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"A REVIEW ON EVAPORATIVE COOLING CHARACTERISTICS OF FALLING WATER FILMS OVER HORIZONTAL TUBES"

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ABSTRACT

Falling liquid film systems operating over horizontal tubes are extensively employed in evaporative cooling and absorption-based thermal systems due to their superior heat and mass transfer performance. This paper presents a critical review of experimental and numerical investigations related to the evaporative cooling of a falling water film on horizontal tube surfaces. Emphasis is placed on understanding the hydrodynamic behavior, flow regime transitions, and heat transfer characteristics of liquid films flowing over multiple horizontal cylinders arranged perpendicular to the flow direction. The influence of governing parameters such as Reynolds number, tube diameter, tube spacing, and surface geometry on film distribution, droplet formation, and evaporation characteristics is analyzed. In addition, studies related to water–lithium bromide (LiBr) falling film absorbers employing small-diameter tubes are reviewed. The role of enhanced tube surfaces, including fluted geometries, in improving film stability and thermal performance is also discussed. The review highlights the critical parameters governing absorber efficiency and provides direction for future research in high-performance evaporative cooling systems.

KEYWORDS: Falling film, Evaporative cooling, Horizontal tubes, Heat and mass transfer, Absorber, Flow regimes.

1. INTRODUCTION

Falling liquid films over horizontal tube surfaces play a vital role in modern thermal systems where high heat and mass transfer rates are required within compact geometries. Such configurations are commonly used in absorption refrigeration systems, evaporative coolers, desalination units, and various chemical and food processing applications. Compared to pool boiling or flooded systems, falling film arrangements offer reduced refrigerant inventory and enhanced thermal efficiency.

In a typical configuration, liquid is uniformly supplied to the uppermost horizontal tube and flows circumferentially as a thin film under the influence of gravity. Upon reaching the bottom of the tube, the liquid detaches and falls freely across the inter-tube spacing before impinging on the subsequent tube. During its descent, the liquid interacts with the surrounding air, resulting in simultaneous heat and mass transfer through evaporation.

The flow behavior and thermal performance of falling films are commonly characterized using dimensionless parameters such as Reynolds, Nusselt, and Prandtl numbers [1]. Depending on operating conditions such as liquid flow rate, physical properties, and tube spacing, different inter-tube flow regimes are observed. These regimes significantly affect the distribution of liquid, evaporation rate, and overall heat transfer efficiency.

2. FLOW REGIMES OF FALLING FILMS

Experimental observations have shown that liquid falling between successive horizontal tubes can exhibit three distinct flow patterns:

1. **Discrete droplet flow**,
2. **Liquid jet or column flow**, and
3. **Continuous liquid sheet flow**.

At low liquid flow rates, the liquid detaches from the tube in the form of discrete droplets. With increasing flow rate, the droplets merge to form liquid columns or jets. At sufficiently high flow rates, a continuous liquid sheet develops between adjacent tubes. Each of these regimes results in different wetting characteristics and heat transfer behavior, making flow regime identification essential for system optimization.

3. REVIEW OF PREVIOUS STUDIES

Several researchers have investigated the hydrodynamics and heat transfer behavior of falling liquid films over horizontal tubes. Jafar and Thorpe conducted combined experimental and numerical studies on liquid films flowing over three horizontal cylinders for Reynolds numbers ranging from 20 to 150. Their results indicated that the formation frequency of large droplets increased with Reynolds number up to a critical value, beyond which it remained nearly constant. In contrast, the generation of smaller droplets increased sharply at moderate Reynolds numbers, indicating strong sensitivity of inter-tube flow behavior to liquid flow rate [4].

Armbruster and Mitrovic experimentally studied the evaporative cooling of water falling between smooth horizontal tubes exposed to upward-flowing air. Their findings revealed that the reduction in liquid temperature was primarily governed by evaporation, with air humidity, airflow velocity, and tube spacing playing dominant roles. The effect of temperature difference between water and air was found to be relatively insignificant under the tested conditions [5].

Numerical investigations by Min and Choi focused on the absorption of water vapor into a LiBr solution flowing as a falling film over horizontal tubes. Using a fully elliptic Navier–Stokes formulation, they demonstrated the presence of recirculation zones near the free surface at low flow rates. These regions significantly influenced mass transfer rates, highlighting the importance of surface tension and free-surface effects in absorber modeling [7].

Comprehensive reviews by Ribatski and Jacobi further emphasized that tube surface modification, such as the use of fluted or enhanced geometries, can substantially improve liquid film stability and evaporation efficiency by promoting better wetting and increased surface area [6].

4. FUTURE RESEARCH DIRECTIONS

Future studies should focus on detailed experimental validation of numerical models for falling film evaporative cooling over enhanced tube surfaces. Special attention should be given to fluted and micro-structured tubes to quantify their influence on film thickness, flow regime transitions, and heat transfer coefficients. With growing concerns related to energy efficiency and sustainability, optimized falling film absorbers can play a key role in next-generation cooling and refrigeration systems.

5. CONCLUSION

The reviewed literature confirms that evaporative cooling performance of falling liquid films over horizontal tubes is strongly influenced by flow regime, operating conditions, and surface geometry. Higher liquid flow rates and improved tube surface designs lead to enhanced heat and mass transfer coefficients. Accurate prediction of absorber performance requires comprehensive consideration of hydrodynamics, evaporation, and surface tension effects. Continued research in this area is essential for the development of compact, energy-efficient evaporative cooling and absorption systems.

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