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Research Paper

Numerical study of the drift and evaporation of water droplets cooled down by a forced stream of air

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HIGHLIGHTS

- A numerical simulation of water droplets falling in a forced air stream was performed.
- Suitable size of water droplets for reducing drift and evaporation was estimated.
- Mass evaporated was between 0.2 and 1.2% of the total droplet mass.
- Droplet diameters between 4 and 10 mm are suitable for reducing water losses.
- Diameter higher than 3 mm and air velocities lower than 5 m/s avoid drifting.

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ABSTRACT

Evaporation is the basic heat transfer mechanism to reduce temperature of water in a cooling tower. Drift is a phenomenon in which water particles are carried by the leaving air stream causing water losses. In both processes the droplet size plays an important role for an effective cooling and minimum losses. A numerical simulation of water droplets falling in a forced air stream was performed by means of an Eulerian-Lagrangian reference framework. The aim of this work is to investigate water droplet size, inlet air temperature and inlet air velocities that reduce water losses. Particularly, the study is focused on the assessment of water losses caused by evaporation, as well as to determine the suitable size of water droplets for reducing water losses caused by drift. The mathematical model includes improvements to represent in a more realistic manner the heat and mass transfer mechanisms. One of these improvements is related to the convective heat transfer coefficient that for this study varies according to the temperature as well as to the instantaneous velocities of the continuous and dispersed phases. The results shows that the amount of mass evaporated for particles of 1 mm in diameter was around 1.2% of the total droplet's mass. On the contrary, for particles of 8 mm that percentage was around 1% for the same residence time. Results also indicate that the minimum diameter of water droplets should be higher than 3 mm and air velocities lower than 5 m/s, in order to avoid drifting.

1. Introduction

Cooling towers are devices widely utilized in industry to dissipate heat from different heat rejection components and processes to the ambient air. Since the basic heat transfer mechanism to reduce water's temperature is the process of evaporation, significant amounts of water are demanded. Losses of water are essentially found in three ways: evaporation, drift and blowdown, being evaporation and drift the most significant. In a cooling tower the energy performance and amount of water losses depend on the correct design and proper management of recirculated water. Therefore, both aspects require a comprehensive understanding of the heat and mass transfer mechanisms occurring between air and water, which in turns allow improvements for reduction of water consumption and for achieving better thermal performance.

Merkel [1] introduced the first mathematical theory about cooling towers that describes the heat and mass transfer phenomena between water droplets and air flowing inside the cooling tower. Although this theory is the most employed for sizing and performance estimation of cooling towers, water losses due to evaporation are not considered. Such a process is relevant because it causes an increase of temperature and moisture inside the cooling tower. Since Merkeĺs model does not

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Nomenclature

Ap	droplet surface area, m^2
b	buoyancy factor
B_m	Spalding mass transfer number
C_D	drag coefficient
Cpv	specific heat capacity of droplet vapor, J/kg K
D_p	drag force, N
d_p	droplet diameter, m or mm
F	Frossling correction for mass transfer
F_m	Momentum source term, $kg/m^2\ s^2$
g	gravitational acceleration, m/s^2
h	convective heat transfer coefficient, W/m^2 K
k_v	thermal conductivity of droplet vapor, W/m K
m_p	mass of the droplet, kg
Nu	Nusselt number
P	pressure, kPa
Pr	Prandtl number
Re	Reynolds number
S	source term in energy equation, kg/s^3 m
Sm	source term in continuity equation, kg/m^3 s
t	time, s
T_g	temperature of surrounding air, K
T_p	temperature of the particle, K
U	air velocity, m/s
U_c	continuous-phase velocity, m/s
U_p	particle velocity, m/s
V	velocity, m/s

Greek symbols

γ	thermal expansion coefficient
ε	dissipation rate
Φ	relative humidity
μ_a	air viscosity, Ns/m^2
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ	shearing-stress

Subscripts

a	air
eff	effective
w	water
in	inlet
out	outlet or exit

completely describe the heat and mass transfer phenomena, some other theories and mathematical models can be found in literature. Kloppers and Kroger [2] suggested a predictive technique considering the water losses caused by evaporation in the energy equation. Afterwards, Baker and Shryock [3] analyzed the same effect, finding that losses of water by evaporation increased 1.34% for every degree of temperature rise. Mohiuddin and Kant [4] developed an analytical model of the behavior of a cooling tower, including correction factors that improved the estimation of the water mass losses. These correction factors were developed considering variable thermal properties of air and water. Tan and Deng [5] presented a method for evaluating the heat and mass transfer characteristics in a reversibly used water cooling tower. The method was developed adding some modifications to the Merkel's equation. More recently, a simple thermodynamic model for analyzing the heat and mass transfer processes occurring in a cross flow wet cooling tower was developed by Naik and Muthukumar [6]. This model allows a quick calculation of the performance characteristics in terms of known inlet parameters. In this case, variations of thermo-physical properties of the fluids with respect to temperature were considered negligible.

Numerical modeling and numerical simulation based on Computational Fluid Dynamics (CFD) have proved to be effective tools for understanding the heat and mass transfer mechanisms present in cooling towers. Halasz [7] and Bourouni et al. [8] reported a numerical study of the water evaporation in a cross flow cooling tower. The losses of water by evaporation were found at 5.1% of the total amount of water entering to the cooling tower. Consuegro et al. [9] have developed a CFD numerical modeling for simulating the drift and deposition of water droplets emitted to a urban environment by a mechanical draft cooling tower. Afterwards, Sánchez et al. [10] have simulated the lifetime of particles under different atmospheric and droplets conditions, using the same experimental facility utilized by Consuegro et al. [9]. Both investigations defined a Eulerian-Lagrangian model to simulate the air-water droplet motion. The droplets under study were those released from the cooling tower. Klimanek et al. [11] presented a three-dimension CFD modeling of natural wet-cooling tower with flue gas injection. The multiphase flow in the rain zone was solved using Euler-Euler approach. The correlation of Ranz and Marshall was used to determine heat transfer, while the correlation of Schiller and Naumann was used to determine the drag coefficient. In the study of Klimanek et al. [11], it was assumed a constant droplet diameter of 5.5 mm. Velandia et al. [12] studied the air flow dynamics in a cooling tower. The complexity of the flow in some elements of the cooling tower such as the filmic fill and the drift eliminator was simplified assuming those components as porous media.

Considering only the water droplet flow behavior, a few experimental and numerical studies have reported the heat and mass transfer processes. Guella et al. [13] and Tissot et al. [14] performed an experimental study to obtain velocity profiles of free-falling droplets. Particularly, Tissot et al. [14] carried out a numerical study about the behavior of water droplets in an evaporative condenser. The simulations were conducted by means of multiple water-air phases modeled as an Eulerian-Lagrangian reference framework. Later, based on the kinetic model along with the mass and heat transfer models, Qi et al. [15] have developed a one dimensional model for studying the motional process and evaporative cooling process occurring at the water droplet in a shower cooling tower. They conclude that the diameter of the water droplets is the most apparent factor affecting the cooling process. Lorenzini and Saro [16] reported an interesting study about evaporation of water particles. Although the study is not directly related to cooling towers, the heat and mass transfer processes of falling droplets surrounded by quiet air were studied to determine the percentage of mass losses. Finally, Terblanche et al. [17] reported an experimental apparatus and a measurement technique developed for determining the drop size distributions in a counterflow rain zone. The air and water flow rates were varied to investigate the influence on droplet size, encountering that droplet distribution varies in diameter from 0.25 mm to 9.75 mm.

The investigations above mentioned have contributed in great extent to the knowledge of the complex mechanisms of heat and mass transfer that take place in cooling towers. Nevertheless, some other important aspects need to be further investigated for other particular conditions. One of those aspects are the water losses caused by evaporation and drift. In addition, a number of adopted assumptions also require some refinements. Such as the convective heat transfer coefficient that is commonly assumed constant [6]. On the other hand, in order to estimate values of the convective heat transfer coefficient more accurately, the modeling of the heat transfer process requires to evaluate the instantaneous velocities of water droplets and air.

In this work, a numerical simulation of the heat and mass transfer