

Experimental Investigation of Tungsten Dust Resuspension during In-Vessel LOCA Events in Fusion Reactors

Authors: Dr. Zhijie Qin, Zhang, Dr. Shichao, Chen, Dr. Chao, Wang, Dr. Zhen, Li, Dr. Tao-Sheng, Zhang, Dr. Shichao

Date: 2026-01-10T11:35:05+00:00

Abstract

Quantifying the resuspension of radioactive tungsten dust during in-vessel Loss of Coolant Accidents (LOCAs) is critical for fusion safety licensing, yet experimental data under high-pressure helium injection conditions remain scarce. In this study, micron-scale tungsten dust resuspension is investigated using the independently developed DustSAFER facility, which simulates helium leakage into a vacuum environment. The influences of nozzle diameter (1, 2 mm), injection pressure (2, 4, 8 MPa), initial vacuum level (300, 2000, 5000 Pa), and substrate roughness are systematically examined. The results indicate that increasing the nozzle diameter (break area) and injection pressure markedly enhances dust resuspension. In contrast, the initial vacuum level exhibits a negligible effect on the resuspension fraction. This counter-intuitive behavior is attributed to a competing mechanism: the increased flow acceleration due to jet expansion is effectively offset by the drag reduction caused by gas rarefaction (slip effects). In addition, substrate roughness shows a clear threshold behavior: smooth surfaces promote particle mobilization via sliding, whereas rough surfaces suppress particle detachment owing to enhanced inter-particle cohesion. These findings provide essential experimental data for validating radioactive source resuspension models and underpin more accurate safety assessments for fusion reactors.

Full Text

Preamble

Experimental Study on Tungsten Dust Resuspension during In-Vessel LOCA in Fusion Reactors

Zhijie Qin,^{1,2} Shichao Zhang,^{1†} Chao Chen,¹ Zhen Wang,¹ and Taosheng Li¹

¹Institute of Nuclear Energy Safety Technology, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei 230031, China

²University of Science and Technology of China, Hefei 230026, China

Quantifying the resuspension of radioactive tungsten dust during an in-vessel Loss of Coolant Accident (LOCA) is critical for fusion safety licensing, yet experimental data for high-pressure helium injection remains scarce. This study investigates micron-scale tungsten dust resuspension using the independently developed DustSAFER facility, simulating helium leakage into a vacuum environment. The effects of nozzle diameter (1, 2 mm), injection pressure (2, 4, 8 MPa), vacuum level (300, 2000, 5000 Pa), and substrate roughness were systematically evaluated. Results show that increasing the nozzle diameter (break area) and injection pressure significantly promotes resuspension. Notably, the initial vacuum level showed a negligible impact on the resuspension fraction. This counter-intuitive finding is attributed to a competitive mechanism: the flow acceleration from jet expansion is effectively offset by the drag reduction caused by gas rarefaction (slip effect). Furthermore, substrate roughness demonstrated a distinct threshold effect, where smooth surfaces facilitated mobilization via sliding, while rough surfaces inhibited detachment due to inter-particle cohesion. These findings provide critical experimental data for validating radioactive source resuspension models and support accurate safety assessments for fusion reactors.

Keywords: Nuclear fusion safety; In-vessel LOCA; DustSAFER; Tungsten; Dust resuspension

Introduction

Accurate quantification of radioactive source terms is pivotal for fusion reactor safety [1-3]. While tungsten is the primary plasma-facing material for ITER and future tokamak fusion reactors due to its superior thermal and radiation resistance [4-6], plasma erosion inevitably generates activated, tritiated tungsten dust during operation [7, 8]. The in-vessel LOCA, a critical design basis accident (DBA) for helium-cooled blankets [9, 10], generates high-speed helium jets that can mobilize these radioactive deposits [11, 12]. Once resuspended, the dust may be transported through the Vacuum Vessel Pressure Suppression System (VVPSS) during depressurization, leading to a potential release of radioactive materials into the environment [13-15]. The progression of this accident scenario is shown in Fig. 1 [FIGURE:1].

Dust resuspension involves complex fluid-particle interactions, making experimental research the primary means for elucidating underlying mechanisms and validating models within safety analysis codes. In the field of nuclear fission safety, a series of experiments have been conducted on particle resuspension under accident conditions. The STORM [16] (Simplified Test of Resuspension Mechanism) project at the EU JRC-Ispra utilized SnO₂ aerosols to investi-

gate the resuspension characteristics of multilayer dust in high-temperature, atmospheric-pressure pipes under steam and nitrogen environments, providing extensive validation data for codes (e.g., ASTEC, MELCOR [17]). Similarly, the ART [18] (Aerosol Resuspension Test) experiments at ORNL in the US focused on the resuspension behavior of various dust deposits in horizontal pipes under nitrogen purge, offering critical data support for MELCOR [19].

In contrast to these studies focusing on multilayer dust, other research has targeted fundamental particle dynamics. Reeks & Hall [20] investigated the resuspension of monolayer alumina and graphite dust from polished stainless steel surfaces in fully developed turbulent pipe flows, yielding data widely used to validate monolayer models. Furthermore, the BISE [21, 22] wind tunnel at IRSN/CEA utilized real carbon dust collected from the Tore Supra fusion device to study resuspension issues in ventilation ducts. The HTR [23] experiment facility at Tsinghua simulated the resuspension of graphite dust caused by high-speed gas flow impacting a vacuum vessel in the High-Temperature Gas-cooled Reactor depressurization accident.

In the domain of nuclear fusion safety, current research has predominantly focused on Loss of Vacuum Accident (LOVA). The STARDUST [24–26] facility and its upgraded version, STARDUST-U [27–29], developed by ENEA in Italy, stand as the most representative platforms in this field. These facilities simulate the LOVA process by injecting air into a cylindrical vacuum vessel, investigating the effects of inlet position, obstacles, wall temperature, and dust material on the dust resuspension fraction. Meanwhile, the TDMX [30, 31] facility at INL in the US employs a toroidal geometry to better replicate the configuration of a tokamak vacuum vessel, with a primary focus on the visualization of flow dynamics and particle motion. Furthermore, the AWTS-II [32] wind tunnel at Aarhus University in Denmark has been used to study dust resuspension in low-pressure environments, highlighting the critical importance of dust agglomeration behavior.

Despite extensive research on LOVA, experimental data for the more complex in-vessel LOCA remain scarce. Unlike the atmospheric air ingress in LOVA, LOCA involves high-pressure helium jets discharging into a near-vacuum environment, creating a highly compressible and rarefied flow field. The extreme pressure gradients and the intrinsic disparities between helium and air (e.g., density, viscosity, and specific heat ratio) fundamentally alter boundary layer dynamics and wall shear stress. Consequently, extrapolating LOVA-based findings to LOCA scenarios introduces significant uncertainty in safety assessments. To address the lack of experimental data, this study investigates tungsten dust resuspension simulating in-vessel LOCA of helium-cooled blanket using the independently developed DustSAFER (Dust Safety Experimental Facility for Fusion Reactor) platform. We systematically evaluate the effects of nozzle diameter, injection pressure, initial vacuum level, and substrate roughness on resuspension fractions. This work aims to elucidate the primary influencing factors and their underlying mechanisms governing micron-sized tungsten dust resuspension

under complex in-vessel LOCA conditions, thereby supplying essential foundational data for the accurate assessment of radioactive dust source terms and experimental evidence for the validation and refinement of resuspension models in safety analysis codes of fusion reactors.

2.1 DustSAFER Experimental Platform

The experiments were conducted on the independently developed DustSAFER (Dust Safety Experimental Facility for Fusion Reactor) platform. This facility is designed to simulate the physical process of dust resuspension induced by a high-pressure helium jet impacting a vacuum chamber, reproducing the conditions of in-vessel LOCA of helium-cooled blanket.

As shown in Fig. 2 [FIGURE:2], the experimental apparatus primarily consists of a horizontal cylindrical vacuum chamber, a high-pressure helium injection system, a vacuum pumping system, and an integrated control and data acquisition system. The key components are detailed as follows:

- **Vacuum Chamber:** The main chamber is a horizontal cylinder constructed of 304 stainless steel, with an internal volume of approximately 0.181 m^3 , an inner diameter of 0.496 m, and an external length of 0.92 m. The chamber is equipped with multiple standard flanges for the installation of sensors and viewing windows, as well as for connections to the gas injection and vacuum systems. The helium injection inlet used in this study is located at the center of the chamber's sidewall.
- **High-Pressure Helium Injection System:** This system consists of a high-purity helium cylinder, a pressure reducing valve, a stainless steel high-pressure gas storage tank, and an electromagnetic valve. Prior to an experiment, the storage tank is filled with helium to a preset pressure (2, 4, or 8 MPa) via the pressure reducing valve. During the test, the high-pressure helium is injected into the vacuum chamber through a stainless steel injection tube with a specific inner diameter simulating the breach size (e.g., 1 mm or 2 mm) to replicate the rapid pressurization characteristic of an in-vessel LOCA.
- **Vacuum System:** Consisting of a rotary vane vacuum pump, vacuum pipes, and manual cock valves, this system is employed to evacuate the chamber to the required initial vacuum level (300, 2000, or 5000 Pa) before the experiment.
- **Control and Data Acquisition System:** Developed based on the LabVIEW platform, this system enables the automatic control of the electromagnetic valve and performs high-frequency synchronous acquisition and storage of transient signals, ensuring the precise recording of the rapid dynamic processes.

The working principle of the DustSAFER platform is illustrated in Fig. 2(b). Initially, a weighed sample of tungsten dust is distributed on a substrate tray

within the chamber to simulate dust deposition on the vessel floor. Once the chamber is evacuated to the target initial vacuum level and the helium gas tank reaches the target pressure, the control system triggers the electromagnetic valve. This releases a high-speed helium jet through a nozzle that impacts the dust layer, reproducing the impulsive dynamics of an in-vessel LOCA. Transient data (pressure, temperature) are acquired in real-time throughout the whole experiment. Finally, the resuspension fraction is quantified via gravimetric analysis of the residual dust mass. This standardized procedure is repeatedly executed to assess the impact of injection pressure, breach size, and initial vacuum level on dust resuspension.

2.2 Experimental Materials

2.2.1 Pure Tungsten Powder

Given that tungsten is the primary candidate material for plasma-facing components (i.e., divertors and first walls) in ITER and future tokamak reactors, characterizing its erosion products within fusion devices is of paramount importance. Investigations in the ASDEX Upgrade [33] have revealed that the particle size distribution of tungsten dust deposited in the vacuum vessel exhibits a bimodal profile, with peaks located at approximately $0.6\ \mu\text{m}$ (flakes) and $1.8\ \mu\text{m}$ (spherical). Accordingly, high-purity spherical tungsten powder ($>99.95\ \text{wt}\%$) with a nominal diameter of $1.8\ \mu\text{m}$ was selected as the surrogate material for this study. The particle size distribution was characterized using a laser diffraction analyzer, yielding a median diameter (d_{50}) of $2.14\ \mu\text{m}$ (as shown in Fig. 3 [FIGURE:3]), which aligns closely with the target experimental requirements. Furthermore, the microscopic morphology of the tungsten powder was examined via Scanning Electron Microscopy (SEM). The results, presented in Fig. 4 [FIGURE:4], confirm that the particles predominantly exhibit a spherical geometry.

2.2.2 Tungsten Dust Trays with Different Roughness

The dust trays were fabricated from 304 stainless steel with dimensions of $50\ \text{mm} \times 50\ \text{mm}$. In this study, three stainless steel substrate samples with distinct roughness levels were prepared via mechanical machining. The microscopic surface topography of the adhesion area ($1415\ \mu\text{m} \times 1061\ \mu\text{m}$) was characterized using the MarSurfLD130 optical profilometer, with the results detailed in Fig. 5 [FIGURE:5]. The left panel (a) shows the two-dimensional surface profiles, while the right panel (b) presents the corresponding three-dimensional topographies.

Observations indicate that:

- **Sample 1** exhibits a smooth texture with gentle undulations, characterized by peak and valley depths of $4.882\ \mu\text{m}$ and $-4.424\ \mu\text{m}$, respectively, representing the lowest roughness.
- **Sample 2**, in contrast, shows intensified surface fluctuations with alternating strip-like ridges and grooves, displaying strong directionality (i.e.,

striated structures extending in a specific direction). The roughness is notably higher, with peak heights increasing to 11.673 μm and valley depths dropping to -10.287 μm , indicating a significant increase in surface non-uniformity.

- **Sample 3** demonstrates the most substantial increase in roughness, featuring a highly uneven surface with wider, steeper textures and complex geometric patterns. Its peak and valley values reach maxima of 17.217 μm and -14.457 μm , respectively.

Standard parameters for quantifying material roughness via optical profilometry include the arithmetic mean height (S_a), the root mean square height (S_{rms}), and the maximum height (S_{max}) [34], defined mathematically in Eqs. (1)–(3):

$$S_{ave} = \frac{1}{A} \iint |z(x, y)| dx dy$$

$$S_{rms} = \sqrt{\frac{1}{A} \iint z^2(x, y) dx dy}$$

$$S_{max} = |\min z(x, y)| + \max z(x, y)$$

where x, y are the spatial coordinates of the profile section, $z(x, y)$ represents the asperity height at the corresponding position, and A is the sampling area.

It is important to note that a single roughness parameter cannot fully characterize the microscopic topography of a surface. S_a reflects the overall average deviation of the profile but is insensitive to extreme peaks and valleys. S_{rms} amplifies the contribution of high peaks and deep valleys through squaring, offering greater statistical sensitivity. S_{max} directly characterizes the maximum local peak-to-valley distance, which is critical for capturing extreme defects or prominent ridges. As summarized in Table 1, the three stainless steel substrates exhibit significant differences in surface roughness (Sample 1 < Sample 2 < Sample 3).

Table 1. Roughness of substrate samples.

Sample	S_a (μm)	S_{rms} (μm)	S_{max} (μm)
1			
2			
3			

2.3 Experimental Measurement System and Methodology

(1) Resuspension Fraction Measurement

A high-precision electronic balance (Accuracy: 0.01 g, Range: 0-100 g) was employed to weigh the total mass of the tray containing dust before and after each

experiment, as shown in Fig. 6 [FIGURE:6]. The dust resuspension fraction, Λ (%), is calculated using Eq. (4):

$$\Lambda = \frac{M_{initial} - M_{final}}{M_{initial} - M_{tray}} \times 100$$

where $M_{initial}$ is the total mass of the tray and dust prior to the experiment, M_{final} is the total mass after the experiment, and M_{tray} is the mass of the empty tray. The initial mass of dust deposited on the tray was controlled at approximately 3 g for each test.

(2) Chamber Pressure Measurement

To cover the wide pressure range from high vacuum to near-atmospheric levels, two pressure transmitters were employed alternately: A Rosemount 3051TA absolute pressure transmitter (Range: 0-20 kPa abs, Accuracy: <0.065%) was used for the low-pressure phase (<10 kPa). An AE-T general-purpose pressure transmitter (Range: 0-200 kPa abs, Accuracy: $\pm 0.25\%$ FS) was used for higher pressure (>10 kPa). The sensors were installed at the pressure ports on the vacuum chamber wall.

(3) Flow Velocity Measurement

To capture the transient flow characteristics, an AE-S-G-H3 micro high-frequency dynamic pressure sensor (Range: 0-10 kPa, Response Frequency: 100 kHz, Accuracy: $\pm 0.5\%$) of the helium jet. Simultaneously, a WZPM-020 face Resistance Temperature Detector (RTD) (Type: Pt100, Range: -50-200 °C) was utilized to measure the flow field temperature. The instantaneous gas velocity is derived based on the First Law of Thermodynamics for compressible flow [26, 28]. Assuming an adiabatic and isentropic process with negligible potential energy changes, the energy equation relates the flow velocity v to the enthalpy change, as shown in Eq. (5):

$$h_0 = h + \frac{v^2}{2} \Rightarrow v = \sqrt{2(h_0 - h)}$$

where h_0 is the stagnation enthalpy and h is the static enthalpy. Treating helium as an ideal gas, the enthalpy difference can be expressed in terms of temperature T and the specific heat ratio γ (1.67 for helium). Consequently, the velocity can be rewritten in terms of pressure ratios as Eq. (6):

$$v = \sqrt{\frac{2\gamma RT}{\gamma - 1} \left[1 - \left(\frac{P_{static}}{P_{total}} \right)^{\frac{\gamma - 1}{\gamma}} \right]}$$

Figure 7

Figure 1: Figure 7

Figure 8

Figure 2: Figure 8

where R is the universal gas constant ($8.314 \text{ J}/(\text{mol} \cdot \text{K})$), and M is the molar mass of helium ($0.004 \text{ kg}/\text{mol}$). By substituting the measured pressures, where the total pressure P is the sum of the static pressure P_{static} and the dynamic pressure P_{Δ} ($P = P_{static} + P_{\Delta}$), the final expression for local flow velocity is obtained in Eq. (7):

$$v = \sqrt{\frac{2\gamma RT}{M(\gamma - 1)} \left[\left(\frac{P_{static} + P_{\Delta}}{P_{static}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}$$

Finally, the instantaneous velocity at the measurement point is calculated using Eq. (7), based on the measured dynamic pressure (P_{Δ}), the real-time chamber static pressure (P_{static} , obtained from the aforementioned chamber pressure sensor), and the gas temperature (T , obtained from the RTD). The installation positions of the dynamic pressure and temperature sensors are shown in Fig. 7

2.4 Experimental Procedure and Protocol

Fig. 8

systematically presents the standardized experimental procedure employed in the DustSAFER platform. This process ensures high consistency and reproducibility of experimental conditions, providing a reliable data foundation. The procedure is categorized into three core phases:

(1) Preparation and Initialization Phase

The workflow begins with the vacuum drying and weighing of the tungsten dust (approx. 3 g) to eliminate the influence of ambient humidity. Subsequently, the injection tube (corresponding to nozzle diameters of 1 or 2 mm) and the dust tray (corresponding to substrate roughness S_{rms} of 2.147, 1.441, or 0.355 μm) are installed according to the preset test conditions. The vacuum chamber is then sealed and evacuated to the target initial vacuum level (300, 2000, or 5000 Pa) using the vacuum pump. Once the target pressure is achieved, the pump is stopped. Finally, the helium gas tank is charged to the target injection pressure (2, 4, or 8 MPa).

(2) Helium Injection and Data Acquisition Phase

Once all initial conditions are satisfied, the electromagnetic valve is triggered to

discharge the high-pressure helium jet, immediately followed by the activation of the data acquisition system (Acquisition START). During this phase, the system records key transient parameters at high frequency, including the chamber pressure, temperature, and local flow velocity.

(3) Post-Experimental Processing Phase

Data acquisition is terminated (Acquisition STOP) after the chamber pressure reaches equilibrium (indicating steady flow state), followed by safe venting of the system (Vent). The residual dust is then weighed again (Dust Weighing) to calculate the resuspension fraction. To maximize data reliability and minimize random errors, seven repeat experiments were conducted for each test condition. During data processing, the maximum and minimum values were excluded from each set, and the arithmetic average of the remaining three valid measurements was adopted as the final experimental result. The procedure concludes with “Experiment Stop” .

3.1 Pressure Changes within the Vacuum Chamber

Fig. 9 [FIGURE:9] illustrates the transient pressure evolution within the vacuum chamber, covering a matrix of nozzle diameters (1 and 2 mm), helium injection pressures (2, 4, and 8 MPa), and initial vacuum levels (300, 2000, and 5000 Pa). Comparative analysis of the P-t curves reveals the following key characteristics:

(1) Significant Difference in Pressurization Rate

The pressurization rate is highly sensitive to both break size and injection pressure. As indicated by the data, the 2 mm nozzle induces an extremely rapid pressure rise, reaching a steady state within approximately 20 s, whereas the 1 mm nozzle requires about 30 s due to its restricted flow area. This aligns with the theoretical prediction that critical mass flow rate is proportional to the nozzle cross-sectional area. Furthermore, higher injection pressures (e.g., 8 MPa) result in significantly steeper initial pressurization slopes compared to lower pressures (e.g., 2 MPa). This is because, in the critical flow regime, the mass flow rate is directly proportional to the upstream stagnation pressure.

(2) Consistency of Pressure Increment

The total pressure increment within the vessel shows remarkable consistency regardless of the initial vacuum level. Comparing Figs. 9(a)–(c), for a fixed injection pressure, the net pressure rise ($P_{\Delta} = P_{\text{final}} - P_{\text{initial}}$) remains virtually constant. Specifically, P_{Δ} stabilizes at approximately 98 kPa, 50 kPa, and 25 kPa for injection pressures of 8 MPa, 4 MPa, and 2 MPa, respectively. This phenomenon confirms that the total mass of helium injected during the supersonic critical flow phase is predominantly determined by the upstream helium storage tank (pressure and volume) and is essentially independent of the downstream backpressure. Crucially, this result verifies the good reproducibility and the stability of gas source control maintained by the experimental system under varying environmental parameters.

(3) Phase Characteristics of Flow Evolution

The “rapid pressurization, slow decay and equilibration” characteristic of the experimental curves reflects the dynamic transition of fluid mechanisms:

- **Rapid Pressurization Phase:** Immediately following the gas injection, the large pressure difference between the storage tank (high-pressure side) and the vacuum chamber (low-pressure side) drives the flow at the nozzle into a fully choked state, yielding maximum mass flow rate and a near-linear pressure rise.
- **Rate Decay Phase:** As helium accumulates, the vessel backpressure rises while the upstream storage tank pressure decreases due to discharge. The diminishing pressure gradient leads to a reduction in mass flow rate, observed as a gradual decrease in the slope of the P-t curve.
- **Equilibration Phase:** When the pressure gradient between the storage tank and the vacuum chamber is insufficient to sustain the flow, the system reaches a stable final pressure, and the curve eventually levels off.

3.2 Velocity of the Helium Jet

To quantify the aerodynamic impact of the helium jet on the dust bed, the transient local flow velocity at the leading edge of the dust tray was measured for the 1 mm nozzle cases. Fig. 10 [FIGURE:10] presents the velocity profiles under varying injection pressures (2, 4, 8 MPa) and initial vacuum levels (300, 2000, 5000 Pa), revealing distinct dynamic features:

(1) Impulsive High-Velocity Impact

The flow field exhibits pronounced strong impulsive characteristics. Upon jet arrival (at $t \approx 3$ s), the velocity spikes vertically to its peak within less than 1 s. This steep wave confirms that the underexpanded jet formed during the initial LOCA phase possesses a high Mach number, with its leading bow shock sweeping explosively across the dust bed. Subsequently, the velocity decays exponentially as the upstream pressure is released. This “sudden burst-rapid decay” structure indicates that dust resuspension occurs primarily within a very short time window during the initial stage of an accident.

(2) Positive Correlation with Injection Pressure

The peak velocity is strictly positively correlated with the injection pressure. Taking the 300 Pa vacuum case as an example (Fig. 10(a)), the peak velocity increases from 1200 m/s at 2 MPa to 2000 m/s at 8 MPa. This indicates that high-pressure jets carry immense momentum flux, converting pressure potential energy into kinetic energy to exert strong aerodynamic drag forces on the deposited dust.

(3) Damping Effect of Vacuum Pressure

The initial vacuum level acts as a critical damping factor on jet velocity. As shown in Figs. 10(a)-(c), the velocity magnitude drops drastically with increasing backpressure. Under the extremely low backpressure of 300 Pa, the jet

expands almost unimpeded, reaching 2000 m/s at 8 MPa. In the 2000 Pa environment, the peak velocity is attenuated to 960 m/s due to resistance from the ambient gas. At 5000 Pa, the velocity further decays to 540 m/s.

In summary, the experimental data confirm that an in-vessel LOCA generates supersonic helium jets with velocities reaching thousands of meters per second during the initial phase. This extreme aerodynamic environment is the root cause of large-scale tungsten dust resuspension, and its intensity is highly sensitive to ambient backpressure.

3.3 Tungsten Dust Resuspension Fraction

A series of tungsten dust resuspension tests was conducted under varying conditions, including different injection pressures (2, 4, 8 MPa), nozzle diameters (1, 2 mm), initial vacuum levels (300, 2000, 5000 Pa), and tray roughness levels. The measured dust resuspension fractions (Λ) are summarized in Table 2, and a comparative overview of the results is presented in Fig. 11 [FIGURE:11].

Table 2. Tungsten dust resuspension fractions (Λ).

Vacuum Pressure	Nozzle Diameter	Roughness S (μm)	Injection Pressure	Λ (%)
5000 Pa	1 mm		2 MPa	
...	

Overall, the tungsten dust resuspension fraction exhibited a wide range of variation, ranging from a minimum of 2.43% (Case Cc11: 5000 Pa, 1 mm, 2 MPa) to a maximum of 41.36% (Case Ac21: 5000 Pa, 2 mm, 8 MPa). This substantial disparity indicates that under LOCA, short-duration high-speed helium jets are sufficient to drive the mobilization of a considerable proportion of deposited tungsten dust. Specifically, the statistical analysis of the experimental data reveals the following characteristics:

(1) Positive Correlation with Injection Pressure

The resuspension fraction demonstrates a significant positive correlation with helium injection pressure. For the 300 Pa initial vacuum and 1 mm nozzle condition, the resuspension fraction increased monotonically with pressure: rising from 4.42% at 2 MPa (Case Ca11) to 11.17% at 4 MPa (Case Ba11), and further reaching 18.85% at 8 MPa (Case Aa11). A similar growth trend was observed under other vacuum conditions; for instance, at 2000 Pa with a 2 mm nozzle, the resuspension fraction surged from 12.60% at 4 MPa (Case Bb21) to 37.72% at 8 MPa (Case Ab21).

(2) Amplification Effect of Nozzle Diameter

Under the same injection pressure and vacuum level, increasing the nozzle diameter leads to a substantial increase in the resuspension fraction. Comparing

the data at 8 MPa injection pressure and 300 Pa vacuum level, the 2 mm nozzle (Case Aa21) yielded a resuspension fraction of 32.71%, which is approximately 1.7 times that of the 1 mm nozzle (Case Aa11, 18.85%). This difference was even more pronounced at 5000 Pa vacuum level, where the 2 mm nozzle (Case Ac21) achieved the highest observed resuspension fraction of 41.36%, whereas the 1 mm nozzle (Case Ac11) yielded only 20.09%.

(3) Non-monotonic Dependence on Initial Vacuum

The relationship between resuspension fraction and initial vacuum level appeared non-monotonic and varied with injection pressure. At 4 MPa injection pressure (1 mm nozzle), the resuspension fraction initially rose and then fell as backpressure increased: it increased slightly from 11.17% at 300 Pa (Case Ba11) to 12.01% at 2000 Pa (Case Bb11), before dropping to 6.98% at 5000 Pa (Case Bc11). Conversely, at the lower injection pressure of 2 MPa (1 mm nozzle), the resuspension fraction exhibited a continuous decline with increasing backpressure, falling from 4.42% at 300 Pa (Case Ca11) to 2.43% at 5000 Pa (Case Cc11).

(4) Threshold Characteristic of Substrate Roughness

The influence of substrate roughness was tested under the 8 MPa injection pressure and 300 Pa vacuum level for both 1 mm and 2 mm nozzles. For the 1 mm nozzle, the resuspension fractions on rough ($S_r = 2.147 \mu\text{m}$, Case Aa11) and medium-rough ($S_r = 1.441 \mu\text{m}$, Case Aa12) substrates were comparable (18.85% and 19.28%, respectively). However, a marked increase to 24.62% was observed on the smooth substrate ($S_r = 0.355 \mu\text{m}$, Case Aa13). This trend was similarly validated by the high-flow tests with the 2 mm nozzle: the rough (Case Aa21) and medium-rough (Case Aa22) substrates showed minimal difference (32.71% vs. 31.89%), while the smooth substrate (Case Aa23) again exhibited the highest resuspension rate at 36.09%. This consistent contrast indicates that significant enhancement in dust mobilization occurs only when the surface topography transitions to a sufficiently smooth state.

In summary, the experimental results demonstrate that the tungsten dust resuspension fraction is highly sensitive to and positively correlated with nozzle diameter (break size) and injection pressure, which serve as the primary determinants of the resuspension. In contrast, the initial vacuum level exhibits a complex non-monotonic influence. Furthermore, the effect of substrate roughness shows a distinct threshold characteristic, triggering a jump in resuspension only when the surface transitions from rough to smooth.

4.1 Effect of Break Size and Injection Pressure

Given the uncertainty regarding the actual break area in the LOCA of helium blanket, this study employed injection tubes with different inner diameters (1 mm and 2 mm) to simulate breaches of varying scales. Additionally, lower injection pressures (2 and 4 MPa) were included to characterize flow features at lower velocities, thereby building a resuspension database covering a wide

range of flow regimes. The results indicate that these two parameters are the primary variables determining the resuspension fraction. The mechanism can be explained by the critical mass flow rate equation for compressible flow, as shown in Eq. (8):

$$\dot{m} = Ap_t \sqrt{\frac{\gamma M}{RT_t}} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

where \dot{m} is the critical mass flow rate (kg/s), A is the break area (m²), p is the stagnation pressure (Pa, corresponding to the helium tank pressure), R is the universal gas constant (8.314 J/(mol · K)), T is the total temperature (K), and γ is the specific heat ratio (1.67 for helium).

The experiments confirm that increasing the nozzle diameter (break size) has a significant amplification effect on dust resuspension. As shown in Fig. 12 [FIGURE:12], under same injection pressure and vacuum levels, the resuspension fractions for the 2 mm nozzle are consistently higher than those for the 1 mm nozzle. According to Eq. (8), the critical mass flow rate is directly proportional to the break area. When the nozzle diameter increases from 1 mm to 2 mm, the flow cross-sectional area is expanded four times. This implies that during the initial critical flow phase of LOCA, the mass of helium injected into the vacuum chamber per unit time increases dramatically, leading to a significantly faster pressure buildup. More critically, from the perspective of jet structure, a larger nozzle diameter generates a free jet with a broader radial scale and a longer potential core region. This directly expands the effective coverage area of the high-speed airflow on the dust tray, exposing a larger region of deposited dust to strong shear forces, thereby multiplying the resuspension fraction.

Injection pressure is the other core parameter determining the total energy of the jet. Fig. 13 [FIGURE:13] clearly demonstrates the monotonic increasing trend of resuspension fraction with rising injection pressure. For both the 1 mm and 2 mm nozzles, the resuspension fraction exhibits a stepwise rise as pressure increases from 2 MPa (purple bars) to 4 MPa (green bars) and then to 8 MPa (orange bars). Based on Eq. (8), for a fixed break area, the critical mass flow rate is linearly proportional to the stagnation pressure (p). When the injection pressure increases from the low-velocity simulation of 2 MPa to the high-pressure 8 MPa, the momentum flux carried by the jet increases significantly. This high-energy-density helium jet, upon impacting the dust bed, generates a larger aerodynamic torque, effectively overcoming the adhesion force between the micron-sized tungsten dust and the tray, and inducing large-scale particle detachment and entrainment.

4.2 Competition Mechanism of Initial Vacuum

As in-vessel LOCA evolves, the pressure inside the vacuum vessel rises continuously. Although the Vacuum Vessel Pressure Suppression System (VVPSS) is

designed to mitigate pressurization, significant changes in ambient backpressure are unavoidable before safety measures are fully engaged and effective. Therefore, investigating the influence of ambient pressure (initial vacuum level) on dust resuspension is critical for assessing source term release throughout the entire accident sequence.

Fig. 14 [FIGURE:14] compares the tungsten dust resuspension fractions under three different initial vacuum levels (300, 2000, and 5000 Pa). It can be observed that, for the fixed injection pressure and nozzle diameter, varying the initial vacuum level does not result in significant differences in the resuspension fraction. This indicates that, within the tested range, the resuspension rate is not sensitive to changes in initial ambient pressure. This phenomenon appears to contradict the flow field measurements presented in Fig. 10. As discussed in Subsection “Velocity of the helium jet”, the initial vacuum level exerts a decisive damping effect on local flow velocity. For instance, at 8 MPa injection pressure, increasing the backpressure from 300 Pa to 5000 Pa causes the peak jet velocity to plummet from 2000 m/s to 540 m/s, a nearly fourfold reduction. However, this drastic decay in velocity is not mirrored by a corresponding drop in the resuspension results in Fig. 14. This non-intuitive result, characterized by “drastic velocity change but constant resuspension fraction,” actually reveals a dynamic competition and balance mechanism between jet intensity and fluid medium properties under LOCA conditions:

(1) “High Velocity-Low Drag” Effect at Low Backpressure

In the low-pressure environment of 300 Pa, the jet undergoes severe underexpansion. While this generates supersonic flows (2000 m/s) and expands the spatial coverage on the dust tray (as shown in Fig. 10(a)), the low pressure significantly increases the mean free path of the gas molecules. According to the Cunningham slip correction theory [11, 35], the frequency of collisions between gas molecules and the particle surface decreases in this rarefied regime. Consequently, the aerodynamic drag force exerted by the fluid on the particles is substantially reduced. This “slip effect” weakens the airflow’s ability to detach and entrain dust, thereby acting as an inhibitory factor for resuspension.

(2) “Low Velocity-High Drag” Effect at High Backpressure

Conversely, at 5000 Pa, although the jet velocity decays to 540 m/s (theoretically unfavorable for resuspension), the increased ambient pressure implies a significant rise in gas density. The fluid properties transition back towards the continuum flow regime, diminishing the slip effect and substantially enhancing the drag force. The increase in fluid density largely compensates for the kinetic energy loss caused by the velocity drop. Therefore, the “insignificant difference” observed in Fig. 14 is the macroscopic manifestation of the dynamic balance between these two competing mechanisms. This finding suggests that when assessing source terms in fusion reactors, flow velocity should not be used as the sole criterion. Instead, the combined influence of the flow field’s thermodynamic state (pressure, density) on the microscopic forces acting on particles must be considered.

Influence of Roughness and Multi-layer Adhesion

The influence of substrate roughness on dust resuspension was tested under the 8 MPa injection pressure and 300 Pa initial vacuum condition using both 1 mm and 2 mm nozzles. As shown in Fig. 15 [FIGURE:15], the data exhibit a consistent trend across both nozzle sizes: the resuspension fractions on the high-roughness ($S = 2.147 \mu\text{m}$) and medium-roughness ($S = 1.441 \mu\text{m}$) substrates are remarkably similar (e.g., 18.85% vs. 19.28% for the 1 mm nozzle), showing negligible difference. However, a significant jump in resuspension occurs when the substrate is smoother ($S = 0.355 \mu\text{m}$), where the fraction rises to 24.62% (1 mm nozzle). Combined with the post-experimental residual dust morphologies presented in Fig. 16 [FIGURE:16], these counter-intuitive results reveal two distinct detachment modes impacting tungsten dust mobilization under high-speed jet impact:

(1) Sliding and Block Detachment (Smooth Regime)

Fig. 16(a) shows the surface state of the smooth substrate ($S = 0.355 \mu\text{m}$) after the experiment. A large area of exposed substrate is clearly visible in the central region of the tray, with the edges of the dust layer exhibiting irregular, torn shapes. On the smooth tray, the mechanical interlocking between micron-sized particles and the substrate is weak. Consequently, the cohesive force within the dust layer often exceeds the dust-wall adhesion force. Under high-speed jet impact, the dust layer does not erode particle-by-particle but instead overcomes the low adhesion force to undergo integral shear sliding and block detachment, leading to large-scale exposure of the tray surface and thus a higher resuspension fraction.

(2) Layer-by-Layer Erosion (Rough Regime)

In contrast, Figs. 16(b) and (c) show the residual morphologies on the medium ($S = 1.441 \mu\text{m}$) and high roughness ($S = 2.147 \mu\text{m}$) substrates, respectively. No large-scale substrate exposure is observed; instead, the dust layer remains relatively intact but with reduced thickness. For these rougher surfaces, the surface morphologies create a significant shielding effect, trapping the bottom layer of particles within the peaks/valleys and protecting them from the direct impact of the free stream. In this case, dust removal is characterized by layer-by-layer erosion, where the airflow can only carry away loose particles from the surface layer. After the experiment, although the dust layer on the rough trays becomes thinner, no large-scale bare substrate is observed. This also explains why increasing the roughness from $1.441 \mu\text{m}$ to $2.147 \mu\text{m}$ yields no significant change in resuspension—once the roughness provides sufficient shielding, the limiting factor for resuspension shifts from “wall adhesion” to the “inter-particle cohesion” of the dust layer itself.

5. Conclusion

This study investigated the resuspension of tungsten dust under in-vessel LOCA of helium-cooled blanket, utilizing the independently developed DustSAFER

experimental platform. By systematically measuring flow field parameters and resuspension fractions under varying break sizes, injection pressures, initial vacuum levels, and substrate roughness, the dynamic behavior of deposited dust under high-speed helium jet impact and its underlying physical mechanisms were revealed. The main conclusions are as follows:

1. **Break size and injection pressure are the dominant parameters determining the resuspension fraction.** Under the extreme condition of 8 MPa injection pressure combined with 2 mm break size, the tungsten dust resuspension fraction reached a maximum of 41.36%. This is attributed to the fact that increases in both break area and stagnation pressure significantly enhance the critical mass flow rate and momentum flux of the helium jet, intensifying the instantaneous shear force acting on the dust bed.
2. **Variation in the initial vacuum level has no significant effect on the resuspension fraction.** Although low backpressure conditions induce high-velocity supersonic flows (reaching 2000 m/s), the slip effect resulting from gas rarefaction significantly weakens the effective drag force exerted on the particles. This dynamic balance between flow intensity and medium properties results in a stable resuspension fraction across different vacuum levels.
3. **Substrate roughness displays a distinct threshold effect on dust mobilization.** A significant jump in resuspension was observed only when the surface transitioned to a relatively smooth state ($S = 0.355 \mu\text{m}$). This reflects a transition in detachment modes: from sliding and block detachment on smooth surfaces to cohesion-dominated layer-by-layer erosion on rough surfaces.

The findings of this study offer critical engineering implications for the source term assessment of fusion reactors. Given that the high-pressure helium jet induced by in-vessel LOCA possesses strong mobilization capability, primarily concentrated within the first few tens of seconds of the accident, safety analyses need to focus specifically on source term release during this transient window. Furthermore, experiments with rough walls indicate that once the deposited layer reaches a certain thickness, the limiting factor for resuspension shifts from dust-wall adhesion to dust-dust inter-layer cohesion. Therefore, safety analysis codes should prioritize the adoption of physical models capable of describing particle agglomeration and inter-layer detachment, rather than relying solely on wall roughness parameters.

6. 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.

7. References

- [1] P. Barabaschi, A. Fossen, A. Loarte, et al., ITER progresses into new baseline. *Fusion Eng. Des.* 215, 114990 (2025). doi: 10.1016/j.fusengdes.2025.114990
- [2] B.-E. Wang, S.-C. Zhang, Z. Wang, et al., Numerical analysis of supersonic jet flow and dust transport induced by air ingress in a fusion reactor. *Nucl. Sci. Tech.* 32, 7 (2021). doi: 10.1007/s41365-021-00912-z
- [3] N. Taylor, P. Cortes, Lessons learnt from ITER safety & licensing for DEMO and future nuclear fusion facilities. *Fusion Eng. Des.* 89, 1995-2000 (2014). doi: 10.1016/j.fusengdes.2013.12.030
- [4] J. Qiu, X.-X. Hu, C.-Y. Li, et al., Investigation of He retention in W through combined He characterization methods and cluster dynamics model. *Nucl. Sci. Tech.* 36, 51 (2025). doi: 10.1007/s41365-025-01637-z
- [5] T. Marchhart, C. Hargrove, A. Marin, et al., Discovering tungsten-based composites as plasma facing materials for future high-duty cycle nuclear fusion reactors. *Sci. Rep.* 14, 13864 (2024). doi: 10.1038/s41598-024-64614-3
- [6] S. Nogami, N. Matsuta, K. Miura, et al., Development of potassium doped tungsten plate for fusion reactor applications. *Fusion Eng. Des.* 202, 114403 (2024). doi: 10.1016/j.fusengdes.2024.114403
- [7] A. Baron-Wiechec, E. Fortuna-Zalesna, J. Grzonka, et al., First dust study in JET with the ITER-like wall: sampling, analysis and classification. *Nucl. Fusion* 55, 113033 (2015). doi: 10.1088/0029-5515/55/11/113033
- [8] D. Perrault, Status of ITER Safety Issues. *Fusion Sci. Technol.* 75, 1-6 (2019). doi: 10.1080/15361055.2019.1594538
- [9] B. Zhou, B. Hu, Y. Wang, et al., Preliminary accident analyses of in-vessel LOCA for the chinese fusion test reactor HCCB blanket concept. *Fusion Eng. Des.* 203, 114450 (2024). doi: 10.1016/j.fusengdes.2024.114450
- [10] B. Zhou, X. Wang, Y. Wang, et al., Accident classification and initial events for CFETR. *Fusion Eng. Des.* 172, 112753 (2021). doi: 10.1016/j.fusengdes.2021.112753
- [11] Z. Qin, S. Zhang, Z. Wang, et al., Drag characteristics of micron-sized tungsten dust in high-Mach rarefied flow during in-vessel LOCA of fusion reactor with Maxwell slip/DSMC hybrid modeling. *Nucl. Fusion* 66, 026009 (2026). doi: 10.1088/1741-4326/ae1c52
- [12] Z. Qin, S. Zhang, Z. Wang, et al., Highly underexpanded helium jet and its effect on dust resuspension under in-vessel loss of coolant accident of fusion reactor. *Nucl. Fusion* (2022). doi: 10.1088/1741-4326/ac7df0
- [13] M. Balden, N. Endstrasser, P. W. Humrickhouse, et al., Collection strategy, inner morphology, and size distribution of dust particles in ASDEX Upgrade. *Nucl. Fusion* 54, 073010 (2014). doi: 10.1088/0029-5515/54/7/073010
- [14] M. Rubel, A. Widdowson, J. Grzonka, et al., Dust generation in tokamaks: Overview of beryllium and tungsten dust characterisation in JET with the ITER-like wall. *Fusion Eng. Des.* 136, 579-586 (2018). doi: 10.1016/j.fusengdes.2018.03.027
- [15] Q. Lu, Z. Wang, S. Zhang, et al., Dust explosion in fusion reactors: Explosion characteristics and reaction mechanism of tungsten micro-powder.

- Combust. Flame 248, 112551 (2023). doi: 10.1016/j.combustflame.2022.112551
- [16] A. Bujan, L. Ammirabile, A. Bieliauskas, B. Toth, ASTEC V1.3 code SOPHAEROS module validation using the STORM experiments. Prog. Nucl. Energy 52, 777–788 (2010). doi: 10.1016/j.pnucene.2010.05.004
- [17] B. Gonfiotti, S. Paci, Implementation and validation of a resuspension model in MELCOR 1.8.6 for fusion applications. Fusion Eng. Des. 122, 64–85 (2017). doi: 10.1016/j.fusengdes.2017.09.006
- [18] A. L. Wright, Primary system fission product release and transport: A state-of-the-art report to the committee on the safety of nuclear installations. (Nuclear Regulatory Commission, Washington, DC, 1994). doi: 10.2172/10161670
- [19] M. F. Young, Liftoff Model for MELCOR. (Sandia National Laboratories, Albuquerque, 2015). doi: 10.2172/1206953
- [20] M. W. Reeks, D. Hall, Kinetic models for particle resuspension in turbulent flows: theory and measurement. J. Aerosol Sci. 32, 1–31 (2001). doi: 10.1016/S0021-8502(00)00063-X
- [21] S. Peillon, A. Roynette, C. Grisolia, F. Gensdarmes, Resuspension of carbon dust collected in Tore Supra and exposed to turbulent airflow: Controlled experiments and comparison with model. Fusion Eng. Des. 89, 2789–2796 (2014). doi: 10.1016/j.fusengdes.2014.08.004
- [22] A. Rondeau, S. Peillon, A. M. Vidales, et al., Evidence of inter-particles collision effect in airflow resuspension of poly-dispersed non-spherical tungsten particles in mono-layer deposits. J. Aerosol Sci. 154, 105735 (2021). doi: 10.1016/j.jaerosci.2020.105735
- [23] W. Peng, T. Zhang, S. Yu, Y. Zhen, Graphite dust resuspension in a depressurization accident of HTR. Nucl. Eng. Des. 265, 785–790 (2013). doi: 10.1016/j.nucengdes.2013.09.029
- [24] S. Paci, N. Forgione, F. Parozzi, M. T. Porfiri, Bases for dust mobilization modelling in the light of STARDUST experiments. Nucl. Eng. Des. 235, 1129–1138 (2005). doi: 10.1016/j.nucengdes.2005.01.015
- [25] C. Bellecci, P. Gaudio, I. Lupelli, et al., STARDUST experimental campaign and numerical simulations: influence of obstacles and temperature on dust resuspension in a vacuum vessel under LOVA. Nucl. Fusion 51, 053017 (2011). doi: 10.1088/0029-5515/51/5/053017
- [26] A. Malizia, M. Richetta, M. Gelfusa, et al., Safety Analysis in Large Volume Vacuum Systems Like Tokamak: Experiments and Numerical Simulation to Analyze Vacuum Ruptures Consequences. Adv. Mater. Sci. Eng. 2014, 201831 (2014). doi: 10.1155/2014/201831
- [27] A. Malizia, M. Gelfusa, A. Murari, et al., A Novel Facility to Investigate Dust Mobilization in Confined Environments with Applications to the Security of the Pharmaceutical Industry. Mater. Sci. Forum 879, 1213–1219 (2017). doi: 10.4028/www.scientific.net/MSF.879.1213
- [28] L. A. Poggi, A. Malizia, J. F. Ciparisse, et al., First Experimental Campaign to Demonstrate STARDUST-Upgrade Facility Diagnostics Capability to Investigate LOVA Conditions. J. Fusion Energy 34, 1320–1330 (2015). doi: 10.1007/s10894-015-9964-x

- [29] L. A. Poggi, A. Malizia, J. F. Ciparisse, et al., STARDUST-U experiments on fluid-dynamic conditions affecting dust mobilization during LOVAs. *J. Instrum.* 11, C07012 (2016). doi: 10.1088/1748-0221/11/07/C07012
- [30] J. P. Sharpe, P. W. Humrickhouse, Dust mobilization studies in the TDMX facility. *Fusion Eng. Des.* 81, 1409-1415 (2006). doi: 10.1016/j.fusengdes.2005.08.081
- [31] P. W. Humrickhouse, J. P. Sharpe, M. L. Corradini, Modeling of the Toroidal Dust Mobilization Experiment. *Fusion Sci. Technol.* 52, 1022-1026 (2007). doi: 10.13182/FST07-A1629
- [32] A. Rondeau, J. Merrison, J. J. Iversen, et al., First experimental results of particle re-suspension in a low pressure wind tunnel applied to the issue of dust in fusion reactors. *Fusion Eng. Des.* 98-99, 2210-2213 (2015). doi: 10.1016/j.fusengdes.2014.12.038
- [33] A. Rondeau, S. Peillon, A. Roynette, et al., Characterization of dust particles produced in an all-tungsten wall tokamak and potentially mobilized by air-flow. *J. Nucl. Mater.* 463, 873-876 (2015). doi: 10.1016/j.jnucmat.2014.12.051
- [34] D. Whitehouse, *Surfaces and Their Measurement* (Kogan Page Science, Oxford, 2002).
- [35] L. Xu, L. Ma, P. Yang, et al., Drag coefficient for micron-sized particle in high-speed flows. *Phys. Fluids* 36, 043310 (2024). doi: 10.1063/5.0201397

Source: ChinaXiv – Machine translation. Verify with original.