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A Review on Dropwise Condensation

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ABSTRACT:
Dropwise condensation (DWC) has been extensively studied for its potential to enhance heat transfer efficiency in thermal management systems. This review synthesizes findings from various studies on optimizing surface properties, improving condensation heat transfer, and exploring advanced surface engineering techniques. Research has demonstrated that micro/nanotextured surfaces, hydrophobic and superhydrophobic coatings, and solid-infused surfaces (SIS) significantly enhance DWC by promoting droplet mobility and reducing filmwise condensation. Computational and experimental analyses have explored the effects of surface inclination, vapor velocity, and environmental conditions on droplet dynamics and heat transfer performance. Innovative surface modifications, including copper-graphene nanoplatelet (Cu-GNP) coatings and phase change material (PCM) microcapsules, have shown promising results in improving durability, corrosion resistance, and frost inhibition. Additionally, individual-based models (IBMs) have provided accurate simulations of droplet growth and heat flux variations, outperforming traditional population-based models (PBMs). While current research offers valuable insights, challenges remain in long-term stability, material scalability, and performance under real-world conditions. The integration of advanced surface engineering, computational modelling, and experimental validation continues to drive the evolution of DWC, paving the way for more efficient and sustainable thermal managementsolutions**.**

Keywords: Dropwise Condensation (DWC), Heat Transfer, Surface Modifications, Hydrophobic Coatings, Superhydrophobic Surfaces, Solid-Infused Surfaces (SIS), Phase Change Materials (PCM), Surface Inclination, Micro/Nanotextured Surfaces, Computational Modelling, Individual-Based Models (IBM), Population-Based Models (PBM), Corrosion Resistance, Wettability, Jumping Droplet Condensation (JDC), Gravity-Driven Condensation (GDC)

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I. INTRODUCTION

Dropwise condensation (DWC) is a highly efficient phase-change heat transfer process, widely recognized for its ability to enhance thermal performance in industrial applications such as power generation, desalination, refrigeration, and heat exchangers.

Unlike filmwise condensation, where a continuous liquid film covers the surface and impedes heat transfer, DWC occurs when discrete droplets form and grow on a hydrophobic or structured surface before shedding due to gravity or coalescence. This mechanism allows for higher heat transfer coefficients—often an order of magnitude greater than those observed in filmwise condensation—making DWC an attractive solution for improving energy efficiency in thermal systems.

The phenomenon of dropwise condensation is governed by the interplay between surface wettability, environmental conditions, and droplet dynamics. When vapor comes into contact with a surface cooler than its saturation temperature, it condenses into liquid droplets rather than spreading as a continuous film, provided that the surface possesses hydrophobic properties. These droplets continuously nucleate, grow, and coalesce before detaching, maintaining a high rate of heat transfer. The efficiency of DWC depends on factors such as contact angle, surface roughness, and the presence of non-condensable gases, which can influence droplet behaviour and heat transfer performance.

Advancements in surface engineering have played a crucial role in promoting and sustaining DWC. Researchers have explored various techniques, including micro/nanotexturing, superhydrophobic coatings, and lubricant-infused surfaces, to enhance droplet mobility and reduce adhesion. Coatings composed of noble metals like gold and silver, hydrophobic polymers such as PTFE, and graphene-based materials have been shown to improve condensation efficiency by facilitating rapid droplet shedding. Additionally, solid-infused surfaces (SIS) and phase change material (PCM) microcapsules have emerged as innovative approaches to further optimize condensation heat transfer and mitigate icing in subzero conditions.

The performance of DWC is also influenced by external factors such as surface inclination, vapor velocity, and ambient humidity. Studies have demonstrated that inclined surfaces and high-velocity vapor flows promote efficient droplet removal, preventing flooding and enhancing heat transfer rates. Computational and experimental investigations have provided deeper insights into the role of droplet size distribution, heat flux variations, and surface renewal mechanisms in optimizing condensation behaviour. Advanced modelling techniques, such as individual-based models (IBMs), have been developed to accurately simulate droplet growth dynamics, outperforming traditional population-based models (PBMs) in predicting heat transfer coefficients and droplet departure radii.

Despite its advantages, sustaining long-term DWC remains a challenge due to surface degradation, fouling, and the accumulation of non-condensable gases, which can gradually transition the surface to filmwise condensation. The durability of hydrophobic and superhydrophobic coatings is a critical concern, as prolonged exposure to harsh operating conditions can lead to loss of surface functionality. Additionally, the scalability and cost-effectiveness of engineered surfaces remain key factors in determining their feasibility for widespread industrial adoption.

To address these challenges, ongoing research focuses on optimizing surface properties, developing self-replenishing coatings, and integrating hybrid surface treatments that balance hydrophobicity with mechanical robustness. The integration of dropwise condensation with emerging technologies, such as waste heat recovery and passive cooling systems, further underscores its significance in advancing sustainable and energy-efficient thermal management solutions. As research continues to refine surface engineering strategies and computational modelling approaches, DWC remains a promising avenue for enhancing heat exchanger performance and driving innovation in next-generation heat transfer applications.

This review analyses key factors influencing dropwise condensation (DWC) heat transfer, focusing on surface modifications, environmental conditions, and computational modelling. Research on micro/nanotextured surfaces, hydrophobic coatings, and solid-infused surfaces (SIS) has shown improvements in droplet mobility and heat transfer. Studies on surface inclination, vapor velocity, and phase change materials (PCM) further enhance condensation performance. Advanced computational models, like individual-based models (IBMs), refine understanding of droplet dynamics. These insights are essential for optimizing DWC in power generation, desalination, and thermal management applications.

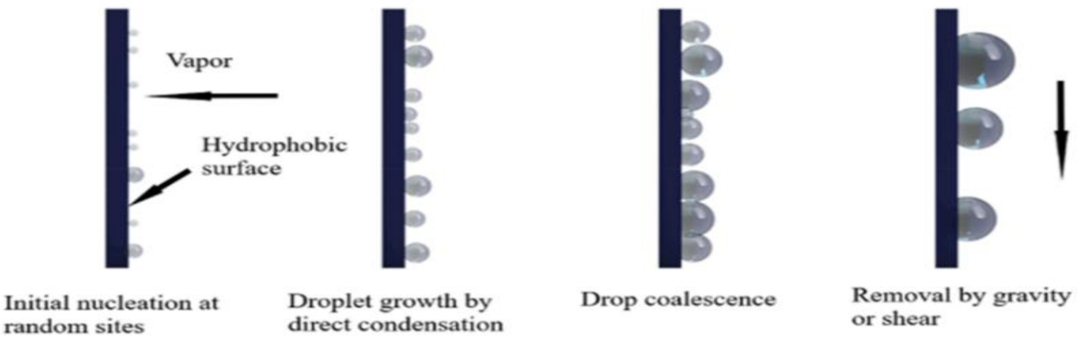

Fig 1 Various stages of DWC[5]

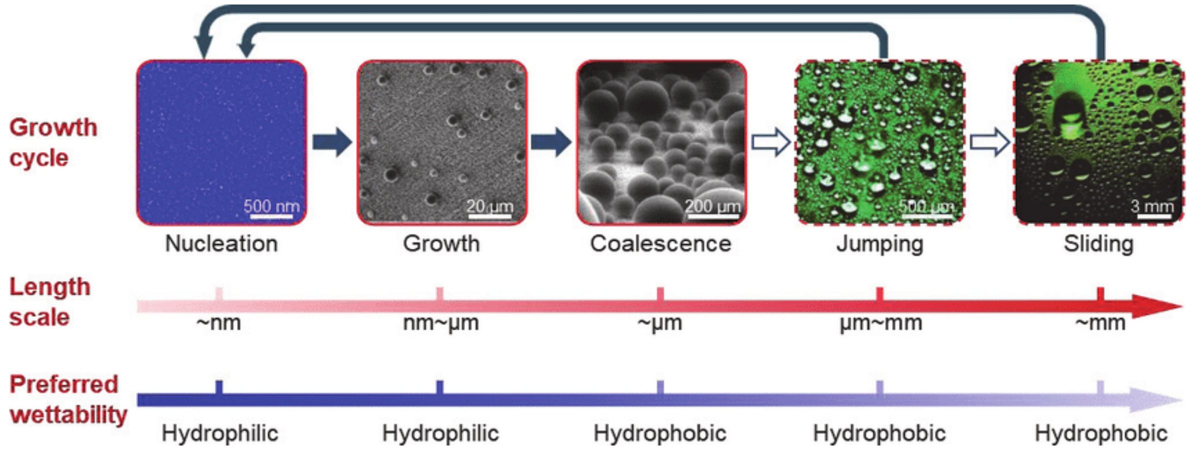

Fig 2 Multiscale characteristics of dropwise condensation and differential preference on wettability for various subprocesses. [11]

II. LITERATURE REVIEW

1. Matteo Miraforiet al [1]presents an individual-based model (IBM) for simulating droplet growth and dynamics in dropwise condensation (DWC), using a hybrid MATLAB-C approach to improve computational efficiency by 10 to 100 times. The IBM accurately captures droplet size distribution (Fig 2) and heat flux, with a time step of 5×10^{-5} s needed for precise small and large droplet predictions, while 10^{-3} s maintains reliable heat flux estimates with increased efficiency.Compared to population-based models (PBMs), IBM avoids the 30% overestimation of small droplet populations, providing a more accurate condensation representation. It also incorporates droplet acceleration, showing a 4% variation in heat flux due to sliding droplets. Experimental validation confirms a 5% mean heat flux deviation, proving its accuracy. IBM proves to be a superior tool for DWC simulations, balancing efficiency and precision.

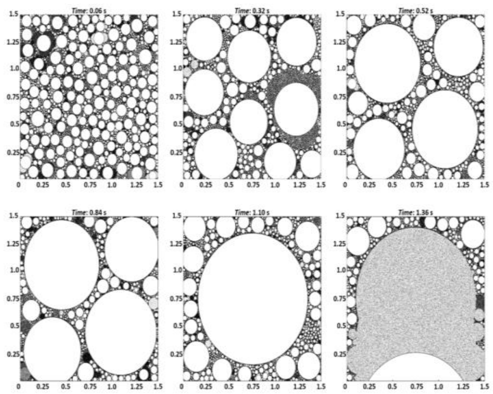

Fig 3 Visualization of the nucleation, growth and sliding of droplets during DWC of pure steam. Simulation parameters: lx = ly = 1.5 mm, Ns = 5 × 1012 m− 2, Δτ =10− 5 s, Δtsim= 1.5 s and, a = 2.6 m s− 1 [1]

2. Marco Tanconet al [2] The study examines the impact of surface inclination (horizontal, 45°, and vertical) and vapor velocity (3.3–13.8 m/s) on dropwise condensation heat transfer. Using experimental and computational methods, it analyses droplet removal, heat transfer coefficient (HTC), and droplet size distribution. At lower vapor velocities (~3.5 m/s), HTC on inclined and horizontal surfaces decreased by 10% and 40%, respectively, compared to vertical surfaces (94 kW/m²K). As vapor velocity increased to 13.8 m/s, HTC improved across all inclinations, reaching 120 kW/m²K due to smaller droplet size and enhanced surface renewal. The study highlights the role of adhesion, gravity, and drag forces in droplet departure. On horizontal surfaces, where gravity is absent, drag force solely drives droplet removal, leading to larger departing droplets. Higher steam velocity promotes smaller droplets, improving heat transfer efficiency. A modified Tancon et al. model accurately predicted droplet departure radius within ±10% of experimental data, and HTC predictions aligned well with experiments. The research provides valuable insights for optimizing condensation-based heat exchangers by balancing surface orientation and vapor velocity. However, it is limited to sol-gel silica-coated aluminium surfaces, and further exploration of micro/nanoscale surface modifications could enhance HTC efficiency.

3. F. TarpoudiBaheriet al [3] conducted a study on condensation freezing and frosting of bituminous surfaces at subzero temperatures (Fig 3), focusing on passive inhibition methods using phase change material (PCM) microcapsules. It explores how environmental factors, such as relative humidity (RH) and cooling rate, influence

freezing behaviour. The results indicate that while initial condensation temperature is strongly dependent on RH, it remains largely unaffected by cooling rate. Lower RH and higher cooling rates lead to freezing at lower temperatures due to the smaller droplet volumes resisting freezing. The study identifies an explosive freezing mechanism, where supercooled droplets rapidly transition to ice, causing a temperature spike to 0°C due to latent heat release. Ice bridging is observed as a key factor in frost propagation, accelerating freezing across the surface. PCM microcapsules embedded in bitumen release latent heat, delaying ice formation. PCM-modified bitumen extends the average freezing time from 85 seconds (on virgin bitumen) to 185 seconds under constant heat flux cooling, significantly reducing frost formation. The findings highlight PCM-modified bitumen as a promising, eco-friendly alternative to chemical de-icers for winter road maintenance. However, further research is needed to assess its real-world durability and long-term effectiveness in outdoor environments.

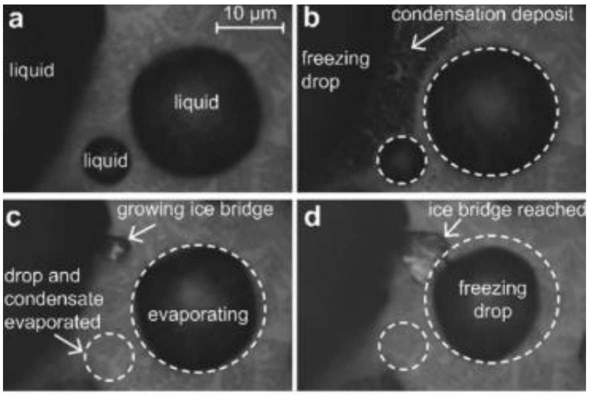

Fig 3 Microscopic ice bridging and freezing propagation on bitumen. a) Three supercooled liquid droplets. b) Freezing of the large droplet forms condensation deposits. c) An ice bridge grows while the condensation deposit and the smallest liquid droplet evaporate. d) The ice bridge reaches the medium size drop and freezes it.[3]

4. Loghman Mohammadpour et al[4]investigated the influence of the Nusselt number (Nu) on dropwise condensation (DWC) heat transfer for a single droplet on inclined and rough surfaces using computational fluid dynamics (CFD) simulations. Increasing Nu from 510 to 740 resulted in a 151.79% rise in average heat flux on a 90° inclined surface and a 152% increase on a rough surface with a roughness index of 0.6. While higher roughness promoted DWC, it reduced Nu's impact on heat flux. Surface inclination had a smaller effect, with water droplets showing a 4.29% increase in heat flux from 0° to 90°, while ethylene glycol showed an 8.73% rise. Higher saturation temperatures consistently enhanced heat flux across all conditions. Increasing Nu led to greater internal heat transfer within the droplet, particularly near the vapor interface on rough surfaces. The study provides a detailed CFD analysis validated against existing literature, with implications for optimizing heat exchangers in power plants and refrigeration systems. However, it lacks experimental validation, long-term roughness analysis, and consideration of multi-droplet interactions

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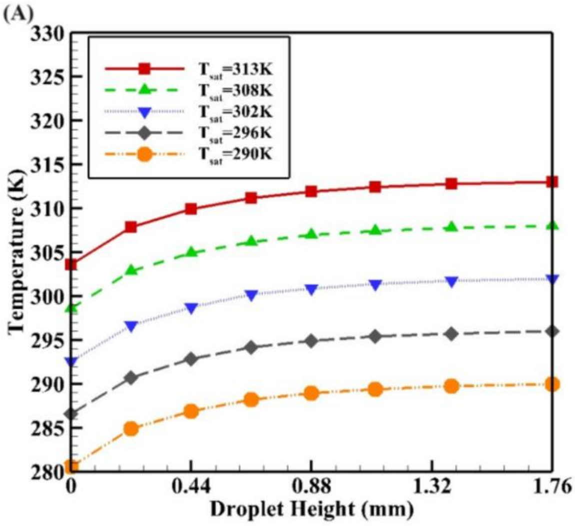
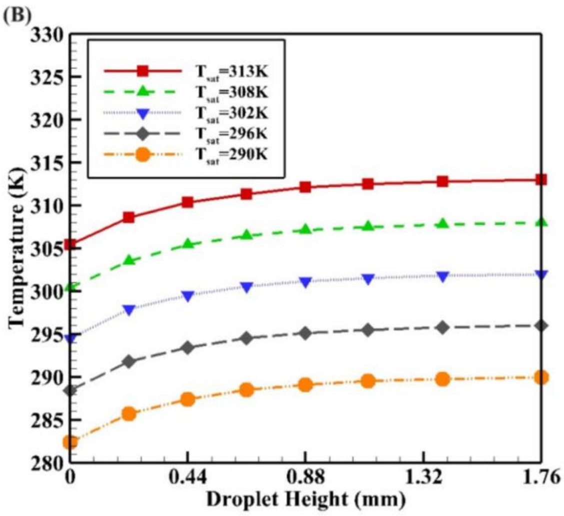
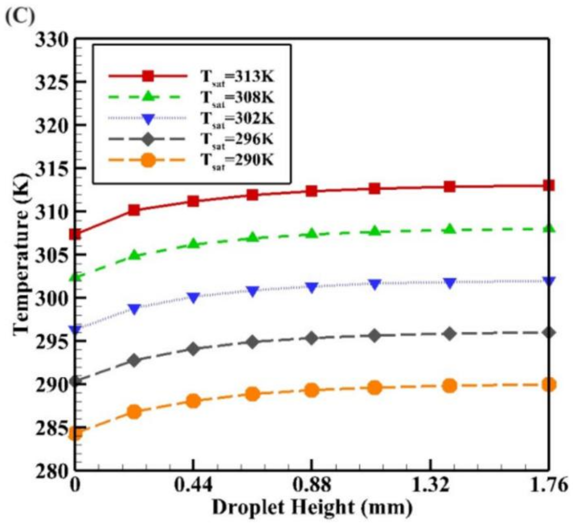
Fig 4 Variation of temperature against droplet height for different saturation temperatures at θ = 160°, V =4 μl, σ = 0.04, δc = 10 μm, Kc = 0.2 W/m K, β = 0° and ri = 0.6 [4]



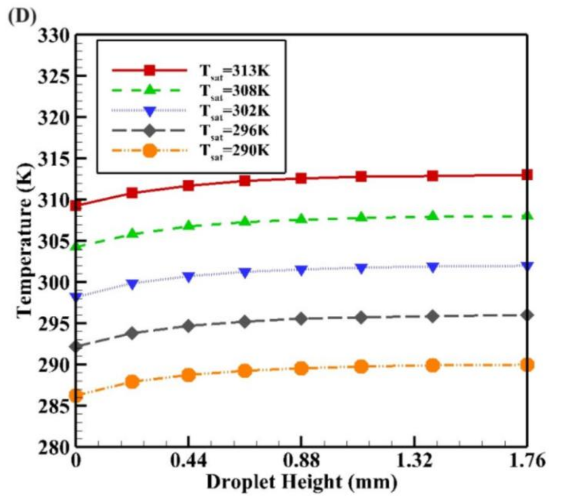
(A) Nu = 740,



(B) Nu = 6



(C) Nu =580



(D) Nu = 510.

5. Sandeep Hatte et al [5]investigated the theoretical and experimental limits of dropwise condensation (DWC) heat transfer on dry nonwetting surfaces (DNS), including hydrophobic (HS), superhydrophobic (SHS), and solid-infused surfaces (SIS). Using a unified fractal model, it identifies an optimal surface roughness ratio ($1.5 < L^* < 3.0$) that maximizes heat transfer before internal thermal resistance reduces efficiency. Experimental results show that SHS improves heat transfer over filmwise condensation but remains below theoretical limits, while SIS surfaces perform closer to the predicted maximum. Jumping droplet condensation (JDC) on nanotextured surfaces excels at low supersaturation but declines under high supersaturation, whereas gravity-driven condensation (GDC) on microtextured SHS and SIS surfaces offers more stable performance. The study underscores the performance gap between existing SHS surfaces and theoretical potential, highlighting SIS as a promising alternative. While it provides a strong theoretical and experimental foundation, further research is needed on temperature effects, the durability of nanostructured surfaces, and lubricant-infused surface performance. These insights have significant implications for improving heat exchangers in power generation, desalination, and cooling systems.

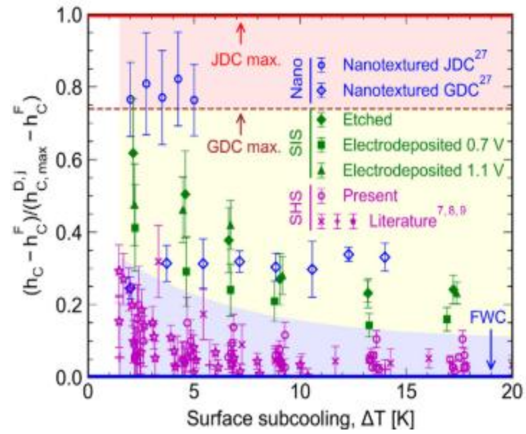


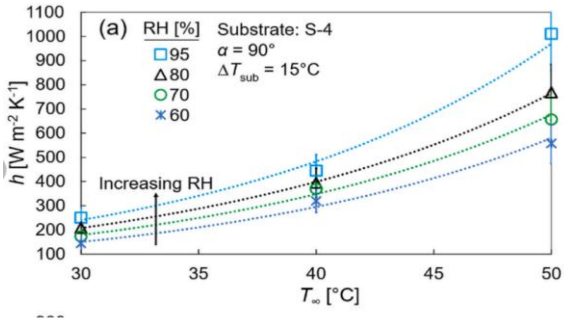
Fig 5. Experimental data relative to the lower and upper bounds on the condensation heat transfer coefficient [5]

6. Amit goswami et al[6] explores surface modifications to enhance dropwise condensation (DWC) for improved heat transfer efficiency in industrial applications like power generation and desalination. It compares various engineering techniques, highlighting that hydrophobic and superhydrophobic surfaces prevent liquid film formation and promote droplet shedding. Roughened surfaces with hierarchical micro/nanostructures further enhance condensation by increasing nucleation site density and droplet removal. Material coatings play a crucial role, with hydrophobic polymer coatings (e.g., PTFE, fluoropolymers) reducing surface energy and improving droplet mobility. Noble metal coatings (gold, silver) enhance DWC through high thermal conductivity and hydrophobicity, while composite coatings offer durability and long-term effectiveness. Optimized DWC surfaces exhibit heat transfer coefficients 7–10 times higher than filmwise condensation, with coatings under 1 μm providing the best balance of performance and durability. However, non-condensable gases reduce efficiency, emphasizing the need for controlled environments. While polymer coatings improve short-term performance, long-term stability remains a challenge due to degradation. Metal and composite coatings offer better durability but require careful selection to prevent oxidation and fouling. The study underscores the importance of

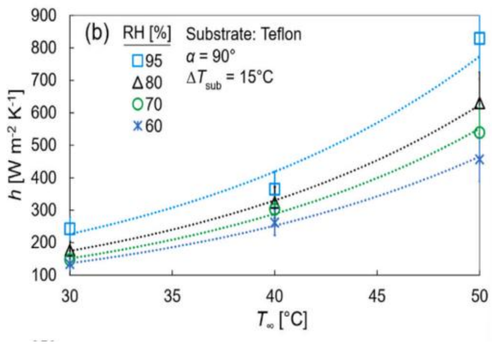
scalable and robust surface modification techniques for real-world industrial adoption, offering valuable insights for optimizing heat exchangers and achieving significant energy savings,

7. Shahriyar Abedinnezhadet al [7] conducted a study on natural dropwise condensation on engineered surfaces, focusing on microtextured and nanotextured substrates. It finds that microtextured superhydrophobic surfaces achieve two to three times higher condensation heat transfer coefficients than nanotextured ones, due to their larger effective heat transfer area despite slightly higher contact angle hysteresis. The apparent contact angle and contact angle hysteresis play crucial roles, with optimal performance at a 150° contact angle. Additionally, the heat transfer coefficient increases linearly with relative humidity, enhancing condensation efficiency. While the study effectively analyses surface characteristics, it does not extensively explore

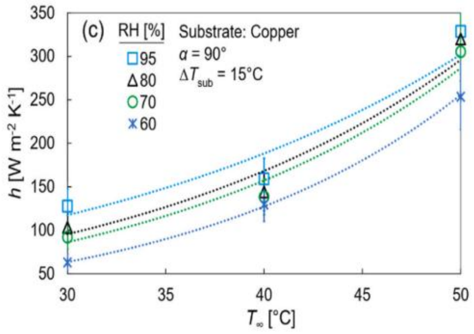
Fig 6 The condensation heat transfer coefficient on a vertical flat surface under different relative humidity levels, and ambient temperatures (ΔT_{sub} =15◦C) for samples of



(a) superhydrophobic;



(b) hydrophobic;



(c) hydrophilic substrates.

8. Matteo Mirafiori et al[8] introduced a validated individual-based model (IBM) for simulating dropwise condensation (DWC) in humid air, achieving a 6% accuracy in predicting heat transfer and droplet behaviour. The study identified the Zheng et al. model with an accommodation coefficient of 10^{-4} as the most accurate, showing a 76% rise in droplet growth as humidity increased from 50% to 90%. Hydrophobic surfaces (θe = 120°) exhibited a higher density of small droplets, while those under 10 μm contributed less than 5% to total heat flux. This research enhances DWC modelling for HVAC and industrial applications but could benefit from further exploration of long-term surface stability.

9. Yuanlin Yao et al [9]examines dropwise condensation on micro-structured surfaces—cylindrical, cubic, conical, and pyramidal—fabricated on silicon with a height of 6 μm. Cylindrical and cubic structures exhibited superhydrophobicity (contact angles of 158.4° and 155.5°), while conical and pyramidal surfaces were hydrophilic (86.4° and 44.4°). The cylindrical surface showed the highest heat transfer coefficient and heat flux, with condensation efficiency decreasing as subcooling increased. Cylindrical structures also facilitated faster droplet shedding, while sharp edges on cubic and pyramidal surfaces hindered mobility. Increased cooling water flow improved heat flux, with cylindrical structures benefiting the most. The study provides valuable insights into surface morphology's role in heat transfer, with applications in heat exchangers and cooling systems. However, it lacks discussion on long-term durability, industrial scalability, and the effects of non-condensable gases.

10. Tahmineh Forati et al[10] investigated copper-graphene nanoplatelet (Cu-GNP) coatings developed via Atmospheric Plasma Spray (APS) and High-Velocity Oxygen Fuel (HVOF) techniques, focusing on wettability and corrosion resistance. The Cu-GNP-LR-HVOF-S sample achieved superhydrophobicity (contact angle 164°,

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sliding angle <1°), with HVOF coatings outperforming APS in uniformity and durability. Cu-GNP coatings significantly enhanced corrosion resistance, reducing the bare copper corrosion rate (0.36 mm/year) to 0.03 mm/year—a 12-fold improvement. Microstructural analysis confirmed HVOF coatings had fewer defects and greater stability. The findings suggest Cu-GNP coatings as a durable, water-repellent solution for condensation applications.

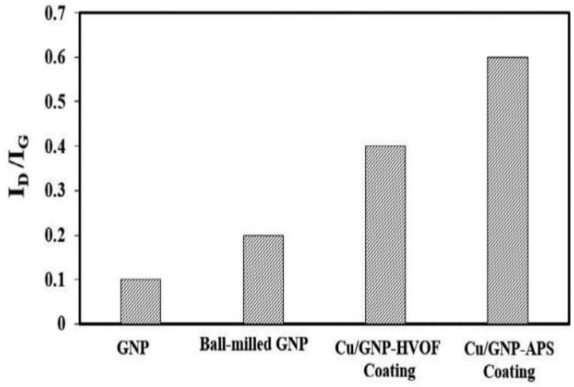

Fig 7 The distribution of ID/IG of pure GNP, ball-milled GNP, the HVOF and the APS sprayed samples. [10]

III. RESULTS TABLE

Factor	**Findings**	**Implications**
Computational Modeling	IBM model with OpenMP parallel computing achieves 10-100× speed improvement. Accurate heat flux prediction with 5% deviation from experiments. [1]	Enables large-scale simulations for optimizing DWC heat transfer in industrial applications.[1]
Surface Inclination	HTC decreases as inclination deviates from vertical (10% lower at 45°, 40% lower at 0°). HTC equalizes at high vapor velocities (~13.8 m/s).[2]	Highlights the need for optimized inclination angles in heat exchanger design.[2]
Humidity and Freezing Effects	High humidity accelerates condensation and freezing. PCM-modified bitumen delays freezing. [3]	Important for designing antifreeze coatings and moisture-resistant surfaces.[3]
Nusselt Number Influence	Higher Nu increases heat flux up to 152%. Roughness reduces Nu impact but improves DWC probability.[4]	Optimization of Nu and roughness can enhance heat transfer efficiency.[4]
Surface Properties and Coalescence	Coalescence-driven growth dominates heat transfer. Optimal asperity scale maximizes performance.[5]	Surface texture should be designed to enhance coalescence for higher efficiency.[5]
Surface Modifications	Noble metals, REOs, and polymer coatings enhance DWC but face durability/cost issues.[6]	Advanced materials research is needed for long-lasting and cost-effective coatings.[6]
Condensation on Humid Air	Microtextured surfaces show up to 3× improvement over nanotextured surfaces. Empirical HTC correlation developed.[7]	Guides the development of condensation surfaces with optimal micro texture.[7]
Humid Air Flow and IBM	IBM model validated with 6% deviation. High humidity increases droplet growth	Confirms IBM’s predictive capability and humidity’s strong influence on

	by ~76%.[8]	DWC.[8]
Micro structured Surfaces	Cylindrical and cubic microstructures enhance heat transfer over conical and pyramidal structures. [9]	Supports tailored surface engineering for maximizing DWC efficiency.[9]
Cu-GNP Coatings	HVOF coatings offer best corrosion resistance. Cu-GNP coatings enhance hydrophobicity.[10]	Useful for developing durable, high-performance coatings for DWC applications.[10]

Table 1 Comprehensive Results Table for DWC

3. FACTORS INFLUENCING DWC

Dropwise condensation (DWC) is a highly efficient phase-change heat transfer process influenced by several key factors, including surface properties, environmental conditions, fluid dynamics, and material durability. Understanding these factors is essential to optimizing DWC performance for industrial applications such as power generation, desalination, and thermal management systems.

3.1. Surface Properties:

A.)Surface Wettability: Surface wettability plays a crucial role in DWC efficiency. Hydrophobic and superhydrophobic surfaces reduce droplet adhesion, promoting efficient droplet shedding and enhancing heat transfer. Various coatings such as copper-graphene nanoplatelet (Cu-GNP) composites, self-assembled monolayers (SAMs) [10], and rare-earth oxides improve surface hydrophobicity. However, excessive roughness can negatively impact performance by reducing nucleation density and limiting droplet mobility [9]

B.)SurfaceRoughness andTexture: Microstructured and nanotextured surfaces significantly influence droplet formation and departure. Cylindrical and cubic microstructures exhibit better heat transfer performance due to easier droplet shedding, whereas conical and pyramidal textures hinder coalescence and reduce efficiency [9]. Excessive roughness can lead to filmwise condensation, reducing the overall heat transfer coefficient (HTC) [4].

C.) Surface Coatings and Modifications:
Various surface modifications enhance DWC efficiency by improving durability and hydrophobicity. Noble metals such as silver and copper exhibit high thermal conductivity but are costly. Polymers and lubricant-infused surfaces (LIS) provide hydrophobicity but face durability issues. Hybrid surfaces combining different coatings offer an optimized solution for long-term performance [6]

3.2. Environmental Conditions:

A.) Relative Humidity (RH) and Vapor Properties:
Higher relative humidity (60–95%) promotes faster droplet formation and improved heat transfer efficiency. Condensation rates increase as more moisture is available for nucleation.[7] However, excessive humidity can lead to frost formation in subzero conditions, reducing efficiency [3]

B.) SubcoolingTemperature(ΔTsub) :The temperature difference between the vapor and the condensing surface is a critical factor in droplet nucleation. Higher subcooling leads to increased droplet formation but can also cause flooding, which reduces DWC efficiency. At lower subcooling levels, nucleation density decreases, leading to reduced HTC [7]

C.) Ambient Temperature and Pressure:
Condensation rates are influenced by external temperature and pressure. Higher ambient temperatures accelerate condensation, whereas lower pressures promote vapor condensation by increasing the mean free path of molecules. These factors must be carefully controlled in industrial applications to maintain consistent DWC performance.

3.3. Fluid Dynamics and Vapor Flow Characteristics:

A.) Vapor Velocity: Higher vapor velocities (up to 13.8 m/s) enhance HTC by increasing droplet renewal rates and reducing residence time on the surface. However, excessive velocity can lead to shear forces that detach smaller droplets before they fully grow, reducing overall heat transfer efficiency [2]

B.) Droplet Growth, Coalescence, and Departure:
Efficient heat transfer in DWC relies on optimizing droplet lifecycle processes, including nucleation, growth, coalescence, and departure. Computational

studies using individual-based models (IBM) confirm that droplet growth dynamics significantly impact HTC [1][8] Larger departing droplets facilitate faster surface renewal, but excessive coalescence can lead to filmwise condensation, which lowers performance.

C.) Inclination Angle: The surface inclination angle affects droplet mobility and heat transfer efficiency. Vertical surfaces (90°) exhibit the highest HTC, whereas inclined (45°) and horizontal (0°) surfaces experience reduced HTC due to gravity-driven droplet behaviour. At high vapor velocities, HTC values tend to converge across all inclinations [1]

3.4. Material Durability and Scalability:

A.) Coating Stability and Longevity: One of the major challenges in industrial-scale DWC applications is maintaining long-term surface hydrophobicity. Coatings degrade over time due to wear, contamination, and thermal cycling. Research on graphene-based and rare-earth oxidecoatings aims toenhance durability while maintaining high thermal conductivity [10]

B.) Scalability of Functional Surfaces:

Bridging the gap between laboratory-scale innovations and large-scale manufacturing is essential for widespread adoption of DWC technologies. Advanced fabrication techniques such as atmospheric plasma spray (APS) and high-velocity oxy-fuel (HVOF) coating processes show promise for creating durable and scalable hydrophobic surfaces [10]

IV. CONCLUSIONS

- Computational modelling using IBM with OpenMP parallel computing improves computational efficiency by 10-100×, enabling large-scale simulations for industrial DWC optimization. [1]
- Surface inclination affects HTC, with a 10% reduction at 45° and 40% at 0°. At higher vapor velocities (~13.8 m/s), HTC equalizes across inclinations, highlighting the importance of optimal surface orientation. [2]
- High humidity accelerates condensation and freezing, while PCM-modified bitumen delays freezing, demonstrating the need for antifreeze coatings and moisture-resistant surfaces. [3]
- Higher Nusselt number (Nu) enhances heat flux up to 152%, but roughness can reduce Nu's impact while improving DWC probability. This suggests an optimal balance of surface roughness and Nu for efficient heat transfer. [4]
- Coalescence-driven droplet growth dominates heat transfer, with an optimal asperity scale maximizing performance, emphasizing the importance of engineered surface textures. [5]
- Surface modifications using noble metals, REOs, and polymer coatings enhance DWC but present durability and cost challenges, necessitating further material research. [6]
- Microtextured surfaces improve HTC by up to 3× over nanotextured surfaces, leading to improved condensation efficiency and optimal microtexture development. [7]
- IBM simulations validate DWC predictions with a 6% deviation from experiments, confirming humidity's role in enhancing droplet growth by ~76% and its impact on HTC. [8]
- Micro structured surfaces such as cylindrical and cubic structures enhance heat transfer compared to conical and pyramidal structures, supporting tailored surface engineering for optimal DWC efficiency. [9]
- Cu-GNP coatings with HVOF offer superior corrosion resistance and hydrophobicity, making them promising candidates for durable, high-performance DWC surfaces. [10]

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