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Characterization, and Coefficient of Performance of Supersaturated Vapor Cooling Unit Used for Crystallization Control

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Abstract

The supersaturated vapor cooling technique is a powerful tool for manipulating phase transitions, studying reaction mechanisms, and fabricating advanced materials. By pushing vapors into a non-equilibrium state through rapid cooling, scientists gain access to otherwise inaccessible phenomena. Whether it's understanding cloud formation, synthesizing nanoparticles, or examining nickel complex antifungal interactions, this technique remains vital to both theoretical insights and technological progress. In this study, a supersaturated vapor cooling system was used to study the effects of vapor pressure and temperature on the supersaturated vapor cooling performance of such system. Also, the coefficient of performance of this system was determined as a function of both variables mentioned above (i.e., vapor pressure and temperature).

Keywords: Cooling systems; Saturated vapor cycle; Supersaturated vapor cooling; Crystallization control

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1. Introduction

The supersaturated vapor cooling technique is a crucial method in physical chemistry, materials science, and atmospheric studies. It involves the rapid cooling of vapor to create a state where it becomes supersaturated, meaning the vapor contains more of a substance than it can theoretically hold at equilibrium at that temperature and pressure. This non-equilibrium state is critical for initiating nucleation, condensation, or crystallization processes and has far-reaching applications in various scientific and industrial fields [1-3].

To appreciate the supersaturated vapor cooling technique, one must first understand the concept of supersaturation. A vapor is said to be saturated when it contains the maximum amount of vapor that can exist in equilibrium with its liquid or solid phase at a specific temperature and pressure. When a vapor contains more substance than this equilibrium allows, it is in a supersaturated state. This state is inherently unstable, and the excess vapor tends to condense or crystallize if given a nucleation site or sufficient energy [4-6].

Supersaturation can be achieved by lowering the temperature of the vapor (cooling), increasing the vapor pressure without changing the temperature, or a combination of both. The cooling method is among the most widely used because it provides precise control over the supersaturation level and can be implemented rapidly through various advanced techniques [7-9].

In the supersaturated vapor cooling technique, a vapor is cooled quickly to a temperature below its saturation point, without allowing it enough time to condense immediately. This sudden temperature drop creates a metastable state where the vapor contains more gaseous molecules than it would at equilibrium for the lower temperature, i.e., it becomes supersaturated [10-12].

The process typically involves rapid expansion of vapor into a vacuum or a lower-pressure chamber, use of carrier gases to assist in maintaining the vapor flow and reduce aggregation, and precise thermal control to avoid premature condensation [13].

One of the most effective ways to achieve this is through supersonic jet expansion, where a gas mixture is expelled through a narrow nozzle into a vacuum chamber. This causes a sharp drop in temperature due to adiabatic expansion, and the vapor becomes supersaturated [14].

When describing the mechanism of cooling and nucleation, as the vapor cools rapidly, the molecules lose kinetic energy and move more slowly. If the cooling rate is high enough, the vapor bypasses the normal condensation temperature and enters a supersaturated state without forming droplets immediately. However, because this state is unstable, any slight disturbance, presence of dust particles, ions, or even fluctuations in density can cause homogeneous nucleation (without any foreign particle) and heterogeneous nucleation (on surfaces or particles present in the medium). Once nucleation begins, it can rapidly grow into droplets, crystals, or even nanoparticles, depending on the nature of the vapor and the cooling environment [15].

Supersaturated vapor cooling is used in various applications. In nanotechnology and materials science, supersaturated vapor cooling is used to produce nanoparticles, quantum dots, thin films, and nanoclusters. The size and shape of the synthesized material can be precisely controlled by adjusting the supersaturation level and cooling rate. Also, supersaturated vapor environments help isolate and stabilize transient molecular species [16]. When cooled rapidly, molecules can be trapped in specific conformations or vibrational states, enabling detailed spectroscopic analysis. In meteorology and climate research, supersaturation plays a critical role in cloud formation. Studying this technique in laboratories helps model the behavior of aerosols, droplet nucleation, and ice crystal formation in the upper atmosphere [17]. Some coordination complexes, such as nickel complexes with mixed ligands, show specific behaviors under supersaturated cooling conditions, aiding in the development of drug delivery systems, controlled crystallization, and bioavailability studies. This technique is important in research due to the ability to control supersaturation has opened new frontiers in both basic and applied sciences. In chemistry, it allows researchers to study reaction intermediates that exist only briefly at room temperature. It also allows to create high-purity crystalline materials for electronics and semiconductors. As well, it allows to observe gas-phase interactions without interference from thermal noise. In physics and engineering, it is used in laser cooling, atomic clocks, and condensed matter studies [18].

Despite its broad applications, the supersaturated vapor cooling technique has several challenges such as the precise thermal control, which is required to avoid uncontrolled nucleation. Supersaturation stability is hard to maintain over long durations. Contamination from particles or ions can alter the condensation process. The instrumentation cost can be high for vacuum systems and rapid cooling setups. However, advancements in microfluidics, cryogenics, and molecular beam techniques are gradually overcoming these limitations [19,20].

2. Experimental Setup

Several experimental setups are used for supersaturated vapor cooling, including:

(a) Supersonic nozzle expansion (fast flow technique). A common method where gas containing the vapor is expanded through a nozzle into a vacuum chamber. The rapid expansion leads to sudden cooling and supersaturation. This method is often used in molecular beam experiments.

(b) Cloud chambers. Originally developed for particle physics, cloud chambers rely on supersaturated vapor cooling to visualize radiation tracks. A sudden expansion in the chamber cools the vapor, leading to visible condensation trails along the paths of charged particles.

(c) Cold traps and cryogenic surfaces. These involve cooling surfaces to cryogenic temperatures to condense vapors from a gas stream. This is a slower but controlled method useful in vacuum systems and analytical chemistry.

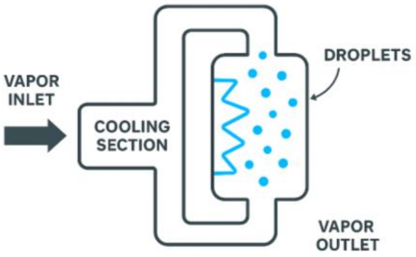

Fig. (1) Scheme of the supersaturated vapor cooling system

3. Results and Discussion

Figure (2) shows how the supersaturation ratio increases as temperature decreases in a cooling vapor system. The vapor becomes increasingly supersaturated as it cools, since the saturation pressure drops while the actual vapor pressure remains constant. This rising ratio indicates the increasing likelihood of condensation as the system cools.

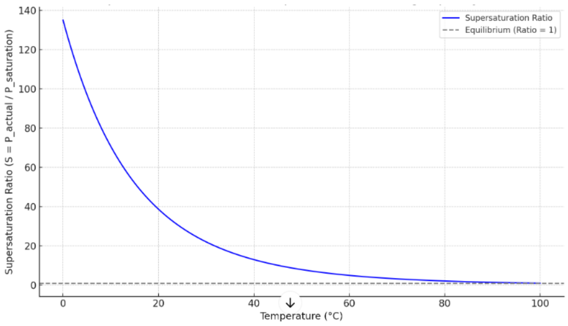

Fig. (2) Variation of the supersaturation ratio with temperature in the supersaturated vapor cooling system

Figure (3) illustrates the relationship between vapor pressure and temperature in a supersaturated vapor cooling system. The green curve shows how the saturation vapor pressure decreases exponentially with temperature. The red dashed line represents the actual vapor pressure, which stays constant in this simplified model. As temperature drops, the saturation pressure falls below the actual vapor pressure, leading to supersaturation—the key condition that drives condensation in the system.

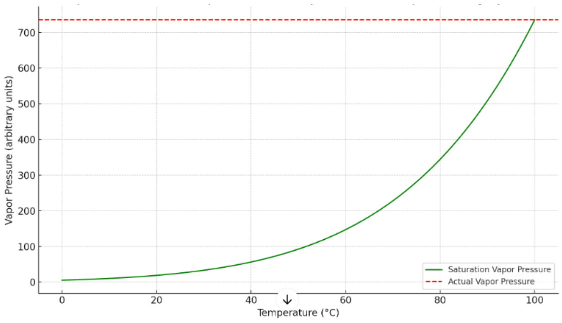

Fig. (3) Variation of the vapor pressure with temperature in the supersaturated vapor cooling system

Figure (4) presents a 3D chart showing how the Coefficient of Performance (COP) of a supersaturated vapor cooling system varies with both temperature and vapor pressure. Higher temperatures generally improve COP due to greater temperature lift efficiency, while lower vapor pressures also increase COP, as the system works less to reject heat. This helps visualize the ideal operating window for maximizing cooling efficiency.

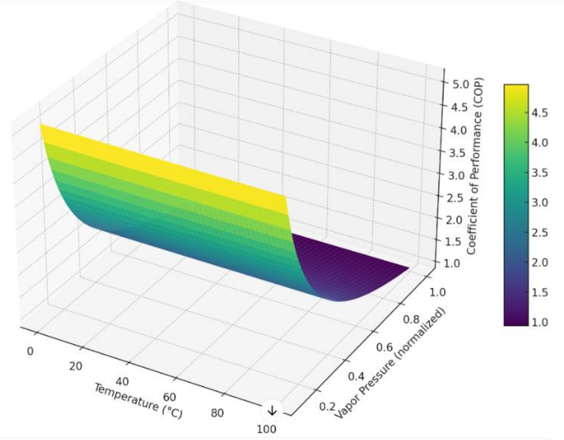

Fig. (4) Variation of the coefficient of performance (COP) of the supersaturated vapor cooling system with vapor pressure and temperature

4. Conclusion

As interest in nanotechnology, pharmaceuticals, and environmental science grows, supersaturated vapor cooling will continue to evolve. Potential developments include portable supersaturation chambers for fieldwork, Machine learning control systems for nucleation prediction, and integration with 3D printing to develop nanostructured materials.

References

[1] L. Kupershtokh, "Simulation of Substrate Cooling during Evaporation of Pure Vapor from the Surface of a Thin Liquid Film and Droplets," *J. Appl. Ind. Math.*, 17(4) (2023) 582–591.

[2] A.D. Nazarov, N.B. Miskiv, A.F. Serov, and V.N. Mamonov, "Single-Phase Cooling of Large Surface by Water Droplet Flow," J. Eng. Thermophys., 33 (2024) 536–546.

[3] D. Kumar, R.A. Memon, A.G. Memon, and I. Ali, "Critical Analysis of the Condensation of Water Vapor at External Surface of the Duct," *Heat Mass Transfer*, 54(7) (2018) 1937–1950.

[4] G. Chen, "Interfacial Cooling and Heating, Temperature Discontinuity and Inversion in Evaporation and Condensation," *arXiv preprint*, arXiv:2307.16043 (2023).

[5] H. Duwairi, A. Bani Yaseen, and M. Alrbai, "Theoretical Study of Superheated Vapor Effect on Liquid Film Condensation in a Saturated Porous Medium Using Forchheimer's Model – Part A", *Heat Transfer*, 52(2) (2023) 1866–1893.

[6] H. Duwairi, A. Bani Yaseen, and M. Alrbai, "Theoretical Study of Superheated Vapor Effect on Liquid Film Condensation in a Saturated Porous Medium Using Forchheimer's Model Part B", *Heat Transfer*, 52(5) (2023) 2775–2784.

[7] H. Liu, Z. Wei, W. He, and J. Zhao, "Thermal Issues About Li-Ion Batteries and Recent Progress in Battery Thermal Management Systems: A Review," Energy Convers. Manag., 150 (2017) 304–330.

[8] J. Okajima and P. Stephan, "Numerical Simulation of Liquid Film Formation and Its Heat Transfer Through Vapor Bubble Expansion in a Microchannel," *arXiv preprint*, arXiv:1903.08321 (2019).

[9] K.O. Sabdenov, T.M. Zhakupov, and M. Erzada, "Modeling of Cooling Tower Operation with Consideration for the Chemical Work in the Steam–Air Mixture," *J. Eng. Phys. Thermophys.*, 96(4) (2023) 1081–1088.

[10] L. Bai, L. Zhan, G. Lin, and G. Peterson, "Pool Boiling with High Heat Flux Enabled by a Porous Artery Structure," Appl. Phys. Lett., 108 (2016) 221602.

[11] L. Xia, W. Wang, and Y. Zhu, "Prediction Models of Saturated Vapor Pressure, Saturated Density, Surface Tension, Viscosity and Thermal Conductivity of Electronic Fluoride Liquids in Two-Phase Liquid Immersion Cooling Systems: A Comprehensive Review," Appl. Sci., 13(7) (2023) 4200.

[12] M. Baghsheikhi and M. Mohammadi, "Experimental Investigation of the Vapor-Compression Cooling System in a Data Center: Energy and Exergy Analysis," J. Therm. Anal. Calorim., 148 (2023) 9079–9097.

[13] R. Jin, E. Keshavarzian, K. Dong, S. Dong, B. Wang, K. Kwok, and M. Zhao, "Numerical Study on the Effect of the Supersaturated Vapor on the Performance of a Gas Cyclone," *Powder Technol.*, 366 (2020) 324–336.

[14] S.R. Tamvada and S. Moghaddam, “Data Center Energy Efficiency Enhancement Using a Two-Phase Heat Sink with Ultra-High Heat Transfer Coefficient,” *arXiv preprint*, arXiv:2207.12508 (2022).

[15] V. Holten, C.E. Bertrand, M.A. Anisimov, and J.V. Sengers, “Thermodynamics of Supercooled Water,” *arXiv preprint*, arXiv:1111.5587 (2011).

[16] W. Jin, X. Mu, Z. Hu, X. Yin, S. Shen, and G. Liang, “Numerical Investigation of Vapor Condensation on a Hierarchical Microstructured Surface with a Phase-Change LB Method,” *Ind. Eng. Chem. Res.*, 62(48) (2023) 20859–20874.

[17] X. Li, L. Lv, X. Wang, and J. Li, “Transient Thermodynamic Response and Boiling Heat Transfer Limit of Dielectric Liquids in a Two-Phase Closed Direct Immersion Cooling System,” Therm. Sci. Eng. Prog., 25 (2021) 100986.

[18] X. Liang, M.Y. Chan, S. Deng, and X. Xu, “Dehumidification Effects in the Superheated Region (SPR) of a Direct Expansion (DX) Air Cooling Coil,” *Energy Convers. Manag.*, 50(12) (2009) 2953–2958.

[19] X. Wu, J. Yang, H. Guo, Y. Zhuang, C. Li, Y. Liu, and X. Han, “Theoretical and Experimental Research on Flow Boiling Heat Transfer in Microchannels for IGBT Modules,” Int. J. Heat Mass Transf., 205 (2023) 123900.

[20] Y. Jing, Y. Wang, and Q. Huang, “Experimental and Simulation Study on the Direct Contact Condensation of Saturated Steam on Moving Droplets at Sub-Atmospheric Pressure,” *Processes*, 11(4) (2023) 1097.