaves the runner with remaining kinetic energy. To recover as much of this energy as possible, the runner outlet is connected to a diffuser, i.e. the draft tube. The draft tube ‘converts’ the dynamic pressure (kinetic energy) into a static pressure (see Figure 1). Not all energy will be recovered, that is why the total pressure is decreasing through the diffuser in the figure. Since the conditions, at the outlet, determine the level (1) of the static pressure, the pressure level (2) must be reduced at the inlet. So the draft tube creates an extra ‘draft’ after the runner, or more correctly: the draft tube enables the utilisation of the available head in the flow.

![Figure 1. The change in pressure and velocity head along a diffuser.](image)

In most installations the runner axis is vertical, so the draft tube has to be bent, to save space and redirect the flow. Often it starts as a cylindrical diffuser (connected to the runner casing) followed by an elbow. Throughout the elbow the flow is generally contracting. After the elbow the draft tube ends with a diffuser (often rectangular in older plants). In Figure 2 the change in area (of a cross section) can be seen for the studied sharp heel draft tube. The sharp heel gives a characteristic discontinuity peak in the curve.

![Figure 2. The area (normalised with the area at the outlet) for the studied draft tube.](image)
To improve the mechanical strength of the construction, piers, which also act as flow guides, might support the outlet diffuser.

Earlier, draft tubes were designed by rules of thumb (e.g. MOSONYI, 1956) and practical experience of the manufacturer. The shape and the number of types of the draft tubes might vary between different manufacturers due to specific problems that their customers might encounter, e.g. limited amount of space.

Older draft tubes often have a low ratio between the height of draft tube and the runner diameter. This was done to avoid cavitation and/or to limit the depth (in the ground/rock) of the construction. They are also short (i.e. a low ratio between the total length of the draft tube and runner diameter) to give a greater safety margin in terms of flow separation. These compact designs often had sharp elbow and sharp corners, which made them simple to build and less space consuming. However, this design philosophy did not produce draft tubes, which minimised flow losses.

Today, draft tubes have become higher with smoother curvature, and in addition they also have a tendency to be made longer. One example of this development is given in HOTHERSALL (1988).

**Background to the research project**

A thorough description of the background to this project can be found in KARLSSON and GUSTAVSSON (1995).

The Turbine 99 project is part of a Swedish program on Water Turbine Technology, and consists of two parts:

2. A computational study of draft tube flow, performed at Luleå University of Technology (by John Bergström).

This thesis summarises the experimental part of the project. In the spring 2000, a Ph.D-thesis will be presented, (BERGSTROM, 2000) on the second part of the project.

The losses in a draft tube are proportional to the velocity head, \( \frac{(Q/A)^2}{2g} \), so from a Swedish perspective, with high-flow low-head hydro resources, the draft tube is a relatively important component, where up to 50 % (at high loads) of the losses occur.

Economically the draft tube is highly interesting from the plant owners’ point of view, since his focus is on higher loads (see Figure 3 plots 2 and 3). Since an improvement in the draft tube is proportional to the velocity head (Figure 3 plot 1). The resulting revenue (Figure 3 plot 4) is of interest even if the improvement is small at the best efficiency point.
The deregulation of the electricity market, pressing the price of electricity rapidly downwards, has also lead to the fact that a range of refurbishment tools is needed, from larger reconstruction works of the entire plant to smaller jobs that will fit into periods of regular maintenance, to give the best possible reinvestments.

The studied draft tube (Figure 4) represents a large group of draft tubes, over 50 installed in Swedish power stations, which will be in need of refurbishment in 5 to 20 years. The old design enables the possibility for efficiency improvements, in the range of 0.3-2.3% (GUBIN, 1973) for this type of draft tube. The hydro power stations of this type represents 6700 GWh/year in electrical generation, i.e. about 10% of the total Swedish hydro power production. (It could also be noted that the refurbishment of a medium sized power station yields as much power as a new larger wind power station.)
The actual draft tube chosen for this study has been improved, and the total efficiency improvement was 0.5 % in model scale and slightly higher in full scale (DAHLBÄCK, 1996). However, to enable the redesign for all draft tubes, a cheap and reliable tool is needed.

**Project goal**

The goal of the Turbine 99 Draft Tube experiments is to provide extensive experimental data, on a well-defined draft-tube flow, which can serve as a test case for validation of CFD codes for draft tube applications, thus contributing to further development in the field.

The scientific results have been published in three articles:

- **Paper 1.** ANDERSSON and DAHLBÄCK (1998) *Experimental evaluation of draft tube flow.* - *A test case for CFD-simulations:* Describes the purpose of the work and tries to inspire people to take part in the Turbine 99-workshop by showing some initial results from the measurements.

- **Paper 2.** ANDERSSON and KARLSSON (1999) *Quality aspects of the Turbine 99 draft tube experiments:* Presents the measurements techniques and special adaptations made for the experiments. Discusses the special quality aspects of each technique and evaluates the resulting accuracy.

- **Paper 3.** ANDERSSON (1999) *Turbine 99 – Experiments On Draft Tube Flow (Test Case T):* Presents the results from the measurements, with focus on the Turbine 99-workshop. The paper presents inlet and outlet data from the outlet sections. It also describes the pressure recovery along the centre lines of the draft tube.
Basic concepts of the experiments

**General measurement systems**

A measurement system and/or single components of a measurement system can be described as a static part that transforms the measured signal together with the noise. The transformed signal then passes through a dynamic filter that affects the frequency characteristics of the observed signal (*Figure 5*).

The part of the static transformation that cannot be calibrated away causes the systematic error. The RMS-value of the signal together with the signal to noise ratio affects the random error. (See ANDERSSON and KARLSSON, 1999, for definitions).

The dynamic transformation affects the distribution of energy in the frequency spectra, but will not cause any affects on the mean value (in a ‘well-behaved’ system). However, the dynamic transformation might affect higher statistical moments such as the RMS-value, e.g. a damping of the real signal will result in a lower observed RMS-value.

For the pressure measurements (ANDERSSON and KARLSSON, 1999) the signal will be affected by the dynamic response of the measurement system, due to a series of ‘hydraulic components’ between the pressure tap and the pressure gauge. However, the main purpose of the design of the measurement system was to reduce the low frequency noise created by the test rig and to save a considerable amount of time (using only one pressure gauge). In the future different solutions that will give information about the RMS-value at some points in the draft tube will be investigated.

**Figure 5.** A general measurement system.

A complex system can be regarded as a series of small systems. To ensure that a single component in a system does not affect the entire system, calibrations are conducted both in a highly controlled environment for the main component (e.g. the pressure gauge) and in-situ at the test-rig with the entire system (e.g. the entire pressure measurement system).

The in-situ calibration also reveals any non-linearities in the ‘local’ measurement range, i.e. the range actually used in the measurement. In most cases this range is less than the total range of the instrument. To discover any hysteresis effects, the calibrations are always conducted both with (at least) one increasing series of readings and one decreasing series of readings.

To ensure the quality of the entire method good measurement procedures have to be followed. From a technical view-point these are quite well described in different standards, e.g. IEC 60193-1 and ASME PTC 18, as well as calibration procedures that specify how the measurements are to be performed to produce reliable data.
Analysis of pressure recovery

To evaluate the performance of the draft tube, the pressure recovery is calculated. The basis of these calculations is the Bernoulli expression (without losses):

\[
\overline{p_1} + \frac{\rho \overline{u_1^2}}{2} = \overline{p_2} + \frac{\rho \overline{u_2^2}}{2},
\]

where \( \overline{p_1} \) is the mean static pressure of cross section \( i \), and \( \frac{\rho \overline{u_1^2}}{2} \) is the mean dynamic pressure of cross section \( i \).

The expression is rewritten and normalised with the dynamic pressure (at the inlet) based on the flow rate \( (Q) \), and one gets the pressure coefficient.

\[
C_p = \frac{\overline{p_2} - \overline{p_1}}{\frac{\rho}{2} \left( \frac{Q}{A_1} \right)^2} = \frac{\overline{u_1^2} - \overline{u_2^2}}{\overline{u_1^2} - \overline{u_2^2}}
\]

(2)

The one-dimensional analysis \( (Q = u_i A_i) \) results in the ideal pressure coefficient:

\[
C_{p_{ideal}} = 1 - \left( \frac{A_1}{A_2} \right)^2
\]

(3)

The exact pressure coefficient can be written as:

\[
C_p = \alpha_1 - \alpha_2 \left( \frac{A_1}{A_2} \right)^2 = \alpha_1 \left( 1 - \frac{\alpha_2}{\alpha_1} \frac{A_1}{A_2} \right)^2
\]

(4)

where the \( \alpha \)-value (the kinetic energy correction factor) can be calculated with:

\[
\alpha = \frac{1}{A U^3_{mean}} \int U (U^2 + V^2 + W^2) dA,
\]

(5)

according to DAUGHERTY (1989). This is the result based on stationary flow, in this case especially at the inlet the flow is clearly periodic (ANDERSSON, 1999) so additional kinetic energy is hidden in the non-uniform distribution of the mean values over a cross section (i.e. an additional integration in time, over one period, would yield a higher \( \alpha \)-value).

To give a better estimate of the pressure recovery a loss term can be added as in ANDERSSON (1999).

The pressure coefficient could be examined with Equation 4, but another way would be from direct pressure measurements. However, internal (accurate) pressure measurements are rather difficult to produce, so wall pressures are used to determine the pressure recovery coefficient:
$$C_{p_i} = \frac{P_{\text{wall}_{-i}IVb} - P_{\text{wall}_{-i}Ia}}{\frac{\rho}{2} \left( \frac{Q_{Ia}}{A_{Ia}} \right)^2},$$  \hspace{1cm} (6)

where $P_{\text{wall}_{-i}}$ is the mean pressure at the circumference of cross section i. Cross section Ia is the inlet section and IVb is the outlet section (for specification see ANDERSSON, 1999).

Both Equation 4 and 6 give an estimate of the pressure recovery. The value defined by Equation 6 can be determined with very high accuracy since both the flow rate (Q) and the wall pressure ($P_{\text{wall}}$) are relatively easy to determine. To make both values comparable, the $C_{p_i}$ from Equation 4 is also normalised with the 'bulk' dynamic pressure and not the total dynamic pressure (which is a factor $\alpha_{Ia}$ higher), which would be a more usual way of performing this calculation.

The local wall pressure is sensitive to acceleration and deceleration close to the wall. A typical example of this can be seen in Figure 6. The flow is decelerated at the outside of the elbow (until $L = 0.16$), i.e. the lower centre-line, and accelerated at the inside as the flow enters the elbow.

![Figure 6](image)

**Figure 6.** The pressure recovery along the centre lines (c.l.) for the elbow. (Offset: $C_{p} = 1.0$ at $L = 1.0$.)

These ‘local’ deformation effects of the pressure profiles at a cross-section (caused by the deformation in the velocity profile) are smoothed out in the streamwise direction even if the variation in velocities remain.
Development and Scientific Results

General comments on the project development

The strategy and details of the measurements can be found in ANDERSSON and DAHLBÄCK (1998) and ANDERSSON and KARLSSON (1999).

Mainly three types of measurements have been performed: visualisations, wall-pressure measurements and LDA (laser doppler anemometry) for velocity measurements.

At the beginning of the project most of the components needed for the experiments already existed. The test rig (described in MARCINKIEWICZ and SVENSSON, 1994) had been used successfully in several projects. One example that involves the chosen draft tube is found in DAHLBÄCK (1996). So the basic characteristics of the draft tube were already known.

The visualisations had to be adapted to fit the special problems in the draft tube, i.e. high velocities, the necessity to seed a large amount of water and a complex three-dimensional geometry. The method works quite well, but there are still a lot of post-processing disadvantages.

The wall-pressure measurements did not meet the high requirements of the project. Most work has focused on reducing low-frequency noise and developing better measurement routines and evaluation algorithms.

The LDA-technique uses the Doppler effect that shifts the reflected light from a particle. The technique can be considered to be non-intrusive. The fluid and walls need to be transparent, which causes some problems since windows need to be inserted into the model. The resulting Doppler frequency is proportional to the measured velocity component so no calibrations are necessary.

For the LDA-system a better positioning procedure and fine mechanical equipment were developed to facilitate the positioning of the measurement volume. To avoid disturbances of the flow (close to the wall) and of the laser beams (closer to the centre) a set-up, which used two different windows, was employed.

Main results from the velocity measurements are the velocity distributions (mean and RMS velocity) at the inlet section Ia, given as inlet boundary conditions for the computations, and the velocity distributions at section III.
In Figure 7 the mean component profiles at the inlet section (Ia) are plotted. The axial profile is quite smooth but has a maximum \((r^* = 0.88)\) that is significant for the hydrodynamics of the cross-section. The tangential profile grows almost linearly, but there is a local maximum (at the left side) and a local minimum (at the right side) around \(r^* = 0.88\), which corresponds to the maximum of the axial profile.

In addition to these mean velocities, one can find turbulence intensities and a time series that reveals the periodic behaviour of the velocity at the cross section in ANDERSSON (1999).

**Figure 7.** The normalised mean velocity components at profile Ia(1).

The axial velocity component at the outlet section (III, for the velocity measurements) can be seen in Figure 8. The highest normalised axial velocities (perpendicular to the cross-section) are found at the right of the figure. The axial \(\alpha\)-value \((\alpha_{ax} = 1.09)\) is quite low so only a little extra (axial) velocity head is lost at this section compared to section Ia.

**Figure 8.** The axial velocity component at cross-section III. (View from downstream side)
The CFD-simulations compared with the experimental results

In the summer 1999, the ‘Turbine 99 workshop on draft tube flow’ was held at Porjus, Sweden. To give a picture of the quite large spread in results, the relative deviation in the results from the simulations, compared to the experiments, are presented. The simulations (of test case T) are discussed here without any name reference since this is supposed to be a more general comment.

The inlet conditions (Figure 9) for the simulations, based on $\alpha_i$, differ slightly from the inlet conditions determined by the experimental investigation. However, for six cases, the inlet conditions differ more than ten percent. A necessary condition, perhaps mandatory, should be that the setting of the inlet conditions lies within a certain limit.

From an engineering point of view, the pressure recovery factor may be considered to be the most important single parameter to be predicted by the simulations.
The resulting $C_p_r$ (**Figure 10**) from the simulations can be divided into three groups. One group lies much higher than the experimental value, another group lies much lower and finally one group predicts the result fairly well.

From an experimental point of view the analysis of the simulations can be divided into three categories:

- **Prediction of the overall performance.** From **Equation 4** one can see that the resulting flow pattern has a rather small impact on the pressure recovery, especially with the big area ratio between inlet and outlet in this case. The flow patterns of the simulations, that have $C_p_r$-values close to the experiments, differ between each other and also compared with the experiments. So a reason for the large differences, in some of the cases, between simulations and experiments need to be understood.

- **The simulations show a great variety in flow patterns at the outlet sections, mainly because small variations into the elbow will result in very big differences out of the elbow.** This could make the classification of the simulation simple, since any differences should appear quite clear in integral values, after the elbow of the draft tube.

- **Further analysis of the simulation could give more information about the physics.** The variation in settings leads to a range of ‘cases’, which tell us something about the effect of these variation on specific phenomena, e.g. the size of the re-circulation zone under the runner hub. This type of analysis would be especially interesting for the first part of the diffuser and in the elbow.
Discussion and Further Development

A sharp-heel draft tube has been studied experimentally. Measurements have been performed with a good knowledge about the quality and performance of the involved systems.

All measurements contain bias information so to produce an accurate test case these effects need to be limited or at least understood. These artefacts set the limit for how good the quality of the measurements can become.

So far, the measurements have mainly been concerned with mean (and RMS) values. However, future studies should look more into the time characteristics of the measured quantities (i.e. velocity and pressure) and in that case a further knowledge of the (effect on) dynamics of the measurement systems will be acquired, especially for the pressure measurements.

The Turbine 99 workshop showed that these types of exercises are necessary to develop the CFD-tool. To enable the evaluation of the calculation extensive measurements, like these, are needed to serve as reference case(s).

The results from the workshop gave some guidelines for the development of the data bank. Three main objectives for the future work could be seen:

1. Most of the pressure recovery takes place in the very first part of the draft tube, so a better hydrodynamical understanding of this part could be desired.
2. Since most of the pressure recovery is determined by the input of energy (with the given choice of area ratio, which is very low) see Equation 4, the CFD-tool should be able to predict the pressure recovery coefficient better than in Figure 10. So in the future more (and better) reference sections of velocity measurements will be needed and preferably closer to the elbow to detect deviations as early as possible.
3. To broaden the usefulness of the experimental data, in a simulation context, they should include the periodic behaviour for (some strategic) measured quantities.

Initial measurements have been made for two test cases, and it is planned to complete this second test case so that there are two test cases with different inlet conditions available at the end of the project.
REFERENCES


