Estimation of the Flow Profile Correction Factor of a Transit-Time Ultrasonic Flow Meter for the Feedwater Flow Measurement in a Nuclear Power Plant

Jae Cheon Jung and Poong Hyun Seong

Abstract—**A new method to estimate the flow profile correction factor (FPCF) for a transit-time ultrasonic flow meter (UFM) having a diametral transducer configuration is introduced in this work. For the adaptation of a diametral UFM for a feedwater measurement, the optimized flow profile correction factor is obtained through experiments and a simulation in actual flow conditions. The log function curve fitting is performed on a combined data set; the velocity ratio of UFM reading versus standard fluid measurement at low flow velocity, UFM reading versus standard fluid measurement at medium flow velocity, and UFM reading versus clean Venturi measurement at high flow velocity. Through an uncertainty analysis, the uncertainty of the FPCF is calculated. The resultant uncertainty of the new FPCF is 0.335%. This value is approximately half the value presented by UFM manufacturers. By adaptation of a diametral UFM with the new FPCF proposed in this work, feedwater flow measurement in nuclear power plants (NPPs) can be easily performed at lower cost than either chordal or cross-correlation UFM.**

Index Terms—**Flow profile correction factor (FPCF), transit-time, ultrasonic flow meter (UFM).**

I. Introduction

An ACCURATE measurement of the feedwater flow is a vital factor in determining the thermal efficiency of a nuclear power plant (NPP). Many research papers have reported that the corrosive particles deposited inside a Venturi flow meter contribute to the increase of the differential pressure (DP) in the flow measurement device, thereby causing an overestimation of the feedwater flow [1]–[3]. Historically, over-estimation of the feedwater flow typically ranges from 0.5% to 3.0% [4].

To prevent thermal efficiency degradation caused by an increase of the DP, an ultrasonic flow meter (UFM) has been used. Also, a 1% power up-rating has been achieved in operating NPPs using UFM.

There are two different types of UFMs currently in use in NPPs: transit-time (contra-propagation) and cross-correlation (time-of-flight). A cross-correlation UFM measures the time-of-flight of the fluid eddies between two transducers. A transit-time UFM measures the contrapropagation of the ultrasonic sound in the flow path. The transit-time UFM is classified into two categories by the axial velocity measurement method; a chordal and a diametral configuration. The chordal configuration integrates the axial velocity over a circular cross-sectional area. The diametral configuration measures the axial velocity averaged over the pipe. Normally, the transducer of the chordal configuration contacts the fluid directly while that of the diametral transducers contacts the pipe surface. The certified accuracy of a chordal UFM by the National Institute of Standards and Technology (NIST) is approximately 0.4%, while the accuracy of an externally mounted diametral UFM is around 1% [5].

TABLE I
COMPARISON OF UNCERTAINTIES BY TYPE OF UFM FOR NPP FEEDWATER MEASUREMENT

Type of UFM	Transducer Installation	Overall Uncertainty	Uncertainty of FPCF
Cross-correlation	Clamp-on pipe Surface	0.42	0.2
Transit-time (Chordal)	Contact on measuring fluid	0.41	0.3
Transit-time (Diametral)	Clamp-on pipe Surface	0.9	0.7

A transit-time UFM having a diametral transducer configuration (hereafter called a "diametral UFM") is more widely used in the industry in consideration of its easier installation and lower cost relative to chordal and cross-correlation UFMs. The Korean Standard Nuclear Power Plant (KSNP) uses a diametral UFM to measure the flow rate of the safety injection line. However, the overall uncertainty of the diametral UFM is higher than that of the chordal and cross-correlation. The higher uncertainty of the diametral UFM arises from the higher uncertainty of the flow profile correction factor (FPCF).

Table I, from the technical information of Amag, Inc. and Caldon, Inc., shows differences in uncertainties between different measurement methods [3], [5].

Caldon, Inc. reports that FPCF increases moderately for Reynolds number (Re) in the range from three million to 20 million. This typifies the difference in the model versus the plant Reynolds number. They extrapolated models that were curve-fitted to hydraulic testing results using a logarithmic fit for NPP application [6].

The cross-correlation UFM uses externally mounted transducers. As seen in Table I, the uncertainty of the cross-correlation is lower than that of the diametral type UFM despite

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that they use the same transducer mounting method. The manufacturer states that they created new formulas for the FPCF. They calibrated UFM at a flow test facility for Re ranging from 0.8 million to seven million. In this work, the FPCF values are obtained by the flow measurement tests at an NPP for a Re range up to 25 million. These values are compared against the extrapolated values from the smooth wall profile test by Nikuradse. Log function curve fitting is performed on the combined data set: 1) the velocity ratio between UFM reading vs. standard fluid measurement at low flow velocity; 2) the velocity ratio between UFM reading versus standard fluid measurement at medium flow velocity; and 3) the velocity ratio between UFM reading versus clean Venturi measurement at high flow velocity.

The main contribution of this work is the development of a methodology to accurately estimate the FPCF for a diametral UFM.

II. Flow–Profile Correction Factor (FPCF) for a Diametral UFM

The diametral UFM measures the line average velocity of the ultrasonic path. Due to the friction of the pipe, the velocity of the fluid at the wall surface is lower than that of the pipe centerline. The maximum velocity in the horizontal direction is also observed at the pipe centerline.

The flow profile is used in converting a flow "reading" at a point or along a particular path to the velocity averaged over the entire cross section of the flowing medium. The flow profile depends on the fluid Reynolds number, the relative roughness and shape of the conduit, upstream and downstream disturbances, and other factors. The conventional UFM uses a smooth-wall circular pipe model. Some equations have been used to convert the velocity reading by UFM to the average velocity [7].

The FPCF can be expressed as (1)

$$K = \frac{V}{V_a} \tag{1}$$

where

- K FPCF;
- V_a area-average velocity;
- V ultrasonic velocity (line average over a path).

FPCF can be derived when the velocity profile is known. The velocity profile in a smooth wall pipe based on a power-law is defined in (2)

$$V(r) = V_{\max}\left(1 - \frac{r}{R}\right)^{\frac{1}{n}} \tag{2}$$

where

- $V(r)$ point velocity at radial distance r,
- $V_{\max}$ maximum velocity at pipe centerline,
- R pipe radius, and
- $R - r$ distance from pipe wall.

The area averaged flow velocity can be derived as in (3) and (4)

$$V_a = V_{\max}\frac{2n^2}{(n+1)(2n+1)} \tag{3}$$

$$V(r) = V_{\max}\frac{n}{n+1}. \tag{4}$$

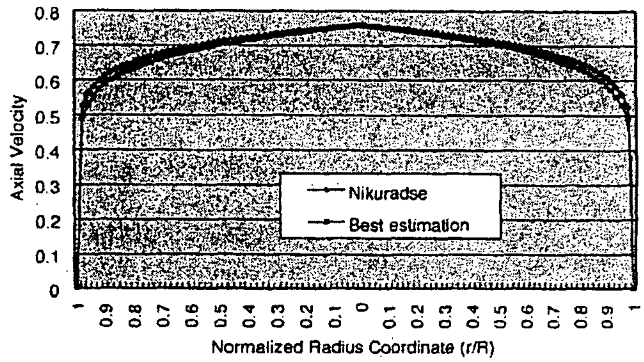

Fig. 1. Axial velocity profile in a radius coordinate of a smooth pipe.

TABLE II
Best Estimation Results

Description	Value	Unit
Reynolds number	1,841,133	
Flow rate (Best estimation)	284.781	m^3/h
Flow rate (Nikuradse)	278.117	m^3/h
Percentage flow difference	2.34	%
Constant (Best estimation)	10.6005254	

The constant "n" is derived from the experiments. However, the flow profile in a smooth wall pipe cannot be accurately curve-fitted. Perhaps some of the earliest and yet most useful illustrations of flow profiles are those measured by Nikuradse [7]. The resultant constant from Nikuradse's curve-fitting is shown in (5) as follows:

$$n = \frac{1}{0.2525 - 0.0229\log(\mathrm{Re})}. \tag{5}$$

In Fig. 1, the axial velocity profile in a normalized radius coordinate (r/R) presented by Nikuradse, as in (5), and the best estimation using Tchebyshef calculus [8], [9] are presented. For the best estimation, the radial distance "r" is decided to be between 0.468 and 0.88. The best estimation result shows a 2.34% difference from Nikuradse's results, as shown in Table II. In this case, the constant "n" is estimated to be 10.6005254. This result shows that an inaccurate model causes a higher measurement error.

For the smooth wall profiles measured by Nikuradse [7], [10], three investigators developed (6)-(8), respectively, to compute FPCF [11]

$$K = 1 + 0.2488\cdot\mathrm{Re}^{-\frac{1}{8}}(3\times10^3 \le \mathrm{R_e} \le 10^6) \tag{6}$$

$$K = 1.119 - 0.011\cdot\log(\mathrm{Re}) \times (3\times10^3 \le \mathrm{R_e} \le 5\times10^6) : \text{Nikuradse} \tag{7}$$

$$K = 1 + 0.01\sqrt{6.25 + 431\cdot\mathrm{Re}^{-0.237}}(3\times10^3 \le \mathrm{R_e} \le 10^6). \tag{8}$$

The applicable Reynolds number (Re) range for these three formulas is less than five million while that of the feedwater flow in NPPs is about 20 million.

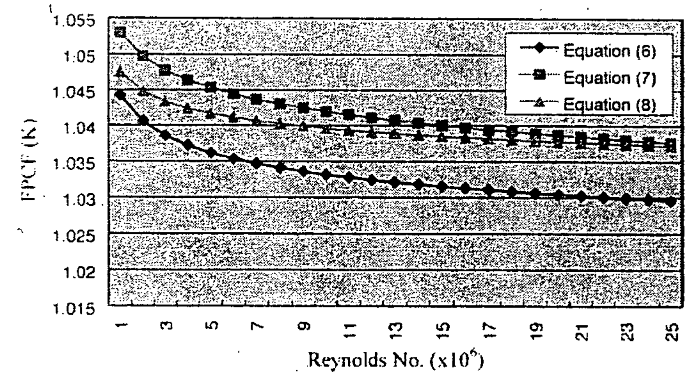

Fig. 2. The flow profiles correction factor for a smooth wall pipe. (Note: Range over the boundary condition is extrapolated.)

In Fig. 2, the extrapolated FPCF for Reynolds number ($1 \times 10^6 \leq \mathrm{Re} \leq 2.5 \times 10^7$) used in (6) to (8) are presented. The maximum error between (7) and (8) is approximately 0.52% [8], [9].

As discussed above, FPCF is a vital factor in determining the uncertainty of UFM. Moreover, the boundary condition of Reynolds number shall be extended to NPP feedwater conditions.

The procedure to estimate the FPCF of a diametral UFM for a feedwater flow measurement in NPP is setup as follows.

a) Iterative flow test by comparison of test results from a standard weight tank and UFM measurement at Reynolds number under one million.
b) Comparison of UFM measurement results with measurement from a clean venturi reading either in newly constructed NPPs or operating NPPs.
c) Approximation of the shape of FPCF.
d) Obtaining the FPCF by a log function curve-fitting using the data obtained from steps "a" and "b".
e) Validation of the model using the flow test result.

III. Estimation of FPCF for KSNP Feedwater Flow

The KSNP has two feedwater loops for heat removal from the reactor. The average velocity of the feedwater flow is about 6 m/s and the Reynolds number is over 20 million.

To analyze the turbulent flow in a feedwater pipe in a NPP, the following assumptions and limitations are applied for simplification of the calculation.

a) The entrance effect of the pipe is neglected.
b) The flow is fully developed.
c) The axial and horizontal flow profile is similar.
d) The Venturi DP output is traced back to the calibration data.

The preceding test results [6], [11]–[13] and the field test results show that the shape of the FPCF curve plot demonstrates a log function-like plot for a higher Re. Therefore, the estimated feedwater flow profile correction curve is determined to be a log curve, as in (9) as follows:

$$K = a - b \cdot \log(\mathrm{Re}). \tag{9}$$

TABLE III
VALIDATION RESULT OF THE FPCF ESTIMATION MODEL

Reynolds No.	K	log(Re)	log(Re)^2	K*log(Re)
1000000	1.053	6	36	6.318
10000000	1.042	7	49	7.294
19000000	1.038934	7.278754	52.98025	7.562142
sum(above)=	3.133934	20.27875	137.9803	21.17414
a= 1.119	P	Q	S	R
b= 0.011				

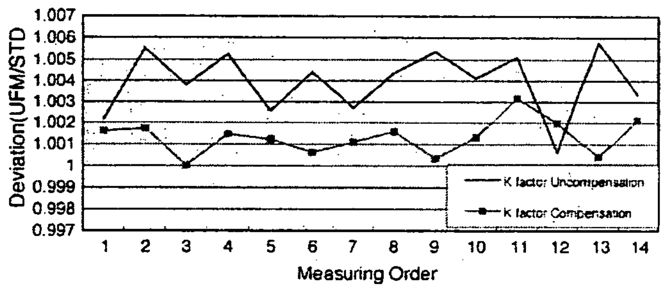

Fig. 3. Deviation of the velocity between UFM and the standard flow test facility (STD).

The optimum values of the unknown parameters "a" and "b" are obtained by minimizing the sum of the square errors "X" as in (10) [14] as follows:

$$X = \sum_{i=1}^{n} [K_i - \{a - b \cdot \log(\mathrm{Re})_i\}]^2 \tag{10}$$

where n = observation.

From (11) and (12), the constants "a" and "b" can be obtained as

$$a = \frac{SP - QR}{nS - Q^2} \tag{11}$$

$$b = \frac{QP - nR}{nS - Q^2} \tag{12}$$

where $P = \sum_{i=1}^{n} K_i$, $Q = \sum_{i=1}^{n} \log(\mathrm{Re})_i$, $R = \sum_{i=1}^{n} K_i \cdot \log(\mathrm{Re})_i$, $S = \sum_{i=1}^{n} \{\log(\mathrm{Re})_i\}^2$.

IV. Experiment Results

Validation of the formula for the estimation of FPCF is performed. Using the K-factors calculated by (7) at three Reynolds numbers, 0.1 million, one million, and 19 million, the unknowns "a" and "b" are calculated from (11) and (12). The results are identical to those of (7). The calculation results are presented in Table III.

In Fig. 3, the test result using the weight tank method at a Reynolds number under one million is presented. The velocity of the standard fluid test facility varies from 0.58 m/s to 1.8 m/s. Where the upper plot is the flow rate before the K-factor compensation while the lower one is that after compensation, using (7). The uncertainty of the weight tank method is around 0.15%.

TABLE IV
COMPARISON OF THE FLOW MEASUREMENT RESULTS BETWEEN VENTURI AND UFM

Measurement Order	UFM Measurement		Venturi Measurement		FPCF
	Velocity (m/s)	Reynolds No.	Velocity (m/s)	Reynolds No.	
1st	5.413424	15,778,187	5.1108	15,376,456	1.059213
2nd	5.493028	16,014,316	5.1418	15,469,518	1.068308
3rd	5.431322	15,840,723	5.1263	15,422,932	1.059501
4th	5.497609	16,043,378	5.1487	15,490,538	1.067766
Average	5.458906	15,919,151	5.1319	15,439,861	1.06372

TABLE V
CALCULATION RESULTS FOR THE UNKNOWN PARAMETERS "a" AND "b"

Reynolds No.	K	log(Re)	log(Re)^2	K*log(Re)
240000	1.068575	5.380211	28.94667	5.749159
400000	1.066349	5.60206	31.38308	5.973751
16000000	1.06372	7.20412	51.89934	7.662734
Sum(above)=	3.198584	18.18639	112.2291	19.38564
a= 1.08023819	P	Q	S	R
b= 0.002316599				

The overall uncertainty of the diametral UFM used in this case is ±0.32%.

The results from the standard flow facility test cannot produce the FPCF normally presented in a NPP due to its flow velocity limitations. Hence, the confirmation of the flow rate between UFM and venturi DP output is important for a higher range of Reynolds number.

Table IV shows a comparison of FPCF between venturi and UFM measurement at an 80% power condition in the feedwater loop of Yonggwang NPP Unit 5. With the data obtained from the above experiments, a new FPCF formula is derived. UFM measured velocity data represents the values that are not compensated for the manufacturer-provided FPCF. The velocity of venturi is obtained by the differential pressure (DP) reading. The overall accuracy of the flow measurement by Venturi DP reading is 0.295%.

The measured data from Venturi to estimate the new FPCF is valid for the given installation of clamp-on transducers and varies according to the pipe geometry. Therefore, the venturi and the feedwater pipe geometry should satisfy the assumptions and limitations discussed in Section III.

In Table V, the calculation results for the unknown parameters "a" and "b" are presented. The proposed FPCF is derived using the data from the experiments as in (13).

$$K = 1.082\,381\,9 - 0.002\,316\,599 \cdot \log(\mathrm{Re}) \tag{13}$$

In Fig. 4, the plots are FPCFs at Reynolds numbers from one million to 20 million. The new formula proposed in this work is different from (7) and (8), which were derived from a smooth-wall model. The difference of the factor K between

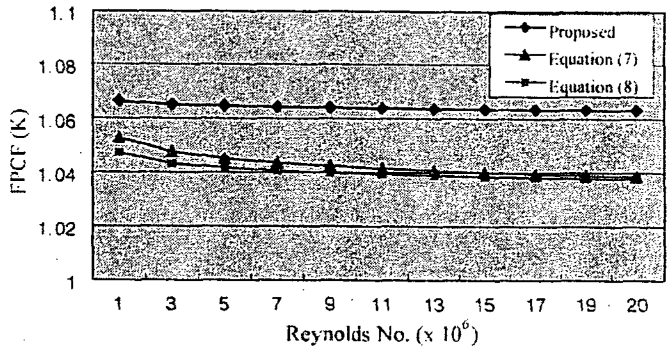

Fig. 4. Comparison of FPCF formulas proposed in this work and Nikuradse's.

Nikuradse's and the proposed method for a Reynolds number of twenty million is around 2.0%.

To derive the theoretical uncertainty of FPCF (ε_K), the natural log is taken on both sides and differentiated in (13). Then, (14) is derived.

$$\frac{dK}{K} = \frac{10^{1.08023}(-0.00231)\cdot \mathrm{Re}^{-0.00231}}{\ln 10^{\{1.08023-0.00231\log(re)\}}} \cdot \frac{d\mathrm{Re}}{\mathrm{Re}} \tag{14}$$

Rearranging (14), (15) is derived.

$$\varepsilon_K = \left[\left\{\frac{10^{1.08023}(-0.00231)\cdot \mathrm{Re}^{-0.00231}}{\ln 10^{\{1.08023-0.00231\log(re)\}}} \cdot \varepsilon_{\mathrm{Re}}\right\}^2\right]^{0.5} \tag{15}$$

where

$$\varepsilon_{\mathrm{Re}} = \left[\varepsilon_{di}^2 + \left(\frac{\partial\rho}{\partial P}\cdot\frac{P}{\rho}\cdot\varepsilon_P\right)^2 + \left(\frac{\partial\rho}{\partial T}\cdot\frac{T}{\rho}\cdot\varepsilon_T\right)^2 + \left(\frac{\partial\mu}{\partial P}\cdot\frac{P}{\mu}\cdot\varepsilon_P\right)^2 + \left(\frac{\partial\mu}{\partial T}\cdot\frac{T}{\mu}\cdot\varepsilon_T\right)^2\right]^{0.5}.$$

The overall uncertainty of the new FPCF can be expressed as (16)

$$\varepsilon_{\mathrm{FPCF}} = \sqrt{(\varepsilon_K^2 + \varepsilon_{STD}^2 + \varepsilon_{\mathrm{Venturi}}^2)} \tag{16}$$

where

- $\varepsilon_{\mathrm{FPCF}}$ the overall uncertainty of FPCF2;
- ε_K the theoretical uncertainty of FPCF;
- $\varepsilon_{\mathrm{STD}}$ the uncertainty of the velocity measurement using a standard flow test facility;
- $\varepsilon_{\mathrm{Venturi}}$ the uncertainty of the velocity measurement using venturi DP output.

The major input data and uncertainty calculation results for FPCF are shown in Table VI, where the overall uncertainty is 0.335%. This value is about half the uncertainty of the FPCF presented in Table I. Consequently, the proposed method will reduce the major uncertainty element of the diametral UFM.

Due to the limited cases of the test samples, the resultant FPCF formula shown in (13) and the uncertainty calculation results in Table VI may not be directly applied to measurement of the feedwater flow in a NPP. However, the proposed method can be used for an optimized FPCF for the diametral UFM of NPPs.

TABLE VI
THEORETICAL UNCERTAINTY CALCULATION RESULTS FOR NEW FPCF

Uncertainty element	Input data	Remarks
Reynolds number (Re)	19,815,461	Measurement at 80% Reactor Power
Uncertainty of Reynolds number (ε_{Re})	0.227%	
Kinetic Viscosity (μ)	$11.6049x10^{-5} \frac{kg}{m \cdot s}$	
Feedwater Density (ρ)	$832.293 \frac{kg}{m^3}$	
Theoretical uncertainty of new FPCF	0.055%	
Flow test facility uncertainty	0.15%	
Venturi measurement uncertainty	0.295%	
Overall uncertainty of FPCF	0.335%	

V. CONCLUSION AND FURTHER STUDY

The method to estimate the FPCF of a diametral UFM for the feedwater measurement in NPPs is proposed in this work. In addition, a new formula from a log function curve fitting that analyzes the ratio between the UFM and known values from a standard fluid system and a clean venturi measurement at 80% reactor power is introduced. The data from the experiments are used to calculate the unknown parameters.

Through the curve fitting of the Nikuradse velocity profile using Tchebyshef calculus, we confirmed that an inaccurate model causes a higher measurement error. Tchebyshef calculus used in this work showed that optimization of the FPCP via experiments requires careful calibration. In addition, the deviation of the resultant FPCF plot in this work and the UFM manufacturer's estimated 2.0% error demonstrates the necessity of calibration of the UFM under actual flow conditions.

Through an uncertainty analysis, the uncertainty of the FPCF is obtained. The resultant uncertainty of the new FPCF is 0.335%. This value is about half the value presented by UFM manufacturers. Consequently, the proposed method will reduce the major uncertainty element of the diametral UFM.

Due to the limited test data and the test condition of an NPP under 80% operating power, the resultant FPCF formula introduced in this work may not be directly applied to measurement of the feedwater flow in NPPs. In addition, the assumption that the feedwater loop has a sufficient straight pipe run may not be applied to some NPPs. Moreover, the reference for a higher Reynolds number from a venturi flow meter should be validated.

The main contribution of this work is the development of a methodology to accurately estimate the FPCF for a diametral UFM.

As a further study, this model can be optimized though iterative tests. It can be used as a supplement or an alternative means to the current feedwater flow measurement in NPPs.

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