15th International Symposium on Exploitation of Renewable Energy Sources and Efficiency

April 10-12, 2025, Subotica, Serbia

EXPRES 2025

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HEAT TRANSFER COEFFICIENT ANALYSIS AT THE LIQUID SURFACE IN FORCED AIRFLOW CONDITIONS

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Analyzing the heat transfer coefficient at the liquid surface under forced airflow conditions is an important topic for improving thermal management in a variety of applications, including evaporative cooling devices, and electronic cooling systems. The aim of this research is to provide the theoretical relationships necessary to determine the value of the convective heat transfer coefficient at the evaporating liquid surface. Additionally, it uses both analytical and experimental methods to study forced convection heat transfer coefficients, emphasizing the increased accuracy of analytical results under turbulent conditions. The study also investigates heat fluxes from water evaporation, looks at the effect of forced convection, and simulates liquid pool evaporation by combining mass and heat transfer techniques. All things considered, the study highlights how crucial it is to precisely calculate heat transfer coefficients in order to improve the dependability and efficiency of thermal systems.

Keywords: *open surface liquid evaporation, heat transfer coefficient, heated vessel, Nusselt number.*

1. Introduction

Accurate determination of convection heat transfer coefficients at the liquid surface in forced airflow conditions is critical in optimizing the design and performance of numerous industrial processes, including evaporative cooling systems, drying technologies. Reliable prediction and precise quantification of heat transfer coefficients directly affect the effectiveness and efficiency of these systems.

Several empirical and semi-empirical correlations have been developed to estimate convection heat transfer coefficients for forced airflow over flat surfaces, each exhibiting varying degrees of accuracy depending on the specific conditions of application. Comparative analyses of these correlations are essential to identify the most appropriate models for practical engineering applications, such as solar collectors employing flat plates[1]. Previous studies highlighted that while many correlations show good general applicability, their predictive accuracy can differ significantly under specific environmental and operational conditions. Ghahfarokhi et al. [2]for instance, employed analytical and experimental approaches to analyze forced convection over flat plates featuring partially unheated surfaces, determining the heat transfer coefficients at various wind speeds using well-known correlations.

In addition to forced convection heat transfer, simultaneous heat and mass transfer phenomena, such as liquid evaporation, significantly influence the overall heat transfer characteristics at liquid surfaces. Beji et al.[3] presented a comprehensive modeling approach for liquid pool evaporation processes, emphasizing the importance of mass diffusion effects. Their results demonstrated that natural convection conditions provided better predictions for vaporization processes compared to turbulent forced convection, emphasizing the complexity of accurately modeling coupled heat and mass transfer phenomena.

Our previous research [4] also investigated heat transfer characteristics at liquid surfaces, specifically examining the heat transfer coefficients associated with evaporation from heated vessels under forced convection conditions. It was shown that the presence of evaporation substantially increases the measured heat transfer coefficient compared to conditions involving purely convective heat transfer. These findings underline the necessity of considering mass transfer effects when predicting heat transfer coefficients at evaporating liquid surfaces.

Moreover, studies on heat and mass transfer processes in practical engineering applications, such as the work conducted by Wan et al. [5], emphasize the interdependence of the Nusselt and Sherwood numbers in vertical channels experiencing film evaporation. This research established correlations considering various dimensionless parameters, aiming to deepen the understanding of coupled heat and mass transfer mechanisms between moist air and water films.

Accurate modeling of convective heat transfer processes is especially critical in situations where evaporation transitions from being mass-transfer-dominated to heat-transfer-driven, such as liquid pool evaporation scenarios frequently encountered in pool fires and other fire safety applications [3]. Previous experimental studies demonstrated that forced convection conditions significantly enhance the performance of solar distillation systems by effectively increasing both heat and mass transfer coefficients[6] . Moreover, earlier investigations have specifically highlighted that local turbulence generated by induced convection substantially enhances the coupled heat and mass transfer processes near evaporating liquid surfaces, thereby intensifying overall evaporation rates [4]. Therefore, existing literature clearly indicates the relevance of forced convection and turbulence effects for improved heat transfer predictions at evaporating liquid interfaces.

Correlations developed through wind tunnel experiments for forced airflow across horizontal flat plates can effectively describe convective heat transfer phenomena [1]. These correlations are particularly relevant for solar collector applications, where external airflow significantly contributes to heat loss from flat plate surfaces. Sparrow et al. conducted wind tunnel experiments on rectangular flat plates with various orientations and obtained an empirical relationship applicable within the Reynolds number range $2 \cdot 10^4 < Re < 9 \cdot 10^4$ [1]:

$$Nu = 0.86 Re^{0.5} Pr^{1/3} \tag{1}$$

Additionally, the forced convection heat transfer coefficient can be represented as follows [1]:

$$\boldsymbol{\alpha = 4.96 v_G^{0.5} L^{-0.5}} \tag{2}$$

Where v_G air velocity $[m/s]$ and L characteristic length $[m]$ is equal to four times the plate area divided by the plate perimeter. As a result, it is not a length that takes wind direction into account.

An essential step in evaluating the performance of a direct evaporative cooling system is accurately determining the convective heat transfer coefficient. For rigid cellulose evaporative media, the convective heat transfer coefficient can be characterized using the empirical correlation proposed by Dowdy and Karabash [7]:

$$Nu = 0.1 \left(\frac{l_e}{l}\right)^{0.12} Re^{0.8} Pr^{0.4} \tag{3}$$

Where l is the pad thickness $[m]$. In this correlation, the effective characteristic length l_e is defined by the following relationship [7]:

$$\boldsymbol{l_e = \frac{V}{A}} \tag{4}$$

where A is the heat transfer surface area of the total wetted surface area $[m^2]$and V is the evaporative pad's volume $[m^3]$.

Heat and mass transfer phenomena occurring during liquid evaporation from open surfaces significantly influence the convective heat transfer coefficient. Several studies have focused on quantifying these combined effects through empirical correlations for the Nusselt number. Based on experimental investigations [8], [9] the Nusselt number for evaporation from both heated and non-heated liquid surfaces can be expressed as:

$$Nu = 0.086 Re^{0.8} \, Pr^{0.33} Gu^{0.2} \tag{5}$$

Additionally, other empirical correlations incorporating evaporation effects propose alternative formulations for the Nusselt number [9]:

$$Nu = 0.083 Re^{2/3} Pr^{1/3} Gu^{0.1} \tag{6}$$

In eqs.(5)-(6) the introduced dimensionless parameter, termed the Gukhman number (Gu), characterizes the influence of mass transfer on the convective heat transfer process and is defined as follows[9]:

$$Gu = \frac{T_a - T_b}{T_a} \tag{7}$$

where T_a ,T_b denote absolute air and liquid-surface temperatures, respectively [9].

Further, considering forced airflow scenarios, other studies have suggested simpler correlations without explicit mass transfer terms, but accounting for airflow characteristics and geometry. For example, under turbulent airflow conditions, the Nusselt number correlation utilizing characteristic length-based Reynolds number is given as [10], [12] :

$$Nu = 0.36 Re^{0.8} Pr^{1/3} \tag{8}$$

This correlation highlights the importance of accurately defining the Reynolds number based on an appropriate characteristic length scale [16].

2. Evaluation technique

A natural process that is essential to heat and mass transport is evaporation from an open water surface. The heat from the water's surface is transferred to the air as air passes over it, which causes the water to evaporate. The temperature differential between the air and water, the air flow velocity, and the characteristics of both the air and the water all affect this heat transfer. The rate of evaporation increases with air velocity because heat is extracted from the surface more efficiently. Furthermore, heat transfer is resisted by the boundary layer that develops between the water's surface and the flowing air; the air's flow parameters determine how thick this layer is. The water's surface cools when latent heat is absorbed during evaporation, which can have an impact on the surface's thermal characteristics and temperature distribution. In many applications, including industrial operations, natural water bodies, and cooling systems, an understanding of these dynamics is crucial.

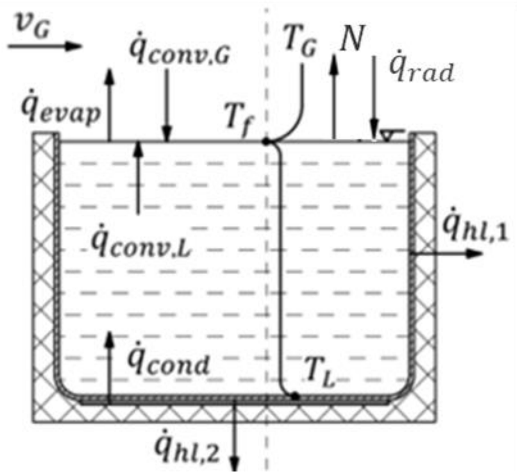

Figure 1. Heat transfer of air flow over liquid surface in open-surface evaporation process.

Figure1 shows the types of heat transfer effects on water surface, in addition radiation heat transfer effect from water to surrounding. Equilibrium heat balance equation written on the surface of the liquid:

$$\dot{Q}_{conv,G} + \dot{Q}_{evap} + \dot{Q}_{conv,l} + \dot{Q}_{rad} = 0 \quad (9)$$

The vessel's bottom liquid layer contains the heat balance equation:

$$\dot{Q}_{cond} + \dot{Q}_{conv,l} + \dot{Q}_{hl,1} + \dot{Q}_{hl,2} = 0 \quad (10)$$

where the heat flux utilized to heat the liquid $[W]$ is represented by $\dot{Q}_{cond}$, the heat flux transported by convection within the liquid is represented by $\dot{Q}_{conv,l}$ and the heat losses on the vessel's side wall $\dot{Q}_{hl,1}$ and bottom are represented by $\dot{Q}_{hl,2}$.The heat balance may be expressed using the following format to represent the heat flow inside the liquid[4]:

$$\dot{Q}_{conv,G} + \dot{Q}_{evap} + \dot{Q}_{cond} + \dot{Q}_{hl,1} + \dot{Q}_{hl,2} = 0 \quad (11)$$

The sign of heat flows can be positive or negative, depending on the direction of the heat flows.

The heat flux used for evaporation can be determined:

$$\dot{Q}_{evap} = NrA_{evap} \quad (12)$$

In this case, r is the latent heat for vaporization $[J/kg]$ and N is the evaporation rate $[kg/(m^2 s)]$. The Δt is the evaporation time $[s]$, A_{evap} is the evaporation surface $[m^2]$. The evaporation rate can be determined by:

$$N = \frac{\Delta m_l}{\Delta t \, A_{evap}} \quad (13)$$

Where Δm_l is the evaporated liquid mass $[kg]$.The following relationship may be used to calculate the heat emitted via the side walls [4]:

$$\dot{Q}_{hl,1} = k_1 A_1 \Delta T_1 \quad (14)$$

The equation's temperature difference is $\Delta T_1 = T_L^f - T_{amb}$, and k_1 is the side wall's overall heat transfer coefficient, and $A_1$is the heat transfer surface [4].

The heat flux leaving from the bottom of the thermo vessel can be calculated using the following relationship [4]:

$$\dot{Q}_{hl,2} = k_2 A_2 \Delta T_2 \quad (15)$$

Reference [11] provides a solution for determining the heat transfer coefficient included in the overall heat transfer coefficient. Since thermal energy is released from the liquid surface as infrared radiation, which affects the evaporation rate and energy balance in a variety of natural and industrial applications.

radiation heat transfer from the water's evaporation surface is essential to the process of heat exchange overall, following equation represent the radiation heat transfer:

$$\dot{Q}_{rad} = \varepsilon\sigma({T_L^f}^4 - {T_G^G}^4) \quad (16)$$

where ε emissivity of the water surface (typical value is ε =0.96 for water) [11], σ is the Stefan-Boltzmann constant $\sigma = 5.67 \cdot 10^{-8}\, W/m^2K^4$ [11], T_L^fmeans the water surface temperature $[K]$, and T_G^G is the ambient temperature $[K]$ [4].

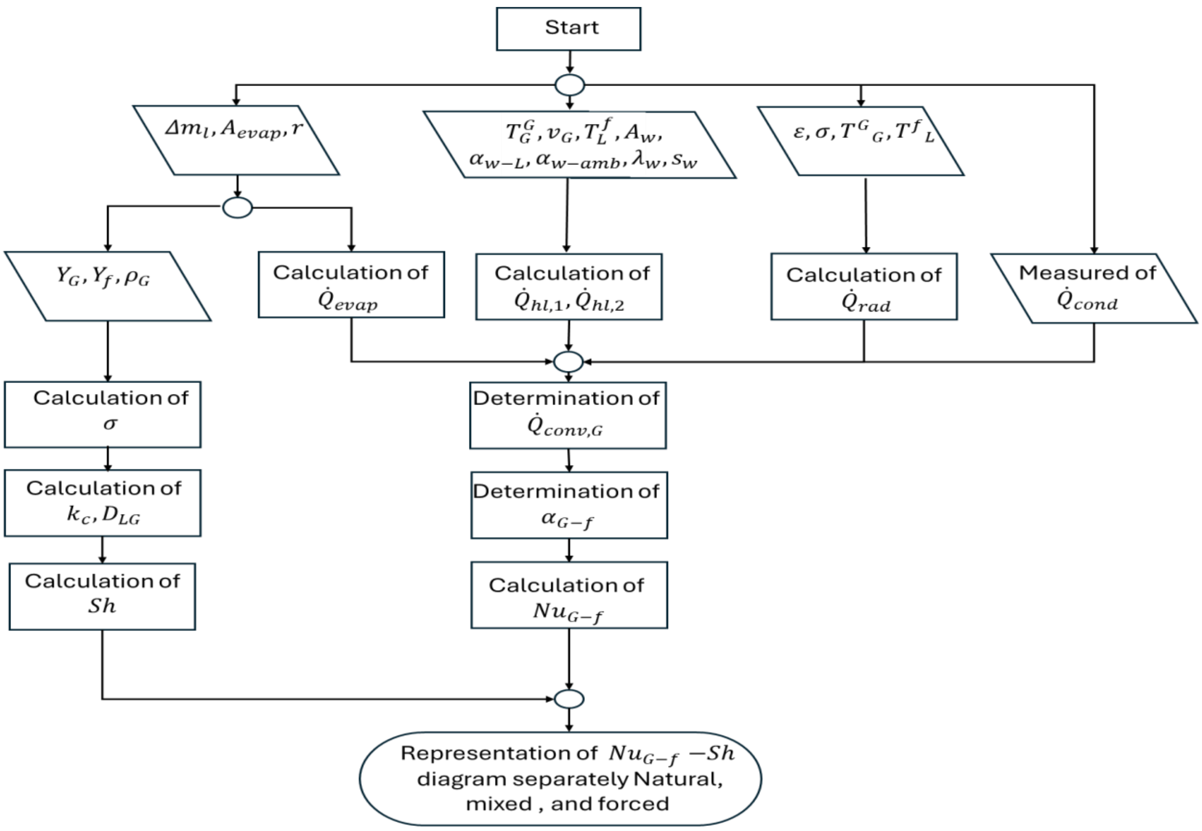

Figure 2. Flow chart for theoritical determination of heat transfer coefficient based on heat balance

The heat flux was mentioned in Eq.(11), between the liquid surface and the flowing air :

$$\dot{Q}_{conv,G} = \alpha_{G-f} A_{evap} \Delta T_G \quad (17)$$

where the temperature difference is between the bulk air temperature and the liquid surface temperature:

$$\Delta T_G = T_L^f - T_G^G \quad (18)$$

Applying the heat transfer balance equation, we determine the heat transfer coefficient.The processes used to analyze the theoritical results in the case of evaporation are illustrated in the flow chart in Figure 2.

3. Conclusion

This study examines the heat transfer coefficient at the liquid surface under forced airflow conditions, focusing on its theoretical and experimental determination. Understanding convection at evaporating liquid surfaces is essential for optimizing evaporative cooling, drying technologies, and thermal management systems. The research evaluates various empirical and theoretical correlations, emphasizing the limitations of empirical models and advocating for theoretical approaches to improve prediction accuracy.

A key aspect is the analysis of heat fluxes from water evaporation under forced convection, where numerical modeling reveals a linear relationship between airflow velocity and heat transfer in turbulent conditions. The study further highlights that forced convection enhances the efficiency of solar stills and underscores the significance of natural convection correlations in modeling evaporation.

Overall, the findings highlight the limitations of conventional empirical formulas and emphasize the need for theoretical frameworks to improve the accuracy and applicability of heat transfer coefficient predictions in engineering applications.

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