

## Article

# Field Testing and Calibration of Building Hermetic Doors Under Extreme Bipolar Pressure Scenarios

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## Abstract

Hermetic doors with high sealing performance are critically important for safety critical buildings, such as hospital operating rooms, biological laboratories, and underground shelters. Nevertheless, field-measured leakage data for such doors under extreme pressure conditions remain extremely scarce, and the underlying leakage characteristics remain largely unclear. In this study, the leakage rates of two sizes (1.2 m × 2.3 m and 4.8 m × 4.45 m) of hermetic doors were measured in a model structure using the fan pressurization method under extreme bipolar pressure ( $\pm 1500$  Pa) with stepwise loading. A correlation curve between the pressure differential and the leakage rate was subsequently established and adopted as a boundary condition in Computational fluid dynamics (CFD) models, and CFD simulations revealed that this curve conveniently calibrates the performance of high-airtightness doors in entire buildings. The results show that this equivalent boundary condition method effectively enhances the efficiency and accuracy of numerical simulations for complex structures, thereby providing a theoretical basis for future building designs requiring high airtightness and facilitating the calibration of leakage characteristics.

**Keywords:** leakage characteristics; high-airtightness enclosing structure; computational fluid dynamics; hermetic doors; equivalent numerical models

## 1. Introduction

High-airtightness enclosing structures constitute essential infrastructure components across high-tech and critical industrial sectors. They play a pivotal role in ensuring industrial safety, environmental protection, and the isolation of specific environments [1]. By establishing a reliable containment barrier, these structures effectively prevent hazardous internal media (such as dangerous chemicals, biological contaminants, or specialized agents) from leaking into the external environment. This function is vital for mitigating environmental hazards and guaranteeing the stable operation of critical internal processes.

Despite their essential nature, the long-term integrity and reliability of enclosing structures remain a major focal point of public and regulatory concern [2]. Major historical breaches of containment, such as significant industrial contamination events [3] and critical facility environmental releases [4], serve as stark warnings. These catastrophic events

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underscore the potential for devastating environmental pollution and prolonged socio-economic impacts should a structural failure occur. Therefore, accurately assessing and quantifying the leakage characteristics of airtightness enclosing structures, as well as implementing effective control measures, are particularly important and urgent. Existing experimental and computational research gaps are discussed separately in subsections 1.1 and 1.2 in our research.

### *1.1. Experimental Evaluation Methods for Hermetic Door Leakage Characteristics*

The airtight testing of nuclear power hermetic doors is a critical step in ensuring their safety performance [5]. At present, a wide range of methods are employed to evaluate sealing performance, including the fan pressurization method [6], blower door method [7], tracer gas method [8], soap bubble leak detection [9], water-immersion testing [10], ultrasonic leak detection [11], and various non-destructive testing techniques [12]. However, not all these methods are suitable for the precise quantitative evaluation of hermetic doors in high-airtightness enclosing structure.

Specifically, methods such as the soap bubble leak detection, ultrasonic leak detection, tracer gas method, water-immersion testing, vacuum-rise method, and various non-destructive testing techniques are primarily used to provide qualitative assessments [13–16]. That is, they can indicate whether a leak is present but cannot accurately quantify the leak rate or magnitude. This clearly cannot meet the strict requirements for the airtight doors of the nuclear power plant. For experimental studies on the leakage characteristics of hermetic doors, the blower door method is currently widely used in the residential and other building sectors [17–19]. This method evaluates the overall airtightness of a building by measuring the airflow required to maintain a specified pressure difference. For example, the airtightness performance of two buildings in the cold zone of China was measured using the blower door method by Chen et al. [7]. The findings indicated that the air tightness performance of Hui'an building only meets the Netherlands' standard, and was lower than the requirements specified in Finland, Belgium, Denmark, Canada, the United States, and the United Kingdom. The blower door method was used by Anuradha et al. [20] to evaluate the airtightness of buildings in disadvantaged communities. The findings indicated that improving the airtightness can lead to reduced energy consumption and improved thermal comfort. However, the blower door method is generally applicable to scenarios with relatively large leakage rates and low-differential-pressure requirements. In contrast, nuclear power hermetic doors must withstand much higher differential pressures and require extremely minimal leakage rates [21]. Therefore, the blower door method exhibits inherent limitations in accuracy and applicability. Consequently, it is unsuitable for detecting minute leakage or for meeting the stringent high-differential-pressure testing requirements of nuclear power hermetic doors. The tracer gas method provides high measurement accuracy. However, its operation is complex and requires strict environmental control [22,23]. In addition, the instrumentation needed for this method is highly expensive.

The feasibility of the experiment, the quantitative requirements for leakage measurement, and the support provided by relevant standards were comprehensively evaluated. Based on these considerations, the fan pressurization method was deemed the most appropriate and was adopted to investigate the leakage characteristics of the hermetic door. The specified pressure differential is maintained by precisely measuring and replenishing the flow. This approach allows for accurate quantification of minute leakage rates. In addition, it is supported by established standards in the nuclear industry and airtightness testing protocols [24–26].

However, despite the adoption of the fan pressurization method, significant challenges are still encountered in practical testing. These challenges include the high cost of

testing, the lengthy experimental cycles, the difficulty in simulating all extreme conditions (such as prolonged performance under high-temperature, high-pressure, or high-radiation environments), and the limited capability to elucidate leakage paths and underlying microscopic mechanisms. To address these limitations, the integration of experimental studies with numerical simulations has emerged as a key approach for overcoming challenges. Such integration not only compensates for the limitations of purely experimental approaches, but also provides a more comprehensive, efficient, and accurate solution for evaluating the leakage characteristics of hermetic doors.

### *1.2. Numerical Simulation Study on Leakage Characteristics*

Computational fluid dynamics (CFD), as a powerful numerical tool, has demonstrated broad application prospects in simulating fluid flow and various types of leakage phenomena [27–30]. It can provide detailed distributions of pressure and velocity fields, which are often difficult to obtain directly in purely experimental studies. At present, CFD has been widely applied to various leakage scenarios. For example, He et al. [31] effectively evaluated the dynamic behavior of an isolated slug driven by pressurized air in voided pipelines with an end orifice in high-airtightness enclosing structure using CFD. Zhang et al. [32] employed CFD to simulate the transient response of condensate-induced water hammer (CIWH) behavior. Their work successfully reproduced the complex water hammer process and laid a solid foundation for subsequent model optimization and studies on the triggering mechanism. Min et al. [33] employed CFD simulations to calculate the gas leakage rate within micro-channels in high-airtightness enclosing structure. In addition, the gas flow characteristics in micro-channels were investigated, with the influencing factors on the leakage rate identified. These studies collectively demonstrate that CFD provides engineers with a powerful means to gain deeper insight into leakage mechanisms, optimize design, and evaluate safety.

However, the simulation of leakage characteristics for hermetic doors in high-airtightness enclosing structure presents unique challenges [34]. The gaps along the door are far from simple geometric openings. Instead, they constitute micro- to nanoscale clearances arising from the combined influences of seal surface roughness, manufacturing tolerances, and material deformations induced by assembly stresses. These microscopic clearances are extremely small, making it difficult to accurately obtain their geometric information using conventional measurement techniques. This poses a fundamental obstacle to CFD modeling. Even more challenging is the fact that while the overall dimensions of hermetic doors typically reach the meter scale, the leakage gaps exist at the micro- or nanoscale. This implies that CFD simulations must simultaneously capture flow behaviors spanning from macroscopic flows to those within microscopic clearances. To accurately capture the fluid behavior within these minute clearances, extremely refined boundary-layer and volumetric meshes must be generated in these regions. Such an extreme disparity in scales causes the total number of computational cells to grow exponentially [35]. The mesh count can reach tens of millions or even exceed one hundred million. This not only results in a significant consumption of computational resources, but also prolongs the simulation time [36]. The complex microscopic structures also make it difficult to ensure mesh quality, which in turn affects the convergence and stability of numerical calculations.

To simplify complex diffuser models, Heikkinen proposed a simplified model known as the basic model method [37]. This method, originally applied to diffusers, replaces the actual diffuser geometry with an idealized opening that has the same effective area. The approach has been widely applied. Zhao et al. [38] used it to simulate wall-mounted perforated, grille, and square ceiling diffusers, approximating the first two as a single opening and the latter as nine openings. Similarly, Djunaedy and Cheong [39] proposed five

schemes to simulate a four-way ceiling diffuser by changing the shape and position of the opening. However, the basic model method has limitations. Chen and Moser [40] found it performs poorly in non-isothermal flow simulations, especially for geometries with a small effective area, and it can sometimes even lead to erroneous results. To simplify complex diffuser models, Chen and Moser [40] proposed a novel approach called the momentum method. The core idea of this method is to reduce the computational complexity of the model by assigning different velocities to the continuity and momentum equations on the diffuser. The method has been successfully applied and extended by various research groups. Chen et al. [41] and Jiang et al. [42] used it to simulate complex diffusers for mixed and displacement ventilation. Huo et al. successfully modeled ceiling supply diffusers by using the jet formula as a prescribed velocity. Furthermore, Luo and Roux [43] and Luo et al. [44] also applied this method to simulate nozzle arrays by adding extra momentum. This study aims to further extend the application of this concept to the simulation of hermetic doors, to validate its effectiveness and versatility under different operating conditions.

Therefore, this study proposes and validates a method that deeply couples flow-supplement experiments with CFD simulations. Firstly, a detailed description of the entire experimental process for investigating the leakage characteristics of hermetic doors using the fan pressurization method is provided. By precisely controlling the pressure differential across the hermetic door, the leakage rates under different operating conditions were systematically measured. On this basis, an accurate empirical relationship between pressure and leakage rate was established. This not only provides a realistic and reliable physical basis for subsequent numerical simulations, but also offers important guidance for the overall airtightness design and safety assessment of nuclear reactors. Furthermore, customized boundary conditions were implemented in the CFD model, enabling the direct mapping of fluid exchange at the door gap to the experimentally determined pressure–leakage correlation. This approach effectively avoids the need for complex meshing of nanoscales and even micro-scale leakage channels while reducing computing time and error. It also enables a dynamic adaptive mechanism based on the calculated internal–external pressure differential. As a result, computational efficiency is significantly improved. The accuracy of simulation results is greatly enhanced, providing a novel solution for the efficient and precise evaluation of leakage characteristics in nuclear hermetic doors. The experimental work herein provides data reference for high-risk hermetic doors. The experimental–numerical coupled study offers a new approach for evaluating the overall airtightness of factory buildings and a novel solution for efficient, precise assessment of leakage characteristics in nuclear hermetic doors, thus informing the design and operation of actual reactor buildings.

### *1.3. Outdoor Field Measurement and Simulation of Leakage for High-Airtightness Structures*

Previous airtightness studies have mainly focused on residential buildings, ordinary building envelopes, and component-level air permeability [6,7]. These studies provide useful references for conventional building airtightness assessment, but their application scenarios are mainly residential or ordinary buildings, where the pressure levels and airtightness requirements are much lower than those of high-risk industrial containment facilities.

Some studies have also examined airtightness at the component or joint level under controlled laboratory conditions. Van Den Bossche and Janssens analyzed the airtightness and watertightness performance of window frames based on laboratory test data [45], while Kayello et al. investigated the thermal and airtightness performance of structural insulated panel joints in an environmental chamber under cold-climate conditions [46]. These works are valuable for understanding leakage through building components and

joints, but they do not represent full-scale hermetic doors installed under actual engineering conditions or subjected to extreme bidirectional pressure loading.

Leakage-flow modeling in hermetic systems, gasketed interfaces, and pressure-driven micro-gaps has also been investigated. For nuclear containment structures, previous studies have examined gas leakage through cracks, corrosion defects, and microchannels in containment vessels, revealing the influence of pressure difference, microchannel size, temperature, and defect geometry on leakage rate [47]. For gasketed sealing systems, contact-mechanics and equivalent-medium models have shown that leakage is strongly affected by surface roughness, gasket compression, contact pressure distribution, and connected micro-flow paths [48]. These studies provide an important mechanistic understanding of leakage through local defects or sealing interfaces. However, they usually focus on idealized microchannels or local gasket contacts and require detailed gap geometry or contact-pressure parameters, which are difficult to obtain for full-scale hermetic doors after actual installation.

Therefore, direct numerical resolution of micro-scale leakage gaps in large airtight structures remains computationally expensive, especially when the overall structure is at the meter or building scale while the leakage paths are at the micro-gap level. CFD-based leakage studies have demonstrated the potential of numerical simulation for analyzing airflow and leakage in building envelopes. For example, Younes et al. developed a three-dimensional multi-physics CFD methodology for simulating air leakage through building envelopes [47]. However, most existing CFD studies still focus on ordinary building envelopes or energy-related infiltration, rather than high-irtightness industrial containment structures under extreme pressure conditions.

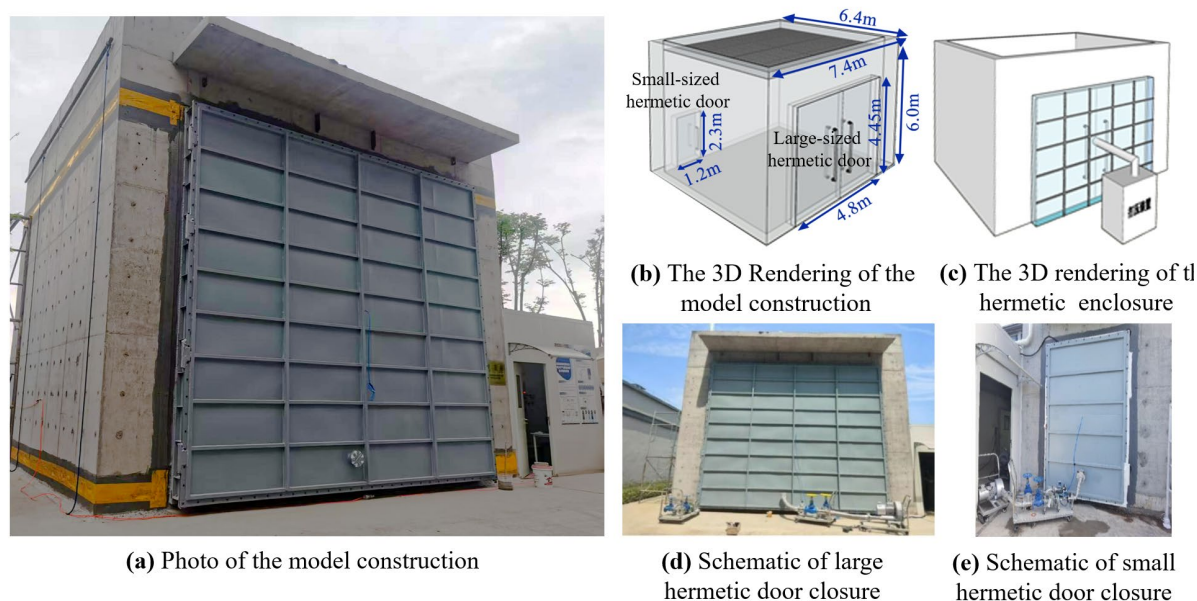
Therefore, there remains a lack of outdoor field measurements and experimentally calibrated simulations for full-scale hermetic doors in high-irtightness industrial structures under extreme pressure conditions. In the present study,  $\pm 1500$  Pa was selected according to the project-specific thermal-hydraulic calculation for a representative design-basis accident involving the rupture of high-temperature and high-pressure pipelines, which may generate a positive pressure difference of approximately  $+1500$  Pa in the adjacent hall relative to the outdoor environment [49,50]. The corresponding  $-1500$  Pa condition was included to account for different door installation orientations and the possible reversal of pressure direction relative to the gasket compression surface; this treatment is consistent with nuclear containment leakage-assessment principles, in which leakage performance is evaluated under calculated accident-related pressure conditions [51,52]. To address this gap, the present study conducts outdoor field tests on full-scale hermetic doors under extreme bipolar pressure conditions of  $\pm 1500$  Pa. The measured pressure-leakage relationships are then introduced into the CFD model as equivalent leakage boundary conditions. This experimental-numerical framework provides a practical approach for evaluating leakage behavior, pressure distribution, ventilation strategy, and accident-release risk in high-irtightness enclosing structure.

## 2. Method

### 2.1. The Fan Pressurization Method Testing Process

#### 2.1.1. Model Construction

To accurately evaluate the airtightness of hermetic doors in newly built high-irtightness enclosing structure workshops with concrete enclosure structures, this study constructed a model construction for analysis by combining practical engineering cases. As shown in Figure 1a, the model construction was consistent with the actual project in terms of key leakage components, material selection, structural form, and construction installation technology, ensuring the reliability of experimental and simulation results.



**Figure 1.** Schematic diagram of hermetic door closure and model construction.

The model construction is located at the Yangtze River Delta Innovation Center, Xitang Town, Jiaxing City, Zhejiang Province, with specific parameters listed in Table 1. Adopting a concrete structure, it measures 7.4 m × 6.4 m × 6.0 m (length × width × height). The 3D rendering of the model construction is shown in Figure 1b, and that with the hermetic enclosure installed is presented in Figure 1c. An equipment room and a control room are arranged adjacent to the tested enclosure structure, serving as spaces for placing testing/control equipment and operating instruments. The model is equipped with two hermetic doors: one is a large hermetic door of 4.8 m × 4.45 m (Figure 1d), and the other is a small hermetic door of 1.2 m × 2.3 m (Figure 1e). The hermetic door is fitted with metal-reinforced EPDM sealing strips. Featuring a closed-cell sponge sealing layer and galvanized steel reinforcement in the base, the strips have excellent elasticity, low compression set, stable mounting performance and good pressure adaptability. The specifications and models of both doors are completely consistent with those used in the actual project. In addition, hermetic enclosures are welded with steel plates on the outer sides of the two hermetic doors for subsequent testing. Considering project workload and cost control, the concrete wall area, floor area, roof area, and construction joint length of the model are all designed in a scaled-down manner according to the proportion.

**Table 1.** Parameters of the model construction.

| Construction Components | Parameters                                             |
|-------------------------|--------------------------------------------------------|
| Construction dimensions | length × width × height = 7.4 m × 6.4 m × 6.0 m        |
|                         | Wall panel thickness = 400 mm                          |
|                         | Roof panel thickness = 350 mm                          |
|                         | Floor slab thickness = 500 mm                          |
| Hermetic door           | 1 small hermetic door: length × width = 1.2 m × 2.3 m  |
|                         | 1 large hermetic door: length × width = 4.8 m × 4.45 m |

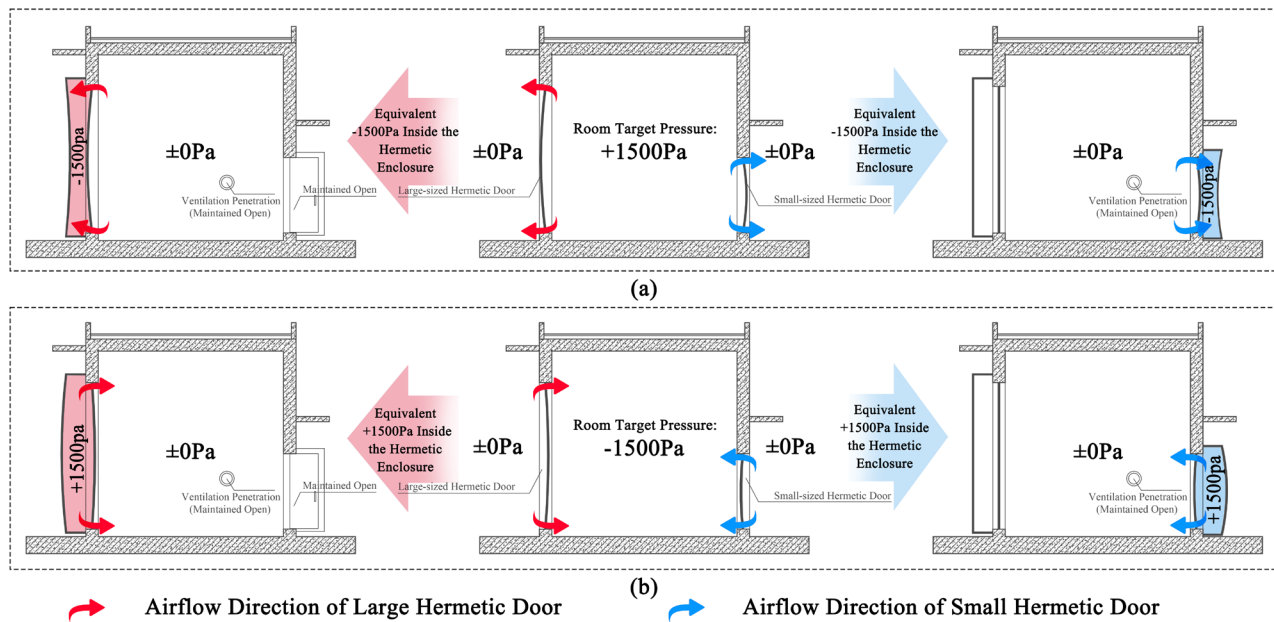
### 2.1.2. Experimental Principle

To obtain the leakage rate data of key components (hermetic doors) in the model and evaluate their leakage patterns under the actual engineering operation conditions, this ex-

periment set two operating conditions: The designed positive pressure and negative pressure of the room are +1500 Pa and −1500 Pa, respectively. Specifically, the positive pressure of +1500 Pa corresponds to a hypothetical design-basis accident in the reactor building with the high-temperature and high-pressure pipelines inside the building rupture. The high-temperature and high-pressure water and steam in the pipelines are rapidly vaporized and heated, resulting in a sharp rise in indoor temperature and pressure. According to thermal-hydraulic calculations, the impact caused by the pipeline rupture accident will generate a positive pressure difference of +1500 Pa in the adjacent hall relative to the outdoor environment. Considering that the enclosure doors may be installed in different directions, the acting direction of the indoor-outdoor pressure difference relative to the compression sealing surface can be opposite. Therefore, to obtain comprehensive test data,  $\pm 1500$  Pa forms a bidirectional extreme pressure verification, so as to achieve full risk coverage. Meanwhile, room negative pressure imposes inward suction load on the door and verifies the anti-negative-pressure airtightness of its sealing structure and frame. Therefore, this experiment tested the leakage rate per unit joint length of the hermetic door under these two pressure difference conditions.

After specifying the target pressures inside the room as +1500 Pa and −1500 Pa, the experimental method for hermetic doors was further refined: this experiment adopted the fan pressurization method, directly applying positive or negative pressure inside the hermetic enclosure of the hermetic door to measure its airtightness. Compared with the indirect measurement method, which “measures the overall leakage rate by exhausting or supplying air to the room with a fan and calculates the difference in leakage rate before and after the hermetic door is sealed”, this direct measurement method can reduce the cumulative error of two tests and avoid the interference of leakage from other parts of the room (such as penetrations and construction joints) on the data.

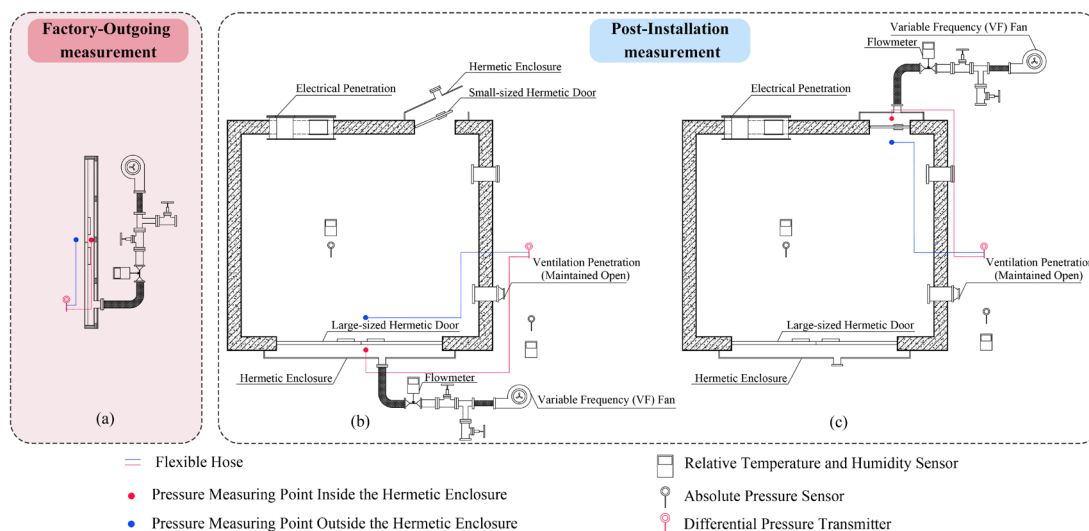
When using the direct measurement method, to equivalently obtain the leakage rate of the hermetic door under the target design pressure of the room, the pressure value inside the hermetic enclosure needs to be set reversely, with the specific reverse principle shown in Figure 2. If the target pressure of the room is positive (e.g., +1500 Pa, meaning the internal pressure of the room is higher than that on the outside), the leakage direction of the hermetic door under actual operating conditions is “from inside the room to outside”. Since the hermetic enclosure covers the outer side of the hermetic door, to simulate the same leakage direction and pressure difference, the pressure inside the hermetic enclosure should be lower than that on the inner side of the hermetic door (the side simulating the positive pressure of the room), i.e., set reversely to −1500 Pa. Currently, the absolute value of the pressure difference (1500 Pa) between the two sides of the hermetic door is consistent with the actual room operating conditions, and the leakage rate data is equivalent.



**Figure 2.** Principle of reverse pressure difference measurement inside the hermetic enclosure. (a) Pressure difference and airflow direction of hermetic enclosures for hermetic doors under a target room pressure difference of  $+1500\text{ Pa}$ ; (b) Pressure difference and airflow direction of hermetic enclosures for hermetic doors under a target room pressure difference of  $-1500\text{ Pa}$ .

During the factory-outgoing phase of hermetic doors, airtightness measurement will be conducted using instrument equipment and testing standards identical to those applied in the model experiment, ensuring the homologous comparability of the two sets of data. On this basis, for the same positive- and negative-pressure working conditions, a systematic comparison will be made between the factory-measured leakage data of the prototype door and the leakage data of the hermetic door in the model. This comparison can not only intuitively quantify the airtightness difference of the hermetic door between the two key stages, but also accurately isolate the influence weight of the construction process on airtightness. Furthermore, it enables identifying the causes of airtightness degradation, guiding engineering optimization, and evaluating the specific impacts of construction issues such as seal deformation and door frame fitting deviation during the installation process.

The tightness test method for this experimental bench was conducted in accordance with NB/T 20018-2021 [48]: containment leak tightness test for PWR nuclear power plants (standard 2021). The fan pressurization method was adopted: the test system measured the local leakage rate of the hermetic door by extracting or supplying air into the hermetic enclosure. The schematic diagram of the test system and the device connection diagram are shown in Figure 3. A variable-frequency fan, in coordination with a straight-through valve and a bypass valve, was used to adjust the air volume for creating positive and negative pressures; a differential pressure transmitter monitored the pressure difference inside and outside the hermetic enclosure in real time, and a flowmeter recorded the leakage rate. Figure 3a illustrates the principle of factory-outgoing measurement. By welding a steel plate on the back of the hermetic door, a space behind the door is constructed to replace the actual room space, thus eliminating the need for pressure difference reversal operation. Figure 3b,c depict the measurement principle of the model. A hermetic enclosure is welded on the outer side of the hermetic door to build a space outside the door; due to the influence of this space simulation method, pressure difference reversal operation is required.



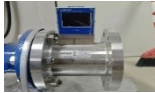
**Figure 3.** (a) Schematic diagram of factory-outgoing measurement; (b) Schematic diagram of sealing test for large hermetic door; (c) Schematic diagram of sealing test for small hermetic door.

### 2.1.3. Measurement Instruments

Taking the hermetic door as the tested component, the hermetic enclosure can achieve external sealing of the door to prevent gas from infiltrating from the outside. The hermetic enclosure is equipped with two openings: one serves as the fan interface, and the other is used for connecting the test hose of the differential pressure transmitter.

The main measuring devices and instrument parameters in this test are listed in Table 2: the relative temperature and humidity sensor (VAISALA-HMP110) and absolute pressure sensor (Druck-PTX5072) are used to monitor indoor and outdoor temperature, humidity, and absolute pressure. They are installed at a height of 1.5 m in the center of the room and under the northern eave outdoors, respectively. The measurement range of the differential pressure transmitter (Rosemount 3051C) is  $-2000\sim 2000$  Pa (for the  $\pm 1500$  Pa operating condition). The pressure measurement tubes at heights of 5.4 m, 3.6 m, and 1.8 m along the door gap inside the room are connected to its Port L, while the pressure measurement tube in the center of the hermetic enclosure of the hermetic door is connected to its Port L to collect the pressure difference inside and outside the hermetic enclosure. The flowmeter (Beijing Jingliang-ACU2OFC) has large and small measurement ranges, and can simultaneously convert the gas leakage rate into the leakage rate under standard conditions (temperature =  $20\text{ }^{\circ}\text{C}$ , atmospheric pressure =  $101.325\text{ kPa}$ ). Its range is selected based on the airtightness pre-test to avoid the measured value being close to the edge of the range and reduce errors; the customized IBEE variable-frequency fans and flowmeters are paired into groups following the principle of “small capacity with small range” and “large capacity with large range”. The straight-through control valve is used for coarse adjustment of pressure difference, the bypass valve for fine adjustment, and the fan frequency for precise adjustment. Additionally, the fan, valves, and flowmeter are connected in series via air ducts to form a pressure difference adjustment and flow measurement system. The air handling unit (AHU) consists of an indoor air handling unit and an outdoor chiller, capable of regulating the indoor air temperature within the range from  $20\text{ }^{\circ}\text{C}$  to  $50\text{ }^{\circ}\text{C}$ . It adopts an air supply mode of upper supply and lower return: the upper air supply utilizes a uniform-flow air supply orifice plate system, which enables air supply from five sides (one top supply and four side supplies), and an independent control of air supply from each side can be achieved.

Table 2. Measuring instrument model and accuracy

| Instrument Name                          | Photo                                                                             | Model and Specification | Measurement Range       | Accuracy            | Instrument Name                       | Photo                                                                               | Model and Specification      | Measurement Range | Accuracy |
|------------------------------------------|-----------------------------------------------------------------------------------|-------------------------|-------------------------|---------------------|---------------------------------------|-------------------------------------------------------------------------------------|------------------------------|-------------------|----------|
| Relative Temperature and Humidity Sensor |  | Finland-VAISALA-HMP110  | −40~60 °C,<br>0~100% RH | ±0.1 °C,<br>±3.5%RH | Low-range flow-meter                  |  | Beijing Jingliang-ACU2OFC-MM | 0.1~10 m³/h       | ±1 FS    |
| Absolute Pressure Sensor                 |  | UK-Druck-PTX5072        | 80 kPa–120 kPa          | ±0.04 FS BSL        | High-range flow-meter                 |  | Beijing Jingliang-ACU2OFC-HM | 5~500 m³/h        | ±1.06    |
| Differential Pressure Transmitter 2      |  | US-Rose-mount-3051C     | −2000~2000 pa           | ±0.2%               | Small-capacity variable-frequency fan |  | China-IBEE Custom-RB-42S-2   | 0~150 m³/h        | -        |
| Anemometer                               |  | China-Xima-AR866A       | 0.3~30 m/s              | 3%                  | Large-capacity variable-frequency fan |  | China-IBEE Custom-1100       | 0~1400 m³/h       | -        |
| Air Handling Unit                        |  | China-IBEE03RST005A7    | 20 °C~50 °C             | ±0.5 °C             | -                                     | -                                                                                   | -                            | -                 | -        |

All instruments meet the accuracy requirements specified in ISO 9972-2015: thermal performance of buildings; determination of air permeability of buildings; fan pressurization method [24]; GB/T 34010-2017: standard for determination of air permeability of buildings; fan pressurization method [25]; NB/T 20018-2021: containment leak tightness test for PWR nuclear power plants [48].

#### 2.1.4. Experimental Process Design

Preparations were conducted before the experiment. Firstly, the external door hermetic enclosure was closed. After closure, sealing gaskets and strips were installed between the enclosure and the hermetic door, with the surrounding area reinforced by bolts. Meanwhile, duct tape was used to door gaps to enhance overall tightness. The ventilation penetrations in the room remained open to balance the indoor and outdoor pressures. Subsequently, the differential pressure transmitter was calibrated: the ventilation hoses at its L and H ports were disconnected, exposing the ports to air. The transmitter was zero-calibrated via a hand-held controller to reduce initial errors. Next, fans, valves, and flowmeters with appropriate ranges were selected, combined, and connected to the reserved fan interface of the hermetic enclosure. The joints of the device were sealed with special gaskets, tightened with screws, and circumferentially wrapped with duct tape to prevent gas leakage. Simultaneously, the pressure hoses inside and outside the hermetic enclosure were connected to the differential pressure transmitter with corresponding ranges, completing all equipment connections.

After the equipment connection was completed, the real-time data monitoring system was activated to display the pressure difference and leakage rate recording curves. Prior to the formal test, the system needed to be checked for leaks: the positive pressure air supply outlet of the fan was connected to the detection position, the fan was started, and the pressure difference was controlled to approximately +1000 Pa. An anemometer was used to check for leaks at the pipeline interfaces, and potential leaks in the hermetic enclosure were inspected with an anemometer or soapy water. After confirming no leaks, the sealed state was maintained; if the sealed state changed, leak detection was performed again.

After the experiment was initiated, the initial pressure difference was first recorded. Meanwhile, a handheld anemometer was used to continuously measure the outdoor wind speed for 2 min, and the maximum wind speed during this period was documented. The wind speed shall be kept below 2.5 m/s during flowmeter reading. Subsequently, the variable-frequency fan was activated to adjust the target pressure difference inside the hermetic enclosure. Data recording began only when the pressure difference curve indicated pressure stabilization (when the fan frequency remained constant, the pressure difference fluctuation range within 10 min was  $\leq 2\%$  of the designed pressure difference). The pressure difference measurement followed the principle of “measuring large pressure differences first, then gradually relieving pressure to measure small pressure differences”. After completing the measurement, the variable-frequency fan was turned off until the indoor and outdoor pressure differences were balanced. The final readings were exported, and the wind speed at the end of the experiment was measured. The collected data included the inflow/outflow leakage rate inside the hermetic enclosure measured by the flowmeter, as well as corresponding parameters such as pressure and atmospheric pressure. The data acquisition frequency was set to 1 time per second. Data were averaged and grouped every 30 s, yielding seven groups in total (210 valid data points). The final measured result was determined as the average of these groups. The entire procedure lasted 3.5 min to obtain the leakage rate of the hermetic door at the target pressure under steady-state conditions.

In the airtightness measurement of large-sized and small-sized hermetic doors, leakage data from five designed pressure difference points were used to fit the formula. Specifically, the pressure difference ranges applied are +1300 Pa, +1400 Pa, +1500 Pa, +1600 Pa, +1700 Pa (positive pressure range) and −1300 Pa, −1400 Pa, −1500 Pa, −1600 Pa, −1700 Pa (negative pressure range), with five points selected within each range for data collection. This fitting scheme meets the requirement of “at least 4 minimum measurement points” specified in the standard [25]. The leakage rate under the target pressure was calculated and determined based on the fitted formulas. This approach can smooth out experimental errors through multiple data points, effectively avoiding the limitations of single-point measurement. Meanwhile, it ensures the authenticity of the law governing leakage rate variation with pressure, providing high-precision data support for subsequent related calculations.

For repeatability and uncertainty control, the reported leakage values were obtained from stabilized measurements and fitted using the multi-point pressure–leakage relation. The instrumentation uncertainty was dominated by the flowmeter accuracy and pressure-control uncertainty, while regression statistics were used to evaluate the quality of the fitted leakage law. This treatment avoids relying on a single pressure point and provides the calibrated input required for the CFD leakage boundary.

## 2.2. Application of CFD

In this section, to address the limitations of the simplified geometric boundary conditions [53,54], we developed a modular boundary condition for the hermetic doors using the momentum method [55] and created a micro-scale ventilation permeation model for CFD simulations. Specifically, the pressure–leakage correlation obtained from experiments was employed as the boundary condition for the hermetic doors to analyze their gas leakage characteristics. As described in the preceding sections, experimental studies were conducted to investigate the gas leakage characteristics of hermetic doors, resulting in the development of a relationship curve between the internal and external pressure differences and the gas leakage rate. Subsequently, the hermetic door was modeled using a modular approach. Specifically, the simplified geometric boundary conditions were replaced with a predetermined number of cells, and experimentally measured boundary conditions were assigned to these cells. The pressure difference–gas leakage rate relationship curve was then integrated into the CFD model to establish the micro-scale ventilation penetration model. This modular approach allows the model to be applied to the CFD simulation of an actual reactor containment building. By simulating gas flow under various operating conditions, the model predicts the gas velocity and pressure distribution inside the reactor containment building, as well as the leakage pathways. The simulation results provide valuable insights for the design optimization and safety assessment of the reactor containment building.

For the positive- and negative-pressure CFD cases, the same reduced-scale geometry, mesh generation strategy, and solver settings were retained. The bidirectional leakage behavior was introduced through the key boundary condition at the door-gap modules: the positive- and negative-pressure pressure–leakage correlations were fitted separately from the tests and assigned according to the corresponding pressure-loading direction. Thus, the model uses a common computational domain while preserving the measured direction-dependent leakage behavior.

## Numerical Methodology

In this study, numerical simulations were performed using the finite volume CFD software Fluent (Fluent2024 R1). Given that the Mach number of the gas flow is significantly less than 1, the gas is considered incompressible. Air is treated as incompressible in the CFD simulations. For the maximum pressure difference of 1500 Pa, a pressure-based upper-bound velocity estimate gives  $U = (2\Delta P/\rho)^{0.5} \approx 50$  m/s when  $\rho = 1.2$  kg/m<sup>3</sup>. This corresponds to  $Ma \approx 0.15$  at room temperature, which is lower than the commonly used  $Ma = 0.3$  criterion for incompressible-flow treatment. Therefore, compressibility effects were neglected in the present room-scale pressure and modular leakage-boundary simulations. The pressure correction method was employed to solve the governing equations, namely The Continuity Equation (The Mass Conservation Equation) and The Momentum Conservation Equation, which are presented as follows:

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \quad (1)$$

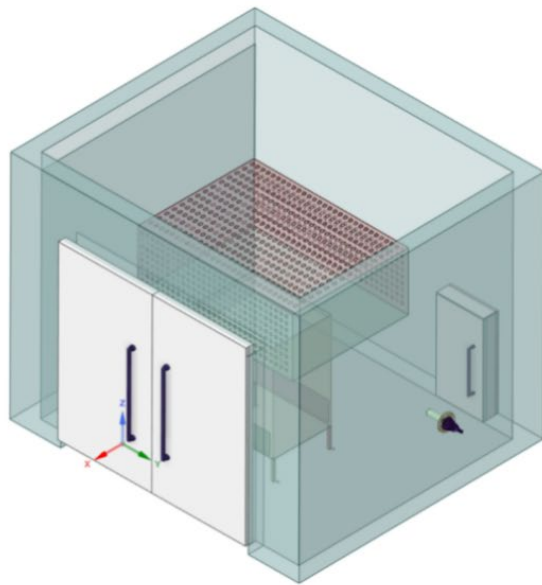
The source is the mass added to the continuous phase from the dispersed second phase and any user-defined sources.

Momentum Conservation Equation:

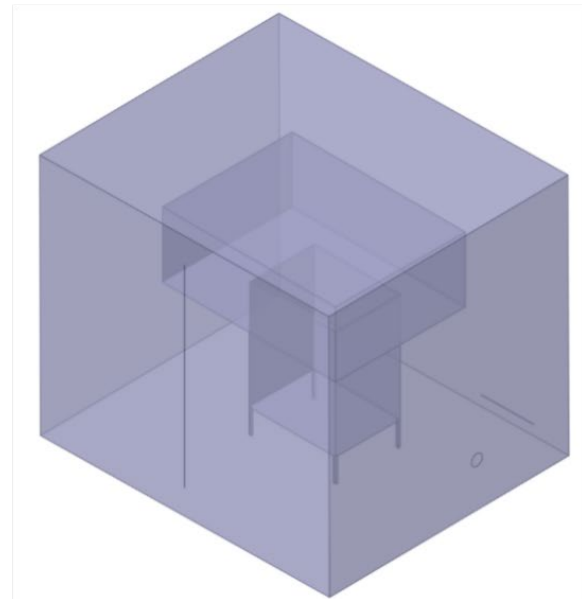
$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\vec{\tau}) + \rho \vec{g} + \vec{F} \quad (2)$$

where  $p$  is the static pressure,  $\vec{\tau}$  is the stress tensor, and  $\rho \vec{g}$  and  $\vec{F}$  are the gravitational body force and external body forces, respectively.

Firstly, the feasibility of the modular treatment was verified in a CFD model of the model construction at a proportional scale (Figure 4). The proportional model of the experimental rig was established using ANSYS Spaceclaim (SPACECLAIM 2024 R1) and then imported into the Fluent Meshing module to create a polyhedral computational mesh (Figure 5). The maximum mesh size was set to 200 mm, and a three-layer boundary layer was applied. If the entrance of the seal door gap was established according to the actual equivalent clearance, it would significantly increase the number of meshes and the computational cost. In addition, a fixed equivalent-gap size cannot represent the measured nonlinear pressure–leakage relationship over both loading directions. Therefore, a modular approach was adopted for both the single and double hermetic doors [56]. The single-leaf door has a total gap length of 7 m and was assigned 1700 modular inlet cells, whereas the double-leaf door has a total gap length of 22.95 m and was assigned 6500 modular inlet cells because of its longer leakage perimeter and additional center joint. At least two cells were maintained across the gap-width direction to avoid concentrating the calibrated leakage flow on a single numerical layer. The physical gasket clearance was not directly resolved; instead, the experimentally fitted pressure–leakage law supplied the integral leakage resistance. An equivalent-gap geometric model would contain about 37,000,000 cells for this configuration, whereas the adopted modular model kept the final mesh at approximately 310,000 cells, corresponding to a cell-count reduction of about 99.2% [37,57]. To ensure simulation quality, all meshes met the criteria of having a minimum orthogonality quality greater than 0.2 and an aspect ratio less than 20.

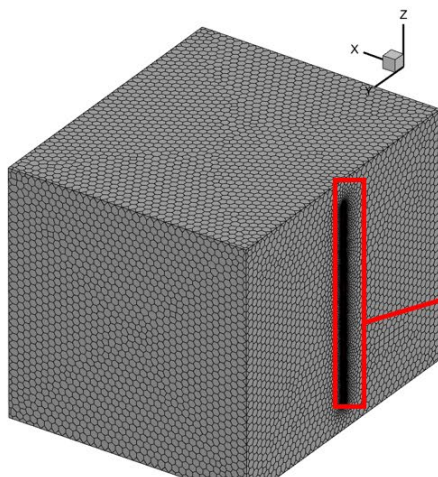


(a) Schematic diagram of the actual design of the model construction

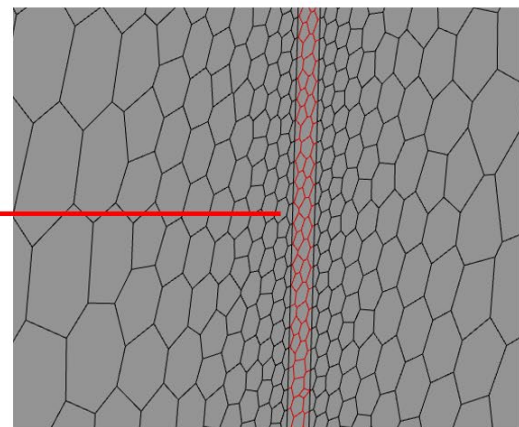


(b) Schematic diagram of the air calculation domain of the model construction

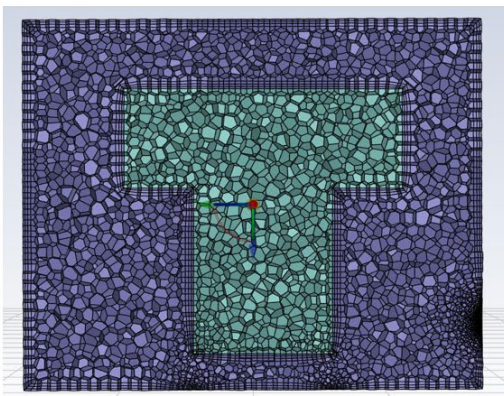
**Figure 4.** The actual model and the three-dimensional model of the test bench.



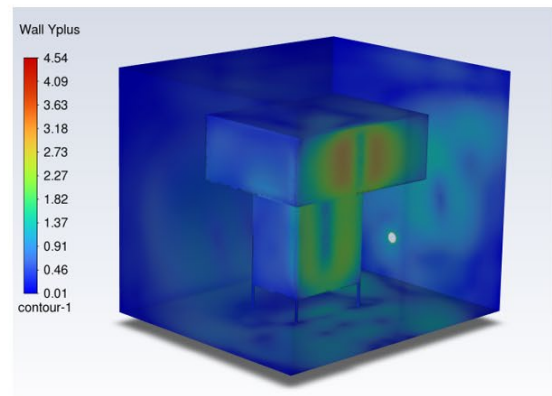
(a) Surface mesh of the reduced-scale model house



(b) The micro-scale ventilation penetration model



(c) Boundary layer mesh and volume mesh



(d) Wall  $y^+$  distribution of the reduced-scale model house

**Figure 5.** Grid division schematic diagram.

A mesh-independence assessment was carried out using three mesh densities of approximately 310,000, 330,000, and 1,540,000 cells. The predicted leakage rate and the average pressure at the monitoring points were selected as the monitored quantities because they represent the main output of the modular leakage-boundary model. The 1,540,000-cell case was used as the refined-grid reference, and the deviations of the coarser meshes are summarized in Table 3.

**Table 3.** Mesh-independence assessment of the CFD model.

| Mesh Cells | Average Pressure at Monitoring Points (Pa) | Predicted Leakage Rate (m <sup>3</sup> /h) |           |
|------------|--------------------------------------------|--------------------------------------------|-----------|
| 310,000    | −1499.9857                                 | Small hermetic door                        | 3.444079  |
|            |                                            | Large hermetic door                        | 17.823252 |
| 330,000    | −1499.9863                                 | Small hermetic door                        | 3.444080  |
|            |                                            | Large hermetic door                        | 17.823260 |
| 1,540,000  | −1499.9858                                 | Small hermetic door                        | 3.444080  |
|            |                                            | Large hermetic door                        | 17.823253 |

As shown in Table 3, further refinement from 310,000 to 330,000 and 1,540,000 cells caused only minor variations in the leakage rate and monitored pressure, while the computational cost increased substantially. Therefore, the 310,000-cell mesh was adopted for the subsequent simulations. The calculation was terminated after the flow field reached a steady state, and the normalized residuals of the governing equations were reduced below  $10^{-3}$ , followed by an additional 1000 iterations to ensure convergence.

In this paper, the experimentally obtained pressure–leakage curves of the hermetic doors were assigned as sign-dependent leakage boundary conditions at the modular door-gap cells. The pressure-based finite-volume solver in Fluent was used. The COUPLED algorithm was employed for pressure-velocity coupling, and second-order discretization was applied to convective terms. Resolved room-scale walls and internal obstacles were treated as no-slip walls. For inlet-type boundaries, the turbulence intensity and turbulence viscosity ratio were specified as 5% and 10, respectively. The turbulence model was the shear-stress transport (SST)  $k$ - $\omega$  model, selected for the resolved indoor airflow because local acceleration, wall effects, recirculation [58,59], and possible separation may occur near the door modules, AHU, and ventilation openings. The microscopic gasket gap itself was not directly resolved; its integral resistance was supplied by the experimentally calibrated pressure–leakage law.

### 3. Results

#### 3.1. Analysis of Experimental Results

Positive- and negative-pressure environments were respectively created inside the hermetic enclosures of the large-sized hermetic door and small-sized hermetic door to directly measure their leakage rates. Data including the initial pressure difference, final pressure difference, target pressure difference, atmospheric pressure readings of the large-sized hermetic door and small-sized hermetic door under positive- and negative-pressure operating conditions, as well as the maximum wind speed during the measurement period, were summarized. For details, see Table 4 (large hermetic door) and Table 5 (small hermetic door).

Table 4. Large hermetic door test record table.

| Room Target Pressure (Pa)                                         |                                     |                                 |                     |                              |                                                                   |                                     |                                 |                     |                              |
|-------------------------------------------------------------------|-------------------------------------|---------------------------------|---------------------|------------------------------|-------------------------------------------------------------------|-------------------------------------|---------------------------------|---------------------|------------------------------|
| −1500                                                             |                                     |                                 |                     |                              | +1500                                                             |                                     |                                 |                     |                              |
| Designed Differential Pressure Inside the Hermetic Enclosure (Pa) | Measured Differential Pressure (Pa) | Outdoor Absolute Pressure (kpa) | Leakage Rate (m³/h) | Max Outdoor Wind Speed (m/s) | Designed Differential Pressure Inside the Hermetic Enclosure (Pa) | Measured Differential Pressure (Pa) | Outdoor Absolute Pressure (kpa) | Leakage Rate (m³/h) | Max Outdoor Wind Speed (m/s) |
| start                                                             | −2.8                                | 101.773                         | 0                   |                              | start                                                             | −1.2                                | 102.014                         | 0                   |                              |
| +1700                                                             | +1711.3                             | 101.760                         | 20.9                |                              | −1700                                                             | −1697.7                             | 101.976                         | −173.33             |                              |
| +1600                                                             | +1602.1                             | 101.738                         | 19.23               |                              | −1600                                                             | −1611.6                             | 101.959                         | −151.85             |                              |
| +1500                                                             | +1504.6                             | 101.723                         | 17.94               | 1.52                         | −1500                                                             | −1505.4                             | 101.93                          | −129.38             | 2.73                         |
| +1400                                                             | +1400.5                             | 101.701                         | 16.35               |                              | −1400                                                             | −1412.8                             | 101.914                         | −111.59             |                              |
| +1300                                                             | +1296.2                             | 101.708                         | 14.99               |                              | −1300                                                             | −1317.4                             | 101.899                         | −94.63              |                              |
| end                                                               | −1.1                                | 101.701                         | 0                   |                              | end                                                               | −3.1                                | 101.884                         | 0                   |                              |

Note: During the measurements of the hermetic enclosure at 1300~1700 Pa, the average indoor and outdoor temperatures were 24.4 °C and 27.0 °C, respectively. At −1300~−1700 Pa, the average indoor and outdoor temperatures were 24.2 °C and 26.4 °C.

Table 5. Small hermetic door test record table.

| Room Target Pressure (Pa)                                         |                                     |                                 |                     |                              |                                                                   |                                     |                                 |                     |                              |
|-------------------------------------------------------------------|-------------------------------------|---------------------------------|---------------------|------------------------------|-------------------------------------------------------------------|-------------------------------------|---------------------------------|---------------------|------------------------------|
| −1500                                                             |                                     |                                 |                     |                              | +1500                                                             |                                     |                                 |                     |                              |
| Designed Differential Pressure Inside the Hermetic Enclosure (Pa) | Measured Differential Pressure (Pa) | Outdoor Absolute Pressure (Kpa) | Leakage Rate (m³/h) | Max Outdoor Wind Speed (m/s) | Designed Differential Pressure Inside the Hermetic Enclosure (Pa) | Measured Differential Pressure (Pa) | Outdoor Absolute Pressure (Kpa) | Leakage Rate (m³/h) | Max Outdoor Wind Speed (m/s) |
| start                                                             | −0.9                                | 101.832                         | 0                   |                              | start                                                             | −1.1                                | 102.095                         | 0                   |                              |
| +1700                                                             | +1691.3                             | 101.835                         | 3.68                |                              | −1700                                                             | −1690.6                             | 102.077                         | −3.83               |                              |
| +1600                                                             | +1604.2                             | 101.844                         | 3.58                |                              | −1600                                                             | −1596.8                             | 101.078                         | −3.70               |                              |
| +1500                                                             | +1495.2                             | 101.842                         | 3.44                | 1.26                         | −1500                                                             | −1502.2                             | 102.076                         | −3.57               | 3.55                         |
| +1400                                                             | +1409.4                             | 101.823                         | 3.33                |                              | −1400                                                             | −1404.9                             | 102.073                         | −3.44               |                              |
| +1300                                                             | +1308.1                             | 101.826                         | 3.19                |                              | −1300                                                             | −1299.8                             | 102.061                         | −3.29               |                              |
| end                                                               | −0.6                                | 101.828                         | 0                   |                              | end                                                               | −1.3                                | 102.064                         | 0                   |                              |

Note: During the measurements of the hermetic enclosure at 1300~1700 Pa, the average indoor and outdoor temperatures were 23.7 °C and 24.3 °C, respectively. At −1300~−1700 Pa, the average indoor and outdoor temperatures were 24.2 °C and 21.2 °C.

For data processing, to account for the influence of natural pressure difference, the five measured pressure difference points were corrected using Formula (3) (derived from ISO 9972-2015 [24]):

$$P = |\Delta P - \left( \frac{\Delta P_{0,1} + \Delta P_{0,2}}{2} \right)| \quad (3)$$

P is the converted value considering the influence of natural pressure difference,  $\Delta P$  is the target pressure,  $\Delta P_{0,1}$  is the natural pressure difference before measurement, and  $\Delta P_{0,2}$  is the natural pressure difference after measurement. To avoid the impact of negative pressure on the fitting formula, all pressure differences are converted to positive values by taking their absolute values. The converted pressure difference values were obtained and fitted with the corresponding leakage rates using Formula (4), yielding the

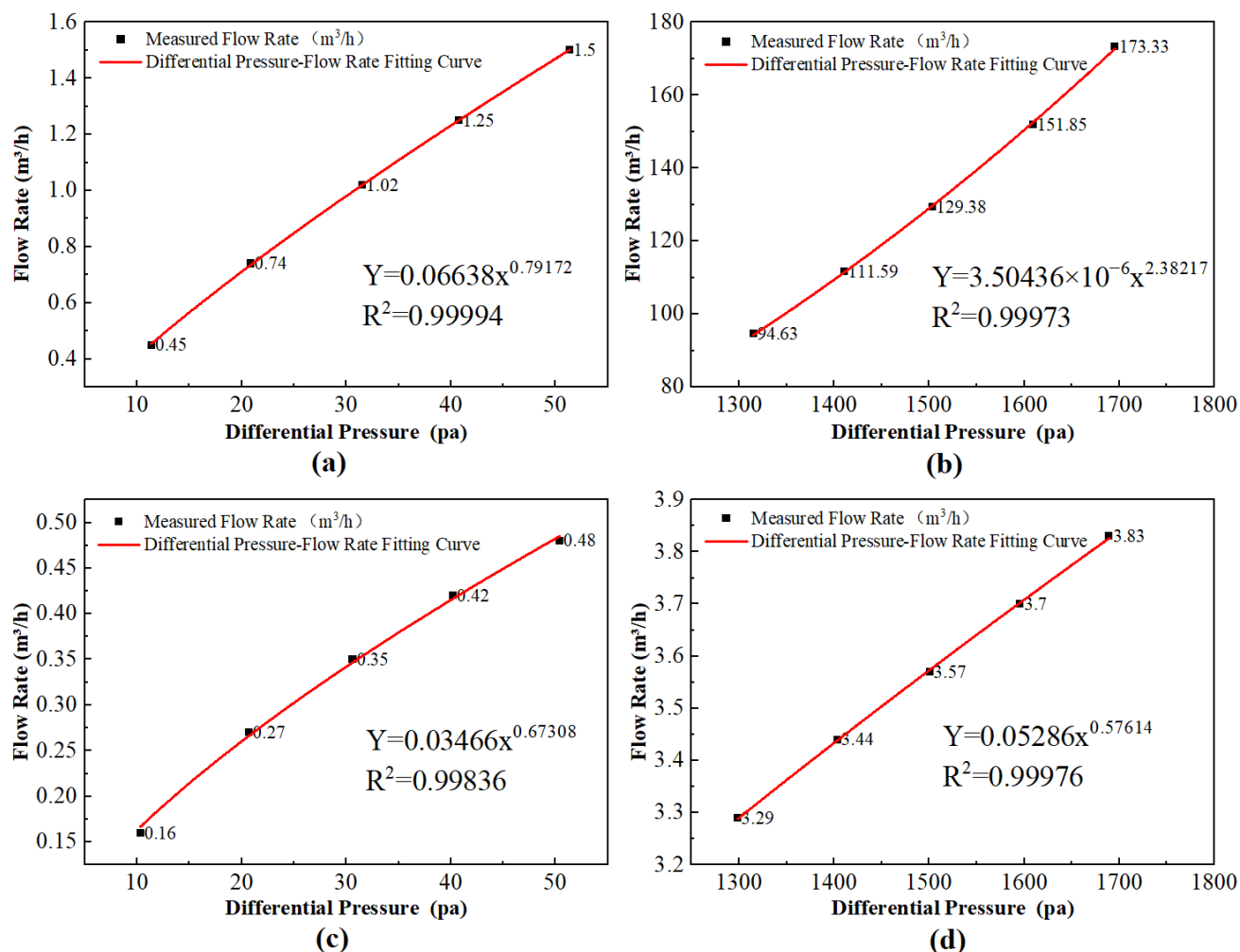
leakage coefficient  $a$  and leakage index  $b$ , as shown in Figure 4. All fitting formulas meet the minimum requirement of  $R^2 \geq 0.98$ , indicating a high correlation between leakage rate and pressure difference. The fitting formulas can accurately describe their relationship, verifying the reliability of the experimental data:

$$Q = C \cdot \Delta P^n \quad (4)$$

(Source of fitting formula: GB/T34010-2017 [25]).

Figure 6 shows the leakage rate-pressure difference fitting curves of large and small hermetic doors over the  $\pm 1500$  Pa range with high fitting accuracy. All fitted equations achieve adjusted  $R^2$  values above 0.999. Figure 6a depicts the large hermetic door under positive pressure, where the leakage rate increases gently with pressure difference; Figure 6b illustrates its negative-pressure curve with a more pronounced growth, conforming to the fluid mechanics principle that leakage intensifies with increasing pressure difference. For the small hermetic door (Figure 6c,d), its leakage rate is much lower at the same pressure difference with a slightly smaller fitting index, owing to its smaller size and reduced total length of leakage channels. Notably, the leakage of the large door is far smaller under positive pressure than under negative pressure, while the leakage of the small door is comparable between positive and negative pressures. The core reasons are as follows: The large door is a double door with a splicing joint between panels, featuring more sealing points and high alignment difficulty, which easily leads to sealing misalignment after long-term use. Under positive pressure (internal high pressure), the outward thrust opposes the door's inward-opening direction, pressing the door panels against the frame and tightening the splicing joint (sealing gaskets fit closely), resulting in low leakage. Under negative pressure (internal low pressure), the inward suction aligns with the door's outward-opening direction, causing panels to expand outward and the splicing joint to open, thus enlarging sealing gaps and significantly increasing leakage. In contrast, the small door (single door) has a simple structure and high stiffness, maintaining stable sealing contact under both positive and negative pressures; therefore, its leakage difference is minor.

The designed pressure differences of  $\pm 1500$  Pa were substituted into the derived formula to obtain the leakage rates of the hermetic door under the room target pressures of  $\pm 1500$  Pa. Based on the total length of the door gaps, the formulas for leakage rate per unit gap length, leakage coefficient per unit gap length, and leakage rate per unit gap length were calculated, as presented in Tables 6 and 7. The measurement uncertainty was calculated in accordance with Appendix NC.3 of DIN EN ISO 9972:2015 [24]. The total uncertainty of four repeated tests is 4.1%, which satisfies the standard criteria of within 10% under windless conditions and 20% under windy conditions. High-pressure difference tests indicate that the leakage rate per unit gap length of the large door is higher than that of the small door: under positive pressure, their per-unit-gap leakage rates are in the same order of magnitude and relatively close; however, under negative pressure, the per-unit-gap leakage rate of the large door is approximately 10 times that of the small door. This is directly related to the structural characteristics of the large double door: it has a longer total gap length and complex force conditions, leading to more severe wear and extrusion of sealing materials and subsequent sealing performance degradation. These combined factors result in a higher per-unit-gap leakage rate for the large double door than the small single door, which also demonstrates the notable negative impact of the adverse outward-opening force condition (under negative pressure) on the airtight performance of the double-door structure.



**Figure 6.** (a) Fitted values of positive pressure difference-leakage rate for large-sized hermetic door; (b) Fitted values of negative pressure difference-leakage rate for large-sized hermetic door; (c) Fitted values of positive pressure difference-leakage rate for small-sized hermetic door; (d) Fitted values of negative pressure difference-leakage rate for small-sized hermetic door.

**Table 6.** Calculation table for leakage rate of large-sized hermetic door.

| Length of Door Gap (m) | Room Target Pressure | Leakage Rate (m³/h) | Formula for Leakage Rate Per Unit Gap Length   | Leakage Co-efficient Per Unit Gap Length | Leakage Index | Leakage Rate Per Unit Gap Length (m³/h·m) | Uncertainty (%) |
|------------------------|----------------------|---------------------|------------------------------------------------|------------------------------------------|---------------|-------------------------------------------|-----------------|
| 22.95                  | −1500 pa             | 17.823              | $Q = 0.00272\Delta P^{1.20161}$                | 0.00272                                  | 1.20161       | 0.7766                                    | 4.1%            |
|                        | +1500 pa             | 129.002             | $Q = 3.50436 \times 10^{-6}\Delta P^{2.38217}$ | $3.50436 \times 10^{-6}$                 | 2.38217       | 5.6210                                    | 4.1%            |

**Table 7.** Calculation table for leakage rate of small-sized hermetic door.

| Length of Door Gap (m) | Room Target Pressure | Leakage Rate (m³/h) | Formula for Leakage Rate Per Unit Gap Length | Leakage Co-efficient Per Unit Gap Length | Leakage Index | Leakage Rate Per Unit Gap Length (m³/h·m) | Uncertainty (%) |
|------------------------|----------------------|---------------------|----------------------------------------------|------------------------------------------|---------------|-------------------------------------------|-----------------|
| 7                      | −1500 pa             | 3.444               | $Q = 0.05866\Delta P^{0.55689}$              | 0.05866                                  | 0.55689       | 0.4920                                    | 4.1%            |
|                        | +1500 pa             | 3.573               | $Q = 0.05286\Delta P^{0.57614}$              | 0.05286                                  | 0.57614       | 0.5104                                    | 4.1%            |

### 3.2. Comparison and Analysis of Factory-Outgoing Data and Actual Installation Data

Factory data and model construction measurement data were obtained using identical measuring instruments and methods, ensuring the data has horizontal comparability. The study first fitted a formula using multiple pressure difference-leakage data points, then substituted the target pressure difference to calculate the fitted target pressure leakage rate. Taking +1500 Pa as a typical test condition, Table 8 compares the leakage data of large and small hermetic doors in both the factory standard state and the post-installation state in actual engineering, so as to quantify the impact of the installation process on the door's sealing performance.

**Table 8.** Comparison of leakage data of hermetic doors between factory-outgoing state and post-installation state in model construction.

|                                               | Large Hermetic Door (+1500 Pa)                   |                                              | Small Hermetic Door (+1500 Pa)                   |                                              |
|-----------------------------------------------|--------------------------------------------------|----------------------------------------------|--------------------------------------------------|----------------------------------------------|
|                                               | Pressure Difference-Leakage Rate Fitting Formula | Leakage Rate at +1500 Pa (m <sup>3</sup> /h) | Pressure Difference-Leakage Rate Fitting Formula | Leakage Rate at +1500 Pa (m <sup>3</sup> /h) |
| Factory-Outgoing State                        | $Q = 1.21597 \times 10^{-4} \Delta P^{1.76725}$  | 49.874                                       | $Q = 0.01168 \Delta P^{0.68172}$                 | 1.709                                        |
| Post-Installation State in Model Construction | $Q = 3.50436 \times 10^{-6} \Delta P^{2.38217}$  | 129.002                                      | $Q = 0.05286 \Delta P^{0.57614}$                 | 3.573                                        |

Under the standard test pressure difference of +1500 Pa, the leakage rates of both types of hermetic doors showed a significant upward trend: the leakage rate of the large hermetic door increased from 49.874 m<sup>3</sup>/h (factory state) to 129.002 m<sup>3</sup>/h (post-installation), with an increase of more than 1.5 times; the leakage rate of the small hermetic door rose from 1.709 m<sup>3</sup>/h to 3.573 m<sup>3</sup>/h, an increase of approximately 1.1 times. This data trend indicates that the full process of actual construction and installation simulated by the reduced-scale model leads to a significant increase in the leakage rate of hermetic doors of both specifications.

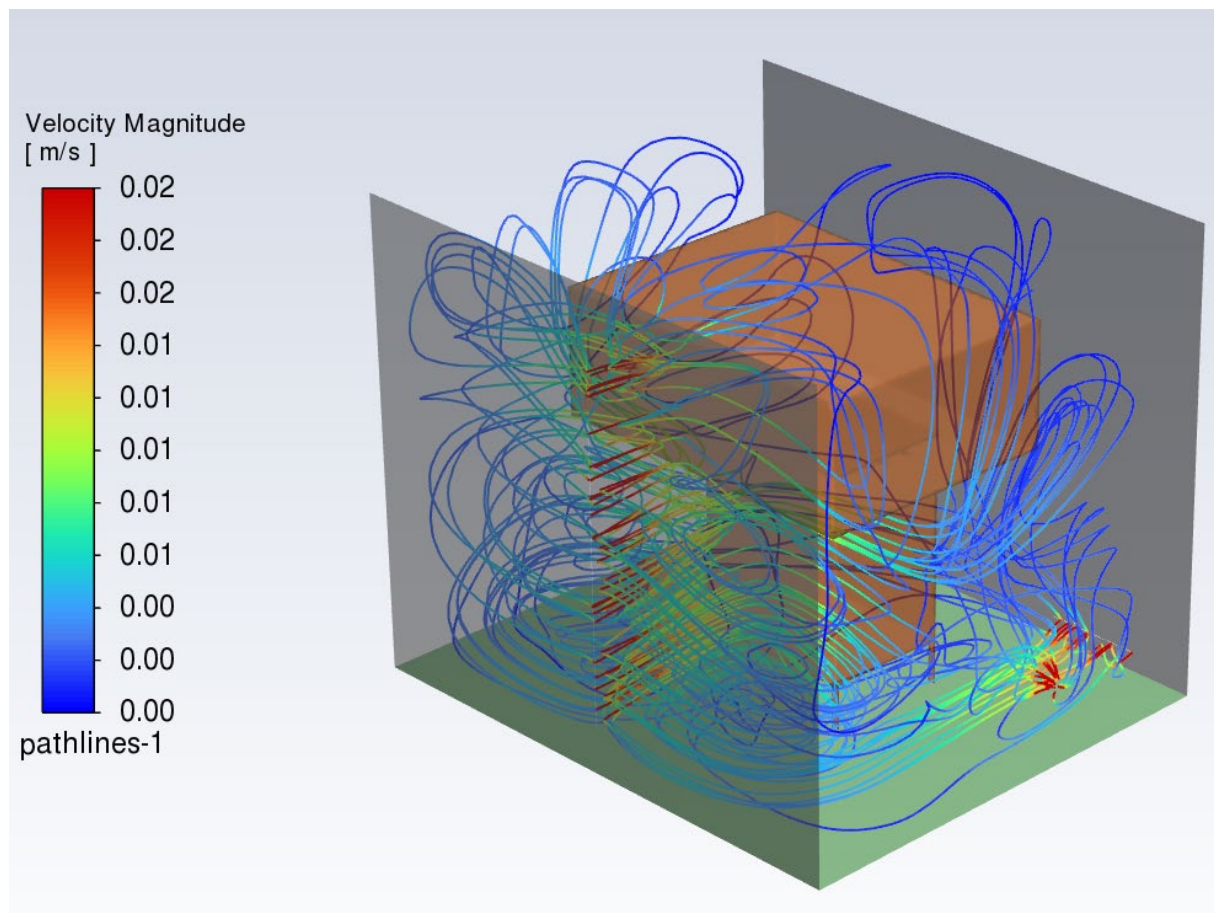
Further analysis shows that the leakage increase in large hermetic doors is more prominent, and the core reasons are closely related to actual engineering scenarios. On the one hand, large doors have large dimensions and heavy weight; therefore, uneven stress during hoisting caused the deviation of embedded parts. On the other hand, large doors have longer sealed strips; if there is a slight deviation in fitting degree during installation, the accumulated leakage channels will be far more than those of small doors, eventually leading to a sharp increase in leakage rate.

The above data fully proves that the standard performance parameters of hermetic doors at the factory cannot fully represent their actual service state after installation. Therefore, in actual engineering, it is necessary to conduct a secondary leakage performance evaluation after the door installation is completed but before it is officially put into use. In this way, the sealing performance of the door can be accurately grasped, the sealing failure caused by installation be avoided, and the overall energy-saving effect and protection function of the high-airtightness enclosing structure be guaranteed.

### 3.3. Analysis of Simulation Results

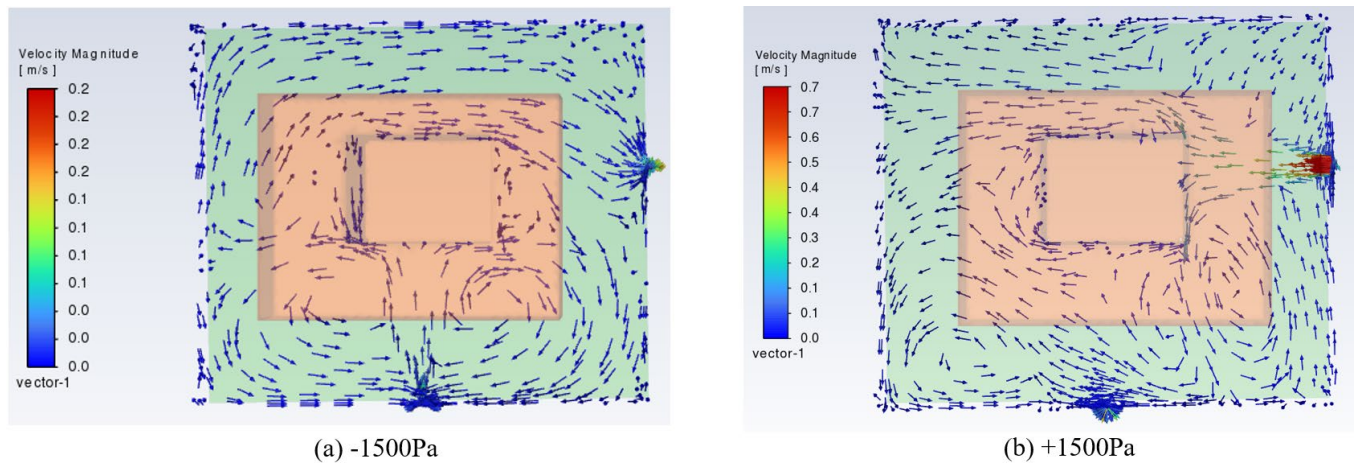
Figure 7 illustrates the airflow path within the scaled-down model at an internal pressure difference of −1500 Pa, which closely matches the actual physical flow field. Specifically, air enters the scaled-down model through the gaps in the hermetic doors, bypasses

the internal air handling unit (AHU), and is finally exhausted through the ventilation outlets. Notably, near the AHU, the airflow accelerates locally due to changes in geometry, forming significant turbulent structures and multiple small-scale vortices.

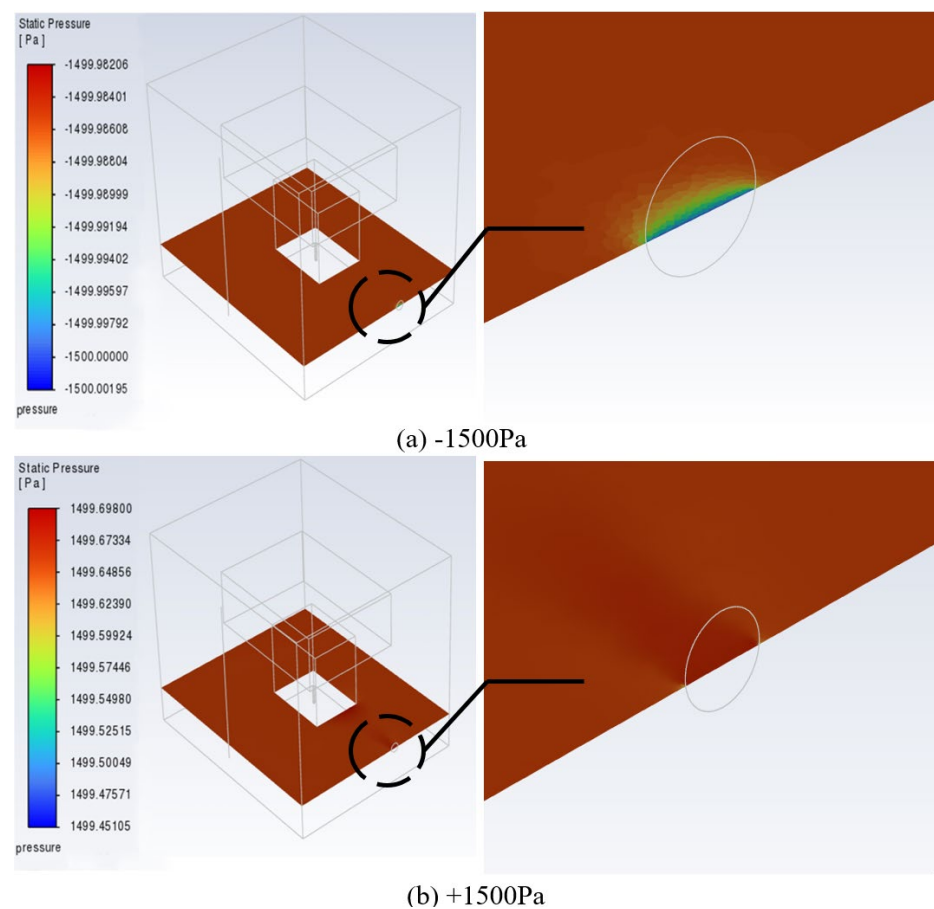


**Figure 7.** Airflow trace diagram of the test bench under  $-1500$  Pa condition.

Figures 8 and 9 present the velocity and pressure distributions at a height of 1.25 m above the ground under the conditions of  $-1500$  Pa and  $+1500$  Pa, respectively. The velocity field in Figure 8a shows that under the  $-1500$  Pa condition, the model construction undergoes exhaust operations through the ventilation penetration, while causing outdoor air to leak into the model construction through the gap of the hermetic door. Under this condition, the leakage rate of the indoor air is relatively low. The AHU inside the model construction acts as a barrier to the air flowing in from the large-sized hermetic doors, resulting in a weak vortex near the rack. The velocity field in Figure 8b indicates that under the  $+1500$  Pa condition, the model construction undergoes supply air operations through the ventilation penetration. Compared with the  $-1500$  Pa condition, the velocity under the  $+1500$  Pa condition is significantly higher. Similarly, the AHU acts as a barrier to the air flowing in from the ventilation penetration, causing a vortex between the rack and the wall. Figure 9 clearly reveals the pressure characteristics under both conditions. For both the  $-1500$  Pa and  $+1500$  Pa conditions, the pressure distribution is relatively uniform within most areas of the model construction. However, slight variations in pressure are observed at the boundary outlet, which are attributed to the boundary effects of the airflow at the exit.

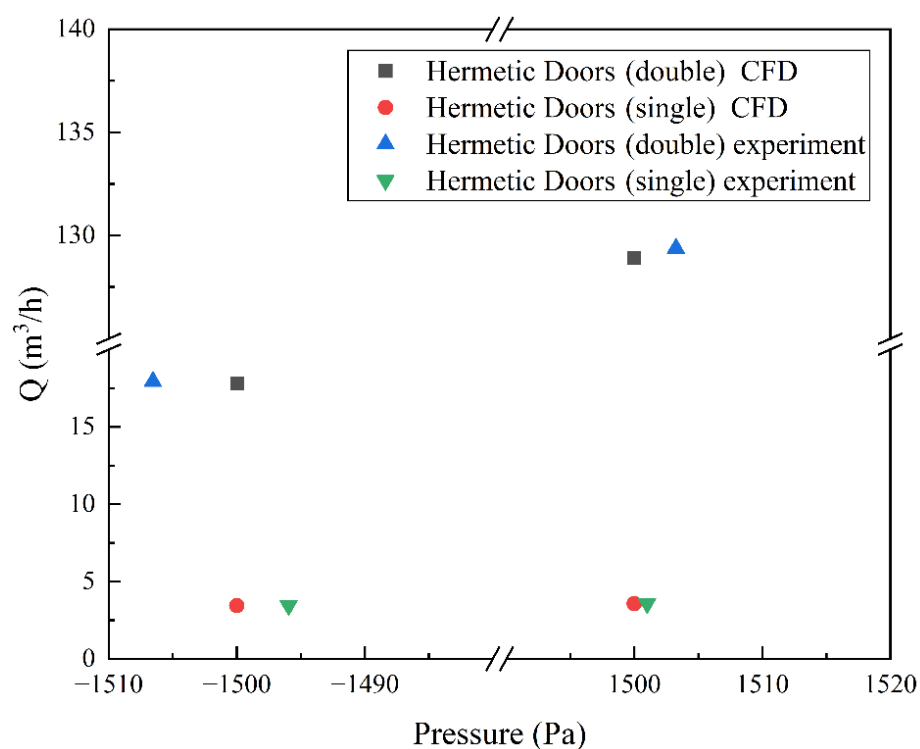


**Figure 8.** Velocity distribution vector diagram at a height of 1.25 m.



**Figure 9.** Pressure map at a height of 1.25 m.

Figure 10 illustrates the comparison between the experimental and simulated gas leakage rates for the small-sized and large-sized hermetic doors under  $-1500$  Pa and  $+1500$  Pa conditions. The experimental and simulated results show good agreement, with an overall relative error of approximately 1.4% for the leakage-rate prediction. The monitored pressure point also shows a small relative deviation of about 0.36% between the simulation and the test. These results indicate that the modular leakage-boundary treatment can reproduce the measured integral leakage behavior and the main pressure response of the model house. Therefore, the proposed CFD model provides a reliable basis for applying experimentally calibrated modular hermetic-door boundaries in future reactor containment building simulations.



**Figure 10.** Comparison of leakage flow of hermetic doors.

#### 4. Discussion

Existing airtightness studies have predominantly focused on residential buildings or standard building envelopes, where pressure levels and airtightness requirements are substantially lower than those of high-risk industrial containment facilities. While previous laboratory studies have analyzed component-level or joint-level airtightness, they fail to replicate the complex behavior of full-scale hermetic doors installed under actual engineering conditions and subjected to extreme bidirectional pressure loading. Furthermore, current computational fluid dynamics (CFD) simulations of leakage in large structures often face significant computational bottlenecks when attempting to directly resolve micro-scale gaps.

This study bridges these gaps by providing full-scale outdoor field measurements under extreme  $\pm 1500$  Pa bipolar pressure conditions. By translating the experimentally measured pressure–leakage correlations into equivalent modular leakage boundaries, this proposed experimental–numerical methodology circumvents the need for complex micro-scale or nanoscale meshing. Our results demonstrate that this framework can accurately capture the dominant integral leakage contributions and macro-airflow responses of hermetic doors while significantly reducing computational costs. This proves that the modular treatment is a highly effective tool for efficiently calibrating the airtightness performance of complex, full-scale enclosure structures.

Despite the robustness of this approach, several limitations must be acknowledged. First, while the modular equivalent boundary improves computational efficiency, it inherently cannot resolve localized micro-scale phenomena, such as local gasket deformation, non-uniform contact pressure, or the detailed fluid dynamics within individual leakage paths. Second, the current CFD simulations were conducted strictly under steady-state conditions. Consequently, transient dynamics resulting from accident-induced rapid pressure fluctuations, cyclic loading, thermal effects, or dynamic door deformation were not captured. Third, regarding the field test data, the observed post-installation leakage

increase is a combined result of multiple construction deviations, including frame alignment, hinge clearance, and gasket compression variations. Due to the constraints of on-site measurement, the independent quantitative impact of specific mm-level mounting tolerances could not be isolated. Finally, for full-scale reactor containment or large airtight building simulations, the main computational challenge is the scale disparity between building dimensions and microscopic door-gap dimensions, which can lead to extremely uneven mesh requirements if gaps are directly resolved. In addition, supply and exhaust system flow rates may be much larger than door-gap leakage rates; therefore, their relative effects on indoor flow characteristics and leakage prediction must be separated. The modular leakage boundary reduces these difficulties by preserving calibrated integral leakage behavior while avoiding direct micro-gap meshing.

To address these limitations and further refine airtightness evaluation, future research will pursue two primary directions. First, to better understand installation impacts, comparative experiments under precisely controlled tolerances will be carried out to isolate the independent effects of mm-level mounting deviations. Second, transient CFD and fluid–structure interaction (FSI) analyses will be integrated into the framework. This will allow for the accurate modeling of sealing component deformation and leakage behavior during transient accident pressure evolution and extreme thermal events, ultimately providing more comprehensive safety assessments for nuclear and biological containment facilities.

## 5. Conclusions

This study conducts fan pressurization tests on two specifications of hermetic doors ( $1.2\text{ m} \times 2.3\text{ m}$  and  $4.8\text{ m} \times 4.45\text{ m}$ ) in a scaled building model under stepwise extreme bipolar pressure loading of  $\pm 1500\text{ Pa}$ . A calibrated CFD method is established to accurately evaluate the overall airtightness of containment structures.

The test results reveal obvious differences in bidirectional leakage performance between double-leaf and single-leaf hermetic doors. Under  $-1500\text{ Pa}$  and  $+1500\text{ Pa}$  pressure conditions, the large double-leaf door presents total leakage rates of  $17.823\text{ m}^3/\text{h}$  and  $129.002\text{ m}^3/\text{h}$ , with linear leakage rates of  $0.7766\text{ m}^3/(\text{h}\cdot\text{m})$  and  $5.6210\text{ m}^3/(\text{h}\cdot\text{m})$ , respectively. Negative pressure significantly impairs its sealing performance due to structural characteristics and middle joints. By comparison, the small single-leaf door exhibits stable and nearly symmetric leakage responses under bidirectional pressures, with total leakage rates of  $3.444\text{ m}^3/\text{h}$  ( $-1500\text{ Pa}$ ) and  $3.573\text{ m}^3/\text{h}$  ( $+1500\text{ Pa}$ ) and linear leakage rates of  $0.4920\text{ m}^3/(\text{h}\cdot\text{m})$  and  $0.5104\text{ m}^3/(\text{h}\cdot\text{m})$ , demonstrating superior pressure adaptability and sealing reliability. Furthermore, the distinct deviation between factory and on-site test data verifies that field installation defects degrade actual airtightness, which emphasizes the essential requirement of post-installation airtightness re-evaluation for engineering applications.

The developed micro-scale air infiltration model achieves excellent consistency between numerical simulations and experimental data. The model precisely captures the indoor airflow characteristics, including weak vortex distribution near air handling units and wall boundaries under extreme positive and negative pressures. The internal pressure field maintains a uniform distribution overall, with slight variations at outlets caused by airflow boundary effects. The high agreement between simulated and measured leakage rates fully validates the accuracy and feasibility of the proposed numerical model.

This work provides authentic full-scale airtightness data of hermetic doors under extreme pressure conditions, offering a cost-effective solution for obtaining actual on-site airtightness parameters of high-performance building envelopes. The research outcomes

can support the performance assessment and engineering optimization of airtight facilities widely used in nuclear safety structures, biosafety laboratories, hospital operating rooms, underground shelters and civil defense containment buildings.

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