

PIPE FLOW MODELING FOR ULTRASONIC FLOW MEASUREMENT

H. Jeanneau, M. Pigué
Research and Development Division
Electricité de France (EDF)
Chatou, France

Abstract: In many industrial applications, the precise measurement of volumetric flow-rates is of crucial importance for economic or safety reasons. Flowmeters are generally installed in perturbed flow conditions. The measured value is then affected by a systematic error which can reach several %. EDF has developed a numerical tool to estimate the error introduced by the flow disturbances on the flow-rate measurement with ultrasonic flowmeters or differential pressure devices.

The tool is based on a 3D CFD program which determines the flow profile. A module allows the simulation of ultrasonic flowmeters and differential pressure devices.

This paper deals with ultrasonic flowmeters which are very sensitive to the flow profile through the parameter K (profile factor). Two configurations are presented in this paper:

- a double bend out of plane,*
- a pipe representative of the primary loop in nuclear power plant.*

In each case, both modelisation and experimental tests have been carried out to determine the profile factor K representative of the flow conditions, which should be used for the measurement with the ultrasonic flowmeter to reduce the error introduced by the disturbances. The influence of different parameters has been studied.

Experimental and calculated profile factors are compared. In both configurations, the simulation results are in good agreements with the experimental data. The tendency is well predicted by the tool and the typical difference between experimental and numerical K is around 2% or 3%.

The profile factors are also compared to the classical K (Prandtl Model) used and proposed by manufacturers, which is calculated from an analytic model of fully developed profile. The gain realized by using simulation is significant.

Keywords: ultrasonic flowmeter, CFD, experimental, profile factor, uncertainties, gain

INTRODUCTION

In industrial conditions, flow-rate is often incorrectly determined due to various phenomena such as wrong calibrations and drifts, erosion or fouling of the flowmeters, incorrect installation conditions (lack of straight lengths required by the standards upstream from the meter)... These phenomena may lead to systematic errors which can reach several percents of the measured value.

Regarding the importance of the flow-rate and the related economic gains, Electricité de France has always been very concerned by the means to improve the actual accuracy of flowmeters. Moreover, in the last two decades significant progress has been made in the development of Computational Fluid Dynamic (CFD) techniques. These developments, continually increasing ease and economy of digital computers, are now making numerical flow simulations customary for various engineering problems.

To support the application of CFD codes to flowmetering problems, the EDF Research and Development Division has developed an integrated software tool for the modeling of flows and the simulation of flowmeters. A module allows the simulation of ultrasonic flowmeters and differential pressure devices.

This paper deals with clamp on ultrasonic flowmeters which are very sensitive to the flow profile through the parameter K (profile factor). Two configurations are presented in this paper :

- a double bend out of plane (internal diameter : 340 mm, Reynolds numbers from 10^4 to 10^6 , clamp-on flowmeter installed 2D then 10D downstream the double bend)

- a pipe representative of the primary loop in nuclear power plant (internal diameter : 16 inches Reynolds numbers from 5.10^5 to 10^7 , flowmeter installed 1,6D then 4,8D downstream the source of disturbance).

In each case, both modelisation and experimental tests have been carried out to determine the profile factor K representative of the flow conditions, which should be used for the measurement with the ultrasonic flowmeter to reduce the error introduced by the disturbances. The influence of different parameters has been studied :

- computation of the profile factor for different axial positions of the meter behind the elbow
- computation of the profile factor for different angular positions
- study of the effects of the Reynolds number on the profile factor

THE MODELING TOOL

Description

The tool, represented in Figure 1, is built around the ESTET in-house code developed at EDF's Laboratoire National d'Hydraulique, which will determine the flow profile. A module allows the simulation of ultrasonic flowmeters and differential pressure devices (see Figure 1).

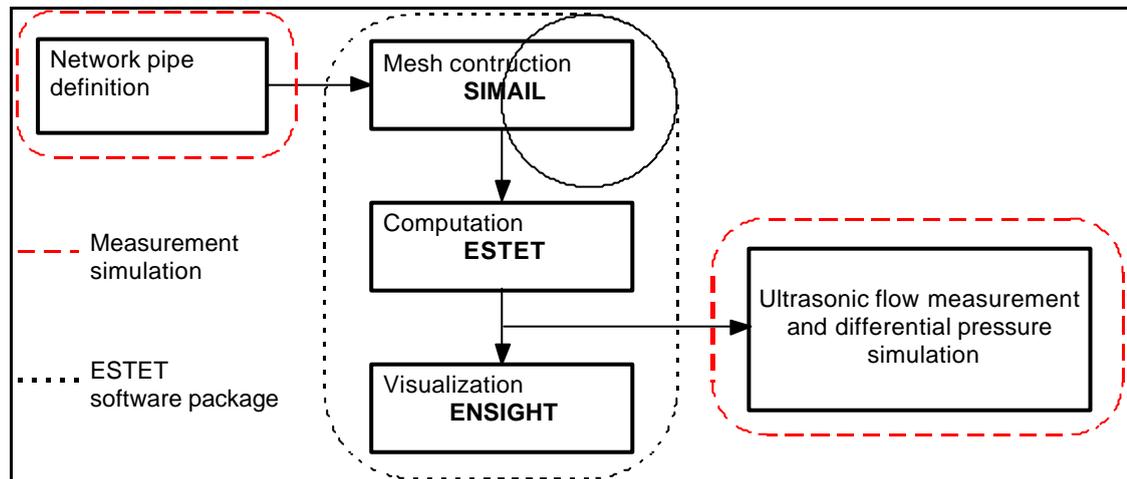


Figure 1 EDF R&D Division tool for flow-rate measurement simulation

ESTET is a 3-D fluid mechanic code using finite difference/volume numerical methods.

ESTET's input section to define the mesh construction for specified geometries is performed with SIMAIL, a 3-D structured or non-structured mesh construction software. ENSIGHT is a post-treatment software for visualization and printing. These two software routines are part of the ESTET package. The added part to the ESTET code is a network pipe definition module that allows the user to easily construct and mesh the pipe network without having knowledge of the SIMAIL software, and a ultrasonic flow measurement and differential pressure simulation module. This second part is the main interest of the tool. It allows the simulation of ultrasonic flow measurements and differential pressure devices. The tool runs on a Hewlett-Packard 700 station and ESTET can either be executed on a workstation or on a CRAY computer.

Ultrasonic module

Ultrasonic flowmeter (transit time principle) are very sensitive to the flow profile. The degree to which the actual flow profile differs from a fully developed profile introduces uncertainty in the flow-rate measurement (see Figure 2). Since the actual flow profile is a function of the piping configuration, the flow profile factor which corrects for this is specific and has to be determined for each piping configuration in order to allow the flow rate measurement uncertainty to be minimized.

The module can be used to determine and correct the bias introduced by flow disturbances on installed flowmeters or to optimize the installation of a new flowmeter (position, configuration).

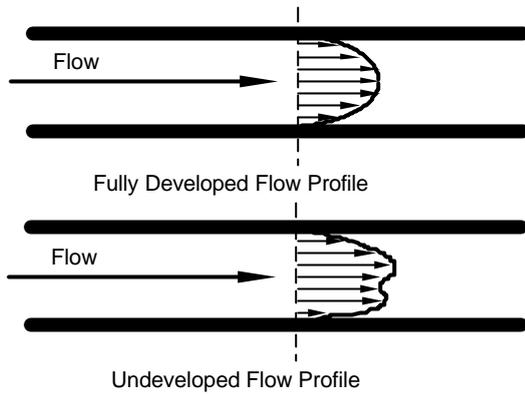


Figure 2 Developed versus undeveloped flow profile

The parameter which is computed to determine the bias is the profile factor K.

Profile factor computation

The profile factor is defined as the ratio of the axial velocity averaged over the pipe cross-section to the average axial velocity in the diametrical plane of the ultrasonic flowmeter. The flow-rate expression is thus:

$$Q_v = S * K * V_{axial}$$

where,

Q_v is the volumetric flow-rate,

S is the cross-sectional area,

K is the profile factor,

V_{axial} is the average axial flow velocity measured along the diametrical chord by the ultrasonic flowmeter.

The profile factor can be computed for different axial positions of the meter and for different angles of the acoustic plane orientation (angle ϕ , see Figure 3).

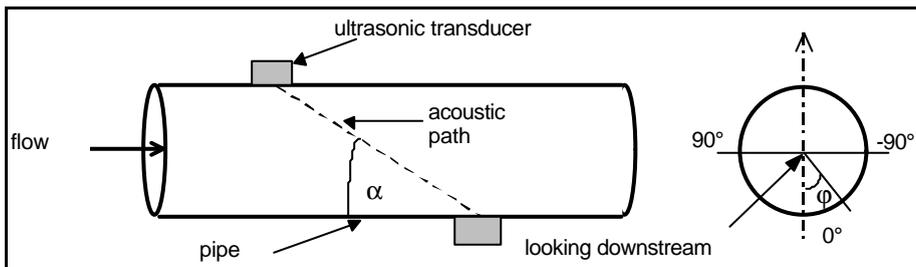


Figure 3 Ultrasonic diagonal path position and orientation

FIRST CASE STUDY

Background

The goal of this first study was to validate the ultrasonic module of the modeling tool. The configuration pipe chosen was a double bend out of plane, which introduces many disturbances on the flow profile. A transit time clamp-on ultrasonic flowmeter was installed two diameters downstream the double bend. Experimental profile factors and calculated profile factors have been compared to determine the validity of the tool's results. LDV (Laser Doppler Velocimetry) measurements have been carried out and have given additional information on the representativity of flow profiles calculated by CFD tool.

Experimental

Within the Research and Development Division of EDF, the experimental studies of liquid flowmetering problems are supported by the EVEREST loop. The loop is designed to offer calibration services for a wide range of flow conditions and to conduct research to provide a fundamental understanding of the phenomena that affect the flow-rate measurement process. For these purposes, the EVEREST loop meets the following performance specifications:

- type of fluid: liquid water
- size of pipe: diameter up to 600 mm
- flow range: $5 \text{ m}^3/\text{h}$ to $1100 \text{ m}^3/\text{h}$ ($\pm 1\%$)
- working pressure: 3 bar to 5 bar (± 0.1 bar)
- temperature range: 15°C to 50°C ($\pm 1^\circ\text{C}$)
- Reynolds number: $2 \cdot 10^4$ to $3 \cdot 10^6$

As shown in Figure 4, the EVEREST loop is made of 3 sections.

- the control section (provided with a pump, an exchanger, a pressurizer, two feedwater tanks and three regulation loops),
- the reference section which is dedicated to reference flow-rate measurements (two different types of standards, differential pressure devices and electromagnetic or Coriolis flowmeters). The accuracy of the measurement is of $\pm 0.3\%$ of the reading,
- the testing section which is variable : the pipe configuration can be modified to meet specific user needs in terms of singularities placed upstream or downstream from the meter (pipe fittings such as bends, valves, tees or reducers). This section is of prime interest when in-situ calibrations are not feasible and piping duplication is necessary.

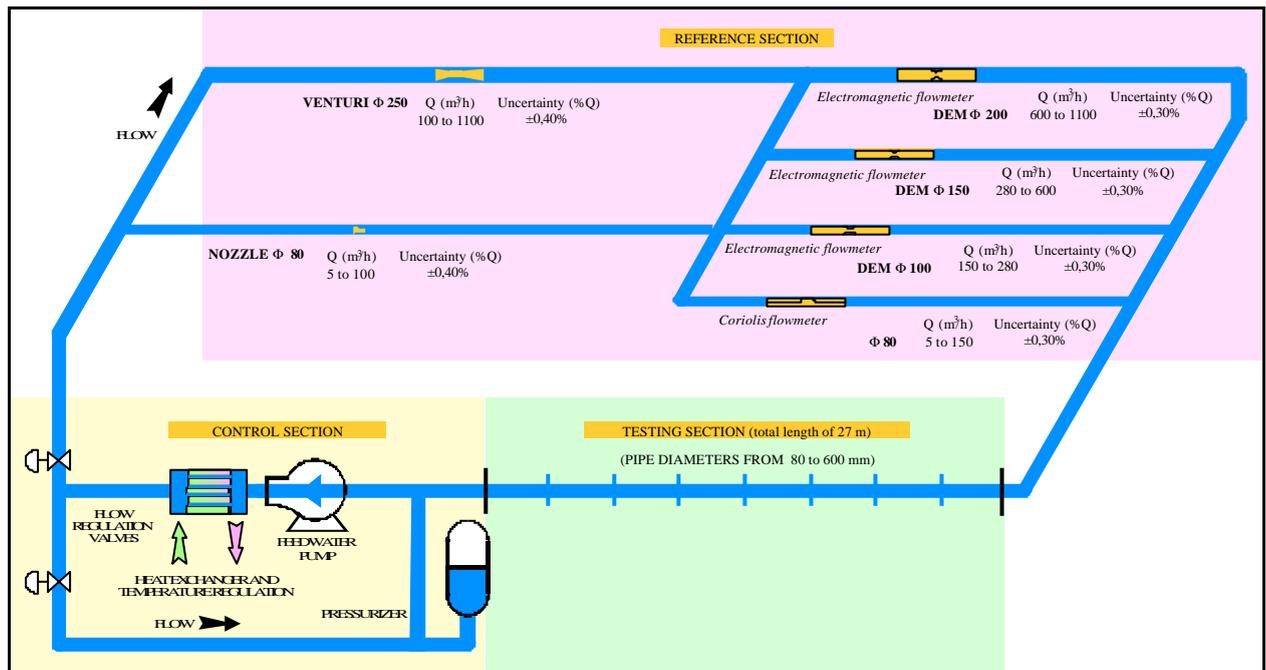


Figure 4 : The EVEREST loop

For this study, the pipe configuration was a double bend out of plane (see Figure 5). A transit time ultrasonic flowmeter has been installed two diameters downstream the double bend. For several flow rates (Reynolds numbers from 10^4 to 10^6) and several angular positions (from -180° to 180° , every 30° , see Figure 3), the ultrasonic flow measurements have been compared to the reference flow measurements. LDV measurements have been carried out on the measurement section (two diameters downstream the double bend).

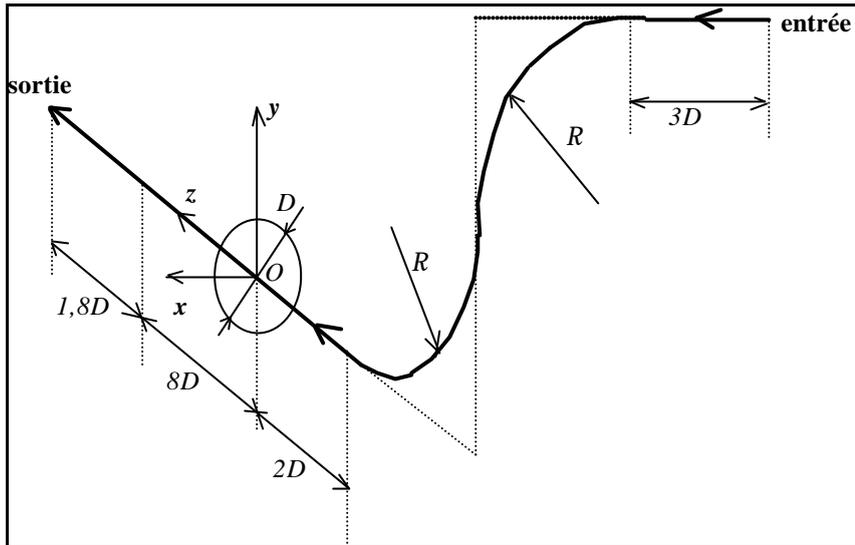


Figure 5 double bend out of plane geometry

Computer runs

The EVEREST hydraulic configuration represents a double bend out of plane. Its geometry is given in Figure 5.

A 3-D stationary flow computation was done with the EDF simulation tool. It is assumed that the flow is incompressible, isothermal and turbulent. The pressure and temperature are respectively set to $1,01 \cdot 10^5$ Pa and 25°C . The computer run was done on a structured mesh and with a quick-upwind convection scheme and a first order turbulence model (k-e). Figure 6 shows the grid in the vertical plane and Figure 7 shows the cross-section.

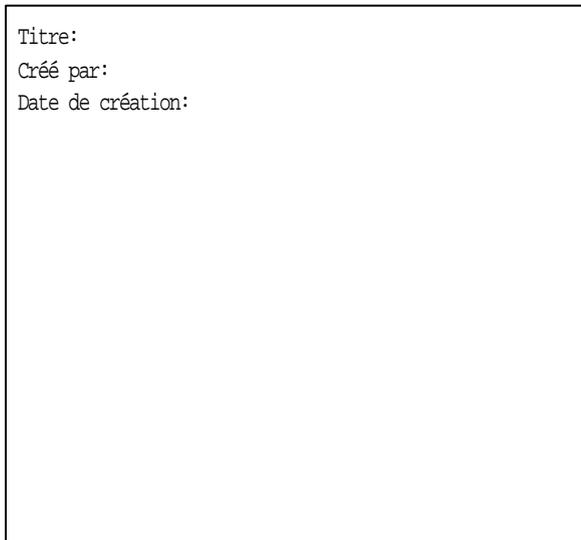


Figure 6 : mesh in the vertical plane

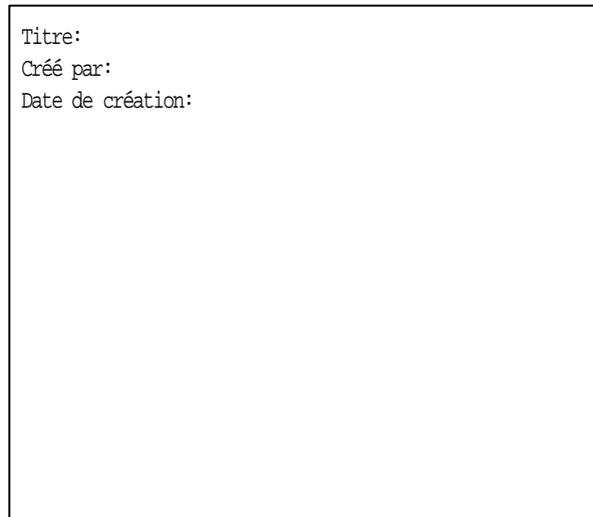


Figure 7 : mesh of the cross section

Representativity of flow profiles calculated by CFD tool

The flow profiles calculated by the CFD program have been compared to the LDV measurements. Figure 8 represents the axial velocity along the horizontal diameter in the measurement section (two diameters downstream the double bend). Figure 9 represents the axial velocity along the vertical diameter.

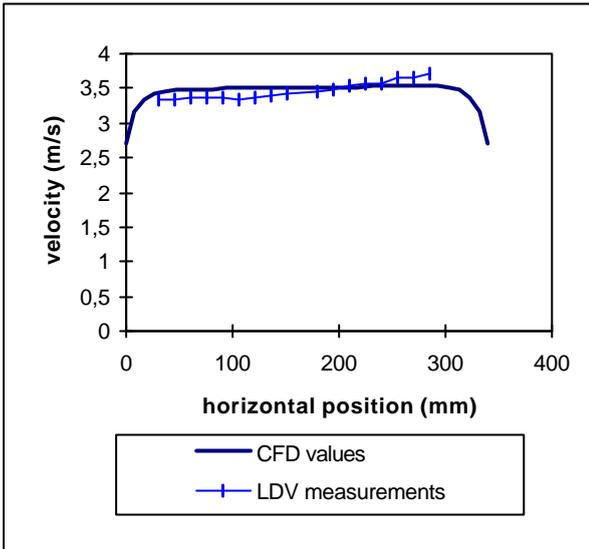


Figure 8 : axial velocity along the horizontal diameter

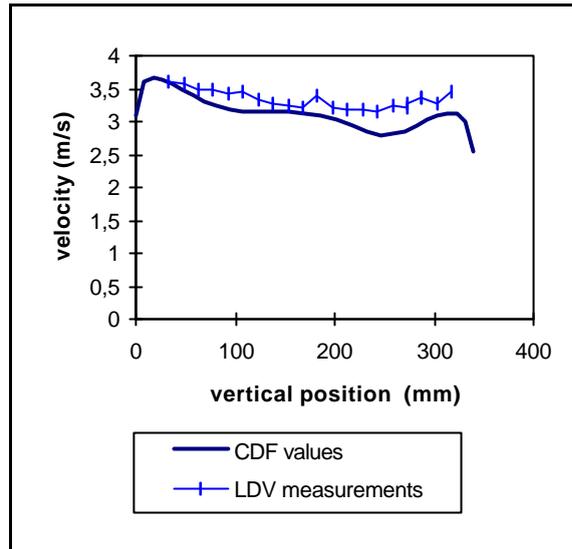


Figure 9 : axial velocity along the vertical diameter

The simulation results are in good agreement with the experimental data: the tendency is well predicted by the tool.

Profile factor computation

The profile factor was computed for different angles of the acoustic plane orientation (from -180° to $+180^\circ$, see Figure 3).

Figure 10 presents the angular variations of the profile factor values computed with the EDF simulation software and those extracted from the experimental data.

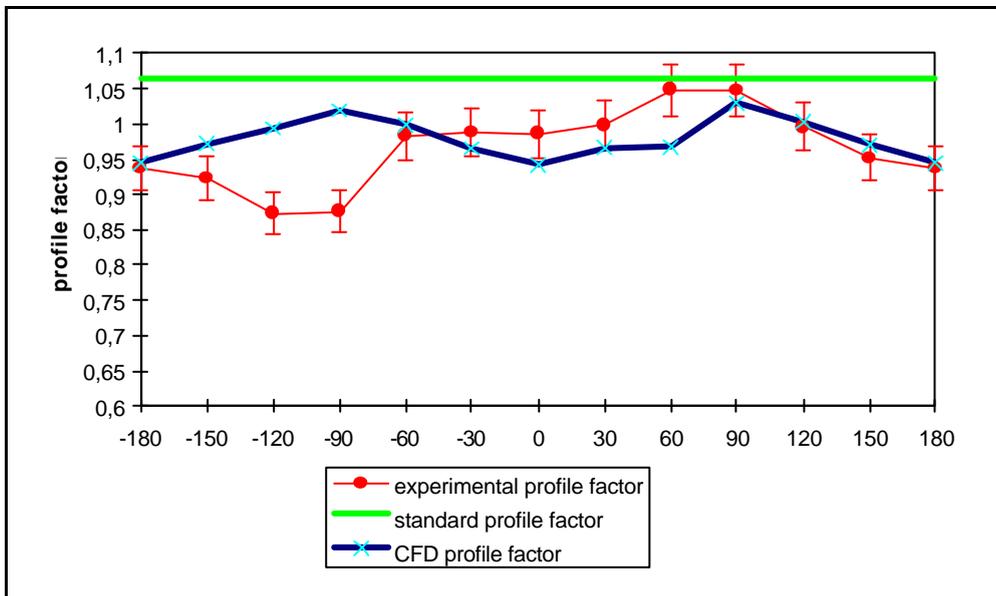


Figure 10 : Variations of the profile factor with the angular position

The red curve represents the experimental profile factor computed from the ultrasonic flow measurements and the reference flow measurements. The uncertainties are represented. The blue curve corresponds to the simulated profile factor. The green curve represents the standard profile factor computed from the Prandtl formula. This is the profile factor which is usually applied by the manufacturers of ultrasonic flowmeters. This profile factor is constant for a given flow-rate, it is only function of the Reynolds Number.

The curves show the influence of the flowmeter's angular position in a perturbed flow profile. They show that the Prandtl profile factor is not adapted to such profiles. That's why people have a great bias when they install a flowmeter downstream singularities like bends, valves...

The simulation results are in good agreement with the experimental data for an angle ϕ between -60° and 180° . For the three other angles, the CFD results are not in agreements with experimental data. It can be improved by a better grid mesh. These results have to be compared to the standard profile factor in term of bias compared to experimental data (see Figure 11). The bias with the standard profile factor can reach more than 20%. Thanks to the EDF simulation software, this bias has been cut down to less than 2% for a some angular positions.

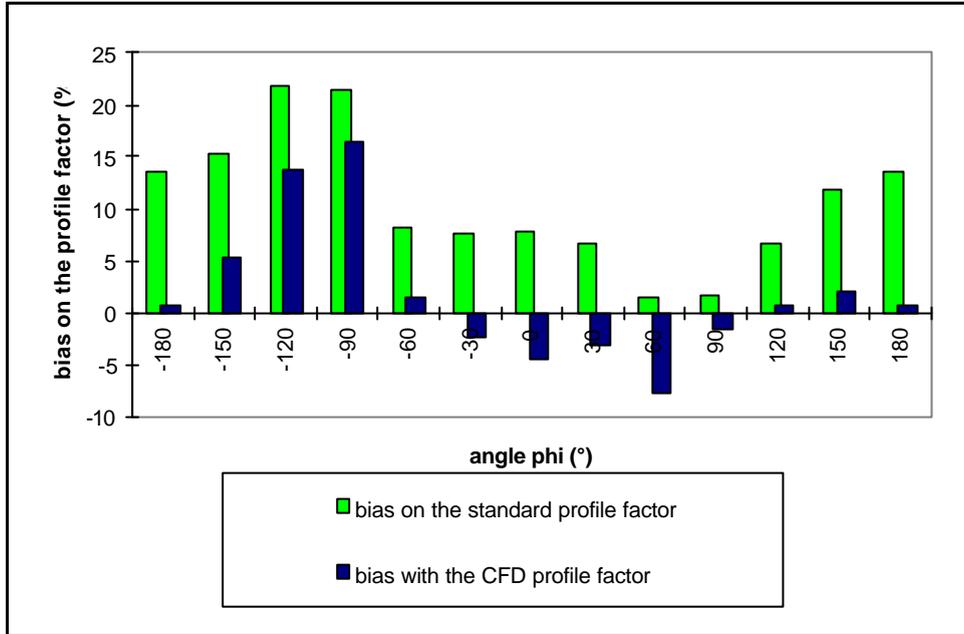


Figure 11 : bias on the CFD profile factor and on the standard profile factor

SECOND CASE STUDY

Background

In Pressurized Water Reactors (PWR), direct measurement of the reactor coolant flow would allow direct measurement of steam generator performance and the heat delivered to the steam generators could then be directly calculated from reactor coolant flow and temperature measurements and compared to calculations of plant thermal power.

To that purpose, the Electrical Power Research Institute (EPRI) has developed a prototype ultrasonic system for the measurement of reactor coolant flow and temperature. The system is based upon some existing technology for the measurement of feedwater flow using externally pipe-mounted ultrasonic systems. The measurement of reactor coolant flow is performed based on the measurement and comparison of ultrasonic pulse times-of-flight downstream and upstream across the reactor coolant pipe diameter. This system can be installed and maintained because it is externally mounted in contact with the coolant piping.

EPRI asked EDF to deal with a case study with its simulation tool. The purpose of the work was to provide a feasibility study on one specific piping configuration on which would be demonstrated the relevance of the modeling approach. EPRI identified one piping configuration developed at the US-based Alden Research Laboratory to simulate flow conditions at a US nuclear plant. The configuration was selected because this choice made possible a comparison between experimental and modeling data.

Computer runs

The Alden Research Laboratory hydraulic configuration represents the bottom of a steam generator modeled by a spherical head with a discharge nozzle. It is called the spherical head model. Its geometry is given in Figure 12.

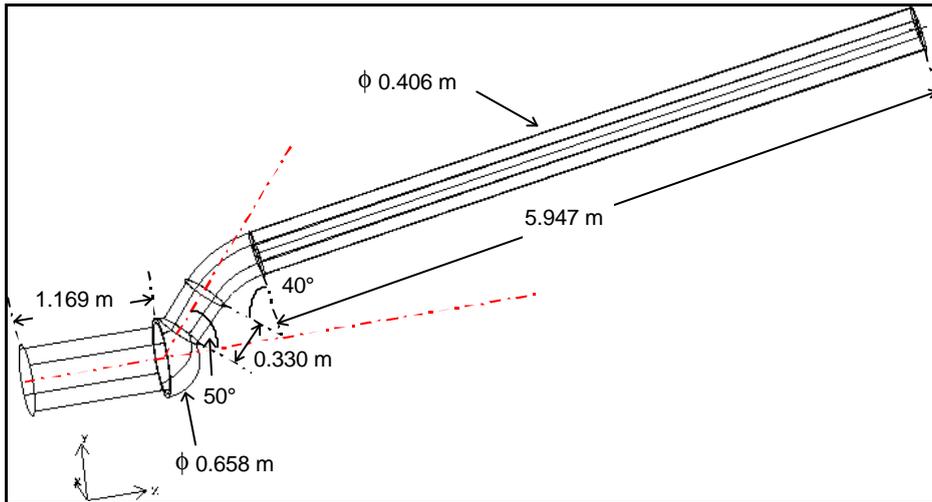


Figure 12 Spherical head model geometry

A 3-D stationary flow computation was done with the EDF simulation tool. It is assumed that the flow is incompressible, isothermal and turbulent. The pressure and temperature are respectively set to 155.10^5 Pa and 560.9 K which are the reactor coolant flow conditions. The computer run was done on a structured mesh and with a quick-upwind convection scheme and a first order turbulence model (k-e). Figure 13 shows the grid in the vertical plane and the cross-section.

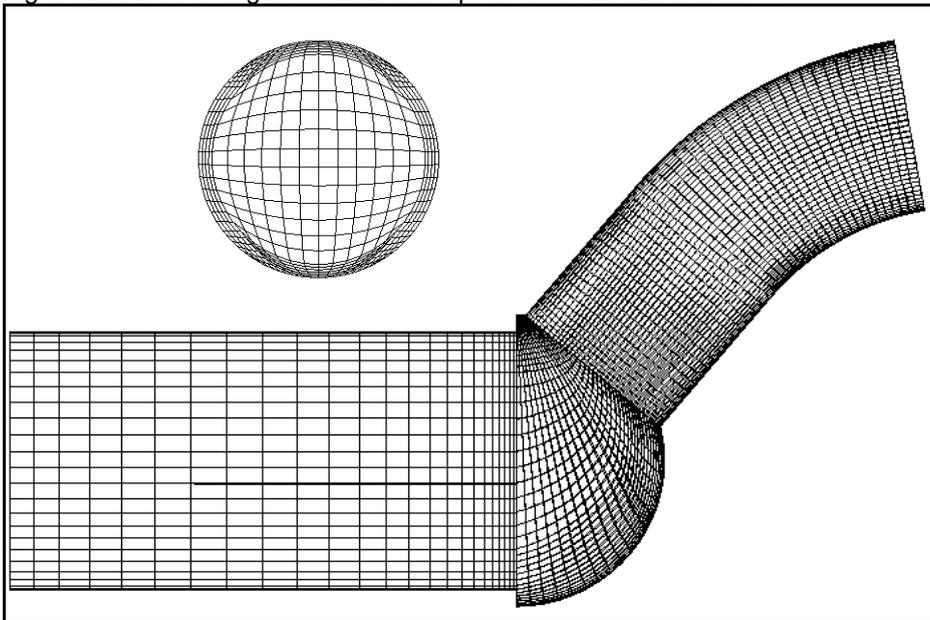


Figure 13 Spherical head model mesh in the vertical plane and the cross-section

Profile factor computation

The profile factor was computed for different axial positions of the meter behind the 40° elbow (at 1.6 and 4.8 pipe diameters downstream from the elbow) and different angles of the acoustic plane orientation (from -90° to +90°, see Figure 3).

Figure 14 presents the angular variations of the profile factor values computed with the EDF simulation software and those extracted from the EPRI experimental data as it has been provided by EPRI. The PF values are given for two axial positions of the meter (1.6D and 4.8D downstream from the elbow).

The simulation results are in good agreement with the experimental data: the tendency is extremely well predicted by the tool and the difference between experimental and numerical PF is lower than 2%, except in the region of 0° at 1.6D where a difference of up to 6% is noticed between experimental and numerical results.

The difference at the 0° angular position may be caused by an under-estimation of the axial velocity at the outlet of the sphere. This error might be reduced with a refinement of the sphere grid.

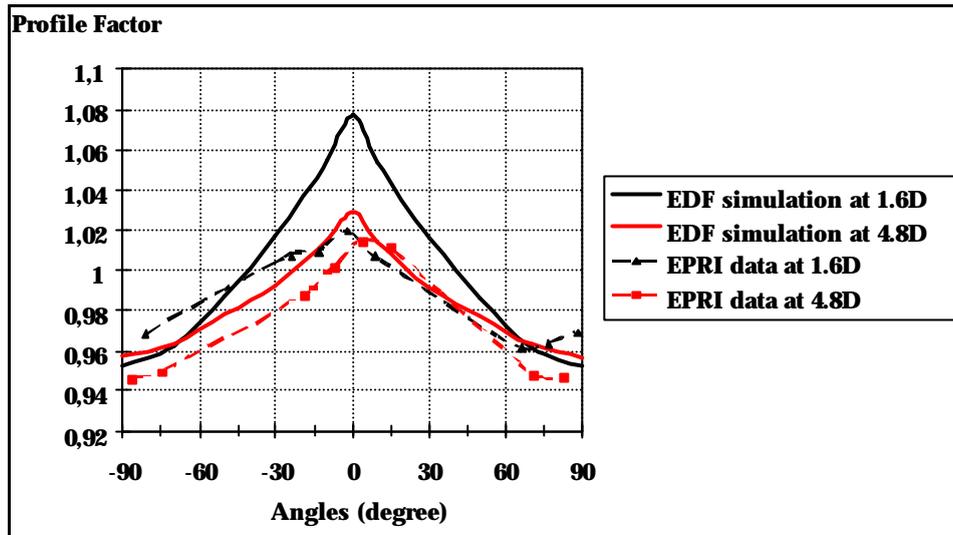


Figure 14 Variations of the profile factor with the angular position

These figures have to be compared to the standard profile factor which is usually applied by default by the manufacturers of ultrasonic flowmeters. The standard value is 0.94, which induces a bias up to 8% in the 4.8D - 0° meter position. Thanks to the EDF simulation software, this bias has been cut down from 8% to less than 2%.

Model study and determination of significant variables

A sensitivity study was performed to determine significant variables that affect modeling results. It is important to identify what parameters must be carefully evaluated for model use in plant-specific applications. The following parameters were evaluated:

- grid size
- turbulence models
- inlet velocity conditions
- physical characteristics of the fluid (pressure and temperature)
- Reynolds number

To illustrate the fourth point, Figure 15 shows the difference between profile factors computed, at the same Reynolds number, at the atmospheric pressure and the ambient temperature and at the reactor coolant flow conditions. These physical modifications lead to a constant difference of about 2% on the profile factor value.

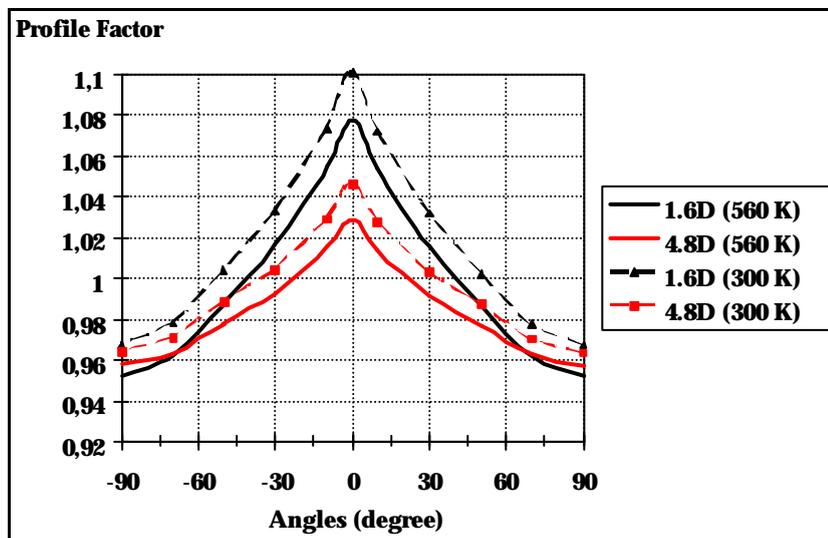


Figure 15 Comparison of profile factors calculated from different physical properties of the fluid :
560 K at $155.0 \cdot 10^5$ Pa and 300 K at $1.0 \cdot 10^5$ Pa

CONCLUSIONS AND FURTHER PROSPECTIVE

The flow-rate has always been a difficult parameter to measure but it is a key parameter for power plant control and safety. The modeling tool used by EDF's R&D Division has been overviewed and two examples of its application have been given. Experimental and calculated profile factors have been compared. In both configurations, the simulation results were in good agreements with the experimental data. The tendency was well predicted by the tool and the typical difference between experimental and numerical K was around 2% or 3% for the second application. The profile factors have also been compared to the classical K (Prandtl Model) used and proposed by constructors, which is calculated from an analytic model of fully developed profile. The gain realized by using simulation is significant. The results showed that the modeling approach is feasible, that it easily permits, at a low additional cost, to identify significant variables and quantify their influence: in the end, it leads to important improvements in flow instrumentation, and to the attached savings.

In the near future, the ultrasonic technique associated to numerical modeling for the determination of profile factors also appears to have a wide domain of application in the hydraulic power generation.

In several hydraulic stations, the flow-rate is not well known which prevents to operate at optimum efficiency. Therefore, half a percent of efficiency ratio represents an average of 100.000 US \$ per station and per year for the downstream stations of the Rhine or the Rhone rivers, which approximately total to twenty. The potential benefits are thus of about 2 million US \$ a year.

Today, station efficiency ratio measurements are done by means of current-meters but they are rare, expensive (typically 200.000 US \$ per each comprehensive on-site testing) and not very accurate (approximately 1.5 to 2%). The combination of numerical modeling to ultrasonic techniques would provide the hydraulic station owners a continuous efficiency measurement, at low cost and with high accuracy.

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AUTHORS : Hélène Jeanneau, Michel Piguet, Research and Development Division, Electricité de France, phone (33) 1 30 87 85 40, E-mail : helene.jeanneau@edf.fr