INVESTIGATION INTO SENSITIVITY OF DARLINGTON BOILER 2 FEEDWATER FLOW CALIBRATION FACTOR TO BOILER LEVEL CONTROL VALVE CONFIGURATION

D. Coppens[1], Y. Gurevich[2], V. Ton[3] and D. Zobin[4]
[1]Darlington NGS, Ontario Power Generation, Bowmanville, Ontario, Canada
[2]Daystar Technologies Inc., Toronto, Ontario, Canada
[3]Inspection and Maintenance Services Division, Ontario Power Generation, Ajax, Ontario, Canada
[4]AMEC NSS Ltd., Toronto, Ontario, Canada

Abstract

The Ultrasonic Cross-Correlation Flow Meter (USCCFM) has been used for regular feedwater flow calibration at Darlington NGS since the early nineties. Typical measurement repeatability over the duration of a calibration run (normally several weeks long) is within ±0.2%. However, it was recently noticed that BO2 calibration factor experienced sudden changes of close to 1%. The paper will describe several different approaches used for identifying the reason for the observed effect. The investigation has revealed that changes in USCCFM readings are due to the complicated geometry of BO2 feedwater piping and that its accuracy can be as high as a fraction of percent if several readings are averaged around the pipe.

1. Introduction

Reactor Thermal Power in CANDU nuclear stations is calibrated to the secondary side power calculated by the Calorimetric Program. The most important contribution to the secondary side power is boiler feedwater flow, which is normally measured by uncalibrated nozzles. Therefore to ensure accurate feedwater flow measurements and reactor thermal power compliance feedwater flow is regularly calibrated using a more accurate flow measurement technique. At Darlington NGS, the Ultrasonic Cross-Correlation Flow Meter (USCCFM) has been used for regular feedwater flow calibration since station start-up in the early nineties.

Calibration is performed several times a year, and typical measurement repeatability over the duration of a calibration run (normally several weeks long) is within ±0.2%. However, during an extensive Unit 1 data collection campaign in 2005, it was noticed that BO2 calibration factor experienced sudden changes of the order of 1%, which were traced to switching of the Boiler Level Control Valve (LCV) duty. Similar changes in BO2 calibration factor were later identified on the other three units, although the actual magnitude of the observed changes varied from unit to unit.

Since station flow indication based on the feedwater flow nozzle reading did not show any dependence on the LCV duty, it was assumed that USCCFM readings were somehow affected, and extensive investigation was conducted in order to identify the reason for the observed effect and to establish the correct value of BO2 calibration factor to be used in the Calorimetric Program. The investigation consisted of the following items addressed in a systematic fashion.

1. Since Darlington USCCFM measurements always had to be corrected to remove correlated noise, an alternative noise reduction algorithm to the one used historically was applied to BO2 data analysis.

2. Unit 1 BO2 ultrasonic feedwater flow measurements were performed for a number of different transducer locations in order to determine whether moving downstream of the current permanent transducer location will reduce the 1% difference between the two LCV configurations.

3. A Computational Fluid Dynamics (CFD) model was developed for BO2 piping configuration, and a series of simulations was conducted to evaluate the effect of the LCV configuration on the hydraulic factor in the vicinity of ultrasonic measurement locations.

4. Finally, tests were carried out in the National Research Council of Canada Hydraulic Laboratory, similar to the tests performed a few years earlier for Darlington feedwater piping configuration, but with a particular emphasis on verifying CFD results.

The investigation has provided valuable information on USCCFM performance under varying upstream conditions and has confirmed that the effect is due to small changes in the hydraulic factor when the LCV duty is switched and that a more conservative value of the calibration factor was used in the Calorimetric Analysis Program. It has also confirmed that USCCFM is a superior non-intrusive flow measurement instrument for detecting changing operating conditions, its accuracy is well within the assumptions of the reactor thermal power uncertainty analysis, and can be as high as a fraction of a percent if several readings are averaged around the pipe.

2. Feedwater flow calibration at Darlington NGS

Feedwater flow is by far the most dominant variable in the calculation of reactor thermal power on the secondary side by the Calorimetric Analysis Program. However, station feedwater instrumentation is not sufficiently accurate to satisfy requirements of reactor thermal power uncertainty analysis. Particularly, not only nozzles used as primary elements for feedwater flow measurements were not calibrated before installation, they are also susceptible to fouling, erosion, tap deterioration, etc. Therefore, in order to achieve required feedwater flow measurement accuracy station indication needs to be verified periodically by a more accurate flow measurement method.

At Darlington NGS, USCCFM has been used for feedwater flow calibration since station start-up in the early nineties, first using portable transducers, and then since 2001 using permanently installed transducers supplied by AMAG Inc., who have installed the USCCFM under a trade name Crossflow™ in a number of nuclear plants worldwide. The cabinet containing the USCCFM system is moved from unit to unit at least once a year, ultrasonic feedwater flow data are collected on that unit for several weeks, compared to station feedwater readings, and calibration factors are derived for input into the Calorimetric Analysis Program.

In addition to ultrasonic calibration of individual flows, the total feedwater flow is also verified on one unit per year using the Deaerator Mass-Energy Balance (DAMEB), or mini-PTC-6 Test [1]. In this test, the total feedwater flow is calculated from a combination of measured flows into the deaerator; the most important of these flows is the main condensate flow, which is measured by an ASME nozzle. Results of the total feedwater flow measurements using USCCFM and obtained from DAMEB tests are shown in Table 1 and are seen to be in excellent agreement. Measurements were carried out at close to 100%FP, when the total feedwater flow is about 1230 kg/s.

Table 1

Comparison between DAMEB and USCCFM Measurements
of Darlington Total Feedwater Flow

Year	Unit	(USCCFM-DAMEB)/ DAMEB (%)
1994	3	+0.2
1995	1	+0.3
1996	2	-0.1
1997	3	-0.1
1998	4	+0.2
1999	1	+0.5
2000	2	+0.1
2001	3	+0.4
2002	4	+0.3
2003	1	+0.2
2004	2	-0.3
2005	3	+0.3
2008	1	+0.7
Average		**+0.2**

2.1 USCCFM design and operation

The USCCFM measures the time that it takes for the fluid in the pipe to travel over the distance equivalent to the effective separation between the two sets of transducer probes. The mass flow (in kg/sec) can then be calculated using the following expression:

$$\mathbf{W = C*A*d*\rho/\Delta t} \qquad \textbf{(1)}$$

Here
C = so-called hydraulic factor (also known as flow profile correction factor)
A = pipe flow area (m^2)
d = effective transducer spacing (m)
ρ = fluid density (kg/m^3)
Δt = time delay measured by the flow meter (sec)

The USCCFM operates in a "continuous mode", which means that two high frequency (between 1 MHz and 3 MHz) but relatively low intensity (about $\pm$13 Volts) ultrasonic beams are propagated simultaneously across the pipe. Both beams are modulated by the turbulence eddies, and when the carrier frequency component is removed by the demodulation process, the remaining turbulence signature is in the low frequency range (below about 200 Hz). The two low frequency signals are further filtered in the range, which depends on flow characteristics but is typically between 10 Hz and 100 Hz. Fluid travel time is then obtained by performing cross-correlation calculations of the two demodulated and filtered signals.

For the purpose of this paper, it is sufficient to mention that the main advantages of the USCCFM meter and its superior high temperature performance is due to the fact that ultrasonic beams enter the pipe perpendicular to the pipe surface and propagate directly across the pipe; therefore, the ultrasonic path is not affected by refraction of ultrasound.

While most of the terms in Eq. (1) are self-explanatory, C deserves a brief explanation. The velocity distribution of the flow in a pipe is not uniform but has a specific shape determined by the flow Reynolds number and pipe geometry [2]. The hydraulic factor is defined as the ratio of the true mass flow over the mass flow measured by an ultrasonic flow meter. In terms of the flow velocity, it is the ratio of the true flow velocity averaged over the pipe cross-section to the velocity measured by an ultrasonic flow meter.

In principle, the hydraulic factor could be calculated if a reliable description of turbulent properties of fluid flow in a pipe was available and a quantitative evaluation of the interaction of the ultrasonic beam with turbulence eddies in the fluid could be carried out. Although recent progress in turbulence theory and in CFD modeling has resulted in a qualitative insight into flow characteristics, in practice, accurate values of the hydraulic factor can only be obtained by calibrating the flow meter for a specific Reynolds number and specific pipe geometry.

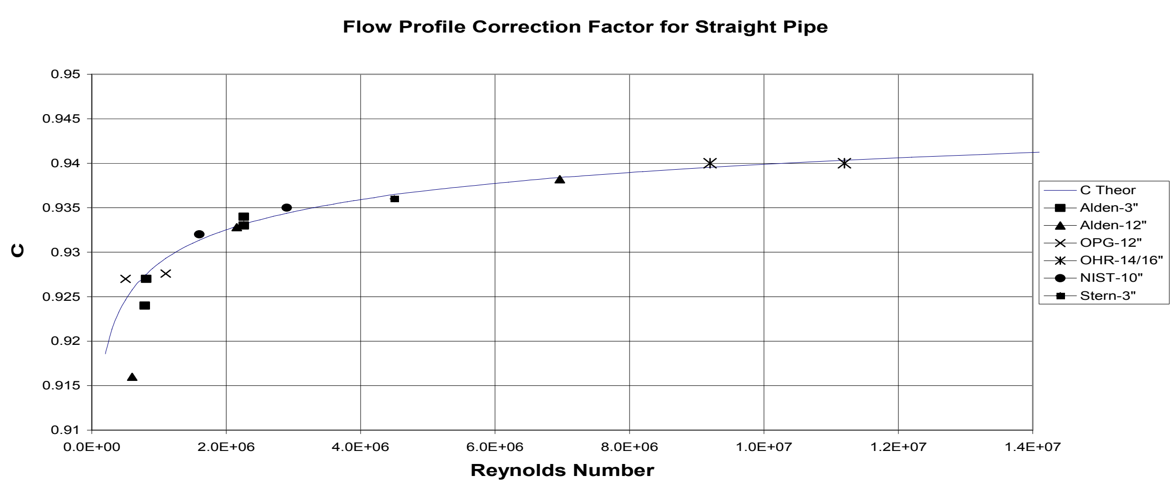

Figure 1 USCCFM hydraulic factor for fully developed flow as a function of Reynolds number

A number of such calibrations were performed at room temperature (Re = 10^6), giving the value of about 0.93 for the fully developed flow. USCCFM calibration for long pipes (fully developed flow) was also done at operating conditions on feedwater size pipes (close to Re = 10^7) and on feeder size pipes (Re = $4 \cdot 10^6$). The values of the hydraulic factor, 0.940 and 0.935, respectively, agree well with the results of a semi-empirical model [3], which combines acoustical and hydraulic phenomena. Calibration results along with the curve obtained from this model are shown in Figure 1.

It is clear from the semi-empirical model and from laboratory calibration that the hydraulic factor for the fully developed flow is a very weak function of the Reynolds number. Therefore, for long pipes, where the flow is fully developed, contribution from the hydraulic factor to the overall flow measurement uncertainty is well within 0.5%. The situation gets more complicated for measurement locations close to flow disturbances such as elbows, valves, etc., and laboratory calibration for a specific configuration is required to reduce measurement uncertainty.

2.2 Darlington feedwater piping configuration

Darlington boiler feedwater system consists of four pipes; each pipe supplies feedwater to one boiler. The pipes are made of carbon steel and have an outside diameter of approximately 14.25 inches and wall thickness of close to 1 inch. Schematics of the BO2 feedwater line from the LCV station to the location of the permanent transducer is shown in Figure 2, and locations of the main components are identified in Table 2. At high reactor power, one of the two large LCV's is normally open, and the valve duty is switched only if maintenance needs to be performed on the valve in service.[1]

Table 2 BO2 feedwater piping components identified in Figure 2

Notation	Component Description
A	LCV 203 outlet
B	LCV 201 outlet
C	First 90-degree elbow downstream of LCV 203
D	First 90-degree elbow downstream of LCV 201
E	Second 90-degree elbow downstream of LCV 203
F	"t" junction and outlet point of the LCV section which includes LCV 203 and LCV 201
G	First 90-degree elbow in horizontal plane downstream of the LCV section
H	Second 90-degree elbow in horizontal plane downstream of the LCV section
I	Third 90-degree elbow in horizontal plane downstream of the LCV section
J	First 90-degree elbow in vertical plane downstream of the LCV section
K	Second 90-degree elbow in vertical plane downstream of the LCV section. Elbows **J** and **K** are out-of-plane and are separated by about 6 pipe diameters
L	Position of the permanent transducer at a distance of about 26 pipe diameters downstream of elbow **K**
M	Position of the temporary transducer (T2) at a distance of about 44 pipe diameters downstream of elbow **K**
N	Position of the temporary transducer (T3) at a distance of about 48 pipe diameters downstream of elbow **K**

[1] Large LCV's are designated LCV **B**01 and LCV **B**03, where **B** is the boiler number

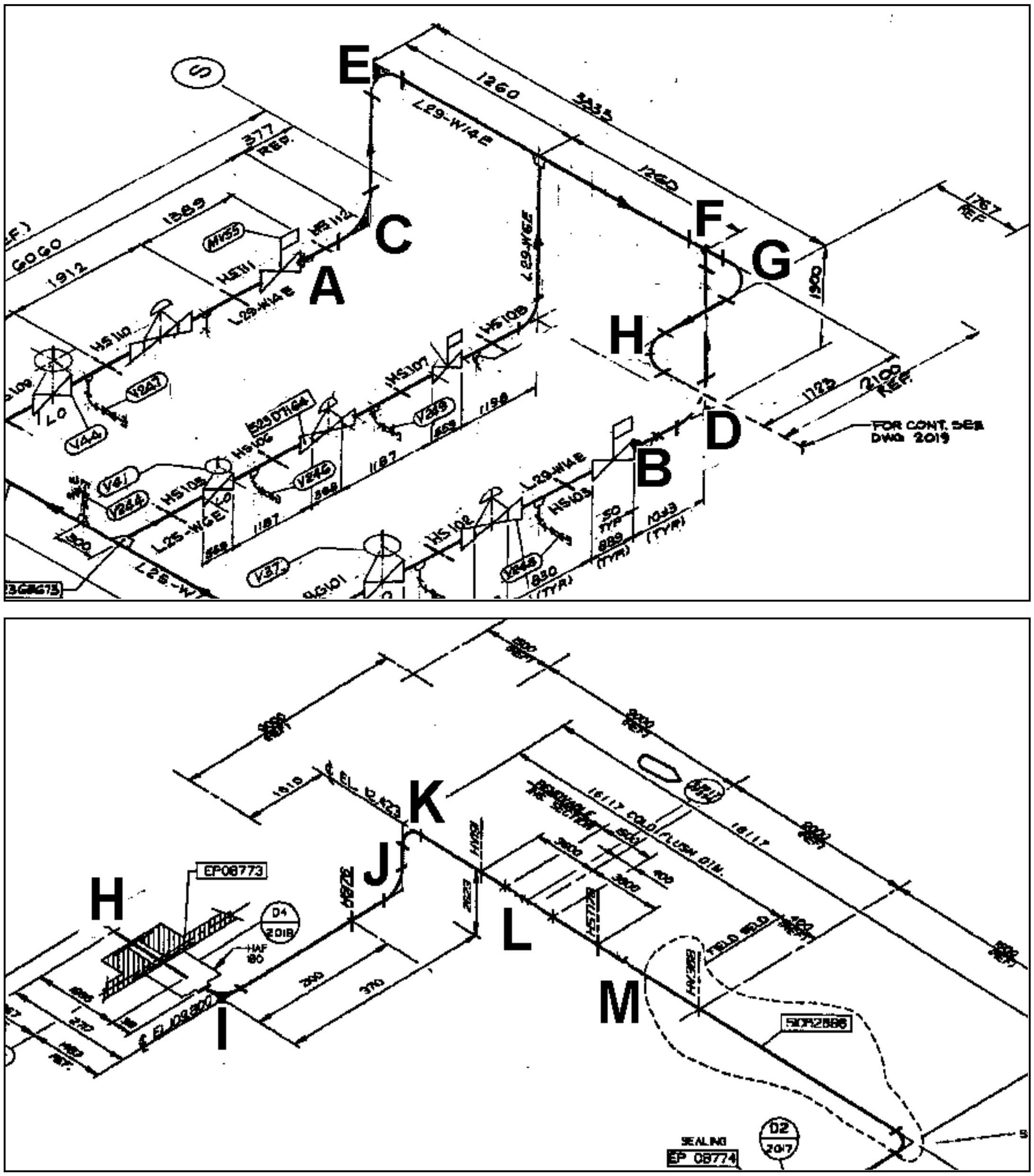

Figure 2 BO2 feedwater piping configuration and locations of main components

Some features in the configurations of the remaining three pipes are similar and some are different from those in the BO2 piping configuration. Specifically, BO1 piping immediately downstream of the LCV station is similar to BO2 piping in that if LCV 101 is in service the flow pah is through a t-junction (denoted by F in Figure 2), but if LCV 103 is in service the flow path is along a straight portion of the pipe (between E and G in Figure 1). In contrast, in the case of BO3 and BO4 piping immediately downstream of the LCV station, flow paths for either LCV in service is through the t-junction.

Moving farther downstream of the LCV station, the elbows in BO1 and BO3 piping upstream of the location of the permanent transducer are all in the horizontal plane, and the length of a straight pipe between the last elbow and the location of the permanent transducer is nearly 50 diameters. However, in the case of BO2 and BO4 there are two out-of-plane elbows (J and K in Figure 2), and the length of the straight pipe between the last elbow and the location of the permanent transducer is only 25-30 diameters.

Prior to about the year 2000, this distance was thought to be sufficient to ensure the fully developed flow profile, and indeed for a single 90 degree elbow deviation from the fully developed value is within measurement uncertainty. However, more complicated flow disturbances such as out-of-plane elbows seen in Figure 2, lead to the existence of swirls, and it takes longer distances for the flow profile to approach the fully developed shape.

Laboratory tests for a series of out-of-plane elbows separated by different distances demonstrated that the hydraulic factor is reduced by about 0.5% for two out-of-plane elbows separated by 6 pipe diameters, as is the case for BO2, and by about 1.5% for two tight out-of-plane elbows, as is the case for BO4. These findings were verified by in-situ measurements, and the resulting hydraulic factors were included in the calibration factors used in the Calorimetric Analysis Program.

3. Effect of LCV configuration on USCCFM readings

Ultrasonic data collection is normally carried out over a period of several weeks, for the same LCV in service. The typical measurement repeatability over the duration of a calibration run is within $\pm$0.2%; however, during an extensive Unit 1 data collection campaign in 2005, it was noticed that BO2 calibration factor experienced sudden changes of the order of 1%, which were traced to switching of the LCV duty. Similar changes in BO2 calibration factor were later seen in the other three units when the LCV duty was switched, with the actual magnitude of the observed changes varying from unit to unit. However, switching LCV duty for the other three boilers resulted in only very small changes in the calibration factor.

Since station flow indication based on the feedwater flow nozzle reading did not show any dependence on the LCV duty, it was assumed that USCCFM readings were somehow affected, and an extensive investigation was conducted in order to identify the reason for the observed effect and to establish the correct value of BO2 calibration factor to be used in the Calorimetric Analysis Program.

3.1 USCCFM measurements in the presence of correlated noise

Darlington feedwater system was identified early on as having a correlated noise present, which if untreated results in a bias in the measured time delay of about 1.5%. An algorithm for on-line removal of the correlated noise as part of cross-correlation calculation was developed in OPG and was qualified in laboratory testing. More recently several installations in the USA were found to exhibit a correlated noise, and an alternate off-line algorithm to remove the noise was independently developed by AMAG Inc.

When sensitivity of BO2 hydraulic factor to the LCV configuration was first identified, it was suspected that the noise reduction algorithm used at Darlington may not have been removing the noise completely, which was manifested in different USCCFM readings for the two LCV configurations. AMAG Inc. was therefore contracted to carry out a set of independent measurements and noise reduction. Calibration factor for all four boiler feedwater flows were found to be within 0.1% of the values used in the Calorimetric Analysis Program, which confirmed that the observed effect was not due to the correlated noise.

3.2 USCCFM measurements for different transducer locations on BO2 feedwater pipe

Unit 1 BO2 ultrasonic feedwater flow measurements were performed for three different transducer locations in order to determine whether moving downstream of the current permanent transducer location will reduce the 1% difference between the two LCV configurations. The results shown in Table 3 demonstrate that moving transducer by additional 20 pipe diameters downstream of the current location of the permanent transducer has very little effect on the difference in the calibration factor for the two LCV configurations.

Table 3 Results of Unit 1 BO2 ultrasonic feedwater flow measurements for three transducer locations

Transducer ID	Transducer Location (L/D)	LCV in Service	Station Reading (kg/s)	USCCFM Reading (kg/s)		USCCFM/Station	
				Noise Reduction A	Noise Reduction B	Noise Reduction A	Noise Reduction B
T1 (Permanent)	26	203	308.8	310.5	310.3	1.006	1.005
T2	44		310.3	315.3	314.4	1.016	1.013
T3	48		307.8	314.2	N/A	1.021	N/A
T1 (Permanent)	26	201	308.6	308.0	307.7	0.998	0.997
T2	44		309.1	311.2	310.8	1.007	1.005
T3	48		308.6	312.3	N/A	1.012	N/A
Difference in USCCFM/Station between LCV 203 and LCV 201 (%)							
T1 (Permanent)	0.8						
T2	0.9						
T3	0.9						

3.3 CFD calculation of the flow characteristics

In order to better understand the behavior of the flow downstream of the boiler level control valves, CFD modeling was done of BO1 and BO2 feedwater piping for the two LCV configurations and for a simplified configuration, which included only two out-of-plane elbows closest to the permanent transducer. The latter configuration was the same as used a few years earlier in laboratory tests to derive the USCCFM hydraulic factor for BO2. The CFD code used in the calculations was FLUENT 6.1. Although CFD accuracy is not sufficient to provide a quantitative estimate of the effect of LCV configuration on the hydraulic factor, it gives a qualitative evaluation of the difference between the two LCV configurations for both BO1, which was used as a reference, and for BO2.

The reason BO1 and BO2 were chosen is because they have similar configurations immediately downstream of the LCV station in that when LCV 201 is open, the flow is through a t-junction and when LCV 203 is open the flow is through a straight pipe before entering a series of 90 degree elbows. On the other hand, BO3 and BO4 (see Figure 2) have no t-junction downstream of LCV 203. This difference could explain why BO3 and BO4 feedwater flow calibration factors show no dependence on the LCV configuration; however, based on this explanation it would seem that BO1 should show dependence similar to BO2.

Sensitivity of CFD results to the choice of a CFD model was evaluated by carrying out sample calculations for the k-ε turbulence model and for the model based on the Renormalization Group (RNG) theory [4]. The k-ε model is closely related to the concept of turbulent viscosity and is based upon coupled transport equations for the turbulent energy density k, similar to the turbulent pressure, and the turbulent dissipation rate ε. The main idea behind the RNG theory is to systematically remove the smallest scales of turbulence to a point where the remaining scales are resolvable with available computer capabilities.

The results showed about 1% difference in the axial velocity profile and only 0.2% difference in the average flow characteristics between the two models. Since the purpose of the modeling was not to obtain accurate absolute values of flow characteristics, but to compare them for different piping configurations and for different upstream boundary conditions, a more widely used k-ε model was therefore chosen for further analysis. Sensitivity to the computational mesh was also evaluated by carrying out calculations at $Re = 10^6$ using the 3D algorithm with 400x100=40000 grid points and the 2D (axially symmetric) algorithm with 22x200=4400 grid points. It was found that results of 3D calculations are practically equal to the results of 2D axially symmetric calculations.

The main result of CFD calculations is that far enough from the disturbance, the general flow behavior for all three configurations mentioned above is similar and is described by an angular non-uniformity in the axial velocity and by rotation of this non-uniformity around the pipe axis. Figure 3 shows the rotation of the non-uniformity in the case of two out-of-plane elbows. The size and the magnitude of the non-uniformity and its rotation velocity are different for different types of upstream disturbance.

The consequence of this dependence is that, while general flow characteristics are quite predictable, the exact angular position of the non-uniformity spot at a given pipe cross-section is difficult to predict because small changes in the angular velocity, acting over a long distance, will result in a significant shift in the spot angular position.

Rotation of the non-uniformity is expected to result in the flow velocity measured by the USCCFM being dependent on the angular position of the ultrasonic beams. However, because the USCCFM measured velocity is affected by the size of turbulent eddies, and not by the beam size, the dependence of the measured velocity on the beam angular position is expected to be weaker than the variation in the average axial velocity.

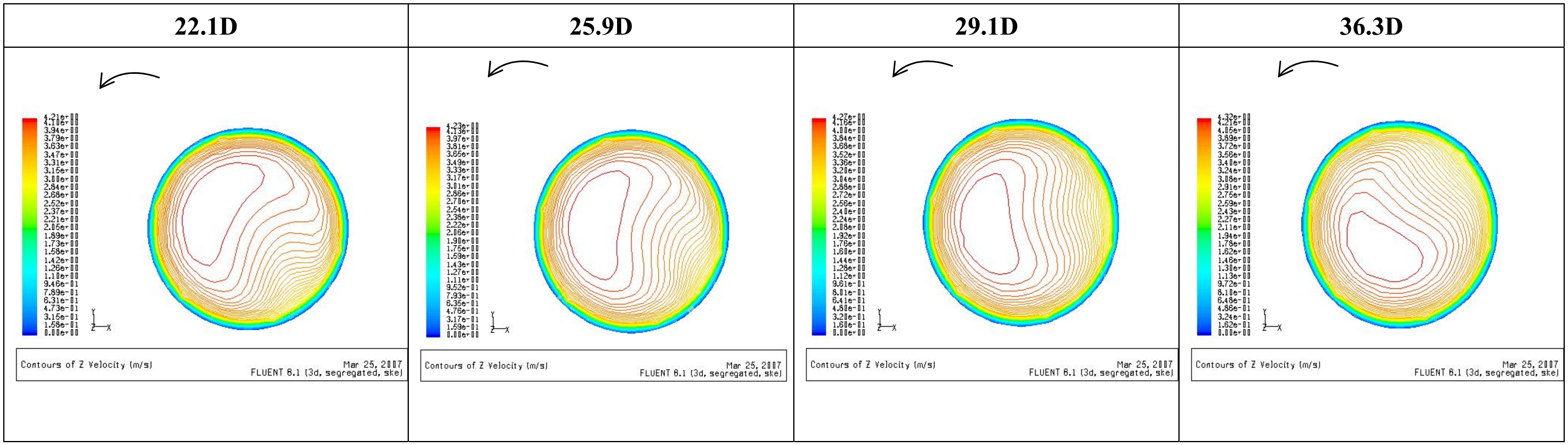

Figure 3 Rotation of the non-uniformity in the axial velocity distribution at four locations downstream of out-of-plane elbows at $Re=10^7$. The locations are specified in units of pipe diameter.

Laboratory tests in the Hydraulic Center of the National Research Council of Canada were conducted to obtain a quantitative estimate of the sensitivity of the USCCFM measured velocity to the angular variation of the axial velocity. The test model and laboratory flow conditions were identical to the CFD model for two out-of-plane elbows. Flow stability during the test was provided by the head tank, and the reference flow rate was measured by the weight tank system with the accuracy of about $\pm$0.2%.

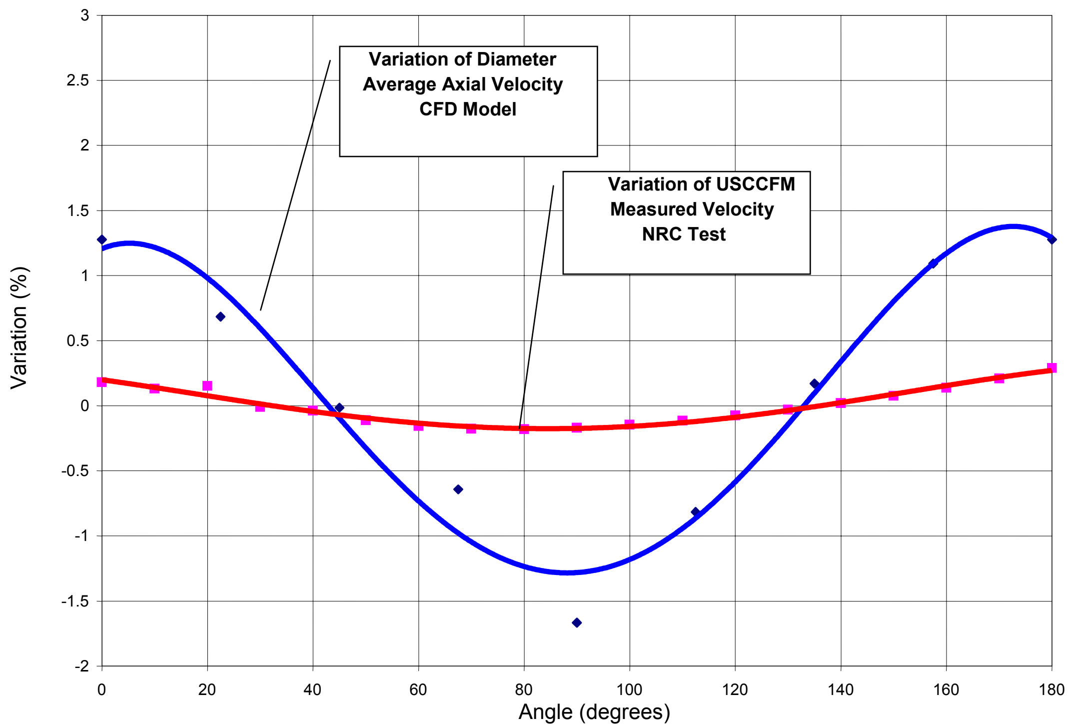

Figure 4 Sensitivity of USCCFM reading to the angular distribution of the axial velocity

USCCFM flow readings were obtained for a number of angular orientations of the ultrasonic beam. The dependence of the USCCFM measured velocity on the ultrasonic beam angle, normalized to the reference flow velocity, is shown in Figure 4, along with the dependence of the average axial flow velocity based on the CFD model. It is seen that the angular dependence of the USCCFM measured velocity correlates well with the average axial velocity but is significantly weaker (0.3% variation in measured velocity, compared with 3%variation in average axial velocity predicted by CFD).

Figure 4 illustrates one of the important characteristics of the USCCFM in comparison with more conventional transit time ultrasonic flow meters. The flow velocity measured by a transit time meter will be equal to the average flow velocity along the path of the ultrasonic signal (if the radial velocity component is negligible). Therefore the difference between the measured velocity and the bulk velocity may vary significantly, depending on the orientation of the ultrasonic path. Therefore, in the case shown in Figure 4, flow readings by a transit time meter would vary by approximately 3%.

On the other hand, variation of the USCCFM flow readings is within 0.3%. Flow velocity measured by the USCCFM is not equal to the average flow velocity along the beam because the flow area, which affects the beam, is not defined by the beam size but rather by the size of turbulent eddies. Therefore, variation of the measured velocity versus the beams angular position is significantly smaller than variation in the average axial velocity. To achieve similar accuracy using a transit time meter, the number of ultrasonic beams would have to be increased significantly.

In summary, results of CFD calculations were found to correlate well with the observations of the USCCFM behavior when the LCV configuration is changed. Furthermore, the CFD model showed that the LCV 201 configuration is more sensitive to inlet boundary conditions and created a more intense swirl, compared with the LCV 203 configuration, and therefore, the flow characteristics for LCV 203 can be predicted by the CFD model more accurately.

Since the CFD model shows similarity in the flow behavior between the LCV 203 configuration and the laboratory test model, which included only two nearest out-of-plane elbows and which was used to derive the hydraulic factor for BO2 ultrasonic feedwater flow measurements, it is concluded that USCCFM readings for LCV 203 with the correction factor derived from laboratory tests provides a more accurate flow reading than for the LCV 201 configuration.

Finally, sensitivity of the flow parameters to inlet boundary conditions for LCV 201, shown by the CFD model, is a likely reason for the observed difference in the change of the USCCFM calibration factor for different BO2 LCV configurations for different Darlington units.

4. Conclusions

The reason for the observed dependence of the USCCFM reading on the Boiler Level Control Valve Configuration for BO2 feedwater pipe at Darlington NGS has been investigated. Investigation included application of different noise reduction algorithms, USCCFM measurements along BO2 feedwater pipe, CFD analysis of Darlington feedwater piping, and calibration tests in the National Research Council of Canada Hydraulic Laboratory using a hydraulic model of BO2 feedwater piping.

The investigation has demonstrated that USCCFM accuracy is well within the assumptions of the reactor thermal power uncertainty analysis and its use for Darlington feedwater flow calibration resulted in a conservative value for the calibration factor used in the Calorimetric Analysis Program.

The investigation has provided valuable information on USCCFM performance under varying upstream conditions and has confirmed that CFD modeling can be a useful tool for gaining qualitative understanding of changes in flow characteristics due to changes in upstream conditions. It has also demonstrated that USCCFM is a superior flow measurement instrument for detecting changing operating conditions, and that it is the only non-intrusive ultrasonic flow meter whose high accuracy can be as high as a fraction of a percent if several readings are averaged around the pipe.

5. References

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