Heliyon 10 (2024) e25736

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Safety assessment of sand casting explosion accidents by testing cavity pressure of the sand mold to protect employee health

Qingwei Xu [a,*], Yaping Zhu [a], Shuyun Qi [a], Kaili Xu [b], Bingjun Li [a], Shuaishuai Geng [a]

[a] College of Information and Management Science, Henan Agricultural University, Zhengzhou 450046, China
[b] School of Resources and Civil Engineering, Northeastern University, Shenyang 110819, China

ARTICLE INFO

Keywords:
Sand casting explosion accidents
Pressure variation
On-site test
Chaos theory
Bow-tie model

ABSTRACT

Excessive cavity pressure may result in a sand casting explosion, and corresponding measures should be adopted to prevent these consequences. In this study, the pressure variations in the cavity were first investigated based upon on-site testing by taking the resin contents into consideration, and then the evolution characteristics of sand casting explosion accidents were analyzed in depth by system dynamics, chaos theory, and the bow-tie model. When the resin contents are 1.3 wt%, 1.4 wt%, and 1.5 wt%, the pressures of the gas vent increase by 27.0 Pa, 32.8 Pa, and 35.6 Pa, respectively. To reduce the pressure of the cavity, the resin content should be reduced. The evolutionary process of sand casting explosion accidents has a noticeable butterfly effect and randomness, whose occurrence is comprehensively affected by human, object, environment, management and emergency subsystems. The leading causes of sand casting explosion accidents mainly include the extensive gas evolution characteristics of foundry sand, cavity exhaust blockage, and inadequate safety monitoring. The leading consequences of sand casting explosion accidents mainly include casualties, secondary disasters, and social panic. The implications of these findings concerning sand casting explosion accidents can be regarded as the foundation for accident prevention in practice.

1. Introduction

Foundry is a metal hot-working technology that provides necessary castings for social development and is the foundation of modern machinery manufacturing [1–3]. There are many classifications of foundry methods, and there can be different classifications according to different standards. According to the type of foundry materials, pouring, and solidification conditions, foundries can be divided into sand casting, lost foam casting, pressure die casting, and continuous casting [4–7]. Sand casting is the primary casting production method, and the castings produced by sand casting account for approximately 90 wt% of the total casting output [8–10]. Sand casting is not limited by the type of casting alloy, the size of the casting, the structure and complexity of the casting, and the number of castings produced, which allows it to have a wide range of applications.

Severe heat conduction phenomena occur when the casting alloy is poured into the cavity of the sand mold [11–13]. The temperature of the sand mold rises rapidly along with the heat conduction phenomena, and the binding element and curing agent in the sand mold rapidly vaporize and pyrolyze to produce a large amount of gas. If the generated gas is released too slowly, a sand casting explosion accident may occur [14–16]. The pressure of the cavity not only affects the safe production process but also affects the

* Corresponding author.
E-mail address: xuqingwei@henau.edu.cn (Q. Xu).

https://doi.org/10.1016/j.heliyon.2024.e25736
Received 29 April 2023; Received in revised form 23 November 2023; Accepted 1 February 2024
Available online 8 February 2024

quality of the castings. If the pressure of the cavity is relatively high, the casting will have blowhole defects [17–19]. To improve the safe production of foundry operations, it is necessary to investigate the cavity pressure of the sand mold and to adopt corresponding measures to prevent sand casting explosion accidents.

On-site pressure testing of the cavity requires designing experimental schemes, preparing sand molds, and smelting metals, which necessitates a significant amount of capital investment. To our knowledge, there is only one report about on-site pressure monitoring of the cavity during the sand casting process [20]. However, Chen [20] did not consider the influence of the adhesive content and the diameter of the gas vent on the pressure of the gas vent. In this study, we will carry out on-site pressure monitoring of the cavity during the casting steel process and consider both the influence of the adhesive content and the diameter of the gas vent on the pressure.

If the pressure in the cavity is too high, a sand casting explosion accident may occur, and it is necessary to respond appropriately to prevent these explosion accidents. Many scholars have studied prevention measures of explosion accidents, mainly focusing on coal mine gas explosion accidents [21–23], the petrochemical industry [24–26], power systems [27–29], the food industry [30–32], the metallurgical industry [33–35] and so on. Sand casting explosion accidents will lead to serious consequences. For example, a sand casting explosion accident occurred in the Anshan Iron and Steel Group, which resulted in 13 deaths and 17 injuries [15]. However, there are few reports on the evolution mechanism and prevention measures of sand casting explosion accidents in recent studies [15, 16]. In this paper, we will conduct an in-depth study on the evolution mechanism of sand casting explosion accidents and propose corresponding prevention measures to improve the safe production of the foundry industry.

The purpose of this study was to monitor the pressure variation in the cavity during the pouring process and investigate the evolution characteristics of sand casting explosion accidents, as shown in Fig. 1. The pressure of the gas vent is monitored during the pouring process to indicate the gas pressure in the cavity. The pressure variation in the gas vent can be monitored using pressure testing equipment. The influences of the content of the binding element and the diameter of the gas vent on the pressure variation were investigated. The factors affecting the cavity gas pressure of the sand mold were investigated based on system dynamics [36,37]. The

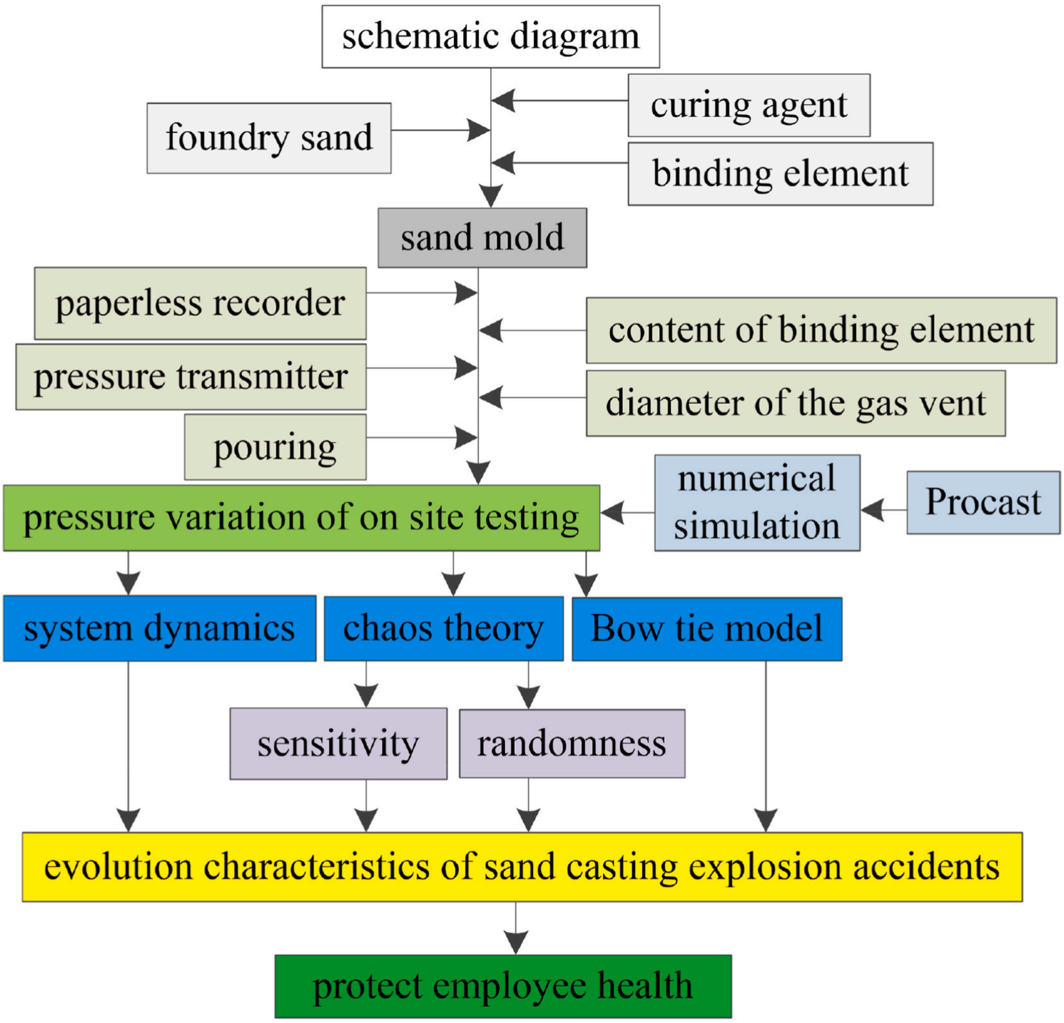

Fig. 1. The framework of this study.

sensitivity and randomness of sand casting explosion accidents were explored by chaos theory [38,39]. The causes, consequences, and prevention measures of sand casting explosion accidents were presented based on the bow-tie model [40–42].

2. Materials and methods

2.1. Experimental materials

The particle size of the rough sand used in this experiment ranges from 40 to 70 mesh, and the mud content is less than 0.3%. The chemical composition of the rough sand is mainly SiO_2, with a mass fraction of 97.5%.

This study adopted organic chemistry binding element sand for on-site testing, and detailed information is shown in Table 1.

The content of furan resin is generally from 0.8 wt% to 1.8 wt% of foundry sand [43,44]. To eliminate influence of different proportions of raw and used foundry sand on experimental results, foundry sand adopted in this study is all raw sand.

To investigate the effect of different contents of furan resin on the cavity exhaust during the casting process, this study set three different contents of furan resin during preparation of the sand molds. The contents of furan resin are 1.3 wt%, 1.4 wt%, and 1.5 wt%.

The content of the curing agent is generally from 30 wt% to 60 wt% of the furan resin. When preparing sand molds on-site in this study, the content of the curing agent is set to 50 wt% of the furan resin.

2.2. Sand mold produced in practice

First, on-site investigations should be performed on this company to understand the casting production process. Second, based on full communication with the company's staff, the on-site test plan was determined. Finally, the size of the sandbox is determined to then produce the sand mold. The length, width, and height of the upper sandbox are 600 mm, 600 mm, and 150 mm, respectively. The length, width, and height of the lower sandbox are 600 mm, 600 mm, and 250 mm, respectively. The length, width, and height of the casting steel are 400 mm, 300 mm, and 50 mm, respectively. The schematic diagram of the sand mold is shown in Fig. 2(a).

The actual outcome of the sand mold can be produced based on the schematic diagram, as shown in Fig. 2(b). To directly monitor the gas pressure in the cavity, a gas pipe on the inner surface of the sand mold should be laid. This layout is too rigorous for testing on-site and is not easy to achieve. During the pouring process, the high-temperature alloy will submerge the gas pipe, resulting in the gas pipe being scrapped, and other connecting devices may also be damaged due to the high temperature. Therefore, the gas vent is drilled on the surface of the upper sand mold for the on-site monitoring process, and the pressure of the gas vent is monitored to indicate the gas pressure in the cavity [20]. The gas vent drilled on the surface of the upper sand mold has a depth of 60 mm and a diameter of 3 mm.

2.3. Testing equipment

The main equipment used in this study to monitor the pressure change in the gas vent in the sand mold during the pouring process are shown in Table 2.

Before pouring high-temperature molten alloy on-site, the test equipment of the gas vent of the sand mold should be connected and ready. The gas-guide tube was inserted into the gas vent of the upper sand mold, and mixed resin sand was used to seal the gap between the gas-guide tube and the gas vent. The gas-guide tube is connected to the high-pressure metal hose, the high-pressure metal hose is associated with the pressure transmitter, and the pressure transmitter is associated with the paperless recorder.

The sand mold preparation and on-site testing of this study were carried out at Shenyang Casting and Forging Industry Company Limited. The type of casting steel is ZG230-450, with a pouring temperature of 1580 °C. The pressure variation in the gas vent during the pouring process can be achieved with the help of pressure monitoring equipment.

3. Results and discussion

3.1. Pressure variation in the gas vent

The temperature of the sand mold rises rapidly along with the heat conduction phenomena, and the binding element and curing agent in the sand mold rapidly vaporize and pyrolyze to produce a large amount of gas. For a given temperature of casting alloy, the higher the binding element and curing agent contents are, the more gas is generated in the cavity, and sand casting explosion accidents may occur more easily. Therefore, it is necessary to investigate the pressure variation in the cavity under different resin contents to prevent sand casting explosion accidents.

Table 1
Organic chemistry binding element sand.

Additive	Chemical component	Density (cm^3/g)	Production company
Binding element	Furan resin	1.10	Ji'nan Shengquan Group
Curing agent	Xylene monosulfonic acid	1.23	

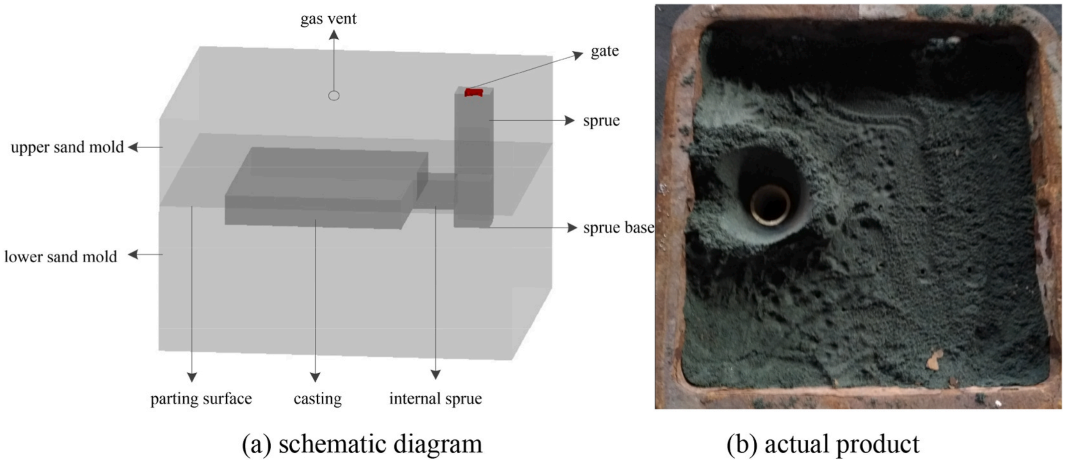

Fig. 2. Sand mold.

Table 2
Pressure monitoring devices of the gas vent during pouring.

Device	Type	Production company	Technical parameter
High-pressure metal hose	G5/8	Jiangsu Fanghua Valve and Filled Device Co., LTD	Impact strength, 15 MPa
Pressure transmitter	MIK-P300G-ZY	Hangzhou Meacon Automation Technology Co., LTD	Accuracy, 0.5% full scale (FS)
Paperless recorder	MIK-9616-ZY		Accuracy, 0.2% FS

3.1.1. Pressure test of the gas vent under different resin contents

(1) Pressure test of the gas vent with a resin content of 1.3 wt%

The resin content of the foundry sand was set to 1.3 wt% when preparing the sand mold. The pressure monitoring device monitors the pressure variation in the upper sand mold during the casting process, as shown in Fig. 3.

The pressure in this study refers to the relative pressure, which is based on atmospheric pressure. As shown in Fig. 3, the pressure of the gas vent is lower before pouring, and the pressure of the gas vent increases after pouring. The temperature of the binder resin in the sand mold increases, and the thermal decomposition reaction produces gases such as CH_4, C_2H_6, and CO [45]. The temperature of the curing agent also increases, and the thermal decomposition reaction produces gases such as CO, CO_2, and sulfur oxides [46,47]. During the pouring process, the binding element and curing agent in the sand mold on the inner surface of the cavity thermally decompose to produce gas. If these gases cannot be exhausted from the cavity in time, the gas pressure in the cavity will increase. The gas in the cavity is mainly exhausted through channels such as the gate, riser, and the permeability of the sand mold itself. When the gas in the cavity is exhausted through the permeability of the sand mold, the pressure of the gas vent of the sand mold will increase.

However, the pressure of the gas vent during the pouring process is not significantly higher than the pressure before pouring. This is

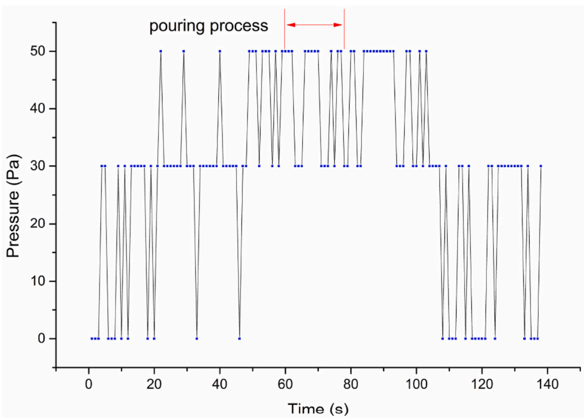

Fig. 3. Pressure variation in the gas vent in the case of a resin content of 1.3 wt%.

because most of the gas generated during the pouring process has been discharged through the gate and the permeability of the sand mold. The pressure data of the gas vent monitored during the pouring process are denser in the high-pressure area than before pouring.

After the pouring process of the molten steel is over, the pressure of the gas vent still maintains a high pressure for some time. This is due to the heat conduction between the sand mold and the molten steel during the pouring process. At the beginning of pouring, the high heat of molten steel makes the binding element, curing agent, and other additives in the sand mold on the inner surface of the cavity quickly vaporize and decompose to produce gas. The foundry sand on the inner surface of the cavity is dried rapidly to form a high-temperature area. Part of the generated gas is exhausted from the sand mold through the gate, and the other part is exhausted from the sand mold through the permeability of the sand mold. As the pouring process progresses, the high-temperature area expands from the inner surface of the cavity to the outer surface of the sand mold. The additives in the newly formed high-temperature area will further vaporize and decompose to produce gas. At this time, a part of the gas is exhausted from the sand mold through the permeability of the sand mold. Therefore, the monitored pressure of the gas vent will still maintain high pressure for some time.

(2) Pressure test of the gas vent with a resin content of 1.4 wt%

The resin content of the foundry sand is set to 1.4 wt% when preparing the sand mold. The pressure monitoring device monitors the pressure variation in the upper sand mold during the casting process, as shown in Fig. 4.

As shown in Fig. 4, the pressure of the gas vent before pouring is different when the resin content is 1.3 wt%. During the on-site test in this study, the sand molds were first uniformly prepared according to the test purpose, and then the molten steel was uniformly poured to monitor the pressure of the gas vent. If one sand mold is poured each time to monitor the pressure of the gas vent, the remaining molten steel needs to be poured into the steelmaking furnace for heat preservation, which will consume considerable energy and waste resources. In the process of on-site testing, the uniform pouring test method was adopted in this study, which not only saves energy but also does not affect the normal production of the company. When conducting a unified pouring test on-site, different sand molds need to use different pressure transmitters for pressure monitoring. Although these devices are manufactured by the same company, slight differences between different devices are inevitable, especially when the pressure is low.

Comparing the results shown in Figs. 3 and 4, it can be seen that the pressure variation in the gas vent when the resin content is 1.3 wt% is similar to that when the resin content is 1.4 wt%. The difference is the duration of the gas vent pressure in the high-pressure area. The duration of the gas vent pressure in the high-pressure area with a resin content of 1.4 wt% is longer than the gas vent pressure in the high-pressure area with a resin content of 1.3 wt%. The greater the resin content in the foundry sand, the more gas that the foundry sand will vaporize and decompose under the action of high temperature during the pouring process. Additionally, as the content of resin increases, the permeability of the sand mold will also decrease [30]. The longer it takes for the gas to be exhausted from the cavity through the permeability of the sand mold. Therefore, the duration of the gas vent pressure is longer with a resin content of 1.4 wt%.

(3) Pressure test of the gas vent with a resin content of 1.5 wt%

The resin content of the foundry sand was set to 1.5 wt% when preparing the sand mold. The pressure monitoring device monitors the pressure variation in the upper sand mold during the casting process, as shown in Fig. 5.

Comparing Figs. 3–5, it can be seen that the pressure variation in the gas vent when the resin content is 1.5 wt% is similar to that when the resin contents are 1.4 wt% and 1.5 wt%.

3.1.2. Statistics of pressure variation in the gas vent

To thoroughly analyze the influence of the resin content on the pressure variation in the gas vent, for this section we conduct a quantitative analysis of the pressure variation in the gas vent. Before the molten steel is poured, we calculate the average pressure of

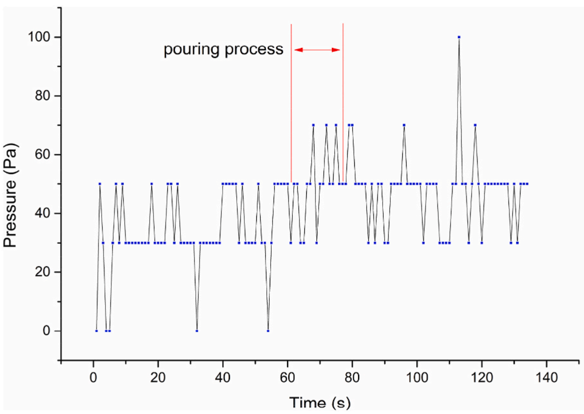

Fig. 4. Pressure variation in the gas vent in the case of a resin content of 1.4 wt%.

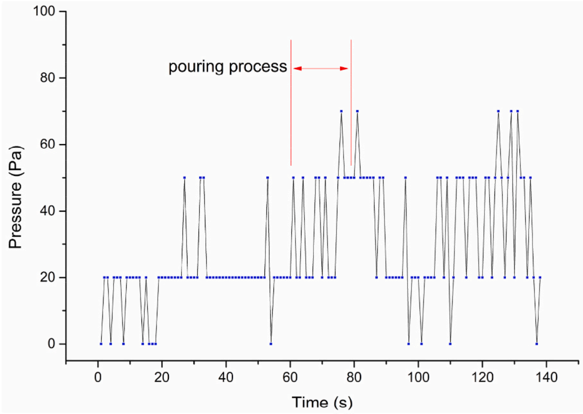

Fig. 5. Pressure variation in the gas vent for a resin content of 1.5 wt%.

the gas vent within 2 min. During the pouring of the molten steel, we calculate the average pressure of the gas vent. The difference between these two values can be regarded as the pressure of the gas vent during the pouring process. The pressure of the gas vent with different resin contents during the pouring process is shown in Table 3.

As shown in Tables 3 and it can be seen that as the resin content increases, the pressure of the gas vent increases. The higher the resin content of the sand mold is, the more gas produced by thermal decomposition during the pouring process and the higher the pressure of the gas vent. However, the pressure of the gas vent increased only slightly. Most of the gas generated in the cavity during the pouring process of sand casting can be discharged through the gate and the permeability of the sand mold itself.

The on-site pressure monitoring of the cavity during the sand casting process has a relatively high requirement for the performance of the test equipment, and the process of sand mold preparation and metal smelting is needed in the early stage, which costs considerable human, material, and financial resources. To our knowledge, there is only one report about on-site monitoring of the cavity pressure during the sand casting process [20]. Chen [20] monitored the pressure of the gas vent to indicate the pressure of the cavity during the iron casting process, which is similar to the research method used for this study. The increased pressure of the gas vent is not very high during the pouring process [20], which is consistent with the findings of the testing for this study. However, Chen [20] did not consider the influence of the adhesive content and the diameter of the gas vent on the pressure of the gas vent. In this study, we confirm that the higher the adhesive content is, the higher the pressure of the gas vent is; the larger the diameter of the gas vent is, the more favorable the exhausting of the gas generated in the cavity is.

3.1.3. Influence of the diameter of the gas vent on the exhaust effect

The size of the gas vent also influences the pressure of the gas vent. To save energy and ensure the safety of testing, a high-pressure nitrogen bottle can be adopted to inject gas into the cavity through the gas-guide tube to simulate the gas generation in the cavity during the pouring process.

The gas-guide tube is inserted into the cavity and sealed at the gate can be seen in Fig. 2(b). We turn on the switch of the high-pressure nitrogen cylinder, adjust the pressure reducing value to 0.1 MPa for testing and take the average value for two or 3 min for each state.

When preparing the sand mold, we puncture the gas vent in the upper sand mold with a diameter of 3 mm, 5 mm and 7 mm, and the depth of each gas vent is 60 mm. The number of gas vents for each type is 3, and the gas vent is above the cavity. A pressure test vent with a diameter of 3 mm and depth of 60 mm is also drilled in the upper sand mold, and the minimum distance from other gas vents is 50 mm.

To test the influence of the diameter of the gas vent on the exhaust effect, only one type of gas vent is blocked at a time, and the pressure variation in the test vent is monitored, as shown in Fig. 6.

Before blocking the gas vent, the monitored pressure of the test vent is lower. As the diameter of the blocked gas vent increases, the pressure of the test vent increases, and the pressure data of the test vent becomes denser in the high-pressure area. During the blocking of the gas vent, we calculate the average pressure of the test vent. The quantitative relationship between the increased pressure of the test vent and the diameter of the blocked vent can be achieved, with the test results as shown in Table 4.

As the diameter of the blocked vent increases, the pressure of the test vent increases. This shows that in the sand casting process, when the depth of the gas vent is consistent, the larger the diameter of the gas vent is, and the more conducive it is to the discharge of the gas generated in the cavity. However, the diameter of the gas vent is not as large as possible. The diameter of the gas vent should be

Table 3
The pressure of the gas vent with different resin contents.

Resin content	1.3 wt%	1.4 wt%	1.5 wt%
Pressure	27.0 Pa	32.8 Pa	35.6 Pa

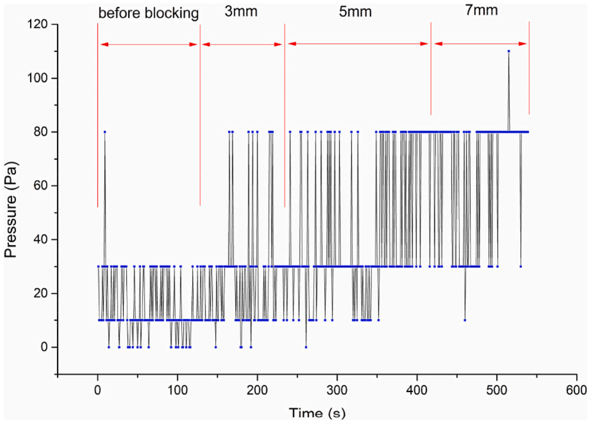

Fig. 6. Pressure variation in the gas vent with blocking.

Table 4
Relationship between the pressure increase and the diameter of the blocked vent.

Diameter of the blocked vent (mm)	3	5	7
Pressure increase (Pa)	8.5	18.6	23.8

comprehensively determined according to factors such as the type and pouring temperature of the cast alloy, the volume of gas generated by the sand mold, and the riser.

3.2. Prevention of sand casting explosion accidents

Although sand casting assists the development of society, it also has adverse effects, such as sand casting explosion accidents. Moreover, sand casting explosion accidents are often accompanied by environmental pollution [48] and casualties [15]. To improve the safe production of foundry operations, it is necessary to adopt corresponding measures to prevent sand casting explosion accidents.

3.2.1. Qualitative analysis of gas vent pressure based on system dynamics

According to the on-site sand casting process, system dynamics are applied to analyze the pressure of the gas vent, as shown in Fig. 7.

To test the effect of the resin content on the pressure of the gas vent, sand molds prepared at different times had different resin contents. Therefore, it can be considered that the resin content is affected by the time of sand molding. The greater the resin content is, the greater the gas evolution of the foundry sand, and the higher the pressure of the gas vent. In addition, the greater the resin content is, the lower the permeability of the sand mold, the more difficult it is for gas to discharge from the cavity, and the higher the pressure of the gas vent. The resin content can cause the pressure of the gas vent to increase from both directions. The higher the temperature of the molten alloy is, the faster the vaporization and thermal decomposition of the additives in the sand mold, which causes more gas to be generated, and the gas vent pressure increases. However, for a specified pouring process, the temperature of the molten alloy is constant. The gate can not only be used as a channel for molten alloy but can also exhaust the gas generated during the pouring process so that the pressure of the gas vent is reduced. Additionally, the riser can prevent casting defects but also play an essential role in the

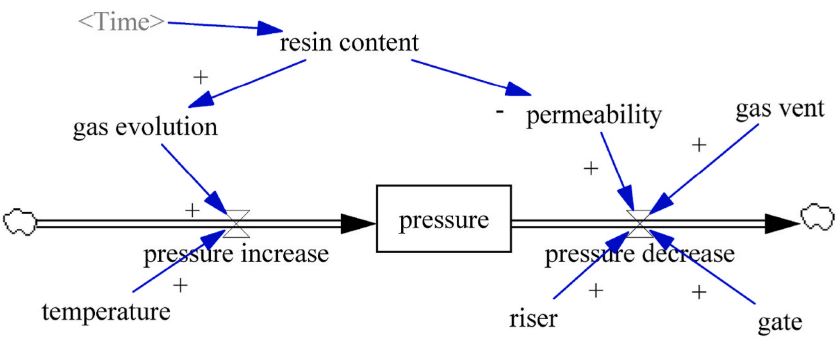

Fig. 7. System dynamics model of the pressure variation in the gas vent.

discharge of the gas from the cavity.

System dynamics is used to analyze the interdependence between system behaviors and internal mechanisms, which have dynamic characteristics. Yin et al. [49] investigated the occurrence mechanism of tourist accidents based on system dynamics. Kontogiannis [50] reviewed the accidents caused by human and organizational processes based on system dynamics. However, there is no study on the evolution characteristics of explosion accidents based on system dynamics, especially in the field of sand casting. In this study, the explosion accident caused by the pressure increase in the cavity during the pouring process is analyzed based on system dynamics, which broadens the application of system dynamics in accident analysis.

3.2.2. *Chaos characteristics of sand casting explosion accidents*

(1) Sensitivity of the evolutionary process to the initial conditions

The sand casting explosion accident process is affected by the cross-coupling among the employee, object, environmental, management, and emergency subsystems. If any change disrupts the balance in the system, sand casting explosion accidents may occur, as shown in Fig. 8.

The direct cause of the sand casting explosion accident is standing water in the cavity. After molten steel is poured into the cavity, the standing water rapidly vaporizes, and the pressure in the cavity suddenly increases, which leads to an explosion accident. In this type of explosion accident, the employee fails to discover standing water in the cavity, which is the main cause of the accident and belongs to the unsafe behavior of the employee. The quality of the pit is unverified and there are many cracks in the waterproof wall, so water can flow into the cavity through the waterproof wall, which belongs to the unsafe state of the object. February in Liaoning is during the icy period of winter. After the water flows into the cavity, it freezes, making it difficult for the employee to observe the situation in the cavity, which is an environmental factor. The steel-casting foundry fails to identify the hazardous and harmful factors in the production process and fails to train the staff, which are management factors. After the explosion accident, the relevant

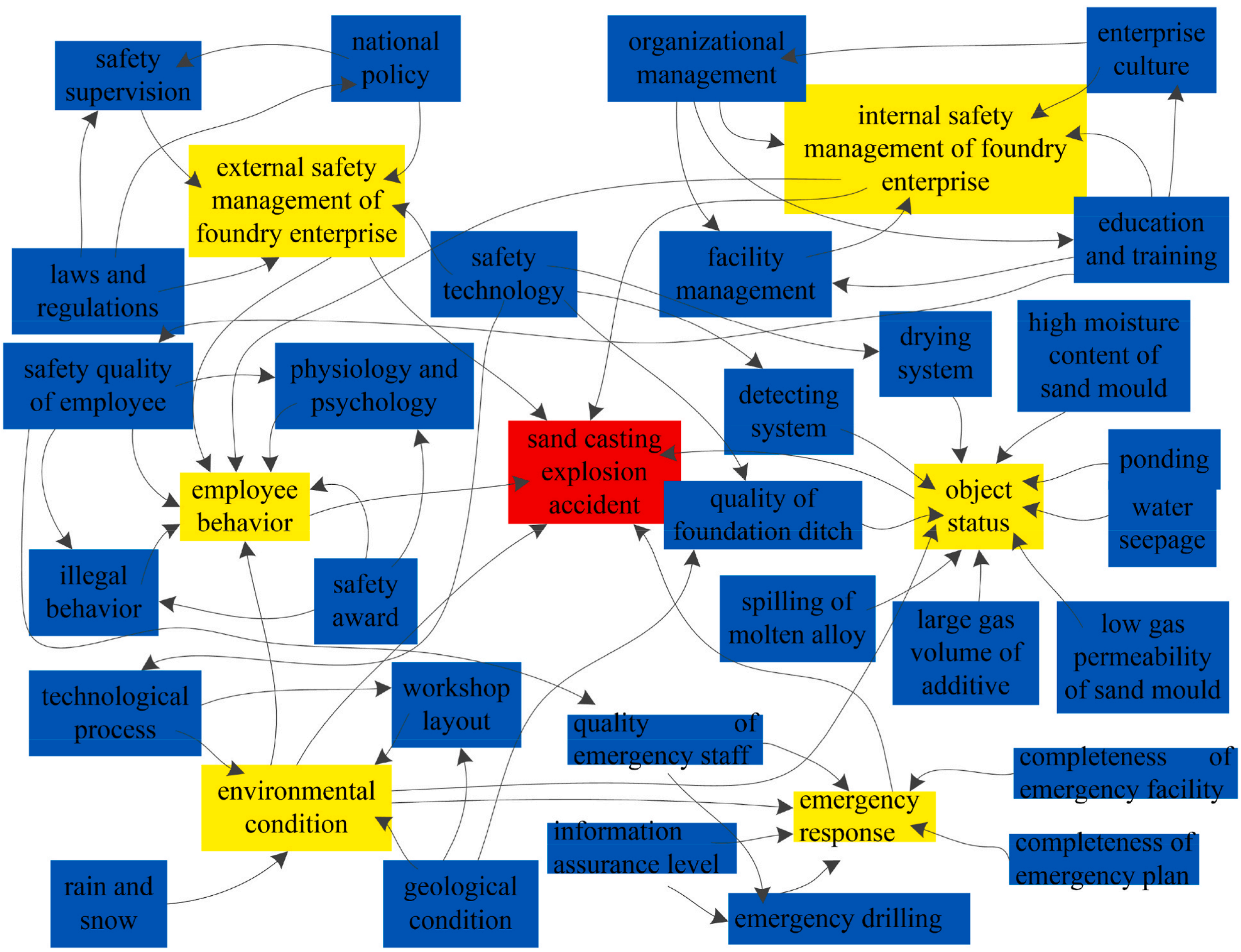

Fig. 8. The butterfly effect of sand casting explosion accidents.

departments immediately launch the emergency rescue, no secondary disaster occurs, and the consequences of the accident are minimized, which belongs to emergency response. In this case, employee, object, environment, and management factors play a role in promoting the occurrence of explosion accidents, and the emergency response plays a restraining role in preventing the expansion of the consequences of explosion accidents.

The butterfly effect indicates that the system is sensitive to the initial conditions [51]. The small errors at the initial moment will be infinitely amplified during the evolutionary process of the system and will finally lead to catastrophic and unpredictable results. The long-term behaviors of the system are sensitive to initial conditions, which is the essential feature that distinguishes the chaotic system from other systems. The initial conditions leading to the accident are often minimal. For example, operating errors may cause other related equipment to become unusable. When these series of factors are superimposed together, accidents may occur. Therefore, the evolutionary process of an accident has a noticeable butterfly effect.

The *Safe Production Law* is a special law in the field of safe production in China [52]. The purpose of the *Safe Production Law* is to strengthen safe production, prevent and reduce production accidents, protect the safety of people's lives and property, and promote the sustainable and healthy development of the economy and society. The requirements of the *Safe Production Law* for relevant factors are shown in Table 5.

To ensure safe production, the enterprise should strictly adhere to the laws and regulations.

Accident causality theory attributes the occurrence of accidents to the unsafe behaviors of humans and the unsafe state of objects, and the unsafe behaviors of humans are the main factor leading to accidents [53,54]. Safety integrated management theory believes that the occurrence of accidents is comprehensively affected by human, object, environmental, and management factors [55–57]. Compared with accident causality theory, safety integrated management theory also considers the impact of the environment and management on accidents. However, previous studies did not consider the impact of emergency response on accidents [15,56]. For the research in this study, we consider the comprehensive impact of humans, objects, the environment, management, and emergencies on explosion accidents and analyze the sensitivity and inherent randomness of explosion accidents.

(2) Inherent randomness of the evolutionary process

In the sand casting process, after molten alloy is poured into the cavity, the additives in the sand mold will be heated to generate gas. The gas generated in the cavity can be exhausted in time through the gas vent and riser under normal conditions. However, the casting system is affected by random factors. For example, the incomplete drying of the sand mold increases the volume of gas generated in the cavity. At the same time, the gas vents on the sand mold are blocked, making the gas unable to be discharged. When these factors are cross-coupled, an explosion accident may occur. In addition, with the advancement of society, companies have combined technological innovation with production practices to improve their intelligence level. However, the safety awareness and professional skills of the employees do not match the intelligence level of the enterprise, which may lead to sand casting explosion

Table 5
Requirements of the *Safe Production Law*.

Factor	Item
Employee	The employees should strictly implement their job safety responsibilities during the operation, abide by the enterprise's safe production rules and operating procedures, obey management, and properly wear and use labor protection equipment.
	The employees should receive safe production education and training, master the safe production knowledge required for their own work, improve safety production skills, and enhance accident prevention and emergency response capabilities.
	The responsibilities of the dominant person in charge of the enterprise are as follows. Organize the formulation and implementation of the corporate safe production rules and regulations and operating procedures. Organize the formulation and implementation of the corporate education and training plan. Ensure effective implementation of the corporate safe production investment. Timely eliminate the hazardous factors. Organize the formulation and implementation of emergency rescue plans.
Object	If new equipment is adopted during the production process, the enterprise must understand and master their technical safety characteristics, take adequate protection measures, and conduct special education and training for employees.
	The enterprise shall set up obvious safety warning signs on equipment with hazardous factors.
	The design, manufacture, installation, use, testing, maintenance, transformation, and scrapping of equipment shall comply with national standards or industry standards.
	The enterprise must conduct regular maintenance and testing of equipment to ensure normal operation.
	The state implements an elimination system for equipment that seriously endangers production safety.
	The dangerous goods containers and transportation facilities must be produced by professional production enterprises by relevant national regulations. Equipment must be tested and inspected by professionally qualified testing and inspection organization, and obtain a safety license or safety mark.
Environment	The enterprise must improve conditions for safe production.
	The enterprise that uses flammable gas shall install a combustible gas alarm and ensure its regular operation.
	Necessary measures shall be taken during the rescue of the accident to avoid or reduce the harm to the environment.
Management	The enterprise must improve the level of safe production and ensure safe production.
	The enterprise must implement the national standards or industry standards formulated following the law to ensure safe production.
	The enterprise shall conduct education and training for employees.
Emergency	The enterprise shall register for major hazardous factors, conduct regular inspections, assessments, and monitoring, and formulate emergency plans to inform employees of the emergency measures that should be taken in emergency situations.
	The enterprise shall take timely measures to treat the wounded employees after a production accident occurs.
	The enterprise shall formulate its emergency rescue plan for production accidents and organize drills on a regular basis.

accidents, such as via illegal operations.

3.2.3. Bow-tie analysis of sand casting explosion accidents

The causes and consequences of sand casting explosion accidents can be discovered through bow-tie analysis, as well as the corresponding water prevention measures, as shown in Fig. 9.

There are many reasons for sand casting explosion accidents, which mainly include the extensive gas evolution characteristic of foundry sand, cavity exhaust blockage, and inadequate safety monitoring.

The lack of time for the gas generated in the cavity to be discharged is the root cause of explosion accidents, and in order to prevent explosion accidents, reducing the gas evolution of foundry sand should be a focus. The main chemical component of foundry sand is SiO_2, which has high thermal stability [45]. The foundry sand will not thermally decompose which can then produce gas during the pouring process. The material that generates gas in the sand mold during the pouring process is mainly the additives. Therefore, the content of additives can be reduced as much as possible under the conditions of the normal production process, which not only ensures safe production but also saves resources. If the adopted additives have a relatively extensive gas evolution characteristic, they can be replaced by additives with small gas evolution characteristics. The sand mold can also be dried to reduce the content of gas-prone materials.

If the gas generated in the cavity can be discharged in time, an explosion accident will not occur. To release the gas in the cavity in time, the permeability of the sand mold can be increased, such as by reducing the ash content in the sand mold. However, taking resource recycling and cost reduction into consideration, sometimes a certain amount of used sand has to be added to the sand mold. If the ash content in the sand mold is difficult to change, gas vents can be drilled on the sand mold to let the gas generated in the cavity discharge more smoothly. The riser can reduce casting defects, and the gas generated during the pouring process can also be discharged from the riser.

According to the theory of accident causation, accidents are mainly caused by unsafe human behaviors [53]. If there are cracks in the waterproof wall, water can flow into the cavity through the cracks. If the water in the cavity is not found during the inspection, an explosion accident may occur during the pouring process. Therefore, the employee should carefully check whether there are cracks in

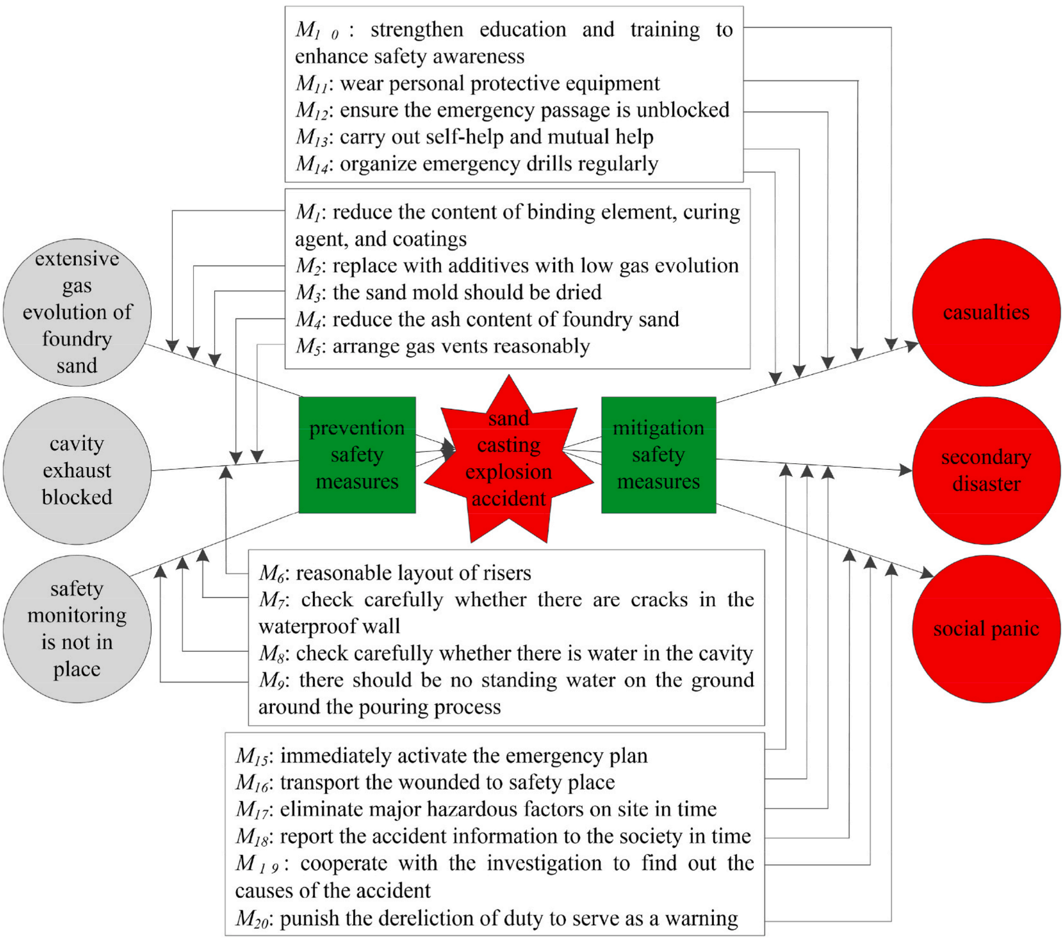

Fig. 9. Bow-tie analysis of sand casting explosion accidents.

the waterproof wall and for the presence standing water in the cavity. Additionally, there should be no standing water on the ground around the pouring process. Otherwise, if the molten alloy runs out of the sand mold during the pouring process, an explosion accident will also occur outside the sand mold once the molten alloy encounters the water on the ground.

There are many consequences of sand casting explosion accidents, mainly including casualties, secondary disasters, and social panic.

The casualties pose a significant challenge for the construction of a harmonious society. After an explosion accident, rescuing the lives of the wounded should be prioritized, and the emergency passage should be unblocked. It takes a certain amount of time from the occurrence of an accident to carrying out emergency rescue actions. During this period, employees should carry out self-help and mutual rescue and try to make them and others suffer as little as possible. For employees who are engaged in hazardous work, personal protective equipment should be worn correctly. Enterprises should also strengthen education and training, enhance employees' safety awareness, and enable employees to master disaster avoidance skills. Enterprises should regularly organize emergency drills to address various disasters and respond immediately when accidents occur.

Explosive accidents can not only cause casualties directly but may also cause other secondary disasters, thereby expanding the scope of disasters. To reduce the consequences of explosion accidents, emergency plans should be activated immediately for secondary disasters. The wounded should be transferred to a safe area in time to avoid secondary disasters. Major hazardous factors at the explosion accident site should be eliminated. Secondary disasters should be eliminated before occurrence as well.

Once an explosion accident causes many casualties or other serious consequences, it will cause a certain degree of public panic in society. The pressure of public opinion caused by social panic may be more severe than the explosion accident itself. Therefore, the social panic caused by the explosion accident should be eliminated in a timely fashion. Reporting accident and disaster information to society promptly and actively guides public opinion. To address rumors spreading in the community, an official announcement should be issued promptly. Active cooperation with the accident investigation organized by relevant departments should occur to determine the causes of the accident and to avoid the recurrence of similar accidents. Corresponding water punishments shall be given to the dereliction of duty in the explosion accident, and other employees shall be warned to handle affairs in strict accordance with the operating rules during their work.

The bow-tie model integrates the causes, consequences, and prevention measures of the accident in a diagram, which is widely used in accident risk analysis [40–42]. Xu et al. [8] carried out a bow-tie analysis of sand casting explosion accidents. However, the causes of explosion accidents were mainly attributed to objective factors only in their study [8], and they did not consider the impact of human factors on explosion accidents. In addition, they did not consider the secondary disasters and social panic caused by the explosion accident [8]. In this study, we conduct a comprehensive analysis of the causes and consequences of explosion accidents and propose corresponding water prevention measures (Fig. 9). Compared with previous studies [8], the analysis of the explosion accident in this study is more in-depth and comprehensive.

3.2.4. *Implication*

The leading cause of sand casting explosion accidents is the gas generated in the cavity is discharged too late. Therefore, the production process can be improved to reduce the gas generated in the cavity during the pouring process or to release the gas generated in the cavity in time. Reducing the content of additives in the sand mold under the normal conditions of the production process can not only reduce the gas generated in the cavity during the pouring process but also save resources. The sand mold should be dried, which can not only reduce the gas volume of the foundry sand but also prevent the formation of water in the cavity. Gas vents should be drilled in the sand mold so that the gas generated in the cavity can be discharged in time.

The production process of sand casting is limited by the level of scientific and technological development. The improvement of the production process requires a large amount of investment in the early stage, which leads to an increase in production costs. If the improvement of the sand casting production process is limited, comprehensive preventive measures should be taken based on the human, object, environment, management, and emergency subsystems (Fig. 8). Strengthen the education and training of employees and improve their safety awareness. Check carefully whether there is water in the cavity and eliminate the hazardous factors in time. Employees should wear personal protective equipment correctly during the production process. The quality of supervision should be strengthened during the construction of the waterproof wall to prevent cracks in the waterproof wall. If there are cracks in the waterproof wall, water can flow into the cavity through the cracks. For sand casting during rainy or snowy days, it should be ensured that there is no standing water on the ground around the production process. If there is standing water on the ground, molten alloy splashing on the ground can also cause an explosion accident if it encounters the standing water. Employees should strictly abide by the operating procedures and prohibit illegal operations. Once an explosion accident occurs, the emergency plan should be activated immediately to minimize the consequences of the explosion accident.

What needs to be emphasized is that both companies and employees should strictly abide by laws and regulations. According to accident causality theory, the occurrence of accidents is caused by the unsafe behaviors of humans and the unsafe status of objects, and the unsafe behaviors of humans are the main reasons [53,54]. Unskilled employees in basic operations, operating in violation of regulations, leaders focusing on production and neglecting safety, and insufficient investment in safety funds are all hazardous factors that lead to accidents. If all of the processes in production are in compliance with regulations, then most accidents can be prevented.

4. Conclusions

In this study, the pressure variations in the cavity were first investigated based upon on-site testing by taking the resin contents into consideration, and then the evolution characteristics of sand casting explosion accidents were analyzed in depth by system dynamics, chaos theory, and the bow-tie model. The higher the binding element content is, the higher the pressure of the gas vent. Therefore, the binding element content should be minimized in the production practice of sand casting. The occurrence of sand casting explosion accidents are comprehensively affected by humans, objects, the environment, management, and emergency subsystems, and the evolutionary process has noticeable butterfly effects and randomness. To reduce the risk of sand casting explosion accidents, corresponding prevention measures should be adopted.

There are few studies on the on-site test of gas vent pressure during the pouring process, and there are insufficient data to construct relevant mathematical models. In this study, only a qualitative analysis of the gas vent pressure was carried out based on the system dynamics. Future studies should focus on the following issues. First, we carry out sufficient on-site tests to obtain the relationship between the gas vent pressure and the pressure in the cavity. Second, we investigate the influence of the additive content, permeability, and gas volume of foundry sand on the pressure in the cavity and determine the mathematical model of pressure in the cavity. Third, we investigate the influence of the diameter, depth, and position of the gas vent on the pressure in the cavity and determine the mathematical model between the pressure in the cavity and the gas vent.

Ethics

This paper does not refer to the Ethics or Animal ethics.

Data accessibility

The pressure data of the gas vent have been uploaded as the electronic supplementary materials.

Funding

This study was supported by the Natural Science Foundation of Henan (Grant No. 232300420297), General Program of Humanities and Social Sciences Research in Henan Universities (Grant No. 2024-ZDJH-035), Research Innovation Fund of Henan Agricultural University in Philosophy and Social Sciences (Grant No. SKJJ2022B06), National Key Research and Development Program of China (Grant No. 2017YFC0805100) and Key Research Programs of Higher Education Institutions in Henan Province (Grant No. 21A630017).

CRediT authorship contribution statement

Qingwei Xu: Data curation, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Yaping Zhu:** Investigation, Software. **Shuyun Qi:** Data curation, Investigation. **Kaili Xu:** Formal analysis, Funding acquisition, Methodology, Supervision. **Bingjun Li:** Formal analysis, Investigation. **Shuaishuai Geng:** Data curation, Methodology.

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.

Acknowledgements

We thank the editor and reviewers for their valuable comments and suggestions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25736.

References

[1] L.R.R. da Silva, F.C. Gaspar, P.C. Goncalves, V.C. dos Santos, M.D.N.M. Melo, G.F. Gomes, An experimental dynamic study of cement mortar with polyurethane residues and foundry sand, Eng. Struct. 274 (2023) 115107, https://doi.org/10.1016/j.engstruct.2022.115107.
[2] F. Liu, H. Qian, J. Ma, P. He, A simple model for predicting dispersion characteristics of high-temperature airflow and particle distribution during smelting process in a thermally stratified foundry shop, Energy Build 278 (2023) 112614, https://doi.org/10.1016/j.enbuild.2022.112614.
[3] D. Duan, P. Leng, X. Li, G. Mao, A. Wang, D. Zhang, Characteristics and occupational risk assessment of occupational silica-dust and noise exposure in ferrous metal foundries in Ningbo, China, Front. Public Health 11 (2023) 1049111, https://doi.org/10.3389/fpubh.2023.1049111.
[4] W. Jiang, G. Li, F. Guan, J. Zhu, D. Zhang, Z. Fan, Preparation of Al2O3/AZ91D Mg interpenetrating composites using lost foam casting combined with layered extrusion forming, Met. Mater. Int. 28 (2022) 1047–1052, https://doi.org/10.1007/s12540-021-00971-2.
[5] W. Jiao, H. Zhao, L. Cheng, Y. Yang, Z. Li, C. Wang, Nonlinear dynamic characteristics of suction-vortex-induced pressure fluctuations based on chaos theory for a water jet pump unit, Ocean Eng 268 (2023) 113429, https://doi.org/10.1016/j.oceaneng.2022.113429.

[6] M. Roman, H. Tekle, D.R. Alla, F. Mumtaz, J.D. Smith, L. Bartlett, R.J. O'Malley, R.E. Gerald, J. Huang, Temperature monitoring in the refractory lining of a continuous casting tundish using distributed optical fiber sensors, IEEE Trans. Instrum. Meas. 72 (2023) 7000511, https://doi.org/10.1109/TIM.2022.3225033.
[7] M. Santiago-Herrera, J. Ibanez, J. Diez-Hernandez, J.A. Tamayo-Ramos, T. Pabel, C. Kneissl, J.M. Alegre, S. Martel-Martin, R. Barros, Comparative life cycle assessment of green sand casting and low pressure die casting for the production of self-cleaning AlMg3-TiO2 metal matrix composite, Ecol. Indic. 144 (2022) 109442, https://doi.org/10.1016/j.ecolind.2022.109442.
[8] Q. Xu, K. Xu, L. Li, X. Xu, X. Yao, Energy release and countermeasures for sand casting explosion accidents, Hum. Ecol. Risk Assess. 26 (2020) 2078–2090, https://doi.org/10.1080/10807039.2019.1650327.
[9] A. Hasanbeigi, Z. Jiang, L. Price, Retrospective and prospective analysis of the trends of energy use in Chinese iron and steel industry, J. Cleaner Prod. 74 (2014) 105–118, https://doi.org/10.1016/j.jclepro.2014.03.065.
[10] Q. Xu, K. Xu, L. Li, X. Yao, Optimization of sand casting performance parameters and missing data prediction, R. Soc. open sci. 6 (2018) 181860, https://doi.org/10.1098/rsos.181860.
[11] L. Huang, Y. Cao, J. Zhang, X. Gao, G. Li, Y. Wang, Effect of heat treatment on the microstructure evolution and mechanical behaviour of a selective laser melted Inconel 718 alloy, J. Alloys Compd. 865 (2021) 158613, https://doi.org/10.1016/j.jallcom.2021.158613.
[12] X. Wang, T. Zhang, R. Zhang, X. Wang, Y. Yuan, Z. Li, Z. Han, Study on the heat transfer at the casting-mould interface in resin-bonded sand mould casting of Mg-Gd-Y-Zr alloy, Int. J. Cast Metal Res. 33 (2020) 1–10, https://doi.org/10.1080/13640461.2020.1729452.
[13] J.H. Jeon, D.H. Bae, Effect of cooling rate on the thermal and electrical conductivities of an A356 sand cast alloy, J. Alloy Compd. 808 (2019) 151756, https://doi.org/10.1016/j.jallcom.2019.151756.
[14] G. Li, T. Ji, Severe accidental water vapour explosions in a foundry in China in 2012, J. Loss Prev. Process Ind. 41 (2016) 55–59, https://doi.org/10.1016/j.jlp.2016.03.001.
[15] Q. Xu, K. Xu, Safety assessment of sand casting explosion accidents through on-site testing and numerical simulation of the temperature variation in sand molds to protect employee health, Process Saf. Environ. Prot. 159 (2022) 452–463, https://doi.org/10.1016/j.psep.2022.01.019.
[16] Q. Xu, K. Xu, X. Yao, J. Zhang, Sand casting safety assessment for foundry enterprises: fault tree analysis, Heinrich accident triangle, HAZOP-LOPA, bow tie model, R. Soc. Open Sci. 5 (2018) 180915, https://doi.org/10.1098/rsos.180915.
[17] M. Guepner, T. Drawert, J. Bliedtner, Process characterization in laser metal deposition of EN AC-43000, J. Laser Appl. 31 (2019) 22315, https://doi.org/10.2351/1.5096114.
[18] B. Han, L. Luo, X. Meng, X. Xue, L. Wang, Y. Su, J. Guo, Generation reason and elimination of blowhole in vacuum suction cast TiAl-based alloy exhaust valve, Rare Metal Mat. Eng 47 (2018) 1631–1636 (in Chinese).
[19] X. Zhao, J. Liang, Z. He, S. Zhang, Blowhole detection based on bidirectional enhancement and omnidirectional analysis for X-ray inspection of castings, Math. Probl. Eng. 2019 (2019) 2468505, https://doi.org/10.1155/2019/2468505.
[20] Y. Chen, Influence of the Gas from Cavity on Quality of the Crankshaft Casting during Mold Filling. Master Degree, Shandong University, Weihai, China, 2016, pp. 10–26 (in Chinese).
[21] S.K. Ray, A.M. Khan, N.K. Mohalik, D. Mishra, S. Mandal, J.K. Pandey, Review of preventive and constructive measures for coal mine explosions: an Indian perspective, Int. J. Min. Sci. Techno. 32 (2022) 471–485, https://doi.org/10.1016/j.ijmst.2022.02.001.
[22] L. Cheng, B. Jiang, H. Guo, Modeling the causes of accidental gas explosions from the perspective of safety information loss, Process Saf. Prog. 41 (2022) 772–782, https://doi.org/10.1002/prs.12356.
[23] J. Zhang, K. Xu, G. Reniers, G. You, Statistical analysis the characteristics of extraordinarily severe coal mine accidents (ESCMAs) in China from 1950 to 2018, Process Saf. Environ. Prot. 133 (2020) 332–340, https://doi.org/10.1016/j.psep.2019.10.014.
[24] Y. Yue, W. Gai, G. Boustras, Exploration of the causes of ammonium nitrate explosions: statistics and analysis of accidents over the past 100 years, Saf. Sci. 158 (2023) 105954, https://doi.org/10.1016/j.ssci.2022.105954.
[25] Y. Gao, L. Hu, Y. Xie, J. Bi, Z. Ma, Understanding the patterns and characteristics of Natech events in China, J. Loss Prev. Process Ind. 84 (2023) 105102, https://doi.org/10.1016/j.jlp.2023.105102.
[26] R. Yang, Z. Wang, J. Jiang, S. Shen, P. Sun, Y. Lu, Cause analysis and prevention measures of fire and explosion caused by sulfur corrosion, Eng. Fail Anal. 108 (2020) 104342, https://doi.org/10.1016/j.engfailanal.2019.104342.
[27] H. Ji, C. Mi, Z. Yuan, Y. Liu, H.M. Zhu, F. Meng, Multicomponent gas detection method via dynamic temperature modulation measurements based on semiconductor gas sensor, IEEE T. Ind. Electron. 70 (2023) 6395–6404, https://doi.org/10.1109/TIE.2022.3194629.
[28] J. Kokalj, M. Ursic, M. Leskovar, R. Meignen, Modelling and simulating of premixed layer in stratified fuel coolant configuration, Ann. Nucl. Energy 185 (2023) 109740, https://doi.org/10.1016/j.anucene.2023.109740.
[29] F. Liu, Z. Sun, M. Ding, H. Bian, Research progress of hydrogen behaviors in nuclear power plant containment under severe accident conditions, Int. J. Hydrogen Energ. 46 (2021) 36477–36502, https://doi.org/10.1016/j.ijhydene.2021.08.151.
[30] P. Travanicek, L. Kotek, P. Junga, Prevention of accidents in facilities for the treatment and storage of selected agricultural products, Saf. Sci. 153 (2022) 105800, https://doi.org/10.1016/j.ssci.2022.105800.
[31] C. Huang, A.N. Lipatnikov, K. Nessvi, Unsteady 3-D RANS simulations of dust explosion in a fan stirred explosion vessel using an open source code, J. Loss Prev. Process Ind. 67 (2020) 104237, https://doi.org/10.1016/j.jlp.2020.104237.
[32] W. Tan, D. Lv, X. Guo, H. Du, L. Liu, Y. Wang, Accident consequence calculation of ammonia dispersion in factory area, J. Loss Prev. Process Ind. 67 (2020) 104271, https://doi.org/10.1016/j.jlp.2020.104271.
[33] L. Chen, Z. Shen, B. Chen, C. Wang, J. Song, M. Li, Steam cavity and explosion intensity of molten copper column interaction with water, J. Loss Prev. Process Ind. 71 (2021) 104470, https://doi.org/10.1016/j.jlp.2021.104470.
[34] J. Deng, Y. Li, H. Lu, W. Wang, L. Bai, C. Shu, Metallurgical analysis of the 'cause' arc beads pattern characteristics under different short-circuit currents, J. Loss Prev. Process Ind. 68 (2020) 104339, https://doi.org/10.1016/j.jlp.2020.104339.
[35] J. Song, C. Wang, B. Chen, M. Li, Z. Shen, C. Wang, Phenomena and mechanism of molten copper column interaction with water, Acta Mech 231 (2020) 2369–2380, https://doi.org/10.1007/s00707-020-02667-x.
[36] H. Abdolabadi, M. Amaya, J.C. Little, Intimate coupling of a hydrologic model with an economic input-output model using system dynamics, Appl. Water Sci. 13 (2023) 75, https://doi.org/10.1007/s13201-023-01872-y.
[37] F.C. Prinsloo, P. Schmitz, A. Lombard, System dynamics characterisation and synthesis of floating photovoltaics in terms of energy, environmental and economic parameters with WELF nexus sustainability features, Sustain. Energy Techn. 55 (2023) 102901, https://doi.org/10.1016/j.seta.2022.102901.
[38] X. Jiao, Y. Liu, J. Wang, W. Liu, A. Wan, S. Wiesner, S. Xiong, The microstructure characteristics and fracture behavior of the polyhedral primary iron-rich phase and plate-shaped eutectic iron-rich phase in a high-pressure die-cast AlSi10MnMg alloy, J. Mater. Sci. Technol. 140 (2023) 201–209, https://doi.org/10.1016/j.jmst.2022.09.014.
[39] X. Zuo, R. Zhu, Y. Zhou, Online tracking and prediction of slip ring degradation using chaos theory based on LSTM neural network, Meas. Sci. Technol. 34 (2023) 055010, https://doi.org/10.1088/1361-6501/acb5b6.
[40] R.S. Almeida, F.V. da Silva, S.S.V. Vianna, Combining the bow-tie method and fuzzy logic using Mamdani inference model, Process Saf. Environ. Prot. 169 (2023) 159–168, https://doi.org/10.1016/j.psep.2022.11.005.
[41] Y. Huang, Z. Zhang, Y. Tao, H. Hu, Quantitative risk assessment of railway intrusions with text mining and fuzzy Rule-Based Bow-Tie model, Adv. Eng. Inform. 54 (2022) 101726, https://doi.org/10.1016/j.aei.2022.101726.
[42] S. Xie, S. Dong, Y. Chen, Y. Peng, X. Li, A novel risk evaluation method for fire and explosion accidents in oil depots using bow-tie analysis and risk matrix analysis method based on cloud model theory, Reliab. Eng. Syst. Safe. 215 (2021) 107791, https://doi.org/10.1016/j.ress.2021.107791.
[43] R.S. Dungan, U. Kukier, B. Lee, Blending foundry sands with soil: effect on dehydrogenase activity, Sci. Total Environ. 357 (2006) 221–230, https://doi.org/10.1016/j.scitotenv.2005.04.032.

[44] F. Liu, L. Yang, Y. Huang, P. Jiang, G. Li, W. Jiang, X. Liu, Z. Fan, Performance of resin bonded sand for magnesium alloy casting, J. Manuf. Process 30 (2017) 313–319, https://doi.org/10.1016/j.jmapro.2017.10.002.
[45] Q. Xu, K. Xu, X. Yao, J. Li, L. Li, Thermal decomposition characteristics of foundry sand for cast iron in nitrogen atmosphere, R. Soc. Open Sci. 5 (2018) 181091, https://doi.org/10.1098/rsos.181091.
[46] M. Monti, H. Hoydonckx, F. Stappers, G. Camino, Thermal and combustion behavior of furan resin/silica nanocomposites, Eur. Polym. J. 67 (2015) 561–569, https://doi.org/10.1016/j.eurpolymj.2015.02.005.
[47] P. Wan, Y. Li, H. Ling, W. Wang, H. Zhi, J. Xue, Development of a new instrument for measurement of high temperature mechanical properties of resin-bonded sand, China Foundry 14 (2018) 286–291, https://doi.org/10.1007/s41230-017-6023-4.
[48] S. Talwar, A.K. Verma, V.K. Sangal, Synergistic degradation employing photocatalysis and photo-Fenton process of real industrial pharmaceutical effluent utilizing the Iron-Titanium dioxide composite, Process Saf. Environ. Prot. 146 (2021) 564–576, https://doi.org/10.1016/j.psep.2020.11.029.
[49] J. Yin, X. Zheng, R.C. Tsaur, Occurrence mechanism and coping paths of accidents of highly aggregated tourist crowds based on system dynamics, PLOS ONE 14 (2019) e0222389, https://doi.org/10.1371/journal.pone.0222389.
[50] T. Kontogiannis, Modeling patterns of breakdown (or archetypes) of human and organizational processes in accidents using system dynamics, Saf. Sci. 50 (2012) 931–944, https://doi.org/10.1016/j.ssci.2011.12.011.
[51] R. Li, X. Meng, B. Chen, L. Zhao, X. Zhang, Gut microbiota in lupus: a butterfly effect? Curr. Rheumatol. Rep. 23 (2021) 27, https://doi.org/10.1007/s11926-021-00986-z.
[52] Safe Production Law, The National People's Congress of the People's Republic of China, 2021. http://www.npc.gov.cn/npc/c30834/202106/02ceac7db412477c9b6d889d9363afc5.shtml. (Accessed 11 January 2023).
[53] P.L. Yorio, S.M. Moore, Examining factors that influence the existence of heinrich's safety triangle using site-specific H&S data from more than 25,000 establishments, Risk Anal 38 (2018) 839–852, https://doi.org/10.1111/risa.12869.
[54] J. Wang, P.X.W. Zou, P.P. Li, Critical factors and paths influencing construction workers' safety risk tolerances, Accid. Anal. Prev. 93 (2016) 267–279, https://doi.org/10.1016/j.aap.2015.11.027.
[55] W. Li, L. Zhang, W. Liang, An Accident Causation Analysis and Taxonomy (ACAT) model of complex industrial system from both system safety and control theory perspectives, Saf. Sci. 92 (2017) 94–103, https://doi.org/10.1016/j.ssci.2016.10.001.
[56] C. Zhu, S. Tang, Z. Li, X. Fang, Dynamic study of critical factors of explosion accident in laboratory based on FTA, Saf. Sci. 130 (2020) 104877, https://doi.org/10.1016/j.ssci.2020.104877.
[57] Z. Huang, T. Le, Y. Gao, X. Yao, H. Wang, W. Zhao, Y. Zhang, N. Nie, Safety assessment of emergency training for industrial accident scenarios based on analytic hierarchy process and gray-fuzzy comprehensive assessment, IEEE ACCESS 8 (2020) 144767–144777, https://doi.org/10.1109/ACCESS.2020.3013671.