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Pump suction performance and its impact on the evaporation dynamics of simulated damaged spent nuclear fuel during vacuum drying

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1. Introduction

In the intricate process of vacuum drying damaged nuclear fuel rods, the challenge posed by residual water remains a significant concern. This water complicates the accurate detection of moisture levels and the measurement of internal pressures or dew points within canisters. The vacuum drying criterion—which mandates maintaining a pressure of less than 3 torr for 30 minutes—is often deceptively met, even when residual water is still present. This paradox opens up a critical area for further research, especially regarding the impact of pump performance on the efficiency and completeness of the drying process. Several studies have addressed various facets of vacuum drying, providing valuable insights and highlighting areas that require further exploration. For instance, Bang, Yu, and Shin [1] focused on the relationship between ice formation and the surface area of water in canisters during vacuum drying. They demonstrated that a stepwise pressure reduction technique is more effective than employing a vacuum pump with a slower flow rate. However, their study did not delve deeply into how different pump performances quantitatively affect the residual water evaporation rates.

Similarly, Lim et al. [2] conducted lab-scale experiments to evaluate the vacuum drying of canisters, identifying a crucial "Evaporation-Acceleration Zone" at pressures between 40 and 50 torr, which marks a phase transition from liquid to vapor. They concluded that maximizing the duration within this phase change zone enhances evaporation efficiency. Despite identifying these zones, their analysis lacked a comprehensive examination of different scenarios involving varied damage extents in the nuclear fuel. In another study, Goode et al. [3] designed a rig for comparing vacuum drying and flowed gas drying techniques for advanced gas reactor fuel with stainless steel cladding. They found vacuum drying to be notably more effective but primarily focused on equipment development rather than the detailed dynamics of residual water evaporation across various extents of fuel damage. This leaves a gap in understanding how different drying methodologies perform under various real-world conditions.

Moreover, Perry [4] compared forced helium dehydration and vacuum drying, noting that the latter was capable of achieving faster drying times with increased decay heat. The research demonstrated conditions under which thorough dryness could be achieved, such as specific vapor pressures and dew points. However, the analysis was mainly centered on criteria adequacy and freezing issues, rather than a comprehensive dissection of how pump rates may influence residual water dynamics. The study by d'Entremont et al. [5] provided useful guidelines and considerations for the drying of spent nuclear fuel, emphasizing potential impacts of residual water like corrosion and radiation breakdown. While offering a broad perspective on drying technologies, the research did not deeply explore the specifics of how pump performance impacts the removal dynamics of residual water in damaged rods.

Given these findings and limitations, further research is imperative to bridge existing gaps in the literature. Specifically, a thorough investigation into how different pump suction rates affect the evaporation and removal of residual water under various damage conditions in nuclear fuel rods is essential. Such research would aim to optimize the balance between energy efficiency and the thermal dynamics involved in the vacuum drying process. Understanding these complexities will not only lead to more efficient drying protocols but also enhance the safety and longevity of dry storage systems for spent nuclear fuel. This knowledge can significantly inform the design and operational strategies of industrial and experimental vacuum drying systems, ensuring safer and more sustainable management of nuclear waste.

2. Experimental Approach

2.1 Overview of Experimental Configuration and Apparatus

The formulation of the vacuum drying system was derived from a comprehensive evaluation of both the apparatus's operational specifications and the experimental requisites. In the absence of defined technical standards, the design process was informed by an extensive analysis of experimental objectives, system capabilities, and operational context. The core function of this apparatus is the extraction of residual moisture from irradiated nuclear fuel, where it must operate within the unique environment of spent nuclear fuel storage. This necessitates not only functional compatibility with the operational environment but also the structural integrity and safety measures required for secure, long-term deployment.

A scaled-down pilot unit was constructed to rigorously assess and optimize the performance of the drying process [6], particularly focusing on the measurement and reduction of residual moisture. The design accommodates ease of relocation using existing crane systems, ensuring stability during operation. Emission control remains a key consideration in the full-scale design, with all gaseous emissions channeled into the facility's HVAC system, while condensed liquids are collected in dedicated containment systems. Radiation protection protocols are strictly adhered to by ensuring that all equipment functions can be monitored and adjusted via a centralized control system. The apparatus integrates a variety of critical systems, including vacuum pumps for pressure modulation, condensation units for moisture removal, drainage systems, and precise pressure control devices. Following the drying process, the residual moisture is quantitatively evaluated via a sophisticated moisture measurement program, ensuring data accuracy and reliability. The modular design of the system offers flexibility to cater to varying experimental setups while maintaining compliance with rigorous safety and regulatory standards, including those outlined by the NRC in NUREG-2215 and ASTM C1553-16.

2.2 Test Specimen Configuration and Fabrication

Simulated damaged nuclear fuel rods were fabricated from ZIRLO material, which closely replicates the properties of real spent nuclear fuel. The rods were dimensioned to the specifications of the PLUS7 and ACE7 designs, each featuring identical outer and inner diameters of 9.5mm and 8.357mm, respectively. The rods were truncated to a length of 100mm, after which an endcap was welded at the bottom, and an M5-tapped open cap was affixed at the top for controlled water introduction. To replicate various degrees of fuel rod degradation, a series of hole-milling operations were performed at the rod's midpoint (50mm from the bottom), resulting in cracks with diameters of 0.3, 0.5, 1.0, and 2.0mm.

2.3 Procedure for Vacuum Drying Experimentation

The procedural methodology for conducting the vacuum drying experiment was as follows: Initially, the vacuum pump was selected and connected to the experimental setup. After powering up the system, the cold trap was allowed to cool to below –20°C. Subsequently, the canister lid was removed using a crane, and a rack was positioned within the canister to support the microbalance, upon which the simulated damaged fuel specimen was placed. The fuel was positioned to ensure that the cracks could be viewed through the observation window. A measured amount of 2g of residual water was introduced into the fuel rod via syringe, and the thermocouple was carefully placed within the water for precise temperature monitoring. The canister was then sealed, and the measurement system was activated via the computer interface. The moisture measurement program was launched, and a file name was entered to facilitate data storage.

The vacuum pump was subsequently engaged, reducing the pressure inside the canister to 1.5 torr, a condition that was maintained for 30 minutes to ensure effective drying. Once these conditions were confirmed, the moisture measurement program was concluded, and the vacuum pump was deactivated. The power to the equipment was turned off, and the internal pressure of the canister was returned to atmospheric conditions. The canister lid was removed, and any residual water was carefully extracted for subsequent measurement and analysis.

3. Experimental Results

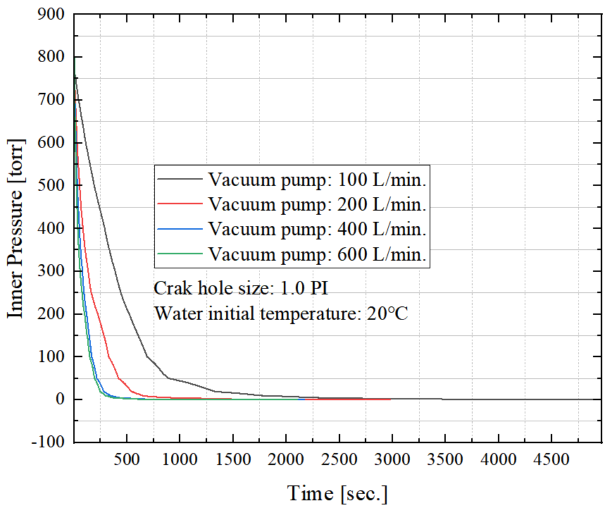

Fig. 1. Temporal Dynamics of Internal Pressure with Varying Pump Capacities

Figure 1 illustrates the changing internal pressure dynamics of a canister as a function of various pump suction capacities—namely, 100, 200, 400, and 600 L/min—when equipped with a compromised nuclear fuel rod exhibiting 1.0mm diameter cracks. Initiating with residual water at 20°C, the results clearly indicate that elevated pump capacities lead to faster depressurization, enabling the system to swiftly attain a target pressure of 1.5 torr and thus shortening the experimental timeline. Specifically, the suction capability at 600 L/min cut the total experimental duration to 2,103 seconds, a significant reduction compared to 4,968 seconds at 100 L/min, demonstrating a 2.36 times difference in efficiency favoring higher capacity pumps. Similar trends are seen across all pump rates tested, with corresponding experimental completions recorded at 2,103, 2,169, 2,980, and 4,968 seconds sequentially for 600, 400, 200, and 100 L/min.

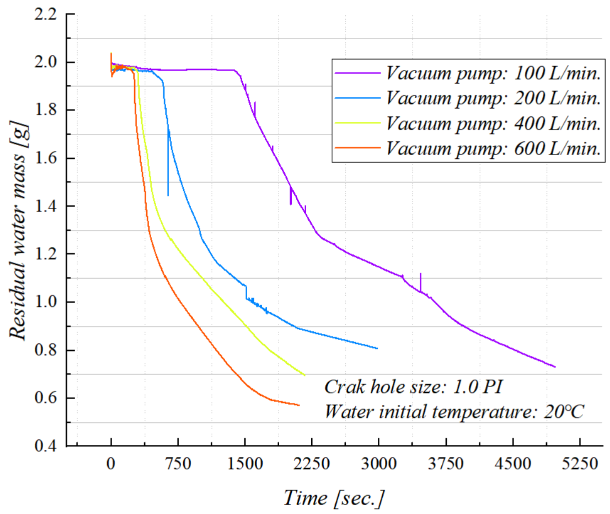

Fig. 2. Temporal Evolution of Residual Water Mass with Different Suction Rates

As portrayed in Figure 2, the pivotal focus in the vacuum drying of damaged nuclear fuel encompasses the mass evolution of residual moisture. Initially stable, this mass experiences a marked decrease upon reaching the critical phase change threshold. Across all pumping scenarios, natural evaporation exhibited minimal impact on water evacuation through the rod's fractures. Notably, the temporal journey to this phase boundary is inversely related to suction power; in detail, 1,500 seconds for 100 L/min versus merely 375 seconds for both 400 and 600 L/min configurations.

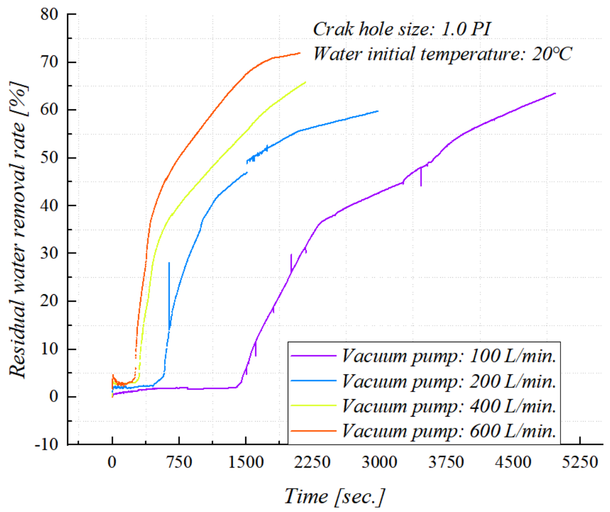

Fig. 3. Time-Dependent Efficiency of Residual Moisture Extraction

Considering the removal efficiency depicted in Figure 3, it is evident that ferocity in suction performance enhances the swiftness of residual moisture extraction. With a 600 L/min setup, approximately 71.95% of the original 2g residual moisture was removed within 2,103 seconds. Although the 200 L/min variant displayed marginally better efficiency over 100 L/min, the time required was notably less, rendering it a more time-effective solution. These patterns imply diminishing returns beyond a specific suction threshold, though the benefit of reduced drying time persists.

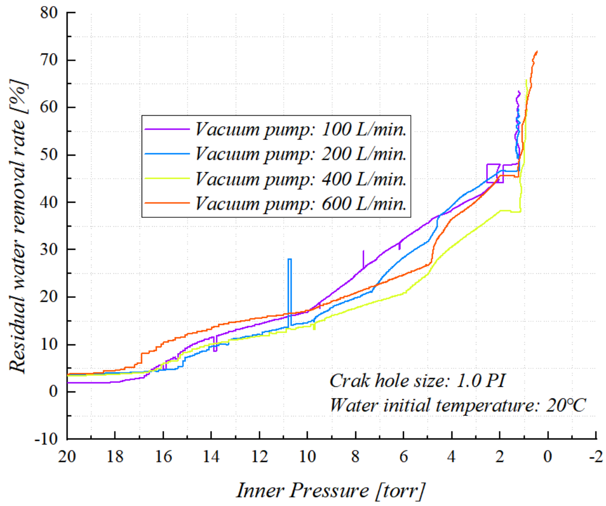

Fig. 4. Pressure Variation and Its Effect on Water Expulsion Efficiency

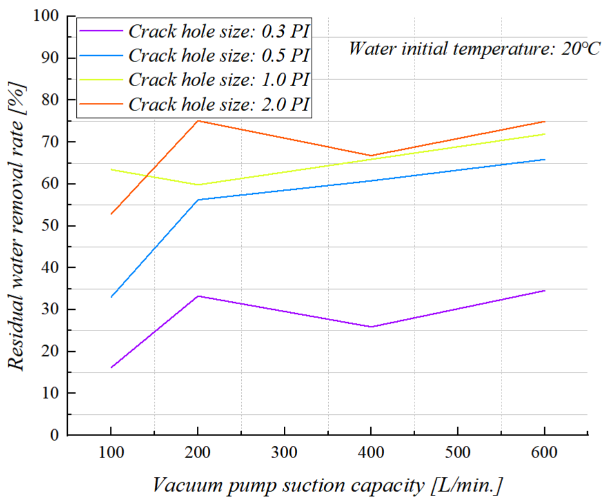

Fig. 5. Success Metrics of Moisture Evacuation Amidst Pump Modulation

A deeper investigation of specific pressure zones, showcased in Figure 4, highlights observable disparities contingent upon pumping force. The 100 L/min condition necessitates prolonged intervals to achieve targeted minimum pressure when juxtaposed with 400 and 600 L/min trials. Subsequently, the 100 L/min scenario consistently results in lower moisture expulsion—in essence, water removal ratios heighten noticeably around ultra-low pressures, such as 1.5 torr, due to the imperative hold duration inherent in the vacuum-drying protocol.

Lastly, the critical measure in vacuum drying processes is the rate of residual water elimination, emphasized in Figure 5. Enhanced pump power correlates directly with expeditious, amplified phases of evaporation, fostering rapid moisture release while maintaining elevated removal ratios. It is observed, albeit infrequently, that advanced pumps may exhibit reduced removal ratios relative to lower capacity models, often due to a decrease in expulsion volume facilitated by the aperture within the fuel rod.

In conclusion, this comprehensive analysis delineates the profound impact of pump effectiveness on moisture evaporation dynamics throughout the vacuum drying process. High suction rates prompt swift entrance into enhanced evaporation conditions, facilitate dynamic boil-off and comprehensive moisture egress via the fuel rod's micro-fissures, and significantly curtail drying times. Nonetheless, optimal performance still confronts barriers from crack dimensions and moisture retention, necessitating innovative solutions for complete desiccation. Therefore, the intricate synergy between pump performance, structural crack attributes, and drying efficiency yields vital insights, informing the evolution of vacuum drying systems in both industrial and research domains.

4. Conclusions

This investigation underscores the profound influence of pump suction performance on the vacuum desiccation of compromised nuclear fuel rods. Elevated suction rates facilitate a more expedited reduction of internal canister pressure, prompting a swifter transition into the vaporization phase and the enhanced expulsion of residual moisture through fissures in the rods. Notably, suction capacities of 400 L/min and above significantly truncate drying durations, with the 600 L/min configuration meeting the drying criterion in the least temporal span. However, the efficacy of moisture removal remains contingent upon the dimensional characteristics of the cracks, with smaller fissures impeding the expulsion of water despite higher suction intensities. The findings elucidate the intricate interplay between suction performance, crack morphology, and thermodynamic behavior. While increased suction rates ameliorate drying efficiency, they concurrently precipitate accelerated thermal dissipation, such as the rapid freezing of residual water, thereby complicating the process. This study accentuates the necessity of optimizing the equilibrium between pump performance and crack dimensions to attain maximal drying efficiency while preserving the structural integrity of the fuel rods. In summation, although elevated suction rates augment the expedience of vacuum drying, challenges persist in the complete removal of residual moisture, primarily driven by crack geometry and moisture retention. Continued refinement of drying systems is requisite to enhance moisture expulsion efficacy and ensure the safe, thorough handling of spent nuclear fuel. Greater focus and further study are necessary for the management of spent nuclear fuel transportation and storage in Korea [7].

Acknowledgements

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