Numerical Validation of Upstream Straight Lengths for Venturi Tube Flowmeter Recommended in KEPIC MPT-19.5; Multiple 90° Bends in the Different Plane Case

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1. Introduction

Domestic nuclear power plants are carrying out In-Service Testing (IST) to check the safety functions of safety-related pumps and monitor/evaluate the degree of vulnerability over time during reactor operation [1]. When performing this pump IST, it is required to measure the differential pressure at the test flow rate indicated on the differential pressure type flowmeter and check whether the corresponding differential pressure magnitude satisfies the acceptance criteria [2]. Therefore, it is essential to confirm whether a differential pressure type flowmeter, such as a venturi tube, guarantees the correct flow rate under various installation environments and wide operating conditions [1].

When the flow passes through the bend of pipe, higher axial velocity region shifts to the outside of pipe due to the centrifugal force [1]. If the straight length downstream of the pipe bend is not sufficiently long, flow with the skewed (distorted) velocity profile, different from the fully developed one, may pass the pressure taps and consequently, degrade the measurement accuracy of a venturi tube flowmeter. In this connection, KEPIC MPT-19.5 [3] recommended upstream straight lengths for a venturi tube on three different configurations of the primary device such as (1) single 90° short radius bend, (2) two or more 90° bends in the same plane, and (3) two or more 90° bends in the different planes.

In this study, as the subsequent research to assess the adequacy of upstream straight lengths for orifice plates recommended in KEPIC MPT-19.5 [1,4,5], numerical simulation of flow inside the multiple 90° bends in the different planes with venturi tube was conducted with commercial CFD software, ANSYS CFX R18.1.

2. Analysis Model

As shown in Fig. 1, the multiple 90° bends in the different planes with a venturi tube flowmeter were used as an analysis model. 25 °C water was used as a working fluid [1]. Geometrical specification for an analysis model was summarized in Table I. Except for both diameter ratio (β) and upstream straight length (L_u), the magnitudes of other parameters were fixed in this study [1]. In case of upstream straight length (L_u), its magnitudes varied from 1*D* to 100*D* [1]. To confirm the effect of diameter ratio (β) on the upstream straight length, three different diameter ratios, i.e. $\beta = 0.5$, 0.6 and 0.7 were chosen [1]. These magnitudes satisfy the recommendation of KEPIC MPT-19.5 for β, that is, $0.33 < \beta < 0.75$. Reynolds number based on the pipe diameter and inlet velocity was about 7.2×10^4 [1].

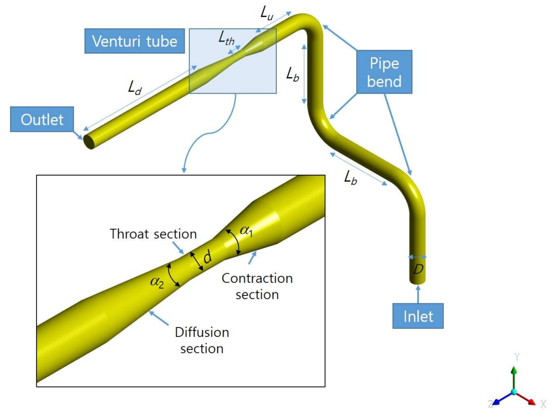


Fig. 1. Schematic diagram of the analysis model.

Table I: Geometrical Specification for the Analysis Model

Parameters	Unit	Magnitudes
Pipe diameter (D)	mm	100
Throat diameter (d)	mm	50, 60, 70
Diameter ratio (β=d/D)	-	0.5, 0.6, 0.7
Throat length (L_{th})	mm	100
Radius of curvature (R_c)	mm	200
Contraction angle (α_1)	Deg.	21
Diffusion angle (α_2)	Deg.	11
Upstream straight length (L_u)	mm	1*D*, 2*D*, 3*D*, 4*D*, 5*D*, 6*D*, 7*D*, 8*D*, 8.5*D*, 9*D*, 10*D*, 15*D*, 17.5*D*, 20*D*, 25*D*, 27.5*D*, 30*D*, 50*D*, 70*D*, 100*D* etc.
Downstream straight length (L_d)	mm	10*D*
Straight length between the bends (L_b)	mm	5*D*

3. Numerical Modeling

It was assumed that flow inside the multiple 90° bends pipe in the different planes with a venturi tube flowmeter was steady, incompressible, single-phase and turbulent flow. Table II summarizes the applied numerical modeling. In most calculations, the residuals of target variables were below 10^{-7}.

In this study, an unstructured hexahedral grid system made by a grid generation software, ICEM-CFD, was used [1]. The total number of grids used in the calculation was in the range of about between 5.9×10^6 and 1.1×10^7

depending on the upstream straight length for a venturi tube. To properly predict the flow pattern, dense grid distribution near the pipe wall and around a venturi tube flowmeter was used.

At the inlet boundary, constant mass flow rate (5 kg/s) and turbulence intensity (5%) was applied [1]. The ‘average pressure over the whole outlet’ option; with a relative pressure of 0 Pa, was used as the outlet boundary condition [1]. No-slip condition was applied at the solid wall [1]. The validity of the numerical modeling applied in this study can be found in the author’s previous study [2].

Table II: Summary of the Numerical Modeling

Parameters	Contents
Momentum equation	High resolution scheme
Turbulence equation	High resolution scheme
Turbulence model	SST k-ω
Near-wall treatment	Automatic wall treatment
Convergence criteria	$< 4\times10^{-4}$

4. Results and Discussion

Fig. 2 shows the streamline and axial velocity distribution at -*D*/2 (upstream direction) from the beginning of the contraction section and the mid of the throat length for $\beta = 0.5$ (see Fig. 3(a)); depending on the upstream straight length for a venturi tube.

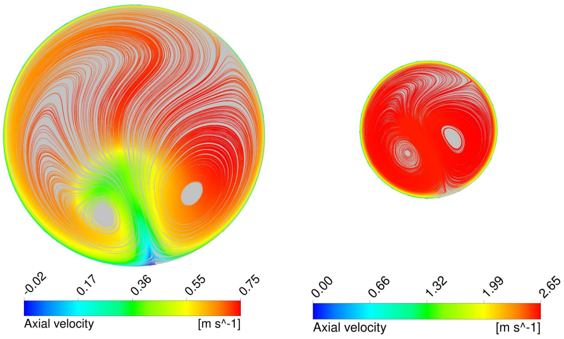
Because of the bends in the different planes, the centrifugal force caused by the curvature acted in different directions, and consequently asymmetric vortex flow pattern was generated for L_u= 1*D*. This type of flow pattern different from the fully developed flow was still maintained for L_u= 8.5*D*, the recommended straight length in KEPIC MPT-19.5 [3]. On the other hand, as the upstream straight lengths for a venturi tube sufficiently increased (e.g. L_u= 100*D*), a pair of vortex flow changed to the weak single swirl flow.

Mass flow rate through a venturi tube flowmeter can be calculated by using the following equation (1):

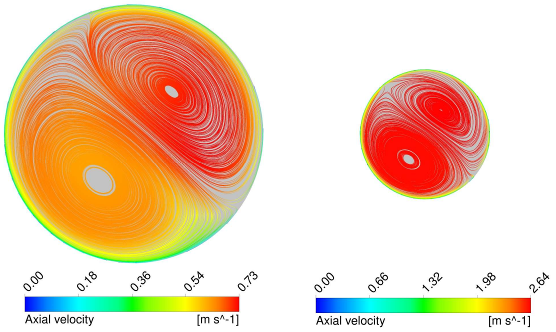
$$q_m = \frac{C_d A}{\sqrt{1-\beta^4}}\sqrt{2\rho\Delta p} \qquad (1)$$

where q_m is the mass flow rate, C_d is the discharge coefficient, A is the area of a venturi throat, β is the diameter ratio, ρ is the fluid density, and Δp is the differential pressure between upstream taps and throat taps. As shown in Fig. 3(a), upstream taps are located on the entrance section at a distance of -*D*/2 from the beginning of the contraction section. Throat taps are installed at the mid of the throat length. Four upstream and throat taps are provided at equal spacing (i.e. 90° apart).

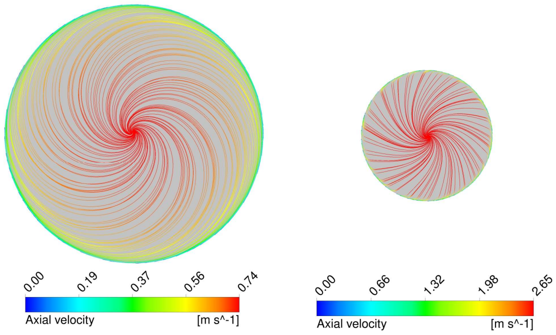
Fig. 3 shows the differential pressure (Δp) magnitude depending on the straight length upstream of a venturi tube. With x/*D*=5 or 6 as the reference points, the differential pressure increased and then decreased.



(a) L_u = 1*D*



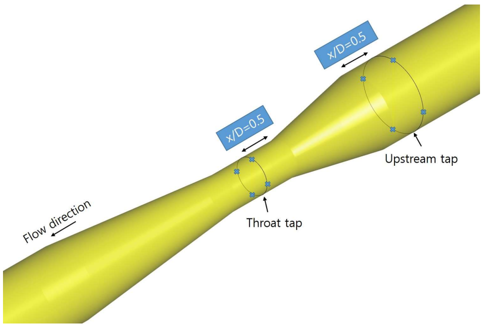
(b) L_u = 8.5*D*



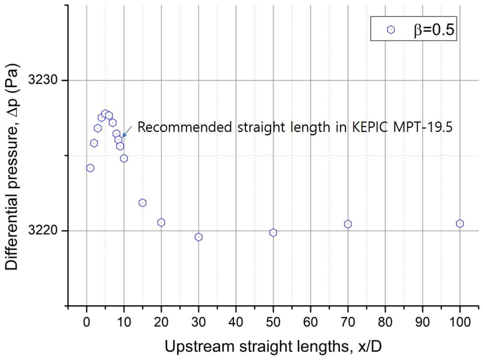
(c) L_u = 100*D*

Fig. 2. Comparison of streamline and axial velocity distribution for β = 0.5; depending on the upstream straight length for a venturi tube (left; -*D*/2, right; mid of the throat length).

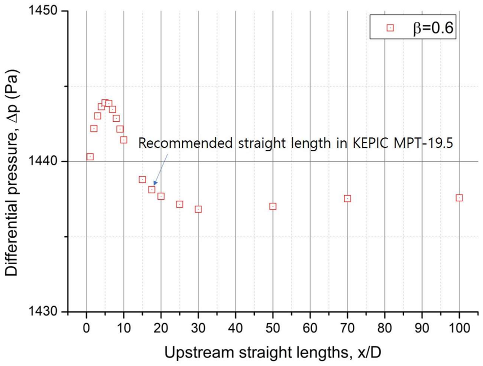
As the upstream straight length for a venturi tube became further longer, the differential pressure gradually decreased and approached the nearly constant magnitude at x/*D*=100. On the other hand, as the diameter ratio (β) increased, the magnitude of differential pressure decreased because flow velocity passed through the throat of a venturi tube became slower.



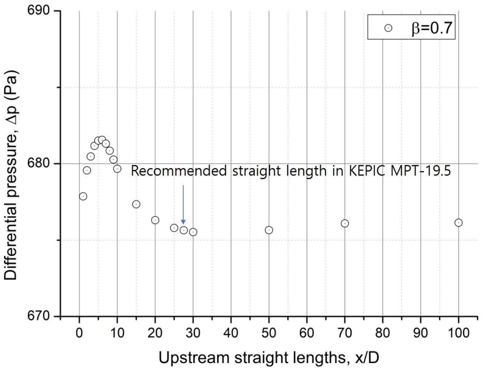
(a) Locations of pressure tap



(b) β=0.5



(c) β=0.6

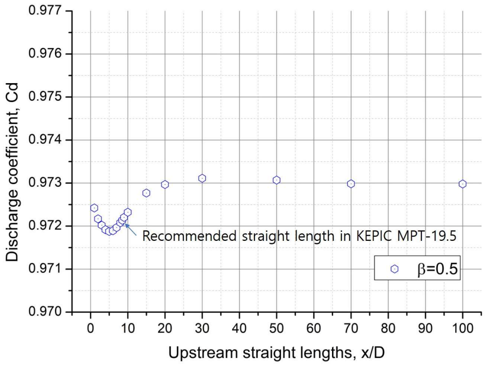


(d) β=0.7

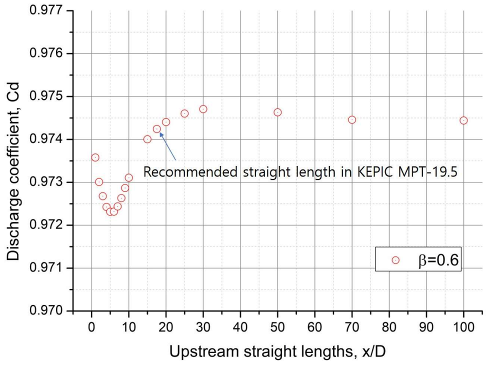
Fig. 3. Variation of the differential pressure magnitude depending on the straight length upstream of a venturi tube.

Fig. 4 shows the discharge coefficient (C_d) magnitude depending on the straight length upstream of a venturi tube. From x/*D*=5 or 6, as the upstream straight length for a venturi tube became longer, the discharge coefficient gradually increased and approached the almost constant magnitude at x/*D* =100. As the diameter ratio (β) increased, the gradient of C_d became much steeper.

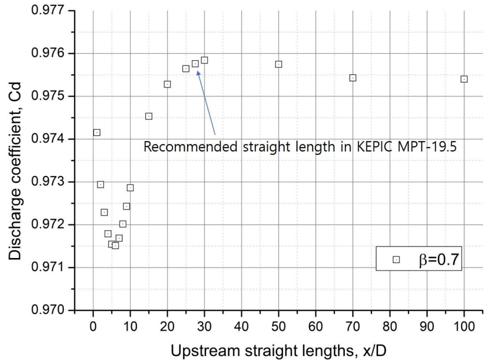
Table III shows the shift of C_d at the recommended upstream straight length [3] for a venturi tube. As shown in equation (1), C_d is needed to measure flow rate using a venturi tube flowmeter [1]. Therefore, an error in C_d may be directly related to the measurement uncertainty [1]. In this study, maximum shift of C_d was estimated to be less than 0.1%.



(a) β=0.5



(b) β=0.6



(c) β=0.7

Fig. 4. Variation of the discharge coefficient magnitude depending on the straight length upstream of a venturi tube.

Table III: Shift of Discharge Coefficient at the Recommended Upstream Straight Length for a Venturi Tube

β	Reference (fully developed flow)		KEPIC MPT-19.5 (2015 ed.)		
	L_u	C_d	L_u	C_d	% shift
0.5	100*D*	0.9729	8.5*D*	0.9721	0.086
0.6	100*D*	0.9744	17.5*D*	0.9742	0.020
0.7	100*D*	0.9754	27.5*D*	0.9757	0.037

5. Conclusions

In this study, to assess the adequacy of upstream straight lengths for a venturi tube recommended in KEPIC MPT-19.5 (2015 edition), numerical simulation of flow inside multiple 90° bends in the different planes with a venturi tube was conducted with ANSYS CFX R18.1. Main conclusions can be summarized as follows:

(1) As the upstream straight length for a venturi tube became longer (e.g. L_u= 100D), the differential pressure and discharge coefficient gradually approached the nearly constant magnitude.

(2) The recommended upstream straight lengths in KEPIC MPT-19.5 could not guarantee the fully developed incoming flow especially for β = 0.5. For the present analysis model, the maximum shift of C_d was estimated to be less than 0.1%. If much higher measurement accuracy should be obtained, it may be essential either to secure the longer straight length or to use a flow conditioner [1].

DISCLAIMER

The opinions expressed in this paper are those of the author and not necessarily those of the Korea Institute of Nuclear Safety (KINS). Any information presented here should not be interpreted as official KINS policy or guidance.

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