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Original Article

Numerical analysis of the venturi flowmeter in the liquid lead-bismuth eutectic circuit after long-term operation

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ABSTRACT

The liquid Lead-bismuth eutectic is used as the coolant for Gen-IV reactor concepts. However, due to its strong corrosive and high operating temperature, it is difficult to accurately measure the flow rate in long-term operating conditions. Venturi flowmeter is a simple structured flowmeter, which plays a very important role in the flow measurement of high-temperature liquid metals, especially since the existing flowmeters are difficult to be competent. It has the advantages of easy maintenance and stable operation. Therefore, it is necessary to study the operating conditions of the venturi flowmeter under high-temperature conditions. This work performs a series of simulations of the fluid-solid interaction between the flow liquid metal and venturi flowmeter with COMSOL software, including the dimensional sensitivity analysis of the venturi flowmeter to explore the most suitable structure and parameters for liquid heavy metal, the sensitivity analysis of the geometric parameters of the venturi tube on the varying conditions. It shows that when the contraction angle of the venturi flowmeter is 33°, the diffusion angle is 13°, the diameter of the throat is 8 mm, and the temperature of the lead-bismuth eutectic is 733.15 K, it is most suitable for the measurement in the lead-bismuth circuit.

1. Introduction

1.1. Background

As one of the main types of Gen-IV reactors, lead-based reactors have been the focus of international nuclear energy research due to their good neutron economy and safety, which provides a solution for the sustainable development process of nuclear energy [1]. Lead-cooled Fast Reactors are fast neutron reactors using lead or lead-bismuth eutectics as coolant. The Lead–Bismuth eutectic has excellent neutronic and safety characteristics and has the advantage of a high boiling point at atmospheric pressure, while having a lower melting point than lead, making it the main material of lead-based reactor coolants [2]. However, due to the corrosive nature of lead-bismuth eutectics and the high temperature, high pressure, and high irradiation operating environment within the reactor, there is an inevitable impact on the reactor components during long-term operation. To ensure its safety, it is particularly important to accurately measure the flow of liquid metal in the circuit [3]. As one of the most widely used differential pressure type flowmeters, the simple structure, wide temperature range, long life, and ease of maintenance of the venturi flowmeter allow it to play an important role in the measurement of high-temperature liquid metals [4]. Therefore, this paper is important for the study of the optimal design of the parameters of the venturi flowmeter in the liquid lead-bismuth circuit and the corrosion under long-term operating conditions.

1.2. Research status

1.2.1. Corrosion characteristics of liquid lead-bismuth eutectic circuit

In the 1960s, due to the good thermal and hydraulic properties and neutronic of lead-bismuth material, the Soviet Union first applied the reactor with lead-bismuth eutectics as a coolant in nuclear submarines, which not only guaranteed the power supply but also significantly reduced the manufacturing cost of the reactor [5]. However, after a long-term operation, the steam generator pipes became clogged, mainly because the liquid lead-bismuth eutectic was very corrosive to the materials of the reactor components in direct contact, and the corrosion products were deposited in the cold pipe section of the circuit, then causing clogging and even heat transfer deterioration. Thereafter, the study of the corrosion characteristics of lead-bismuth eutectics became

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the key to solving the current problem.

In recent years, some famous international nuclear energy research institutes and laboratories have conducted experiments related to liquid lead-bismuth eutectics, such as Karlsruher Institut für Technologie, Los Alamos National Laboratory, the Russian Institute of Physics and Power Engineering, etc. [6]. With the continuous in-depth study of the corrosion mechanism, it was found that in the liquid lead-bismuth eutectic circuit, the reactor components will undergo a combination of several forms of corrosion, including dissolution, oxidation, erosion, and abrasion [2].

China is currently carrying out the KYLIN series of lead-bismuth experimental circuit research and has completed the construction of China's first thermal convection lead-bismuth experimental circuit, comparing the corrosion of martensitic stainless steel T92 and austenitic stainless steel 316L in the experimental circuit for 1000 h. The results show that the metal specimens all undergo oxidation corrosion. And whether the oxide layer on the metal surface can prevent the internal eutectic elements from dissolving in the liquid lead-bismuth eutectic depends on the denseness of the oxide layer. The experimental circuit KYLIN-II for medium-sized forced convection lead-bismuth is still under study due to the high energy consumption for maintaining a long time and high-temperature circuit [7].

In addition, the China Institute of Nuclear Energy Safety Technology has carried out a comprehensive design and development of the China LEAd-based Reactor (CLEAR) since 2011 [7]. Based on the operating conditions of the China LEAd-based Reactor CLEAR-I, a study on the corrosion characteristics of martensitic steel T91 and austenitic rigid 15-15 Ti in the lead-bismuth circuit has been carried out. The experiment has compared the oxidation corrosion characteristics of the two metallic materials at 773.15 K, 1–3*10–^{6} wt% oxygen concentration, and 1 m/s liquid lead-bismuth eutectic flow rate for up to 5000 h. During the experiment, it was found that the specimens of both materials produced an oxide layer on the surface, the outer oxide layer was looser, and the oxide layer gradually flaked off to the inner layer under the effect of the erosion, and as the contact area between the inner metal and the liquid lead-bismuth eutectic gradually increased, the flaked area was oxidized again to form a new oxide layer, and so the flaking and regeneration of the new oxide layer were repeated [2].

A medium-sized liquid lead-bismuth eutectic forced convection loop DELTA Loop was constructed at Los Alamos National Laboratory in collaboration with the University of Nevada to study the material and thermodynamic properties of the liquid lead-bismuth eutectic system [8].

Studies have shown that the corrosion of metal materials in liquid lead-bismuth loops is to some extent similar to the corrosion of iron in the air, with the outermost part directly in contact with the lead-bismuth eutectic being oxidized and corroded first, and then gradually penetrating the inner material over time. At the same time, this corrosion characteristic is closely related to the oxygen concentration in the liquid lead-bismuth eutectic [5].

According to the researches, there are two primary methods for mitigating corrosion in LBE: Active oxygen controlling and surface coatings. The oxygen content in LBE significantly influences system safety, acting as a corrosion inhibitor by forming a protective oxide layer on the material surface. The methods to control oxygen concentration include solid-state, gaseous oxygen control, and oxygen pumping, which adjust the oxygen levels to prevent aggressive corrosion of structural materials. To enhance the compatibility of structural steel with LBE, various coatings have been studied, such as poly coatings, composite coatings, ceramic, refractory metal, ODS, high-entropy alloy coatings and so on. These coatings work by forming a dense oxide layer that protects the substrate and prevents element loss due to dissolution and penetration of lead and bismuth. Techniques like powder embedding and physical vapor deposition are used to apply these coatings, which have shown effectiveness in preventing LBE corrosion [9].

1.2.2. *Venturi flowmeter research*

Considering the harsh operating environment in the reactor, the throttling differential pressure flowmeter with its simple structure, long operating life, easy maintenance, and other characteristics can be widely used in single-phase and multi-phase flow measurement. The throttling differential pressure flowmeter is based on the principle of partial conversion of pressure energy into kinetic energy in the process of fluid flow through the throttling device to produce a differential pressure signal.

The Venturi flowmeter is the most commonly used differential pressure flowmeter, its basic structure is composed of an entrance section, a contraction section, a throat, a diffusion section, and an exit section. In the entrance section and throat, each set a pressure port for measuring differential pressure signal, the basic structure is shown in Fig. 1, and the actual is shown in Fig. 2.

The Venturi flowmeter is designed based on the continuity equation and Bernoulli's equation. According to the continuity equation, the fluid flow in the pipe follows the law of mass conservation:

$$\frac{1}{4}\pi D^2 \bullet v_{in} = \frac{1}{4}\pi d^2 \bullet v_t \tag{1}$$

D is the diameter of the entrance section, d is the diameter of the throat, v_{in} is the inlet velocity, v_t is the throat velocity.

According to Bernoulli's equation, the fluid flow through the venturi flowmeter before and after the energy is conserved, in the case of not considering the loss along the fluid pressure, potential energy and kinetic energy remain constant:

$$Z_1 + \frac{P_1^2}{\rho g} + \frac{v_1^2}{2g} = Z_t + \frac{P_t^2}{\rho g} + \frac{v_t^2}{2g} \tag{2}$$

P is the pressure (Pa), ρ is the fluid density (kg/ m^3), $P^2/\rho g$ is the pressure head, $v^2/2g$ is the velocity head, Z is the position head (m), the sum of the three heads is called the total head, the total head remains constant without considering the losses.

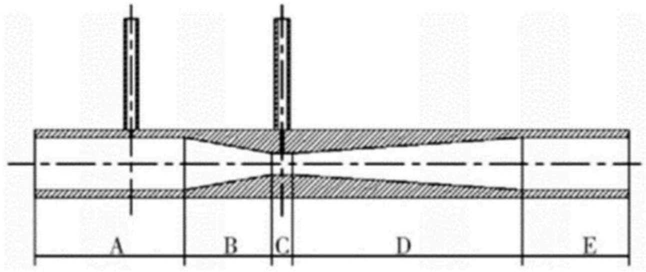
Therefore, the joint continuity equation and Bernoulli's equation, the expression of fluid mass flow can be obtained as follows:

$$q_m = \frac{\pi d^2}{4} \bullet \sqrt{\frac{2\rho(P_1 - P_t)}{1 - \beta^4}} \tag{3}$$

q_m is the mass flow rate of fluid (kg/s), β is the pipe diameter ratio, i.e., the ratio of the diameter of the throat to the diameter of the inlet section.

1.3. *Main work of this paper*

According to the above analysis, this paper carries out the optimized design of dimensional parameters in a liquid heavy metal environment and combines the fluid-solid interaction analysis to simulate the stress and corrosion after the long-term operation, the main work is as follows:



A-entrance section; B-contraction section; C- throat;

D- diffusion section; E- exit section

Fig. 1. Venturi flowmeter basic structure.

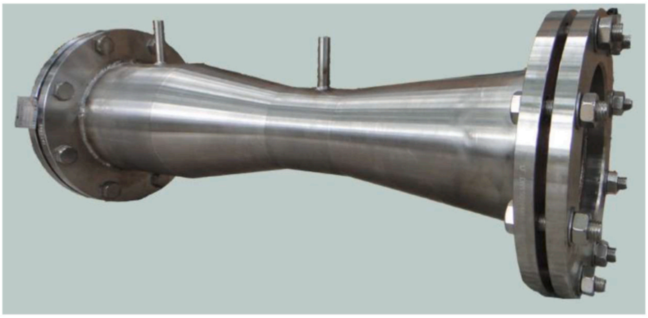


Fig. 2. Venturi flowmeter actual picture.

(1) The creation of a three-dimensional model for the fluid domain inside the venturi flowmeter, and the determination of the model, boundary conditions, and several meshes suitable for the flow.
(2) Analyze the simulation results to derive the distribution of pressure and flow velocity inside the flowmeter.
(3) Designing orthogonal experiments to consider the effects of different structural parameters and work temperatures on the measurement results, and conducting range analysis and variance analysis on the results to finally determine the most suitable dimensional parameters for measuring the flow of liquid lead-bismuth eutectic.
(4) Add the study of a solid domain based on the fluid domain and establish a three-dimensional fluid-solid interaction model to study the stress and strain distribution on the pipe wall and the influence of the inner diameter change on the measurement results under long-term operation conditions.

2. Theory and modeling

In this paper, we simulate the flow of liquid lead-bismuth eutectics inside the venturi flowmeter in COMSOL software, and establish a three-dimensional incompressible flow model for different environmental temperatures and different structural parameters, to study the velocity field and pressure field distribution inside the venturi flowmeter.

2.1. COMSOL multi-physics software

COMSOL Multiphysics is a simulation software that supports coupled modeling of single and multi-physics fields based on advanced numerical methods. In engineering practice, COMSOL covers many modules and coupled analysis of multiple modules [10]. This work utilizes modules of fluid mechanics and solid mechanics.

2.2. CFD introduction

Computational Fluid Dynamics (CFD) is an emerging interdisciplinary discipline in which computer science, numerical mathematics, and fluid dynamics are integrated to obtain approximate solutions to fluid control equations from computational methods using the rapid computational ability of computers. With the rapid development of computers after the 1990s, CFD has developed rapidly and gradually become an important tool in product development together with experimental fluid dynamics.

Among the numerical methods of fluid dynamics, the widely used ones are the finite difference method, finite element method, boundary element method, finite volume method, and finite analysis method. COMSOL is based on the Finite Element Method (FEM), which decomposes the system into a geometric model consisting of several interconnected, simple, and independent points, and then applies the equilibrium equations derived from the selected physical fields to the equilibrium equation derived from the chosen physical field is then applied to each point to obtain a system of equations. The actual physical phenomena are simulated by quickly solving the partial differential equation or system of equations [10].

2.3. Modeling of fluid domain

During the simulation of the fluid domain, it is assumed that the liquid lead-bismuth eutectic fills the flow channel, and the simplified geometry of the internal fluid is designed concerning the classical venturi parameters, as shown in Fig. 3. To ensure that the fluid inside the flowmeter is fully developed, the length of the inlet circular pipe section is set to 15D and the length of the exit section is set to 12D, where D is the pipe diameter.

2.4. Determination of the flow model

The fluid flow model is chosen by calculating the Reynolds number. For the flow of liquid lead-bismuth eutectic in the flowmeter, it is assumed that the mass flow rate is 2 kg/s, and the eutectic and environmental temperatures are: 673.15 K, 703.15 K, 733.15 K, 763.15 K, and the diameter of the main section is 32 mm. For the physical parameters of the lead-bismuth eutectic [11,12] in the calculation, the density ρ (kg/m3) and the dynamic viscosity μ (Pa • s) are required:

$$\rho = 11096 - 1.3226T \tag{4}$$

$$\mu = 4.94 \times 10^4 e^{\frac{757.1}{T}} \tag{5}$$

The Reynolds number is calculated as shown in Table 1:

From the calculation results, it can be seen that the Reynolds number at different temperature conditions is larger than 2300, so it is considered a turbulent flow. The most common and standard turbulent k-ε model is chosen, which is suitable for simulating high Reynolds number unidirectional flow for incompressible flow. The following boundary conditions are set in this paper:

(1) Fluid inlet boundary condition is set to mass flow 2 kg/s inlet;
(2) Fluid outlet boundary condition is set to pressure outlet;
(3) The direction of flow is normal and backflow is suppressed;
(4) Set the vertical downward volume force considering the effect of gravity;
(5) The outer boundary of the model is set to be a non-slip wall surface.

2.5. Mesh delineation and sensitivity analysis

Mesh delineation is an important process in simulation computation, and a high-quality mesh is helpful to shorten the computation time, improve the simulation accuracy and enhance the convergence.

Using the mesh division module, the venturi flowmeter inlet section

Fig. 3. Geometric model of the fluid domain.

Table 1
Re calculation results.

Temperature(K)	673.15	703.15	733.15	763.15
Re	52312	54885	57357	59734

is divided into free triangle meshes, and then the inlet section as the beginning sweeps for the exit section. For the area where the cross-sectional area changes and the throat, the mesh sweep is an appropriately detailed, and appropriate simplification for the straight pipe section.

When the pressure difference at the pressure ports gradually stabilizes with the increase of meshes, choose the minimum number of meshes as the final choice [13]. In this paper, when the number of meshes is 10,000, 20,000, 30,000, 40,000, 50,000, and 60,000, the meshes changes at the entrance surface are shown in Fig. 4, and the pressure difference at the pressure ports is shown in Fig. 5.

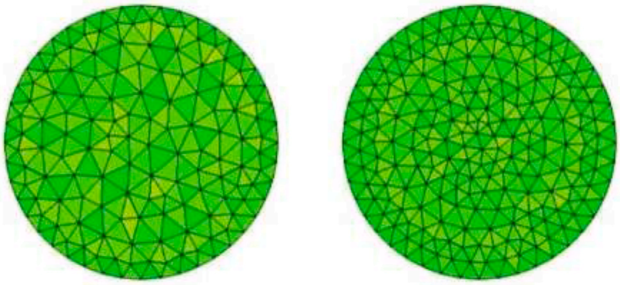
According to Fig. 5, when the number of meshes rises to 30,000, the pressure difference of the venturi flowmeter pressure ports remains the same, so considering the accuracy and calculation efficiency, the final choice of the number of meshes is 30,000.

3. Analysis of simulation results

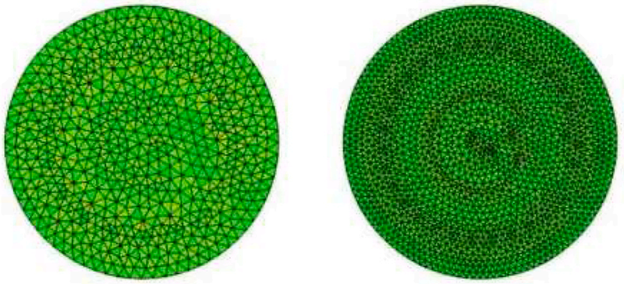
A set of structural parameters was selected as a representative for a steady-state study of the fluid domain inside the venturi flowmeter to derive the distribution of its velocity and pressure.

3.1. Model validation

According to the research [1], when the venturi flowmeter is used for flow measurement in the lead-bismuth eutectic circuit, take an example of the following parameters: the environment temperature is 673.15 K, the contraction angle and diffusion angle are 27° and 9°, and the throat diameter is 14 mm. The outflow coefficient of this example is 0.9621. In the model of this paper, the same structural parameters and the environment temperature are used for steady-state analysis, and the outflow coefficient is 0.9648, which is different from the existing but the difference is only 0.28 %.



(a) 10,000 meshes　(b) 20,000 meshes



(c) 30,000 meshes　(d) 60,000 meshes

Fig. 4. Entrance section meshes.

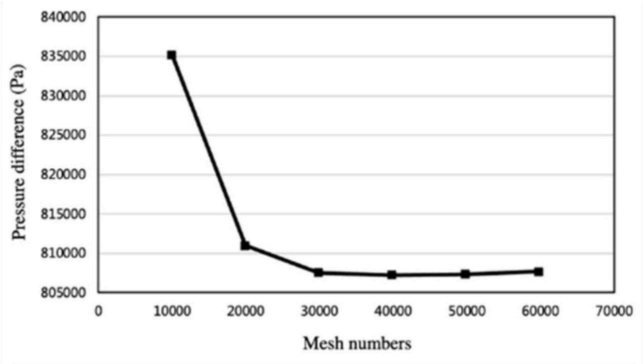


Fig. 5. Mesh sensitivity analysis.

According to the research [14], the pressure loss of the venturi flowmeter is acceptable between 5 % and 20 %. The pressure loss of the model in this paper is 16.7 %, which is in line with the standard given by the national standard (See Fig. 9).

3.2. Velocity field analysis

According to the fluid velocity distribution in Fig. 6, it can be seen that when the liquid lead-bismuth eutectic flows through the contraction section, the flow channel cross-section decreases, and the flow velocity increases; when the eutectic flows through the diffusion section, the flow channel cross-section increases and the flow velocity decreases. From the continuity equation, the fluid flow rate in the flowmeter is negatively related to the flow channel cross-section. Because the contraction angle of the venturi flowmeter is larger than the diffusion angle, resulting in the gradient of flow velocity change in the contraction section is larger than that in the diffusion section, and the trend can be seen more clearly in Fig. 7 and 8.

The inlet velocity of a Venturi flow meter significantly impacts the velocity field within the meter. As fluid enters the Venturi flow meter's contraction section, its velocity increases due to the conservation of mass principle. This dictates that as the cross-sectional area decreases at the meter's throat, flow velocity must increase to maintain the same flow rate. When fluid enters the diffusion section where the fluid velocity decreases and pressure recovers, too high inlet velocities might

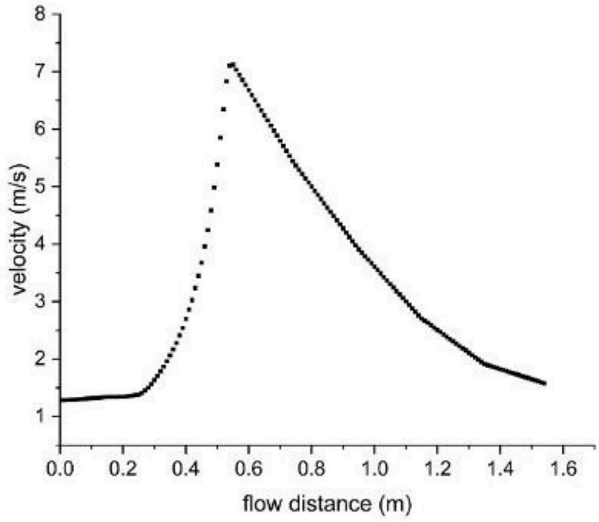


Fig. 6. Central axis velocity distribution.

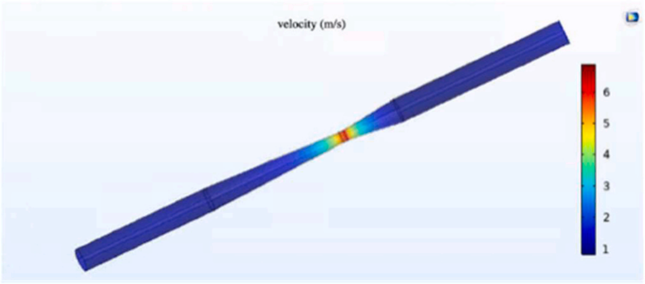


Fig. 7. Velocity distribution.

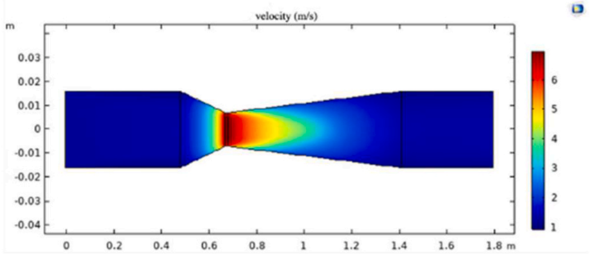


Fig. 8. Cross-section velocity distribution.

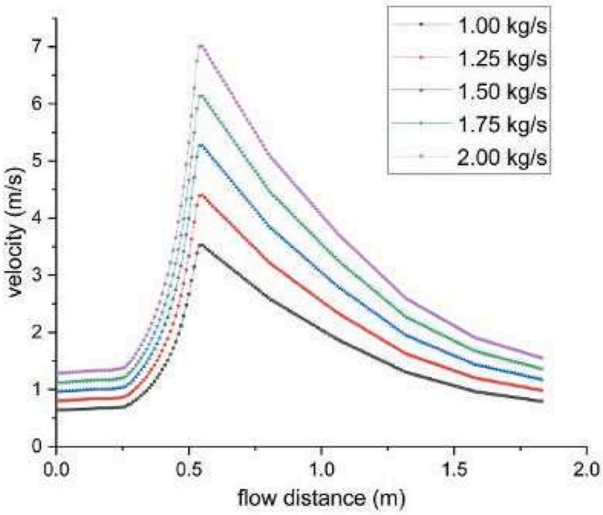


Fig. 9. Velocity distributions of different inlet mass flow rate.

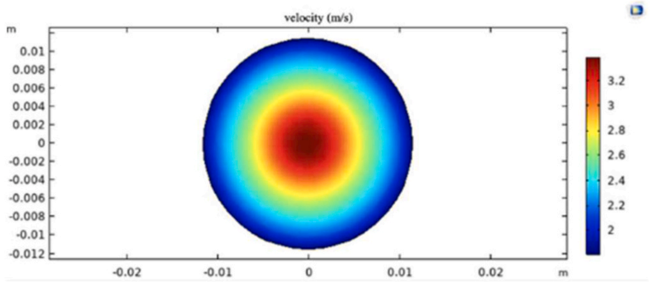


Fig. 10. Cross-section velocity distribution of the diffusion section.

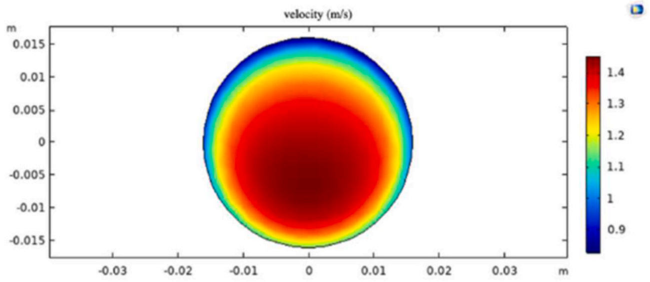


Fig. 11. Outlet section velocity distribution.

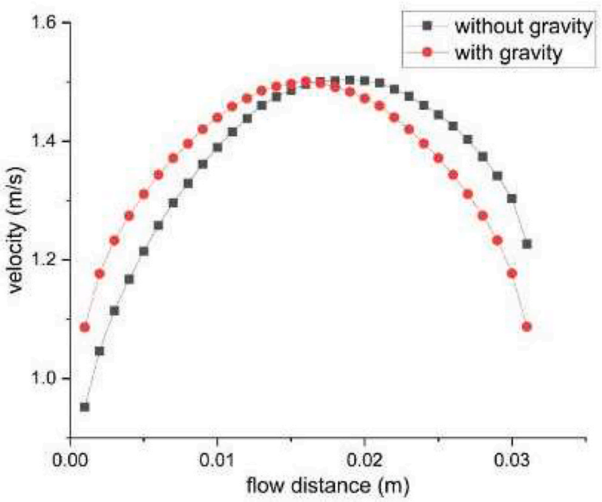


Fig. 12. The exit section velocity distributions.

lead to flow separation and the formation of reflow regions, especially if the diffusion angel is not properly designed. Besides, higher inlet velocities may induce flow instabilities, increasing perturbations within the flow, which can affect the uniformity of the velocity field. In the application in LBE circuit, CFD simulations can be employed to assess the impact of inlet velocity on the velocity field distribution beforehand, allowing for design adjustments as necessary.

According to Fig. 10, Fig. 11 and 12, a symmetrical velocity band is formed in the diffusion section and the exit section. The intensity of the velocity band gradually decreases with flow [15], and at the exit section, the central fluid velocity band is shifted in the direction of gravity due to the influence of gravity.

3.3. Pressure field analysis

As can be seen from Fig. 13, the venturi flowmeter entrance section fluid static pressure is high, when the fluid flows through the contraction section, according to the velocity field analysis, the fluid flow velocity increases, as can be seen by the Bernoulli equation, in the case of not considering the hydraulic losses, the total fluid head and position head in the contraction section remains constant, the velocity head rises, so the pressure head decreases. Due to the throttling acceleration, the tube static pressure drops sharply, showing a negative pressure region in the throat. And between the entrance section there forms an obvious pressure difference, brought into formula (3) can calculate the flow rate. Conversely, when the fluid flows through the diffusion section, the flow rate decreases, and the static pressure rises. As can be seen from Fig. 13, the static pressure of the exit section is slightly smaller than that of the entrance section. Since the exit section is the same size as the entrance section, the pressure loss before and after is only caused by the friction between the liquid lead-bismuth eutectic and the pipe. According to the pressure drop form of the Darcy-Weisbach Formula [16]:

$$\Delta P = \lambda \bullet l/d \bullet \rho v^2/2 \qquad (6)$$

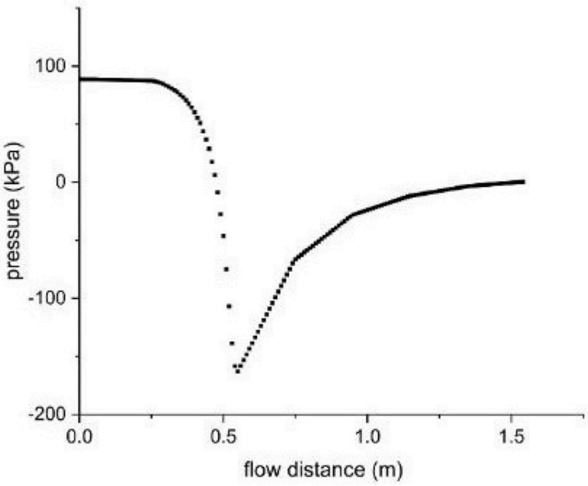


Fig. 13. Central axis pressure distribution.

The pressure lost along the path increases with the flow distance, where λ is the Darcy friction factor with a magnitude of 1, generally determined experimentally, and is a function of the Reynolds number and the relative pipe wall roughness Δ/d, i.e., $\lambda = f(Re, \Delta/d)$. l/d is the length-to-diameter ratio of the pipe. v is the fluid flow velocity. The pressure variation gradient in the pipe can be visualized according to Fig. 14 and 15. Unlike the velocity field, the equivalence surface of the pressure field is less affected by the boundary layer effect, so it is approximately vertically distributed in the flow direction, while the gradient of variation in the velocity field is significantly different between the basin near the wall and the central basin.

According to Fig. 16, the surface roughness of a Venturi flow meter impacts the pressure field and measurement accuracy. Increased surface roughness adds friction between the fluid and the meter's surface, which leads to higher pressure losses along the flow path. This increased friction due to the roughness alters the pressure distribution within the flow meter. Besides, the operation of a Venturi flow meter relies on a pressure differential created as fluid flows through the constricted throat section. Additional pressure losses caused by surface roughness can result in measured flow rates being lower than the actual rates. According to the simulation results, when the surface roughness of the inner wall of the Venturi flow meter increases from 0 μm to 32 μm, the discrepancy in the measurement results is approximately 1.28 %.

4. Orthogonal experiment design

The orthogonal experiment is a design method to study multiple factors and levels, which is an efficient, comprehensive, and economical experiment method. There are many factors affecting the measurement accuracy of the venturi flowmeter, to avoid the research process being too complicated, the method of the orthogonal experiment is chosen to consider the magnitude of different flow temperatures, contraction angles, throat diameters, and diffusion angles.

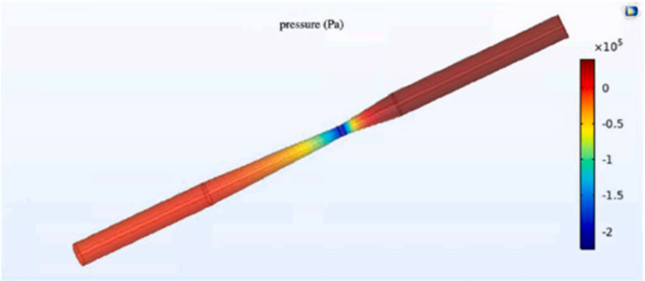


Fig. 14. Pressure distribution.

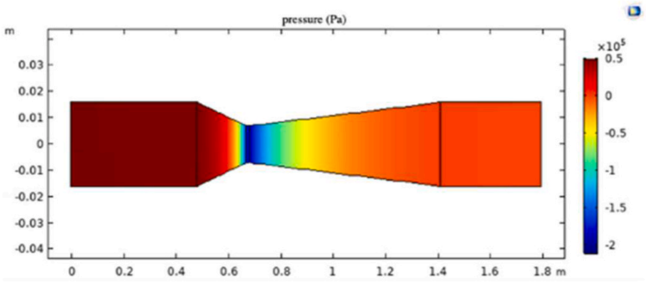


Fig. 15. Cross-section pressure distribution.

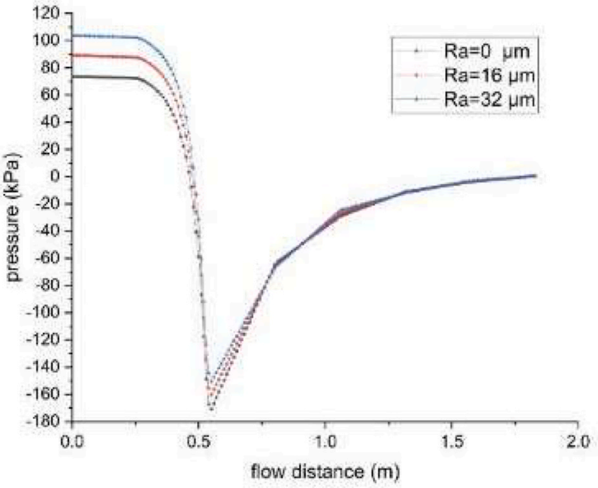


Fig. 16. Pressure distributions of different surface roughness.

In this orthogonal experiment, the outflow coefficient and the pressure loss ratio are introduced as reference quantities. Outflow coefficient is numerically equal to the ratio of the actual flow rate to the simulated flow rate because the fluid flow in the tube will have a certain amount of along-range loss and local loss, so the closer the outflow coefficient to 1, the better the measurement effect. At the same time, a venturi flowmeter in the circuit is equivalent to a throttle, from the perspective of economics, the smaller the pressure loss generated by the flowmeter the better, so it needs to use the pressure loss ratio as a reference, the pressure loss ratio is numerically equal to the ratio of the pressure loss caused by fluid flow through the flowmeter and the pressure difference between the pressure ports [14].

4.1. *Influencing factors and levels selection*

The main structural parameters of the venturi flowmeter are selected as influencing factors in this experiment including contraction angle (A), diffusion angle (B), and throat diameter (C). At the same time, because the temperature change will affect the physical properties of liquid lead-bismuth eutectic density and dynamic viscosity, temperature (D) is also included in the factors to be examined. The levels of each factor were selected as shown in Table 2.

Table 2
Influencing factors and levels of selection.

Level	A (°)	B (°)	C (mm)	D (K)
1	15	7	8	673.15
2	21	9	10	703.15
3	27	11	12	733.15
4	33	13	14	763.15

4.2. *Experiment results*

According to the structural parameters and fluid temperature at each level of each factor in Table 2, the measurement process of the venturi flowmeter is simulated in COMSOL to derive the outflow coefficient and pressure loss ratio at each factor level, and the results are shown in Table 3.

4.3. *Analysis of ranges*

The range analysis, also known as intuitive analysis, for this experiment has two reference quantities of the outflow coefficient and pressure loss ratio, the comprehensive balance method is used to visually analyze the degree of influence of the venturi flowmeter structural parameters and environment temperature from the perspective of the outflow coefficient and pressure loss ratio, respectively, to derive the best combination of parameters under the reference quantities. Then, according to theoretical knowledge and engineering practice, the final results are derived [17].

4.3.1. *Analysis of the outflow coefficient*

From Table 4 it can be seen that $R_A > R_C > R_D > R_B$, the degree of influence on the outflow coefficient from largest to smallest is: constriction angle, throat diameter, temperature, and diffusion angle. Because the venturi flowmeter's two pressure ports are set before the diffusion section, according to the definition of the flow calculation formula and the outflow coefficient, there is no direct involvement between the diffusion section and the exit section of the term, so the influence of the diffusion angle on the results is small. Therefore, from the perspective of the outflow coefficient, the highest measurement accuracy is achieved when the temperature of liquid lead-bismuth eutectic is 733.15 K, the contraction angle is 33°, the diffusion angle is 11°, and the throat diameter is 8 mm.

4.3.2. *Analysis of the pressure loss ratio*

From Table 5 can be seen $R_C > R_B > R_A > R_D$, the degree of influence on the pressure loss ratio from the largest to the smallest: throat diameter, diffusion angle, contraction angle, and temperature. Therefore, from the perspective of the pressure loss ratio, when the temperature of liquid lead-bismuth eutectic is 673.15 K, the contraction angle is 33°, the diffusion angle is 13°, and the throat diameter is 8 mm, the venturi flowmeter as a throttle in the circuit causes the smallest pressure loss.

According to the range data of the two reference quantities, the diffusion angle has the least influence on the measurement accuracy. When the diffusion angle is taken as 11° and 13°, the k-value of the outflow coefficient is not much different. Therefore, 13° is the best diffusion angle considering the economy. The temperature has the least effect on the economy. When the temperature is 673.15 K and 733.15 K, the difference of the k-value of the pressure loss ratio is also very small. Therefore, a temperature of 733.15 K can be chosen to improve the measurement accuracy with little effect on the economy.

Table 3
Experiment results.

Group	A (°)	B (°)	C (mm)	D (K)	Outflow coefficient	Pressure loss ratio
1	15	7	8	673.15	0.9631	0.1816
2	21	9	10	673.15	0.9673	0.1680
3	27	11	12	673.15	0.9672	0.1672
4	33	13	14	673.15	0.9693	0.1670
5	15	9	14	703.15	0.9542	0.2068
6	21	7	12	703.15	0.9626	0.2054
7	27	13	10	703.15	0.9710	0.1442
8	33	11	8	703.15	0.9755	0.1368
9	15	11	10	733.15	0.9659	0.1646
10	21	13	8	733.15	0.9702	0.1372
11	27	7	14	733.15	0.9657	0.2120
12	33	9	12	733.15	0.9705	0.1738
13	15	13	12	763.15	0.9568	0.1736
14	21	11	14	763.15	0.9612	0.1858
15	27	9	8	763.15	0.9740	0.1476
16	33	7	10	763.15	0.9728	0.1787

Table 4
Outflow coefficient range analysis.

Factors	A (°)	B (°)	C (mm)	D (K)
K_1	3.8400	3.8642	3.8829	3.8670
K_2	3.8613	3.8661	3.8770	3.8633
K_3	3.8779	3.8699	3.8572	3.8723
K_4	3.8882	3.8673	3.8504	3.8649
k_1	0.9600	0.9661	0.9707	0.9667
k_2	0.9653	0.9665	0.9693	0.9658
k_3	0.9695	0.9675	0.9643	0.9681
k_4	0.9720	0.9668	0.9626	0.9662
R	0.0120	0.0014	0.0081	0.0023

Table 5
Pressure loss ratio range analysis.

Factors	A (°)	B (°)	C (mm)	D (K)
K_1	0.7266	0.7778	0.6032	0.6839
K_2	0.6964	0.6962	0.6555	0.6933
K_3	0.6710	0.6544	0.7201	0.6876
K_4	0.6564	0.6221	0.7717	0.6857
k_1	0.1817	0.1944	0.1508	0.1710
k_2	0.1741	0.1741	0.1639	0.1733
k_3	0.1678	0.1636	0.1800	0.1719
k_4	0.1641	0.1555	0.1929	0.1714
R	0.0176	0.0389	0.0421	0.0023

To sum up, the best measurement result of the venturi flowmeter is achieved when the temperature of liquid lead-bismuth eutectic is 733.15 K, the contraction angle is 33°, the diffusion angle is 13°, and the throat diameter is 8 mm.

4.4. *Analysis of variance*

Since this experiment involves multiple factors, the degree of influence of each factor can not be accurately determined simply by visual analysis, and the analysis of range cannot determine the error. To accurately derive the most suitable Venturi flowmeter structure parameters for the lead-bismuth circuit, the analysis of variance is also required [17].

4.4.1. *Variance of the outflow coefficient*

From Table 6, it can be seen that $F_A > F_C > F_D > F_B$. The effects on the outflow coefficient are, in descending order, contraction angle, throat diameter, temperature, and diffusion angle. The effect of contraction angle is the most significant, followed by the throat diameter, and the temperature and diffusion angle have less effect on the outflow coefficient. The mean square of the diffusion angle is smaller than the mean square of the error, so the effect of the diffusion angle can be considered an error. Therefore, through the analysis of variance, the measurement accuracy is the highest when the temperature of liquid lead-bismuth eutectic is 733.15 K, the contraction angle is 33°, the diffusion angle

Table 6
Analysis of variance of the outflow coefficient.

Factors	*SS*	*df*	*MS*	*F*
A (°)	0.000332	3	0.000111	51.560823
B (°)	0.000004	3	0.000001	0.658212
C (mm)	0.000181	3	0.000060	28.145020
D (K)	0.000012	3	0.000004	1.813192
Error	0.000009	3	0.000003	
Error Δ	0.000013	6	0.000002	

is 11°, and the throat diameter is 8 mm.

4.4.2. Variance of the pressure loss ratio

From Table 7, it can be seen that $F_C > F_B > F_A > F_D$. The effects on the outflow coefficient are, in descending order, throat diameter, diffusion angle, contraction angle, and temperature. Among them, the diffusion angle and throat diameter have the most significant effect on the pressure loss ratio, followed by the contraction angle, and the temperature has less effect on the pressure loss ratio. Therefore, through the analysis of variance, when the temperature of liquid lead-bismuth eutectic is 673.15 K, the contraction angle is 33°, the diffusion angle is 13°, and the throat diameter is 8 mm, the pressure loss caused by the venturi flowmeter as the throttle in the circuit is the smallest and the most economical.

Through the analysis of variance, when the temperature of liquid lead-bismuth eutectic is 733.15 K, the contraction angle is 33°, the diffusion angle is 13°, and the throat diameter is 8 mm, the venturi flowmeter has the best measurement effect.

From the analysis of the range and analysis variance can be seen: comprehensive the outflow coefficient and the pressure loss ratio, when the contraction angle of the venturi flowmeter is 33°, the diffusion angle is 13°, the diameter of the throat is 8 mm, and the temperature of the lead-bismuth eutectic is 733.15 K, it is most suitable for the venturi flowmeter to measure the flow of the lead-bismuth circuit.

5. Fluid-solid interaction

Fluid-solid interaction mechanics is an interdisciplinary discipline based on fluid mechanics and solid mechanics, studying the interaction between two media. For venturi flowmeters in lead-bismuth circuits, the tube wall may deform due to fluid loads, and the deformation of the wall in turn affects its throttling form, thus changing the magnitude and distribution of fluid loads. For such fluid-solid interaction problems, it is not possible to analyze them by a single fluid mechanics field or solid mechanics field [18].

5.1. Fluid-solid interaction modeling

Fluid-Structure Interaction (FSI) module of COMSOL enables users to simulate the effects of interaction between fluids and structures.

In COMSOL, FSI is achieved by coupling fluid dynamics and structural mechanics equations. The fluid dynamics are typically governed by the Navier-Stokes equations, which describes the relationship between the velocity and pressure of fluid. These equations can be modeled for either laminar or turbulent flow, depending on the size of the Reynolds number. On the structural side, COMSOL utilizes linear or nonlinear elasticity theory to describe material deformation. The most commonly used structural equations are the stress-strain relationships, described by Hook's law for linear elastic materials.

In FSI, the pressure and shear force exerted by the fluid on the structure affect its shape and displacement, which in turn impacts the flow distribution. The FSI module in COMSOL automatically handles the interactions between the fluid and the structure, ensuring consistency and accuracy of the solution.

Based on the fluid domain, the outer solid domain of the tube wall is created with a wall thickness of 8 mm, a contraction angle of 33°, a diffusion angle of 13°, and a throat diameter of 8 mm according to the above-optimized design. Fixed constraints are set at the inlet and outlet sections. The interaction surface is set as the interface of two phases. The complete model is shown in Fig. 17.

Table 7
Variance of the pressure loss ratio.

Factors	*SS*	*df*	*MS*	*F*
A (°)	0.000704	3	0.000235	103.152441
B (°)	0.003427	3	0.001142	502.066856
C (mm)	0.004097	3	0.001366	600.227920
D (K)	0.000039	3	0.000013	5.731520
Error	0.000007	3	0.000002	
Error Δ	0.000007	3	0.000002	

5.2. Stress and strain analysis

The stress and strain distribution are obtained from the transient calculation of the fluid-solid interaction model.

According to Fig. 18–20, the stress distribution on the pipe wall is roughly symmetrically distributed along the xz plane, and the stresses are higher in the upper and bottom, and lower in the middle. And the stresses in the entrance and exit sections are larger, and the stresses in the contraction and diffusion sections and the throat are lower.

According to Fig. 21–23, it can be seen that, unlike the stress distribution, the strain distribution is influenced by the gravitational field and does not show a symmetric distribution. The strain in the bottom part of the flowmeter is more obvious than that in the upper part.

In conclusion, under long-term operating conditions, it is necessary to carry out regular maintenance for the stress concentration areas such as the entrance and exit sections.

5.3. Sensitivity analysis of inner diameter on flowrate

When the venturi flowmeter in the liquid lead-bismuth circuit is used for a long-term operation, the inner diameter will decrease due to corrosion. This paper assumes that the corrosion of the pipe wall is uniform and that each flowmeter part is corroded to the same extent. As shown in Fig. 24, when the tube wall thickness is changed from 8 mm to 7.4 mm, the pressure difference between the pressure ports gradually increased to cause the measurement change.

According to the flowrate calculation formula, when the corrosion of the inner diameter is within 0.3 mm, the measurement error is within 5 % and when the corrosion exceeds 0.6 mm, the measurement error is more than 10 %. Therefore, in long-term operation, even if a certain degree of corrosion occurs, the venturi flowmeter from the principle can still be competent for the measurement of the lead-bismuth circuit.

6. Conclusion

As an important part of the liquid lead-bismuth circuit, the accuracy of flow measurement directly affects the operation condition adjustment and safety of the lead-based reactor. The Venturi flowmeter as the most widely used differential pressure flowmeter plays an important role in many fields, but the research on the venturi flowmeter in the lead-bismuth circuit is less. This paper through the method of numerical simulation, design an orthogonal test to study the most suitable lead-bismuth circuit structure parameters and the influence of corrosion characteristics of lead-bismuth eutectic on the flowmeter in long-term operating condition, the main conclusions are as follows:

The corrosion behavior of the lead-bismuth circuit is mainly based on oxidation and erosion. The inner pipe wall is first oxidized to generate a loose oxide film, and then the oxide film is peeled off due to erosion, exposing the internal metal layer. This cycle causes the inner diameter of the pipe to change;

According to the simulation results, the distribution of velocity and pressure fields inside the venturi flowmeter follow the continuity

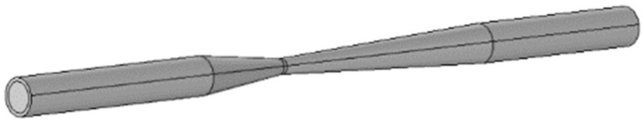


Fig. 17. The fluid-solid interaction model.

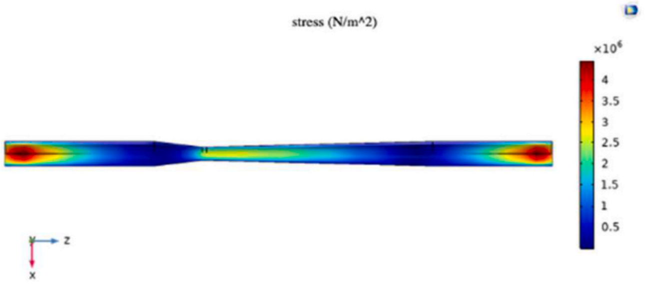


Fig. 18. Top view of stress distribution.

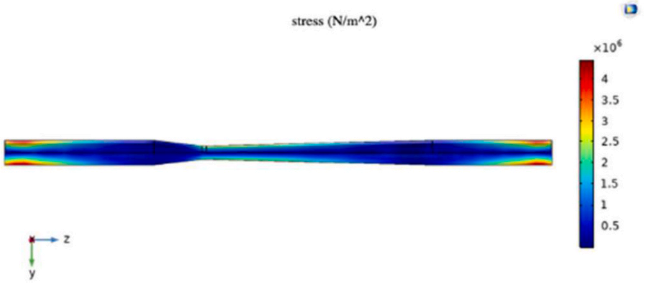


Fig. 19. Main view of stress distribution.

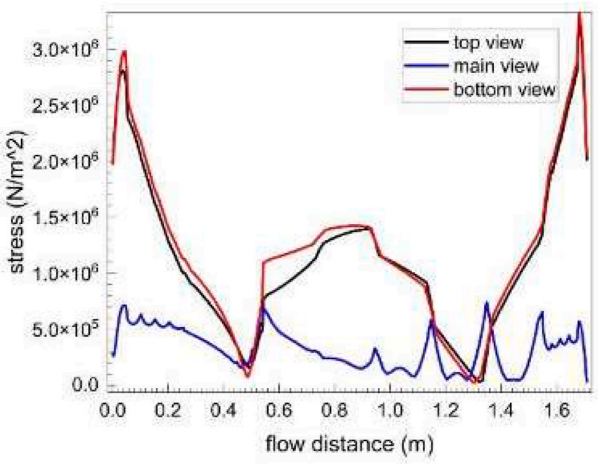


Fig. 20. Stress distributions of three views.

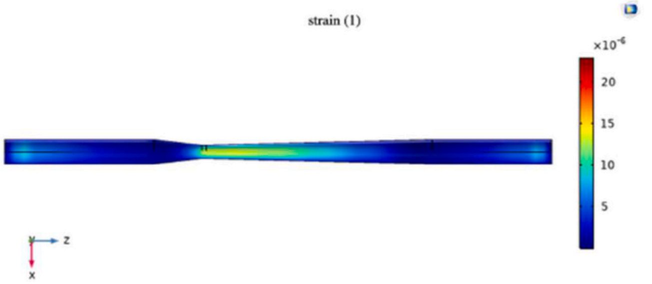


Fig. 21. Top view of strain distribution.

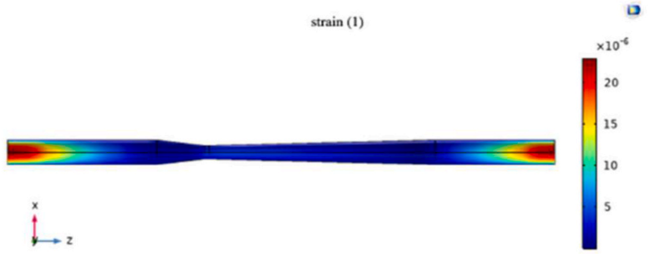


Fig. 22. Upward view of strain distribution.

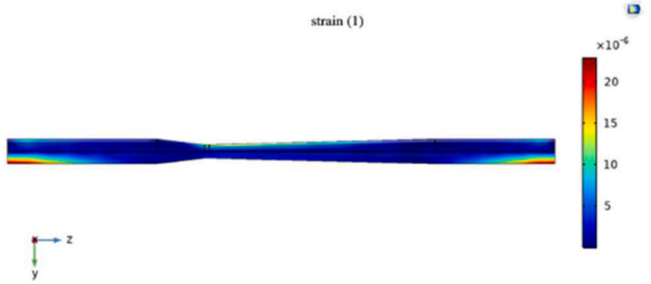


Fig. 23. Main view of strain distribution.

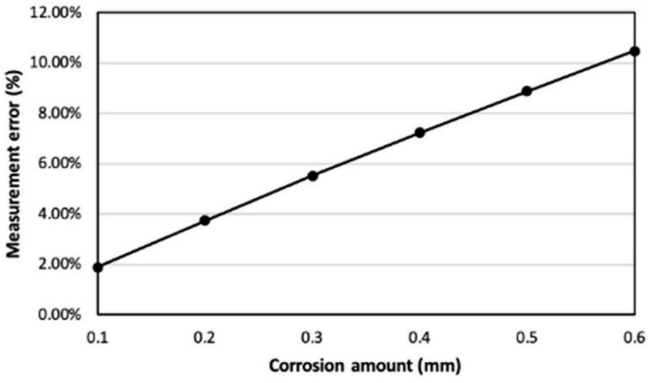


Fig. 24. Sensitivity analysis of inner diameter.

equation and Bernoulli equation;

According to the analysis of range and variance, when the contraction angle of the venturi flowmeter is 33°, the diffusion angle is 13°, the diameter of the throat is 8 mm, and the temperature of the lead-bismuth eutectic is 733.15 K, it is most suitable for the measurement in lead-bismuth circuit;

According to the analysis of the fluid-solid interaction model, the parts of the tube wall where the stress and strain are concentrated are the entrance and exit section and the throat. It is necessary to focus on the maintenance of these areas due to the harsh operating environment in the reactor;

Due to the strong corrosive liquid lead-bismuth eutectic, the internal diameter of the flowmeter gradually decreases under long-term operating conditions. When the corrosion amount is less than 0.3 mm, the measurement error is within 5 %. When the corrosion amount exceeds 0.6 mm, the measurement error is larger than 10 %, and maintenance is required. Theoretically, the venturi flowmeter is well suited for the measurement of liquid lead-bismuth circuits.

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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