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Original Article

Numerical investigation of the large over-reading of Venturi flow rate in ARE of nuclear power plant

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ABSTRACT

Venturi meter is frequently used in feed water flow control system in a nuclear power plant. Its accurate measurement plays a vital role in the safe operation of the plant. This paper firstly investigates the influence of the length of each section of pipeline, the throat inner diameter of Venturi and the flow characteristics in a single-phase flow on the accuracy of Venturi measurement by numerical calculation. Then the flow and the accuracy are discussed in a multi-phase flow. Numerical results show that the geometrical parameters and the characteristics of complex turbulent flow in the single-phase flow have little impact on the accuracy of Venturi flow rate measurement. In the multi-phase flow, the calculated flow rate of Venturi deviated from the actual flow rate and this deviation value is closely related to the amount of steam in the pipeline and increases sharply with the increase of the amount of steam. The over-reading of Venturi flow rate is present.

1. Introduction

The feed water flow control system (ARE) in the second circuit of a nuclear power plant is designed to send the high-pressure water heated from high pressure heater into the steam generator. The quantity of the feed water is adjusted by the Main Control Valve (MCV) and the bypass control valve (BCV). The general layout is shown in Fig. 1. The water level in the secondary side of the steam generator (SG) which is connected to the steam turbine under variable loads [1] must be maintained within the safety range. The control and regulation of feed water plays a key role in the safe operation of nuclear power plants. When the feed water is abnormal, the water level protection of the steam generator will be triggered if the level is too high or too low. That would lead to the emergency shutdown of the reactor [2]. In present design of ARE, a Venturi meter is installed between the feed water control valve and the inlet of the steam generator in each feed water pipeline to monitor the quantity of feed water to SG. Recently, it was reported that the feed water mass flow rate(Venturi measured flow rate) was significantly higher than that of steam leaving SG during the switching of the main control valve and bypass control valve in the process of power reduction of some nuclear power unit, shown in Fig. 2. As seen in Fig. 2, the mass flow rate of Venturi in green was higher than the mass flow rate of steam in dark blue. The deviation of these two mass flow rates was up to 140 t/h when the opening of MCV is less than 5%. At the same time, the liquid level in the steam generator continued to drop. That presented the phenomenon of mass non-conservation in the system or artificial high flow rate of Venturi (called “Over-reading”, OR). These problems have been found in many nuclear power stations in China. It is very important to figure them out to make sure the operating safety of nuclear power stations. It was doubted that the large difference between Venturi measured flow rate and steam flow rate out of SG was caused by Venturi meter. However, the damage of Venturi meter was excluded during regular check and maintenance of the nuclear power plant. Based on the system design, it was suspected that the deviation of Venturi measured flow rate is caused by the influences of the complex turbulent flow characteristics or the various parameters (the length of *a*, *b*, *c*, *d* and throat inner diameter of Venturi) in the arrangement.

With the rapid development of both traditional and emerging industries and processes including petroleum transportation, nuclear systems and metallurgical processing, a Venturi meter as pressure meter has been widely employed in scientific research and industrial process because of its advantages of simple structure, easy production of standard parts and relatively small pressure loss

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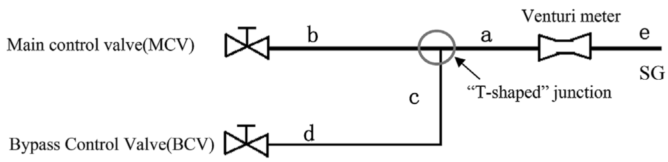

Fig. 1. Schematic figure of the layout.

[3–5]. For its proper application, researchers have been making a lot of effort. Reader Harris et al. [6]conducted a large number of experimental studies using water as the fluid medium and analyzed the measurement accuracy of Venturi meters with different inner diameters and contraction angles. It was proved that the precision of Venturi meter with a single phase flow (water) was closely related to the geometrical parameters of Venturi meter. In many applications, Venturi meters were used to measure the flow rate in different flow patterns and multi-phase flows [7]. In some cases, accurate flow rate measurements were demanded [8,9]. And they were often concerned with multi-phase flow. However, it was reported that the deviation arised in measured flow rate of Venturi meter and presented artificially high, OR with multi-phase flows [10–12]. Researchers have been studying the flow in the Venturi meter experimentally and numerically to figure out the reason of OR and tried to correct it. Steven [13] carried out an experimental study on flow measurement of horizontal Venturi tube in NEL laboratory. The experimental data was used to compare with the different prediction models and made two phases flow Venturi corrections. Fang et al. [14–16] conducted flow measurement experiment under low pressure by using symmetric Venturi tube. A new flow prediction model has been established based on the experimental data. The newly built flow prediction model was analyzed and compared. It was found that it had a better measurement accuracy. Reader-Harris et al. [17] numerically investigated wet gas flow through Venturi meters, in which the Euler-Euler multi-phase model was employed to simulate two phases flow. It was noted that the numerical results had good tendency with the experimental OR data. He et al. [18] and Xu et al. [19] used Fluent Software with Discrete Phase Model (DPM) to conduct numerical studies on the flow characteristics of wet natural gas in Venturi meter. The factors affecting the artificial height of wet natural gas flow measurement are analyzed. The numerical results showed that the pressure in the throat area drops significantly and the pressure in the throat drops faster with the increase of the liquid fraction when the wet natural gas flows through Venturi. Xu et al. [20] used the DPM to predict the OR characteristics of Venturi. It was reported that the maximal relative error of OR was 5.14%. Reader-Harris et al. [21] investigated the different turbulent models with different media on Venturi. It was noted that the standard $k-\varepsilon$ model had better agreement with experimental data than the Reynolds Stress Model. Duan [22] in his thesis employed the RNG $k-\varepsilon$ model and DPM to compute wet gas flow in flow meter. Results showed that the CFD model worked well on the OR prediction. Kumar [23] studied with Fluent software and analyzed the influence of geometrical parameters of the Venturi meter on the OR. It was found that the OR of Venturi meter decreased with the increase of the diameter ratio, but it was independent of the contraction angle. Kumar and Sim [24] investigated the influence of contraction angle with Fluent Software and expansion angle on wet natural gas measurement. It was found that the pressure drop generated by the fluid flowing through Venturi metre was not related to the contraction angle and expansion angle of the Venturi meter, but the measured OR of Venturi meter was significantly affected by the expansion Angle. Pan et al. [25] developed a linear correlation and compared the computational results with experimental data to predict gas flow rates in multi-phase flows. The method could be used in a wide range of void fraction (vapor fraction) of the flow and worked well for different Venturis and fluid media.

As stated above, numerical simulation has been applied to compute the flow rate through Venturi for years. It is known that the accuracy of measured flow rate could be affected by the parameters of Venturi meter in a single phase flow. And the OR of Venturi meter is widely present in a multi-phase flow. In this paper, numerical method is employed to simulate the fluid flow through the pipeline system. The Standard $k-\varepsilon$ model and Mixture multiphase model are used to compute turbulent water flow or water-steam multi-phase flow through meter. The Venturi flow rate is calculated by numerical methods. This study focuses on identifying the reasons causing the large difference (the deviation up to 140 t/h) between Venturi measured flow rate and steam flow rate out of

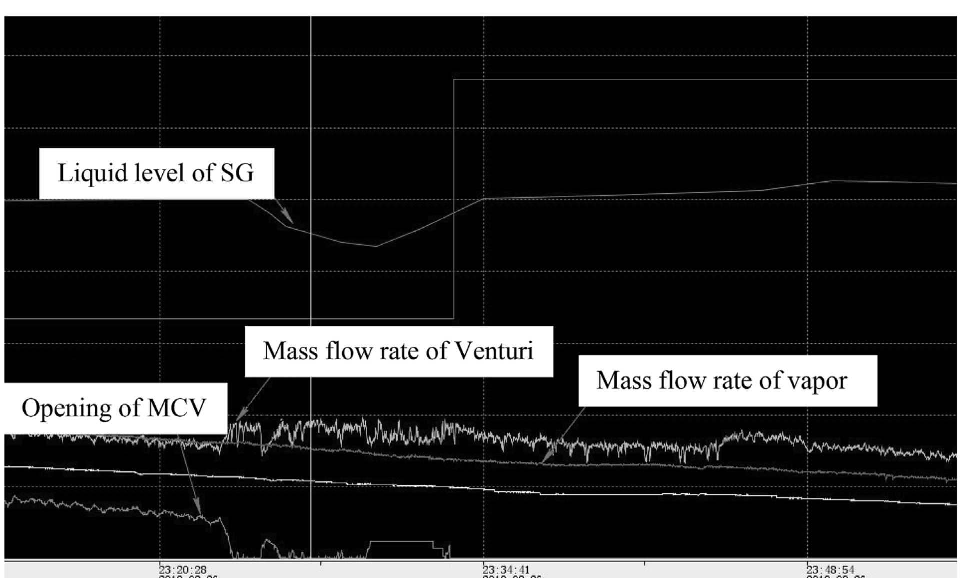

Fig. 2. Monitoring curves of parameters during the process of power reduction from Hongyanhe nuclear power unit4.

SG. The influences of the length of each section of pipeline, the throat inner diameter of Venturi and the flow characteristics inside the pipe are numerically investigated in the single-phase flow. Then the accuracy of Venturi measurement is analyzed in the water-vapor multi-phase flow. The numerical results will provides reference for nuclear power plant maintenance.

2. Numerical details

2.1. Numerical method

The CFD software package ANSYS Fluent 17.0 is used to perform numerical simulations. The calculations are carried out for three-dimensional flow simulations. The standard $k-\varepsilon$ turbulence model is chosen to compute the turbulent viscosity which was proposed by Launder and Spalding [26] in 1972 and has been widely used in engineering calculation due to its good convergence and accuracy. The Mixture multi-phase model is employed to simulate the water-vapor flow through the pipe and Venturi. The pressure–velocity coupling is handled by the SIMPLE algorithm. The second-order upwind schemes are used for the convection terms and the viscous terms of each governing equation respectively to minimize the numerical diffusion. The convergence criterion for all parameters is 10^{-3}.

2.2. Geometrical model and computational mesh

Based on the problem analysis, the geometrical model is simplified and built using software UG shown in Fig. 3, including the pipelines where the main and bypass control valves are located and the Venturi meter. The detailed dimensions of each part are given in Table 1. A structured mesh is generated using software ICEM with a total of about 1.36 million grids as shown in Fig. 4.

2.3. Initial and boundary conditions

Mass flow rate boundary conditions are specified at the MCV and BCV inlets and outflow boundary condition specified at the pipe outlet since outlet boundary pressure is not available. All the wall of pipe and Venturi are defined as nonslip. The medium in the pipeline system is water. Heat transfer between fluid and walls are not taken into account. The gravity is in the direction of -z and 9.81 m/s^2.

The grid independence is carried out before further calculation. At last, a structured grid with a number of about 2.3 million elements is selected for the following calculations.

3. Validation and correction to numerical results

The flow rates corresponding to the opening of valves are theoretically calculated based on the flow coefficient C_v curve of BCV and MCV provided by the nuclear power plant. The calculated details are given using the equation (A.1) in Appendix 1. The

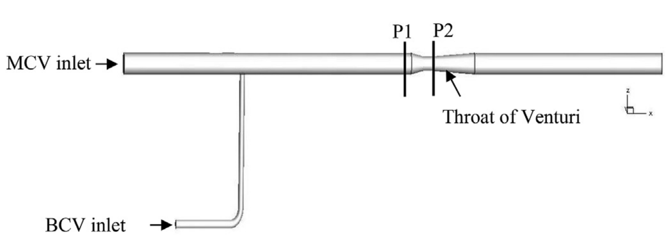

Fig. 3. Geometrical model.

Table 1
Dimensional details of different parts of pipeline system.

	a	b	c	d	e	Venturi meter
Length, mm	3200	3209	2761	1755	4000	1764
Inner diameter, mm	362	362	143.3	143.3	362	214

theoretical calculated flow rates based on C_v curve are employed as the inlet flow rates at the inlets of BCV and MCV. The sum of two inlet flow rates is called as "actual flow rate" in the pipe system.

Before further discussion, the actual flow rate is validated against the on-site data. Here are three conditions including MCV with 50% opening, 60% opening and BCV with 100% opening whose flow rates are got with the equation (A.1). Fig. 5 gives the comparison of the on-site data and theoretical calculated data. A maximum deviation ratio of 4.27% is an acceptable value in this study. Because the operating conditions on site are varied with time, that leads to the pressure differences of inlet and outlet of the valve changed. Therefore, in the following discussions, the inlet flow rates of MCV and BCV are calculated in this way according to the given opening and the sum of both as inlet flow rate and called as the actual flow rate in the system.

As known, Venturi meter is a typical differential pressure flow meter which is one of the applications of Bernoulli equation. In the numerical calculation, the static pressures of position P1 and position P2 (as shown in Fig. 2) which are the two pressure positions of Venturi are monitored. The average static pressure values of P1 and P2 are taken and the Venturi flow rate is calculated by equation (1) [27]:

$$Q=\beta\rho A_2\sqrt{\frac{2g(p_1-p_2)}{\rho g\left[1-\left(\frac{A_2}{A_1}\right)^2\right]}} \tag{1}$$

Where, p_1, A_1 and p_2, A_2 are respective pressures on the cross-section P1 and P2 and the areas of them. The flow coefficient β is 1 in an ideal condition. In practical application, the uneven velocity distribution on the cross-sectional area caused by viscosity and the energy loss in the flow should be taken into account. Therefore, the value of β should be corrected according to the actual working conditions.

Here are two typical cases reported during the operating of Hongyanhe nuclear power plant including Case1 (BCV with 100% opening and MCV with 60% opening) and Case2 (BCV with 100% opening and MCV with 60% opening), detailed in Table 2. The flow rates under these two conditions are selected to correct the calculated flow rate of Venturi. The value of β is determined against the actual flow rate and the numerical method is validated. Table 3 presents the average static pressures of P1 and P2, the calculated flow rate of Venturi and the actual flow rate (the sum of flow rates of both MCV inlet and BCV inlet). It is found that the ratio of the actual flow rate and the calculated flow rate was 0.9711 and 0.9708 respectively. Two values are quite close and the deviation is in the acceptable range. Finally, 0.9708 is used as the value of β to correct the calculated flow rate of Venturi in the subsequent calculations of this study.

4. Result discussions

4.1. Analysis in a single-phase flow

Based on the corrected calculation formula of the numerical model, different conditions are chosen to analyse and discuss the

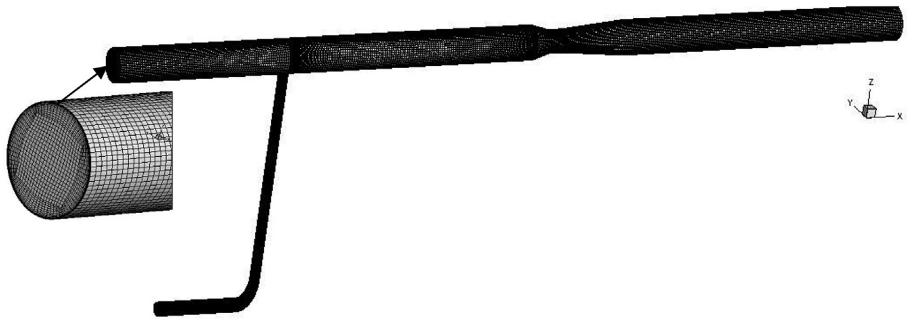

Fig. 4. Computational grid.

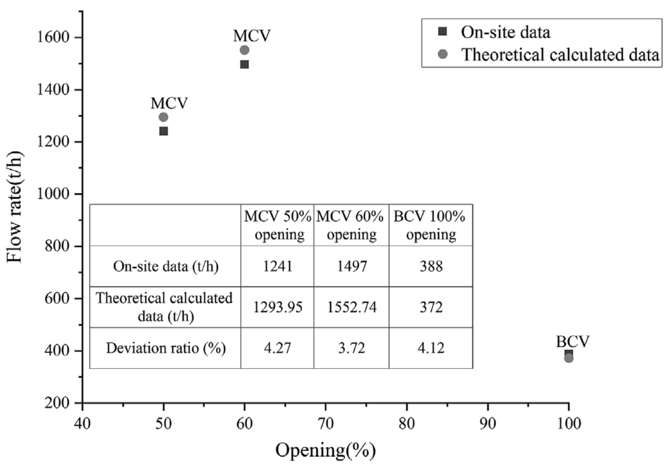

Fig. 5. Comparison of on-site data and theoretical calculated data for three valve openings.

Table 2
Inlet flow rate and opening of MCV and BCV for two cases.

	MCV Inlet (t/h)		BCV Inlet (t/h)	
Case1	1293.95	(50% opening)	372	(100% opening)
Case2	1552.74	(60% opening)	372	(100% opening)

influence of the flow characteristics inside the pipe and geometrical parameters of the pipeline system on the calculated flow rate of Venturi in a single-phase flow.

4.1.1. Influence of flow characteristics on calculated flow rate of Venturi

According to the arrangement of nuclear power plant on site, it is found that there is a "T-shaped" junction in the vertical direction of the pipelines. Under different conditions, the two flows emerge and mix with each other which could result in turbulent mixing. In this section, three typical conditions are selected to analyze the effect of flow characteristics at the junction on the calculated flow rate of Venturi and the details are given in Table 4.

Fig. 6 shows the contour of the velocity on the vertical section

Table 4
Inlet mass flow rate and opening of MCV and BCV for three cases.

	MCV Inlet (t/h)		BCV Inlet (t/h)	
Case1	0	(0% opening)	372	(100% opening)
Case2	1018.98	(40% opening)	372	(100% opening)
Case3	1989.44	(80% opening)	372	(100% opening)

under three different conditions. In Case1 with MCV 0% opening, the flow from BCV plays the main role in the "T-shaped" junction mixing. The jet impinges on the wall and disperses on both sides. With the increase of the MCV inlet flow rate for Case2 and Case3, the flow in the pipe is controlled by the MCV inlet flow and presents violent mixing.

Turbulent intensity is commonly used to identify the degree of fluid velocity fluctuation. It is commonly defined as the ratio of turbulent fluctuated velocity to average velocity [28] with equation (2), which is a relative concept,

$$I = \frac{u'}{u} \tag{2}$$

Where, u' is the mean square root of turbulent fluctuated velocity (also called as the standard deviation of the fluid), u is the average velocity. They are calculated by equations (3) and (4),

$$u' = \sqrt{\frac{1}{3}\left(u_x'^2 + u_y'^2 + u_z'^2\right)} \tag{3}$$

Where, u'_x, u'_y and u'_z are the fluctuated velocity of u in x, y and z direction.

$$u = \sqrt{u_x^2 + u_y^2 + u_z^2} \tag{4}$$

Where, u_x, u_y and u_z are the components of the average velocity u_{avg} in the x, y and z directions. In Fluent, turbulent intensity is expressed as $I = \sqrt{\frac{2}{3}*\kappa}\Big/u_{avg}$ [29], where κ is the turbulent kinetic energy of the fluid and u_{avg} is the average velocity. Fig. 7 shows the contour of turbulent intensity on the vertical profile under different conditions. It is seen that the flow is controlled by the BCV inlet

Table 3
Average static pressure of P1 and P2, Venturi calculated flow rate and actual flow rate for two cases.

	Position1 (Pascal)	Position2 (Pascal)	Calculated flow rate (t/h)	Actual flow rate (t/h)	Ratio
Case1	−11188.5	−88497	1715.53	1665.95	0.9711
Case2	−12371.3	−115611	1982.48	1924.74	0.9708

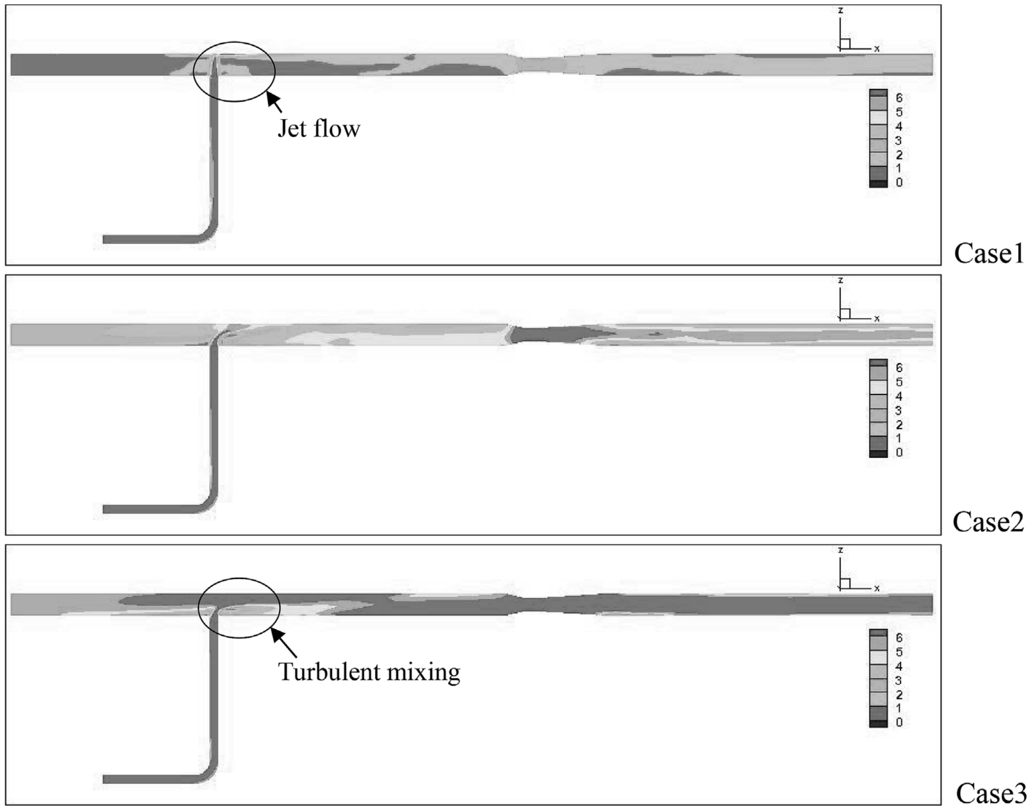

Fig. 6. The contour of the velocity on the vertical section under different conditions.

Fig. 7. The contour of the turbulent intensity on the vertical section under different conditions.

Table 5
Calculated, actual flow rates, deviations and deviation ratios for the three cases.

Opening of MCV inlet	Case 1 (0%)	Case 2 (40%)	Case 3 (80%)
Calculated flow rate (t/h)	373.65	1391.25	2359.16
Actual flow rate (t/h)	372	1390.98	2361.44
Deviation (t/h)	1.65	0.27	2.28
Deviation ratio (%)	0.44	0.02	0.10

flow in Case1. At the junction, there is a wall impinging jet with a large turbulent intensity. With the increase of MCV flow rate, the turbulent intensity is weakened at the junction and the large turbulent intensity is present after the Venturi.

In order to further study the influence of the large turbulent intensity before or after Venturi, the calculated flow rate, the actual flow rate, the deviation of these two flow rates and the deviation ratio for the three cases are given in Table 5. It is found that the maximum relative calculated flow rate deviation is 2.28 t/h in Case3 (MCV with 80% opening). The deviation between the calculated flow rate and the actual flow rate is very small with the deviation ratio only 0.10%. In fact, the turbulent mixing in the tube don't obviously affect the accuracy of Venturi meter.

4.1.2. *Influence of geometrical parameters on calculated flow rate of Venturi*

In this section, the influences of the length of sections *a*, *b*, *c*, *d* (as shown in Fig. 1) and the throat inner diameter Φ of Venturi on the calculated flow rate are discussed respectively under the conditions at inlets of MCV with 5% opening and BCV with 100% opening.

Tables 6–9 respectively give the calculated flow rate, the actual flow rate, the deviation and the deviation ratio of these two flow rates with different lengths of *a*, *b*, *c* and *d*. It can be seen that the calculated flow rates of Venturi increase gradually and the deviation also increases gradually as the length of sections *a*, *b* and *c* increases. When the length of *b* is 3379 mm, the maximum deviation value is about 7.79 t/h and the deviation ratio is only 1.86% relative to the actual flow value. When the length of *d* changes, the

Table 6
Calculated, actual flow rates, deviations and deviation ratios for different lengths of *a*.

	Calculated flow rate (t/h)	Actual flow rate (t/h)	Deviation (t/h)	Deviation ratio (%)
a = 2700	413.17	417.89	−4.72	1.13
a = 3000	418.27	417.89	0.38	0.09
Orig a = 3200	423.70	417.89	5.80	1.39
a = 3400	423.65	417.89	5.75	1.38
a = 5200	424.37	417.89	6.47	1.55
a = 9200	425.08	417.89	7.19	1.72

Table 7
Calculated, actual flow rates, deviations and deviation ratios for different lengths of *b*.

	Calculated flow rate (t/h)	Actual flow rate (t/h)	Deviation (t/h)	Deviation ratio (%)
b = 3000	421.53	417.89	3.64	0.87
Orig b = 3209	423.70	417.89	5.80	1.39
b = 3379	425.68	417.89	7.79	1.86

Table 8
Calculated, actual flow rates, deviations and deviation ratios for different lengths of *c*.

	Calculated flow rate (t/h)	Actual flow rate (t/h)	Deviation (t/h)	Deviation ratio (%)
c = 2200	421.50	417.89	3.61	0.86
Orig c = 2761	423.70	417.89	5.80	1.39
c = 3000	425.29	417.89	7.40	1.77

Table 9
Calculated, actual flow rates, deviations and deviation ratios for different lengths of *d*.

	Calculated flow rate (t/h)	Actual flow rate (t/h)	Deviation (t/h)	Deviation ratio (%)
Orig d = 1755	423.70	417.89	5.80	1.38
d = 1900	420.48	417.89	2.58	0.62
d = 3000	425.08	417.89	7.19	1.72

Table 10
Calculated, actual flow rates, deviations and deviation ratios for different inner diameters of Venturi.

	Calculated flow rate (t/h)	Actual flow rate (t/h)	Deviation (t/h)	Deviation ratio (%)
$\Phi = 200$	426.15	417.89	8.26	1.98
Orig $\Phi = 214$	423.70	417.89	5.80	1.39
$\Phi = 230$	423.73	417.89	5.84	1.40

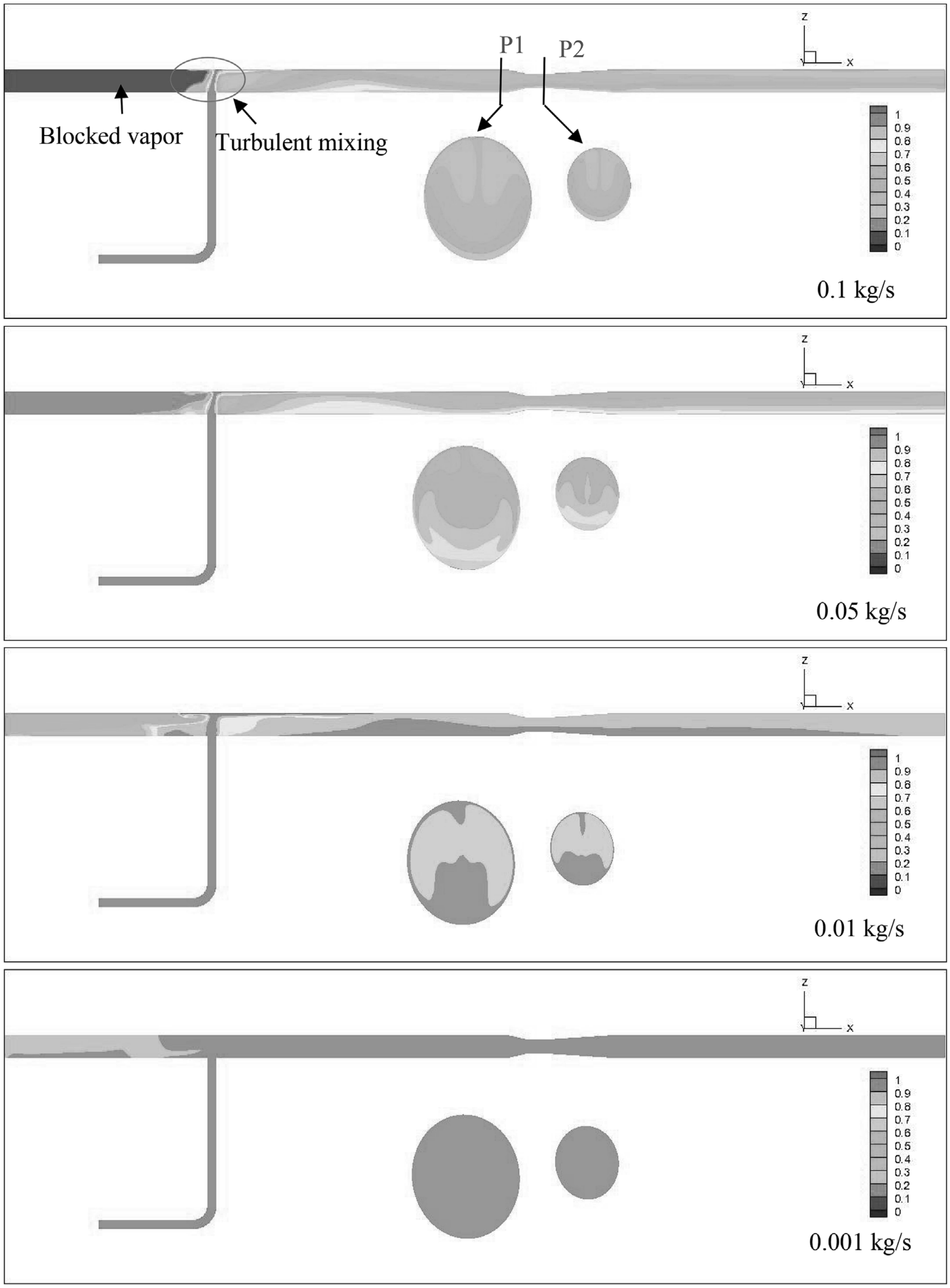

Fig. 8. The contour of the liquid fraction on the vertical section with different quantities of vapor at MCV inlet.

minimum deviation is 2.58 t/h with $d = 1900$ mm while the deviation value increases to about 7.19 t/h with $d = 3000$ mm which deviation ratio from the actual flow value is just 1.72%. The value of the deviation is acceptable in this study. Table 10 presents the results with different throat inner diameters of Venturi. The results show the deviation is reduced as throat inner diameter of Venturi increases. The maximum deviation value is 8.26 t/h with $\Phi = 200$ mm and the deviation ratio is 1.97%. The numerical results show that the lengths of a, b, c, d and Φ do cause calculated flow rate fluctuated. However, the deviations from actual flow rate are very small. All the deviation ratios are less than 2%. Therefore, the variations of the geometrical parameters in a single-phase flow have little impact on the calculated flow rate. There are no great deviations from the actual flow rate and the large OR of Venturi flow rate doesn't occur.

4.2. Analysis in a two-phase flow

In the discussions above, it is found that the calculated flow rate of Venturi in a single-phase flow is very little affected by various geometrical parameters. Based on the layout of the feed water flow control system, it is suspected that vapor could be generated during

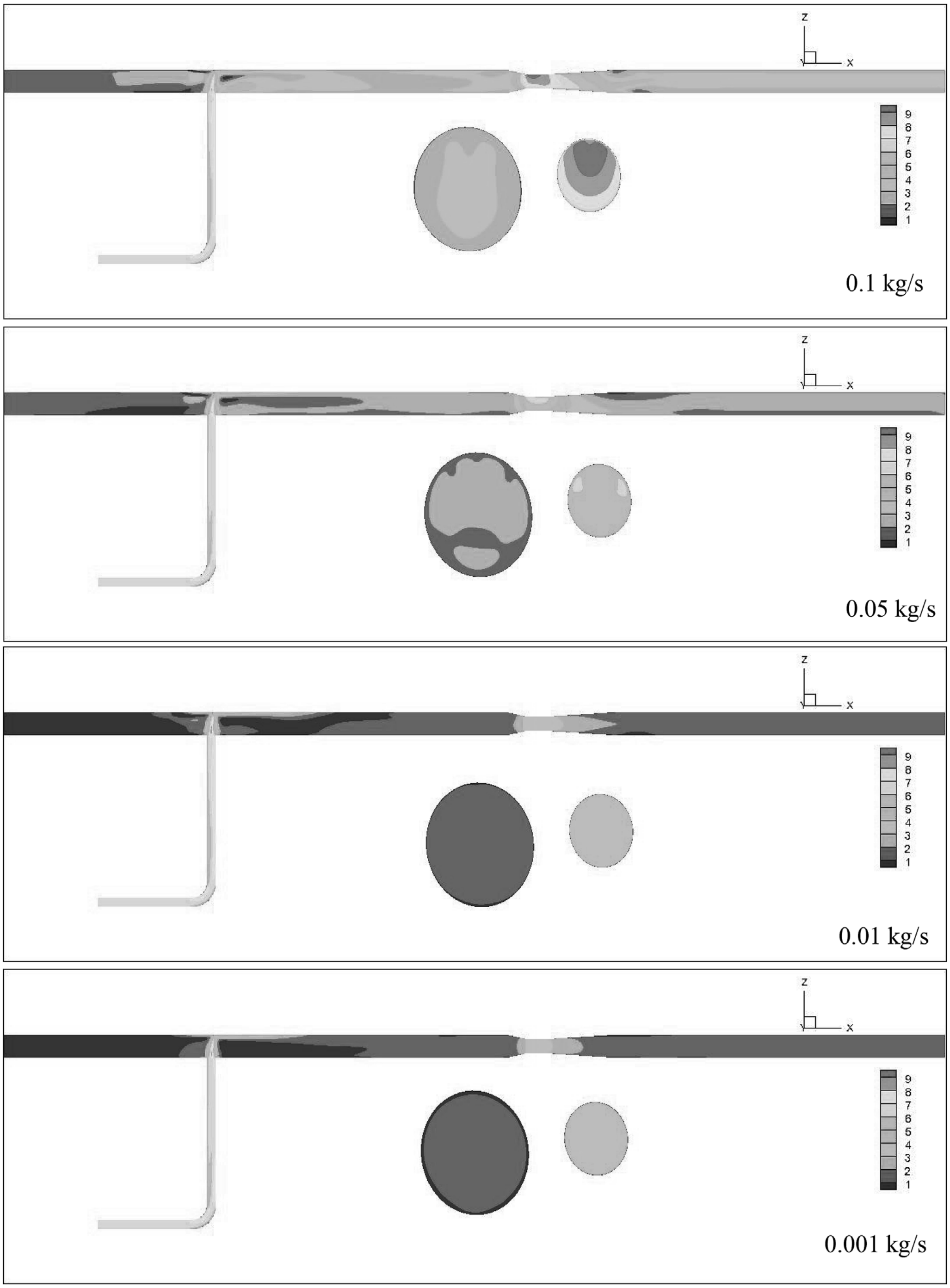

Fig. 9. The contour of the velocity on the vertical section with different quantities of vapor at MCV inlet.

Table 11
Deviations and vapor fraction of P1 and P2 with different amounts of vapor.

Mass flow rate of vapor	Deviation ratio(%)	P1-Vapor fraction	P2-Vapor fraction
0.1	60.47	0.60541	0.60269
0.05	35.08	0.44116	0.41557
0.01	9.42	0.11573	0.11854
0.001	2.51	0.01193	0.01152

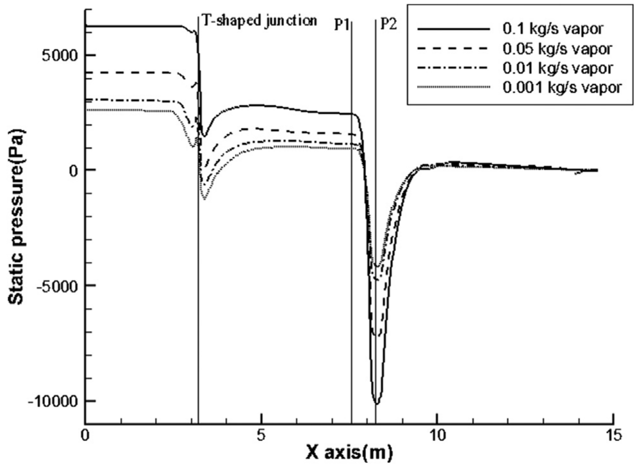

Fig. 10. Comparison of static pressure along x direction with different quantities of vapor at MCV inlet.

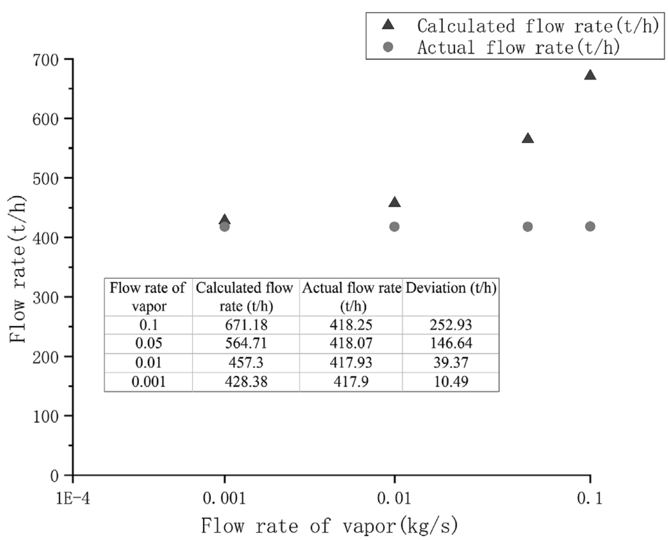

Fig. 11. Comparisons of calculated flow rate and actual flow rate with different amounts of vapor and deviations.

MCV closing process and operation parameters during power switching because of the cavitation flow. In this section, a multi-phase flow in the pipe system is analyzed. It is assumed that a certain amount of vapor is produced from the MCV inlet and flows through the pipe with the flow rates of 0.1, 0.05, 0.01 and 0.001 kg/s respectively. The mass flow rate at the MCV inlet is 12.75 kg/s (5% opening) and 103.33 kg/s (100% opening) at the BCV inlet.

Figs. 8 and 9 respectively show the liquid fraction and the velocity contour of the pipeline with different vapor flow rates at MCV inlet. It can be seen in Fig. 8 that the space at the upstream of the junction of the two pipes is full of vapor with MCV inlet vapor flow rate of 0.1 kg/s and vapor is blocked there. Turbulent mixing takes place between the vapor and water from BCV at the junction. It is found that the liquid is located at the lower part of the cross-sections P1 and P2 under gravity. For the vapor flow rate of 0.1 kg/s, most of P1 and P2 sections are full of vapor. With the decrease of vapor flow rate, less vapor is present at P1 and P2 sections and the effect of vapor is becoming weaker. Their corresponding exact vapor fractions are given in Table 11. As can be seen from the velocity contour (shown in Fig. 9), the flow in the main pipe is greatly disturbed by the vapor when the amount of vapor is relatively large and a high-speed area appears at the throat of Venturi because of much lower density of vapor. The velocity and its profile at the sections of P1 and P2 are greatly influenced by the liquid fraction.

Static pressure at the sections of P2 (monitoring point at the throat) is obviously affected by the quantity of vapor as compared in Fig. 10. The greater the flow rate of vapor is, the faster the throat pressure declines. The larger pressure difference between sections P1 and P2 leads to a large over-reading as illustrated in Fig. 10. The static pressure fluctuates at the "T-shaped" junction. However, the quantity of vapor has little effect on the static pressure. The deviation is becoming larger with the increase of the amount of vapor shown in Fig. 10. The calculated flow rate of Venturi is much higher than the actual inlet flow with the vapor flow rate of 0.1 kg/s. The deviation or OR reaches as high as 252.93 t/h. As the vapor flow rate decreases to 0.05 kg/s, the deviation between the calculated flow rate and the actual flow rate is reduced to 146.64 t/h. As the vapor flow rate further decreases, the deviation decreases to 39.37 t/h with 0.01 kg/s vapor and 10.49 t/h with 0.001 kg/s. The corresponding deviation ratios and the vapor fractions of P1 and P2 are listed in Table 11. The deviation ratio is as high as 60.47% with the vapor of 0.001 kg/s. Therefore, when a water-vapor multi-phase flow occurs in the pipe system, the calculated flow rate of Venturi deviates from the actual flow rate and this deviation is closely related to the amount of vapor in the pipe system. It increases sharply with the increase of the amount of vapor in the pipe system and emerges the large OR of the flow rate of Venturi (seen in Fig. 11).

5. Conclusions and suggestions

As it is reported that the OR of Venturi is present during the switching of the MCV and BCV in the process of power reduction of some nuclear power unit. The reasons causing the OR of Venturi flow rate are needed to identify. Under these circumstances, numerical simulations are conducted to calculate the effects of the geometrical parameters and the characteristics of flow pattern on the accuracy of Venturi measurement in the single phase flow and in the multi-phase flow. Conclusions are as follows:

The turbulent mixing inside the pipe don't significantly affect the accuracy of Venturi meter in the single-phase flow. The geometrical parameters including the lengths of *a*, *b*, *c*, *d* and the throat inner diameter Φ of Venturi have little impact on calculated Venturi flow rate in the single-phase flow. There are no large deviations between the calculated flow rate and actual flow rate. The flow rates of Venturi are accurate and reliable when the flow is in the single-phase flow. It can be concluded that there is no over-reading phenomena in a single-phase flow.

In the water-vapor multi-phase flow, the calculated flow rate of Venturi deviates from the actual flow rate and this deviation value is closely concerned with the amount of vapor in the pipe system. The deviation increases greatly with the increase of the amount of vapor and a large OR could be present. It can be said that the flow rates of Venturi presents the OR when the flow is in a two-phase flow.

Based on the calculated results, the reason resulting in the OR of Venturi could be that the water inside the pipeline undergoes the phase change and generates vapor. The water-vapor through Venturi meter leads to the OR of the flow rate. One suggestion is given to the maintenance engineers and operating engineers of the nuclear power plant to check the valves, pumps installed in the pipeline and the junction design to eliminate the possibilities of vapor generation, such as cavitation during the opening and closing of valves. The other is to employ multi-phase Venturi meter to decrease the effect of multi-phase flow or to make proper correction to measured data of Venturi to eliminate the effect of OR.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Valve flow rate calculation

The valve flow rate is calculated based on the given flow coefficient curve. Flow coefficient C_v of a valve was first proposed by the American fluid control association in 1952. It is defined as the flow of US gallons (US gal/min) per minute of water at a temperature of 15.6 °C at a standard pressure drop of 1 pound per square inch (1bf/in^2) through the valve. The flow coefficient C_v of the valve varies with the size, type and structure of the valve. The values of flow coefficient C_v must be gained by test. The formula for calculating the value of C_v is:

$$C_v = Q\left(\frac{G}{\Delta P}\right)^{0.5} \Rightarrow Q = C_v\left(\frac{\Delta P}{G}\right)^{0.5} \tag{A.1}$$

Where C_v is the flow coefficient, Q is volume flow rate (US gal/min), ΔP is the pressure difference of inlet and outlet of valve (1bf/in^2), G is the relative density of water, here $G = 1$. Therefore, the valve flow rate is evaluated after knowing the value of the flow coefficient C_v and pressure difference.

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