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Original Article

Design Development and Performance Verification of Passive Ventilation Device

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Abstract:
To reduce reliance on safety-grade emergency AC power, the safety-grade ventilation system functions are implemented through passive technologies. For fuel buildings with relatively low sealing performance, a passive exhaust system for the fuel operation hall was designed. A set of emergency passive ventilation devices suitable for high spaces in nuclear power plants was developed. The experimental test, seismic analysis and wind load resistance analysis were carried out. The test results show that when the outdoor wind speed is 1 m/s, the ventilation volume of the passive ventilation device is 485 m^3/h; when the indoor thermal pressure is 5 Pa, the ventilation volume is 3080 m^3/h; when the indoor thermal pressure is 5 Pa and the outdoor wind speed is 1 m/s, the ventilation volume is 3130 m^3/h. It can be seen that the ventilation volume increases slowly with the increase of outdoor wind pressure and significantly with the increase of indoor thermal pressure. The indoor thermal pressure plays a key role in the ventilation volume. After installing the purification device, the exhaust volume of the device decreased but still met the technical requirements and all the requirements of radiation protection in the nuclear safety guidelines. Through analysis and calculation, under eight typical equivalent seismic load combinations, the equivalent stress of the steel structure members, the surface stress of the wind turbine and the global deformation of the passive ventilation device are all within the limits, meeting the seismic functional requirements. Under the action of wind load, the mechanical indicators of the protective cover plate, the column and the wind turbine also meet the requirements of the specifications.
Key words: Nuclear power plants; passive ventilation device; test validation; seismic and wind load analyses.

Introduction

Unpowered fans have been maturely applied in the turbine rooms of thermal power plants for passive hydrogen exhaust in case of accidents. Furthermore, in the civilian field, scholars at home and abroad [1,13] adopt turbine ventilators for passive ventilation. Usually, unpowered fans are installed on the roof. By taking advantage of the natural wind force and the air thermal convection caused by the temperature difference between indoors and outdoors, the turbine is driven to rotate, thereby expelling the stale hot air in the room through centrifugal force and negative pressure effect. In addition, some scholars have adopted wind catcher[14,15] to achieve natural ventilation by utilizing the chimney effect. However, if the existing research results are directly applied to the nuclear island plant, it is also necessary to meet the functional requirements of anti-flying projectile, shock waves and rain, and be able to conveniently switch between different working conditions to achieve passive safe operation of the emergency ventilation system in the nuclear power plant.

For the HPR1000 1.0 version nuclear power unit, when a fuel operation accident or a water loss accident in the spent fuel pool causes a high radioactive level, the ventilation system usually switches from the normal operation mode to the low-flow exhaust operation mode. The low-flow exhaust subsystem is of safety grade, equipped with two 100% capacity exhaust fans and a quick-closing isolation valve. In order to maintain the negative pressure of the fuel plant during normal operation or accident conditions, the low-flow exhaust subsystem is powered by the emergency power supply when the external power supply is lost, which is not economically viable.

In the development and design of the new pressurised water reactor models, the safety level emergency AC power supply has been cancelled, and the safety level ventilation system function needs to be realized using passive ventilation technology. The fuel operating hall of the AP1000 reactor model employs a release panel, which is security level and seismic class 1. When the ambient temperature of the fuel operation area reaches 73.9°C, the panel disengages and opens completely within 15s to release the radioactive gases directly to the outdoors, with a short retention time for the pollutants.

In order to solve the deficiencies of the existing design scheme and based on the functions and structures of the fuel plants in the HPR1000 series nuclear power plants, a structural innovation was carried out on the traditional unpowered fans. A set of passive ventilation devices with functions such as working condition conversion, rainproof, anti-flying object, anti-shock wave and anti-earthquake was developed. When in standby mode, they are closed to ensure airtightness, and when needed, they automatically open by gravity. After the power is restored, they are reset by the winch. The ventilation volume under the design outdoor wind speed and thermal pressure need to be greater than 800 m^3/h and the mechanical structure can meet the seismic functional requirements under the ultimate safe earthquake (SL-2). Performance tests, seismic analysis and wind load resistance analysis were conducted on the device to verify that both its dynamic performance and mechanical performance could meet the design requirements.

2. Methods

2.1. Experiments

2.1.1. Description of Passive Ventilation Device

The passive ventilation device developed in this study has an elevating structure, including a passive fan and frame, equipment frame and guiding device, passive drive mechanism (fixed pulley and weight) and winch power system, the structure of the device is shown schematically in Fig. 1.

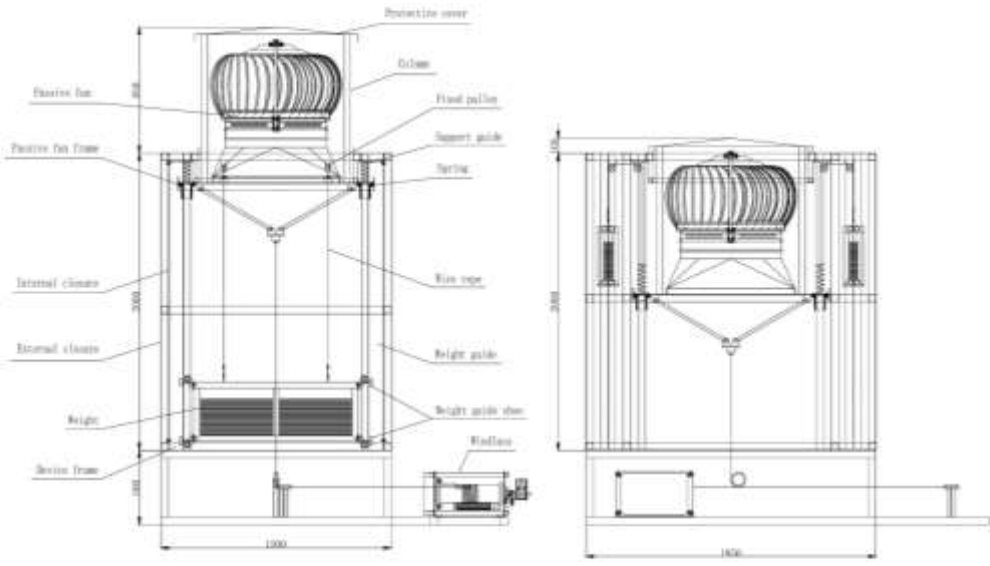


Fig. 1. Schematic diagram of the structure of passive ventilation device

The passive ventilation device adopts the basic principles and theories of gravity, heat pressure and wind pressure. Relying on gravity to start, the natural wind force and the thermal convection of air caused by the difference between indoor and outdoor temperatures are used to push the passive fan to rotate, so that the centrifugal force and the negative pressure effect can be used to discharge the indoor non-fresh hot air.

2.1.2. Test Platform

In order to verify that the dynamic performance of the developed passive ventilation device meets the technical requirements, a prototype was manufactured for experimental test. The principle prototype is shown in Fig. 2. A hot pressure test platform was build to conduct tests on the air leakage rate of the test chamber, the dynamic performance of the passive ventilation device under external wind speed, the dynamic performance under thermal pressure, and the dynamic performance under the combined effect of thermal pressure and external wind speed. In addition, the exhaust characteristics of the passive ventilation device were tested under the conditions of a filter at the inlet of the passive fan and negative pressure in the test chamber.

Fig. 2. Principle prototype of the passive ventilation device

The indoor thermal pressure was simulated by supplying air to the test chamber to create a positive pressure inside the chamber. By adjusting the frequency of the supply fan, the test chamber was kept at a certain stable internal pressure. The ventilation volume of the passive ventilation device in the test chamber was tested respectively under the thermal pressure conditions of 5Pa, 10Pa, 15Pa, 20Pa and 25Pa.

The external wind speed (wind pressure) is simulated by the outdoor parallel air supply bellows. The wind speed at the throat of the passive fan is tested under the outdoor wind speed of 1m/s, 2m/s, 3m/s and 4m/s, and take the arithmetic average value, and then calculate the ventilation volume.

The dynamic performance test platform of the passive fan under the combined action of thermal pressure and external wind speed consists of an outdoor parallel air supply bellows, an passive fan, test chamber, and a positive pressure air supply device in the test chamber. The layout diagram of the test platform and measuring points is shown in Fig. 3.

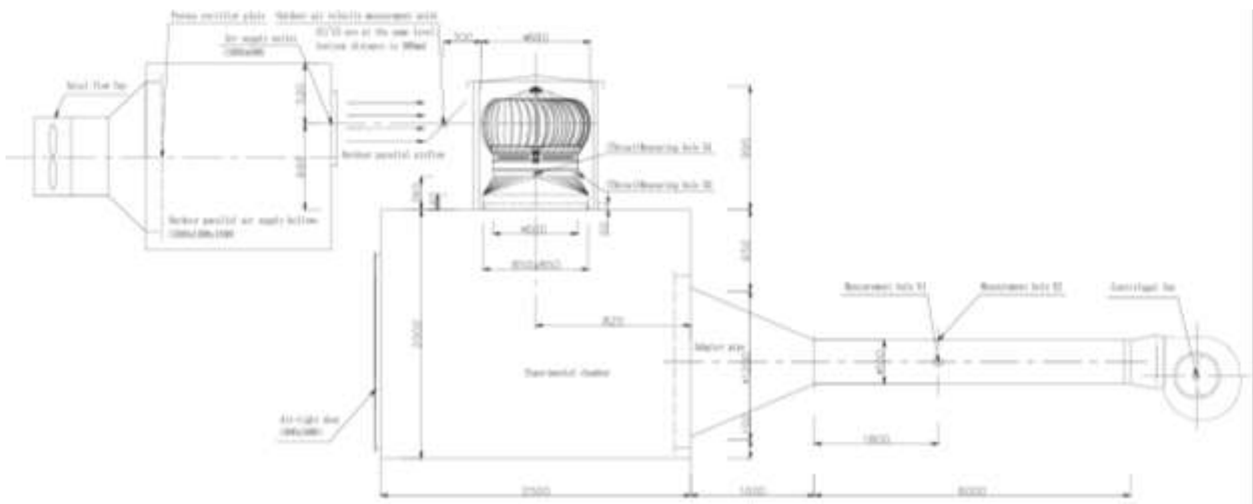


Fig. 3. Schematic diagram of the test platform for the performance of passive ventilation device under the combined effect of thermal pressure and external wind pressure

2.1.3. Operating Mode

Under normal (power supply) working condition, the wire rope power mechanism of the winch is in tension state, which confines the passive fan frame to the cylindrical shell within the concrete foundation. The weight connected to the pulley of the frame is in the high position, and the protective cover covers the top of the cylindrical shell smoothly and fully. Moreover, the cover is equipped with the functions of preventing projectiles, shockwave, rain, and sealing.

Under the power loss condition, the power mechanism of the wire rope releases the wire rope, and the two weights fall steadily and synchronously. The falling speed of the weight is controlled by its own gravity, the damping effect formed by the winch and the rolling guide boots. The passive fan frame is driven to rise smoothly along the support guide rail to the throat of the passive fan all located outdoors.

Under the condition of reset (after the power supply is restored), the steel wire rope power mechanism or hand-cranked wire rope is used to make the passive fan frame drop smoothly along the support guide rail, while the two weights rise synchronously. So that the passive fan can be all in the cylinder, and the protective cover can be fully covered again at the outer edge of the ventilation vent.

2.2. Simulations

In the phase of prototype research, it is an economical and effective method to verify the mechanical properties of passive ventilation device by using computational analysis instead of test. In this study, the finite element structural analysis software Dlubal RFEM 6 was used to analyze the seismic and wind load resistance of the device.

2.2.1. Structural Model

According to the general assembly drawing of the passive ventilation device and the prototype, the combination of surface and rod is adopted. Eight anchor points and suitable material properties are set according to the actual installation situation, and a 1:1 scale model was created. The three-dimensional model and load of the rod are shown in Fig. 7.

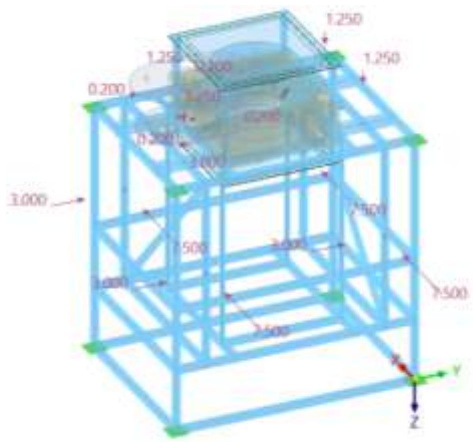


Fig. 7. Simplified model and load distribution of passive ventilation device

2.2.2. Seismic Analysis

In this study, the equivalent static load method is used for analysis and calculation. The peak values of the three components of earthquake are directly combined. The peaks of one directional component are considered as 100%, while the peaks caused by the other two components are considered as 40%, and the symbols of the three components are also considered. Due to the structural symmetry of the passive ventilation device, the following eight representative seismic combinations are considered in the calculation:

①X+0.4Y+0.4Z；②0.4X+Y+0.4Z；

③0.4X+0.4Y+Z；④-X-0.4Y-0.4Z；

⑤-0.4X-Y-0.4Z；⑥X-0.4Y+0.4Z；⑦0.4X-Y+0.4Z；⑧-0.4X-0.4Y+Z

2.2.3. Wind Load Analysis

When the passive ventilation device is operating, the protective cover plate, the column and the throat of the passive fan are in the outside environment. And the wind load is applied to the rods and surfaces of the calculation model to simulate their mechanical properties under the action of a tornado.

2.2.4. Load Combination

For seismic analysis, the load combinations to be considered under SL-2 condition include:

--Dead load: 1g;

--Seismic load: peak acceleration ax=ay=az=6g.

The weights are considered to be 250 kg per side.

Considering the single failure criterion, the load combinations to be considered for tornado conditions include:

--Dead load: 1 g;

--Tornado differential pressure load: a F4 class tornado is adopted for calibration, the maximum wind speed is based on 80 m/s, and the maximum pressure load is about 5000 Pa.

3. Results and Discussion

3.1. Experimental Results

3.1.1. Test Chamber Air Leakage Rate

In order to ensure the accuracy of the exhaust volume test of the passive ventilation device, the air leakage test was carried out on the chamber before the test. By testing the pressure of the sealed experimental chamber and at the same time testing the air volume on the supply air pipe using a pitot tube and an electronic micro pressure gauge, the air leakage rate of the test chamber under different internal pressures is obtained.

The test results show that the air leakage of the chamber increases linearly with the pressure inside the chamber. The air leakage is 4.0 m^3/h at

25 Pa and 4.2 m^3/h at 30 Pa, which indicates that the overall sealing of the chamber is good.

3.1.2. Dynamic Performance of Passive Ventilation Device Under the Action of Outdoor Wind Speed

When the outdoor wind acts alone, the airtight door is opened and the inlet of the test chamber variable diameter pipe is closed. The ventilation volume and speed of the passive ventilation device are tested at different outdoor wind speeds, and the results are shown in Fig. 4.

Fig. 4 reflects that the ventilation volume and rotational speed of the passive fan have a linearly increasing relationship with the outdoor wind speed. When the outdoor wind speed increases from 1 m/s to 4 m/s, the ventilation capacity increases from 485 m^3/h to 1010 m^3/h, and the rotational speed of the passive fan doubles.

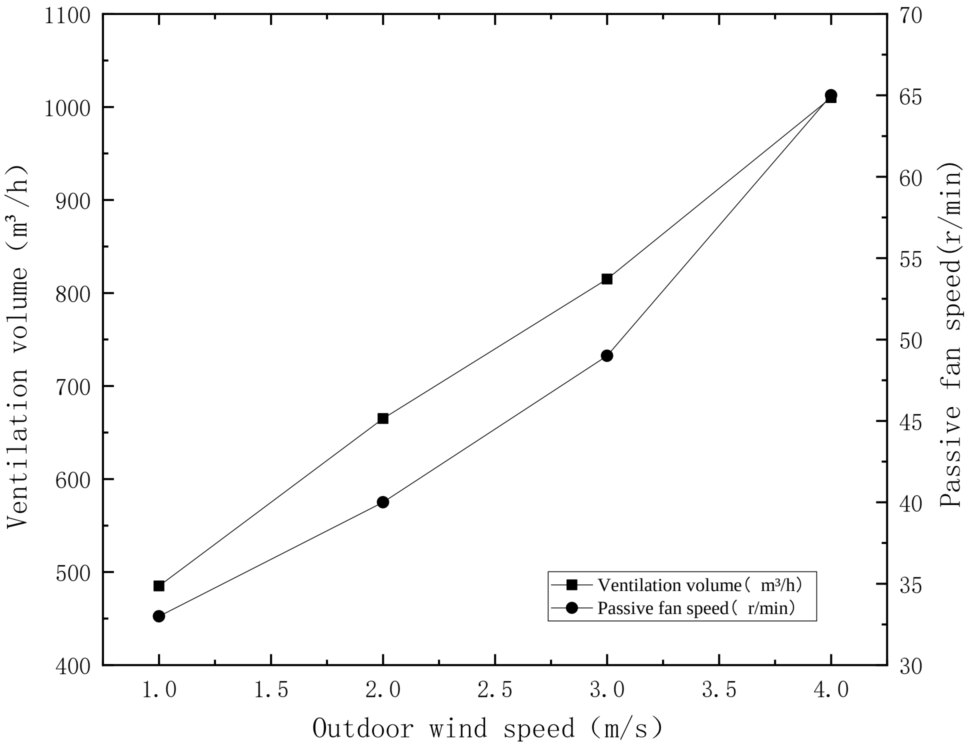


Fig. 4. Exhaust performance of the passive ventilation device under single action of outdoor wind speed

3.1.3. The Dynamic Performance of Passive Ventilation Device Under Indoor Thermal Pressure

When the indoor thermal pressure acts alone, the centrifugal air supply fan is turned on and air is supplied to the test chamber. The ventilation volume and rotational speed of the passive fan under different indoor thermal pressure conditions are tested respectively, and the results are shown in Fig. 5.

From Fig. 5, it can be concluded that the ventilation volume and rotational speed of the passive fan rises with the increase of indoor thermal pressure. When the indoor thermal pressure is increased from 5 Pa to 25 Pa, the ventilation volume enhances from 3080 m^3/h to 6790 m^3/h, and the rotational speed of the passive fan is increased from 57 r/min to 160 r/min. What's more, the indoor thermal pressure is increased from 5 Pa to 15 Pa, the ventilation volume increases rapidly, by about 96.75%. Compared with the outdoor wind pressure existing alone, the exhaust air volume of the passive fan is significantly increased, which indicates that the influence of indoor thermal pressure on the exhaust air volume is much greater than that of outdoor wind pressure.

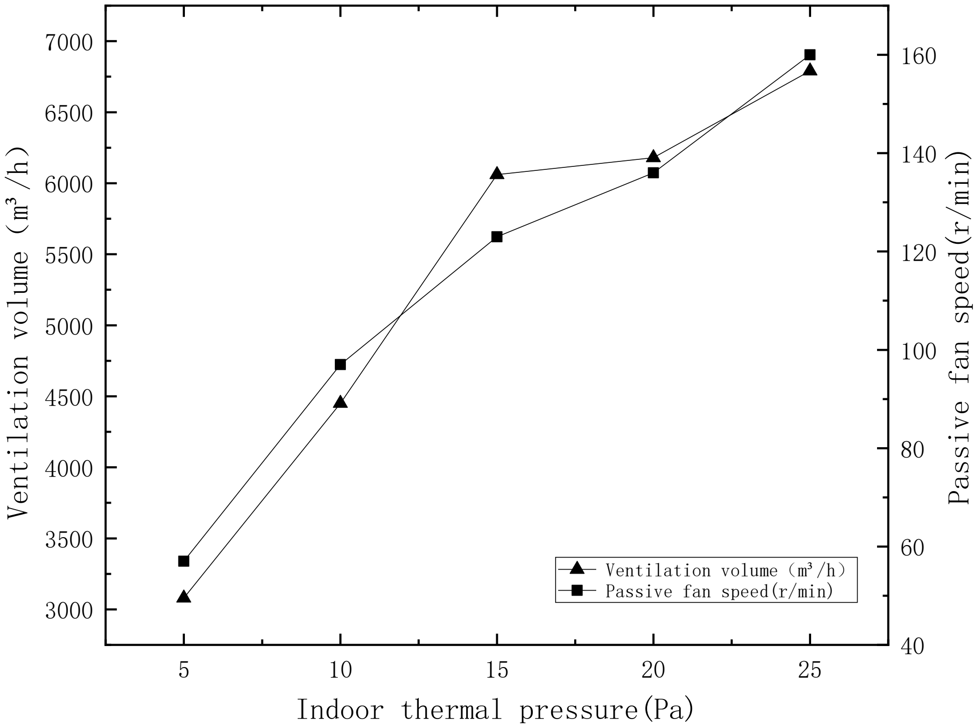


Fig. 5. Exhaust performance of the passive ventilation device under indoor thermal pressure alone

3.1.4. The Dynamic Performance of Passive Ventilation Device Under the Combined Effect of Outdoor Wind Speed and Thermal Pressure

Open the positive pressure air supply device in the test chamber and the outdoor parallel flow air supply box to test the exhaust air volume of the passive ventilation device under the combined action of different indoor thermal pressure and outdoor wind pressure, the results are shown in Fig. 6.

From Fig. 6, it can be concluded that with the increase of outdoor wind speed, the ventilation volume slightly increases when the indoor thermal pressure is 5 Pa, 15 Pa, 20 Pa and 25 Pa. When the thermal pressure is 10 Pa, the ventilation volume basically does not change with the outdoor wind speed. The reason may be that when the wind speed is low (1m/s~4m/s), the wind pressure formed on the windward side prevents the passive fan from discharging air on the windward side.

With the increase of indoor thermal pressure, the ventilation volume rises sharply. When the thermal pressure is 5 Pa and the outdoor wind speed is 4 m/s, the maximum exhaust air volume of the passive ventilation device is 3280 m^3/h. When the thermal pressure is increased to 25 Pa and the outdoor wind speed is 4 m/s, the maximum exhaust air volume is 7490 m^3/h, which is 2.28 times of the former. It is observed that the structure of the passive fan is complete and the operation is normal. Once again, it is proved that the ventilation volume is determined by the internal thermal pressure, and the influence of outdoor wind speed is weak.

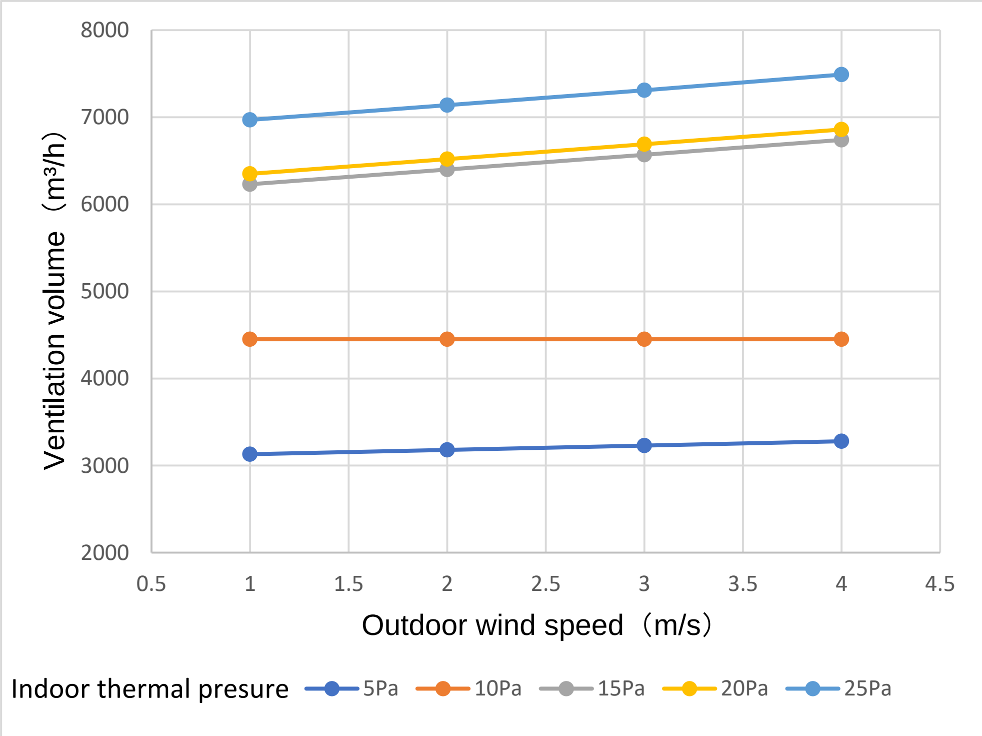


Fig. 6. Exhaust volume of the passive ventilation device under the combined action of outdoor wind speed and indoor thermal pressure

3.1.5. The Influence of Filters on the Dynamic Performance of Passive Ventilation Device

Most nuclear power plants are built in coastal sites with better atmospheric dispersion conditions. If the passive ventilation device is applied in a site with poor diffusion conditions or dense surrounding personnel, a low-resistance air filter can be selected. And the ultra-thin structure of the HEPA filter material and activated carbon bed is designed to further reduce the release of radioactive materials to the outdoors by adsorbing radioactive aerosols and iodine.

In this study, a G1-level coarse effect filter with local resistance of about 25 Pa was installed at the base entrance of the passive fan in the sky circle to test the ventilation volume of the passive fan under different working conditions. The test results are shown in Tab. 1.

From Tab. 1, it can be summarized that in the presence of the G1 class filter, the ventilation volume is substantially reduced. When the outdoor wind speed is 2 m/s, the ventilation capacity of the passive fan is 480 m^3/h with the filter and 665 m^3/h without the filter (refer to section 3.1.2 for details). The indoor thermal pressure is 10 Pa, the ventilation volume without filter is 4450 m^3/h (refer to section 3.1.3 for details). When the filter is set, the air flow of the passive fan is only 920 m^3/h, which is 79.33% lower than that of the former. Under the condition of 2 m/s outdoor wind speed combined with 10 Pa indoor thermal pressure, when there is no filter, the ventilation volume of the passive fan is 4450 m^3/h (refer to Section 3.1.4 for details). When the filter is set, the ventilation volume is only 990 m^3/h, which is 77.75% lower than the former. It can be seen that the exhaust resistance has a significant impact on the ventilation volume, but it still meets the technical requirement of ventilation volume greater than 800 m^3/h.

Tab. 1. Exhaust volume of the passive ventilation device with the filter installed

Test items	Outdoor wind speed		Indoor thermal pressure		Outdoor wind speed + indoor thermal pressure	
ventilation capacity (m³/h)	1 m/s	2 m/s	5 Pa	10 Pa	2 m/s+5 Pa	2 m/s+10 Pa
	330	480	490	920	520	990

3.1.6. The Exhaust Characteristics of the Passive Ventilation Device under Negative Pressure inside the Chamber

The air supply fan of the positive pressure air supply unit is changed to exhaust fan, and the exhaust characteristics of the passive fan under -5Pa and -10Pa in the test chamber are studied.

The clockwise rotation of the passive fan is defined as the forward rotation and it is in the exhaust state. Counterclockwise rotation is reverse rotation and it is in the air intake state. The actual measurement shows that when the pressure inside the chamber is -5Pa, the initial state of the passive fan is reverse. When the outdoor wind speed gradually increases, the rotational speed of the passive fan gradually decreases. When the external wind speed is 4.36m/s, the critical point of forward and reverse rotation (0 speed) is reached, and at this time, the static pressure at the throat of the passive fan is -13Pa. When the outdoor wind speed increases to 6 m/s, the passive fan starts to rotate forward, with an exhaust volume of approximately 2000 m³/h. When the pressure inside the cabin further drops to -10Pa, even if the outdoor wind speed is 6m/s, the passive fan cannot reach the critical point of forward and reverse rotation, and the passive fan remains in the intake state all the time.

However, due to the chimney effect, there is a pressure gradient in the height direction, and the phenomenon of outdoor air backflow will not occur at the top of the fuel operation hall.

3.2. Simulation Results

3.2.1. Seismic Analysis

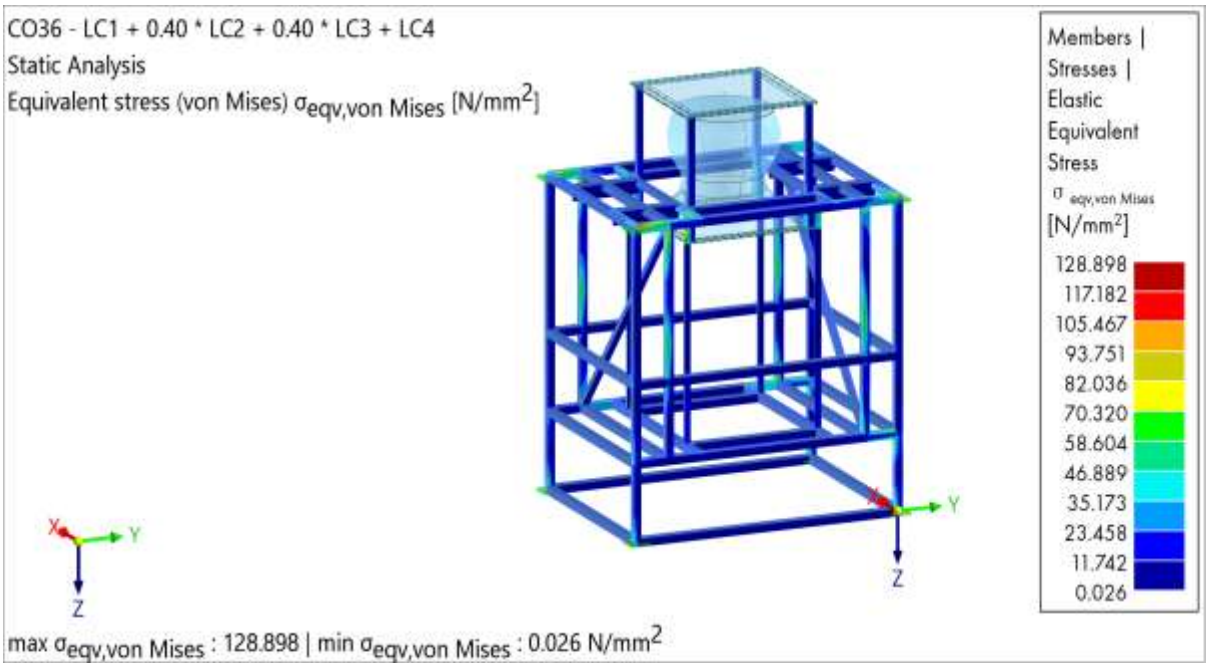
The seismic analysis and evaluation of the passive ventilation device includes the equivalent stresses of the steel structure rods, the stresses on the surface of the passive fan, and the global deformation. The calculation results and evaluation are shown in Tab. 2.

Tab. 2. Evaluation of the results of seismic analyses of passive ventilation device

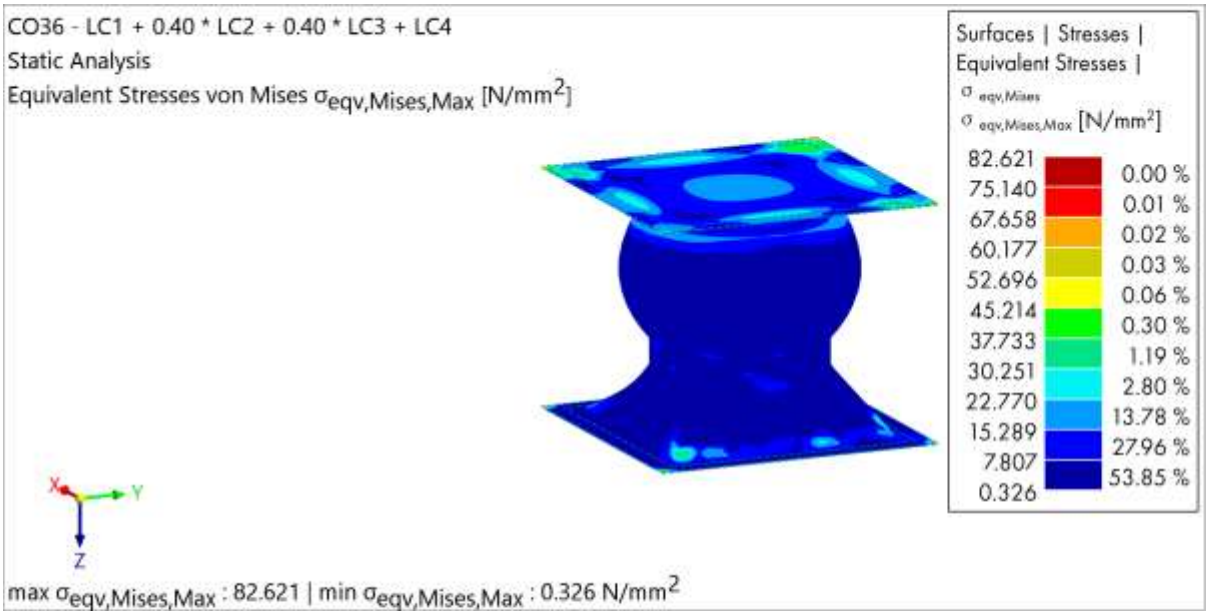
Load combination	Maximum equivalent stress of the rods (N/mm^2)	Maximum equivalent stress of passive fan (N/mm^2)	Maximum film stress of passive fan(N/mm^2)	Global deformation (mm)
X+0.4Y+0.4Z	174.37	100.66	10.34	4.24
0.4X+Y+0.4Z	144.82	104.74	11.75	4.06
0.4X+0.4Y+Z	128.90	82.62	11.14	4.79
-X-0.4Y-0.4Z	150.16	92.34	9.56	3.67
-0.4X-Y-0.4Z	130.48	99.27	10.19	3.47
X-0.4Y+0.4Z	161.78	100.43	10.29	4.24
0.4X-Y+0.4Z	148.47	104.91	11.76	4.07
-0.4X-0.4Y+Z	129.08	81.49	10.69	4.80

According to the C-level evaluation criteria specified in NB/T 20038-2011[16], the permissible stress of steel structure rods of passive ventilation device is 235 N/mm^2, the maximum deformation is not more than 17.1 mm, the equivalent stress of the passive fan is less than 300 N/mm^2, and the film stress is less than 150 N/mm^2. After calculation, for the above 8 load conditions and combinations, all mechanical indexes of the passive ventilation device meet the limit value in

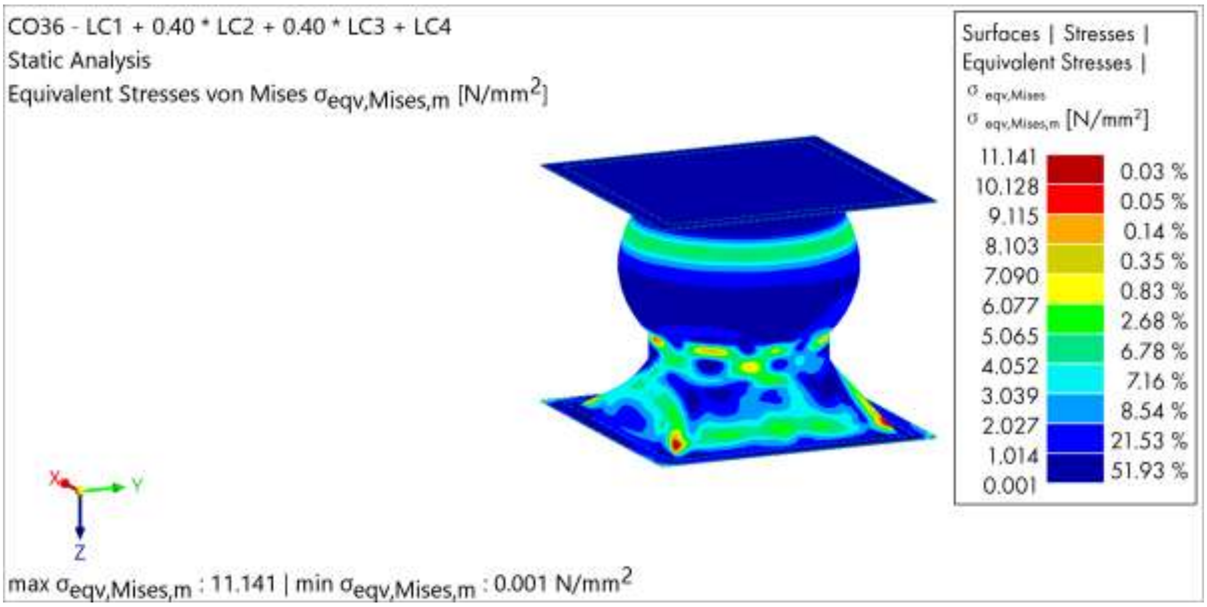
NB/T 20038-2011[16] under equivalent seismic load, and the mechanical mechanism can realize the seismic functional requirements of SL-2. Among them, under the load combination of case 3, the elastic equivalent stress of the steel structure rods is the smallest, which is 128.9 N/mm^2, but the global deformation is relatively large, which is 4.79 mm. The equivalent stress of the passive fan is 82.62 N/mm^2, and the thin film stress is 11.14 N/mm^2. Taking the Case 3 as an example, the calculation results are shown in Figure 8 (a)-(d).



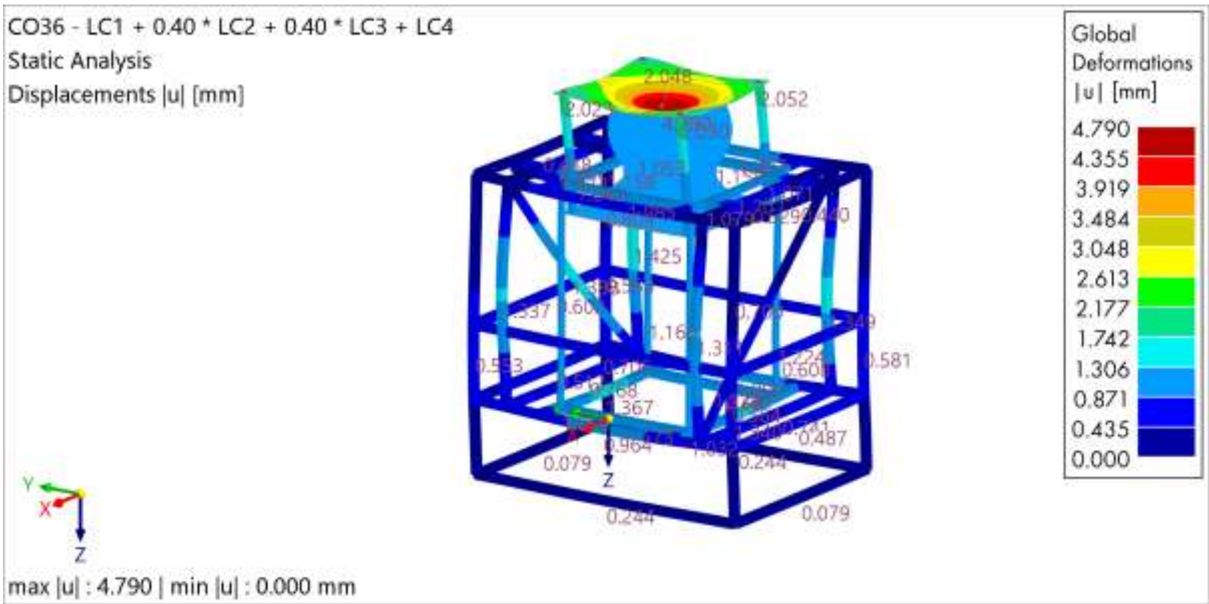
(a) Elastic equivalent stress of steel structure rods



(b) Equivalent stress of the passive fan



(c) Film stress of the passive fan



(d) Global deformation of the passive ventilation device

Fig. 8 Mechanical properties of the passive ventilation device

3.2.2. Wind Load Analysis

After calculation, the maximum equivalent force of the four columns is 26.39 N/mm^2, and the maximum deformation is 0.39 mm. The maximum equivalent force of the protective cover plate is 103.84 N/mm^2, the maximum film stress is 10.17 N/mm^2, and the maximum deformation is 5.64 mm. The maximum equivalent force of the passive fan is 59.02 N/mm^2, the maximum film stress is 16.74 N/mm^2, and the maximum deformation is 0.94 mm. It can be seen that, under the action of wind load, the mechanical indexes of the protective cover plate, the column and the passive fan can satisfy the relevant requirements in the specification NB/T 20038-2011[16].

3.3. Radiation Protection Analysis

The activation conditions of the passive ventilation system include: when a fuel handling accident occurs during normal operation and shutdown of the power plant, and the small flow exhaust subsystem of the fuel building is unavailable, the passive ventilation system should be activated. When the fuel building loses power and a fuel handling accident occurs, the passive ventilation system should be operated. In the event of a loss of cooling function in the fuel building's spent fuel pool, the passive ventilation system can be activated to remove steam, heat and contaminants.

Under the design basis accident, this system can prevent the backflow of air and rain due to outdoor wind pressure, and prevent the unorganized diffusion of radioactive air in the bottom area of the pool. Additionally, it can provide an exhaust driving force of 5-10 Pa under the combined effect of indoor thermal pressure and outdoor wind pressure. The effective operation of this system creates suitable environmental conditions for personnel to safely evacuate within 30 minutes and re-enter after 72 hours. Compared with the analysis assumption of direct release of radioactive substances into the environment, considering the passive ventilation system, the radiation dose received by the public outside the site within 2 hours after the accident can be effectively reduced, which meets the principle of as low as reasonably achievable[17].

3.4. Innovative Analysis

For the first time in China, the passive fan and gravity energy storage have been combined to achieve passive ventilation in radioactive workshops. The innovation points mainly lie in the structural design of the passive ventilation device and the measurement method of ventilation volume.

Based on the principle of gravity, it is proposed that under the condition of power failure, the passive fan is driven by a heavy hammer and starts up passively in the cylindrical shell through the transmission mechanism of the steel wire rope pulley block, thus achieving passive ventilation. After the power supply is restored, the winch pulls the frame of the passive fan to reset it, and at the same time, the heavy hammer is stretched to a high position to store gravitational potential energy. The passive fan moves smoothly up and down within the fixed protective cover through a lifting mechanism, ensuring that it can be turned on when needed and remain off when in standby mode effectively, realizing flexible switching of operating conditions to meet different design functional requirements.

By applying the theory of fluid mechanics, the changes in the internal pressure of the test chamber after considering the outdoor wind speed (decrease/increase) were tested. The frequency of the centrifugal supply fan was adjusted (increase/decrease), and the supply air volume was increased/decreased to restore the internal pressure of the test chamber to the internal pressure under the effect of thermal pressure alone. The air volume measured at this time is the ventilation volume after superimposing the indoor thermal pressure and the outdoor wind speed.

4. Conclusion

This study proposes a set of passive ventilation device for the fuel operation hall, which combines a passive fan with a gravity-lift structure. It can achieve passive ventilation for the high and large space in nuclear power plant buildings by utilizing the outdoor wind pressure and indoor thermal pressure after a power failure. Through experimental tests, seismic analysis, and wind load analysis, the dynamic and mechanical performance of the device has been verified. The research results show that:

1) The ventilation volume of the passive ventilation device increases slowly with the increase of outdoor wind pressure and significantly with the increase of indoor thermal pressure. The indoor thermal pressure plays a key role in determining the ventilation volume.

2) When the outdoor wind speed is 1 m/s, the ventilation volume of the passive ventilation

device is 485 m³/h; when the indoor thermal pressure is 5 Pa, the ventilation volume is 3080 m³/h; when the indoor thermal pressure is 5 Pa and the outdoor wind speed is 1 m/s, the ventilation volume is 3130 m³/h.

3) Under the influence of outdoor wind pressure and indoor thermal pressure, the passive ventilation device can generate a certain negative pressure to overcome the initial resistance of the G1 grade coarse filter. Under the condition of an outdoor wind speed of 2 m/s and a thermal pressure of 10 Pa, the ventilation volume is approximately 1000 m³/h. It still meet the system design requirement of a ventilation volume greater than 800 m³/h.

4) Under eight representative equivalent seismic load combinations, the equivalent stress of the steel structure members, the surface stress of the passive fan, and the global deformation of the passive ventilation device all meet the limit values specified in NB/T 20038-2011. The mechanical structure can meet the seismic functional requirements under SL-2. Moreover, under an outdoor wind speed of 80 m/s, all mechanical indicators of the protective cover plate, columns, and passive fan also meet the code requirements.

5) This passive ventilation device can be widely applied to other large spaces in nuclear power plants, achieving flexible switching between different working conditions. When used in a diesel generator plant, by changing the control mode, the ventilation device runs continuously when the diesel engine is in standby mode. After the diesel engine is put into operation, the device stops and maintains airtightness to the outside to avoid airflow short circuits due to mechanical exhaust.

6) The design of the passive exhaust system in the fuel operation hall complies with the relevant provisions of section 4.7 in "Heating, Ventilation and Air Conditioning Systems" in the current Chinese guideline "Design of Auxiliary Systems and Support Systems for Nuclear Power Plants" (HAD102/22-2022).

Credit Authorship Contribution Statement

Jing Liu: Writing-original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Bei Hu: Writing-review and editing. Haonan Chen: Resources, Project administration.

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.

Data Availability

Data will be made available on request.

References

1. Li PQ, Kong RT, Li MZ, et al. Design of a ventilation system with passive fan for photovoltaic-complemented logistics warehouses[J]. Energy and Energy Conservation, 2023,(12):75-79. DOI:10.16643/j.cnki.14-1360/td.2023.12.010.
2. Kang SY. Research on the natural ventilation characteristics of industrial plants under the action of non powered wind caps driven by solar energy [D]. Xi'an university of architecture and technology, 2022. DOI:10.27393/d.cnki.gxazu.2022.001357.
3. Gao JH, Ma BY, Gao ZQ. Application of unpowered fans on offshore platforms [J]. HVAC, 2021, 51 (11): 77-80. DOI:10.19991/j.hvac1971.2021.11.014.
4. Sun YJ, Shen HG. Industrial ventilation [M]. 4th edition Beijing: China architecture & building press, 2010: 295.
5. Liu ZQ. Application of unpowered fan on arched corrugated steel roof [J]. New industrialization, 2021,11(07):184+186. DOI: 10.19335/j.cnki.2095-6649.2021.7.085.
6. Zhang Y, Wang Q. ANSYS result analysis of

two types of unpowered fan outer blades [C]. Proceedings of the 25th academic annual conference of Beijing society of theoretical and applied mechanics. School of mechanics and civil engineering, China university of mining and technology (Beijing), 2019: 625-626.
7. C. Lai. Experiments on the ventilation efficiency of turbine ventilators used for building and factory ventilation. Energy & Buildings 35 (2003) 927–932. DOI: 10.1016/S0378-7788(03)00024-0.
8. C. Lai, I.S. Kuo. Assessment of the potential of roof turbine ventilators for bathroom ventilation. Building Services Engineers: Technical note 26.2, 2005, pp. 173–179.
9. C. Lai. Prototype development of the rooftop turbine ventilator powered by hybrid wind and photo-voltaic energy. Energy & Buildings 38 (2005) 174–180. DOI: 10.1016/J.ENBUILD.2005.06.004
10. S. West. Improving the sustainable development of building stock by the implementation of energy efficient, climate control technologies. Building & Environment 36 (1999) 281–289.
11. J.D. Dale, M.Y. Ackerman. Evaluation of the performance of attic turbine ventilators. ASHRAE Transactions 99 (1) (1993) 14–22, USA.
12. Jason Lien*, Noor Ahmed. Numerical evaluation of wind driven ventilator for enhanced indoor air quality. Procedia Engineering 49 (2012) 124–134. DOI: 10.1016/j.proeng.2012.10.120.
13. N.A.Ahmed. Wind-solar driven natural electric hybrid ventilators. Wind Power (2010) 537-558. DOI: 10.5772/8349.
14. L. Li, L.M. Mak. The assessment of the performance of a wind catcher system using CFD. Building & Environment 42 (2005) 1135–1141. DOI: 10.1016/j.buildenv.2005.12.015.
15. A.A. Elmualim. Effect of damper & heat source on wind catcher natural ventilation performance. Energy & Buildings 38 (2006) 939–948. DOI:10.1016/j.enbuild.2005.11.004.
16. National nuclear safety administration. Design safety regulations for nuclear power plants: HAF 102-2016 [S]. Beijing: National nuclear safety administration, 2016: 51.
17. National energy administration. Code on nuclear air and gas treatment general requirement on design and fabrication: NB/T 20038-2011 [S], 2011: 8.