International Journal of Thermal Sciences 50 (2011) 2122–2131

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Air cooling by evaporating droplets in the upward flow of a condenser

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ARTICLE INFO

Article history:
Received 18 January 2011
Received in revised form
6 June 2011
Accepted 6 June 2011
Available online 13 July 2011

Keywords:
Spray
Droplet
Evaporation
Cooling
Refrigerating system

ABSTRACT

A numerical study has been carried out on a sprayed air flow. The droplet evaporation and the resulting balances for humidity and temperature of the air were investigated for various loadings, spray characteristics and injection solutions. An Eulerian–Lagrangian model simulating droplet motion in an air flow was used. Validation was achieved for the various sub-models, especially concerning the behavior of individual droplets in a given air flow. Numerical simulations were then performed on a geometry corresponding to an experimental device that will allow the study of the heat exchange in a real condenser. Even with low water flow rates (0.025 L/min), the use of very fine droplets with size between 25 and 50 μm results in a significant air cooling (up to 10° with local increase in humidity up to 5 g of water per kg of dry air). Optimal conditions have been sought regarding their size, as too small droplets were found to flow in a concentrated manner with a poor dispersion ability resulting in a less effective mixing, despite their better expected capacities when considered as individual particles. Strong coupling and non linear effects were observed and will require further studies. Effective cooling of the air before the condenser is achievable and can be used for the optimization of refrigerating systems.

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1. Introduction

The air cooled condensers (fin and tube heat exchangers) are the most widespread category for low and average refrigeration capacities because the cooling medium (air) is a natural and free source. They are dimensioned from the air average temperature, therefore leading to high condensing pressures. Their energy performances are governed by the thermodynamic properties, e.g. heat capacity and heat transfer. However, as air is not an efficient cooling medium, it implies high air flow and significant exchanger area. In other words, a refrigerating machine equipped with this type of condenser will consume more energy and will require a larger internal volume. In addition, the thermodynamic performances of refrigeration and air conditioning systems coupled with an air cooled condenser will depend on climatic conditions, which are not stable during the year. A lower refrigerating efficiency or a dysfunction of the system can occur when the difference between the nominal and outside temperature is high, especially in hot summer periods.

Evaporative cooling towers can overcome this disadvantage and are widely encountered in large refrigeration and air conditioning applications. They combine a spray of water falling onto the condenser pipes with air which is simultaneously blown over the tubes. The water that is not evaporated then drains to the bottom of the condenser unit and is pumped back up to the sprayers with a water pump. One of the advantages of the cooling tower is that, through evaporation, the circulating water temperature may reach the atmospheric wet bulb temperature rather than the dry bulb temperature (Fig. 1) [1]. Hence, the condensing temperatures of such systems can be 8–12 K lower than those of air cooled condensers. Consequently, systems with these types of condensers have higher coefficients of performance and refrigeration capacities than systems with air cooled condensers [2]. The energy saving can reach up to 10–25%. However, cumbersome and generally fitted outside, cooling towers require continuous checking and quality preventive maintenance, which is not always undertaken. Therefore, they have been recognized as being responsible for a well known medical risk. Indeed, water stagnation, as well as temperature and moisture conditions, might be favorable to bacteriological development as pathogenic *Legionella*, which can lead to a serious pulmonary infection for citizens.

Then, adding a spray of a controlled and small quantity of fine water droplets at the air inlet seems to be a potential solution that deserves to be investigated and analyzed. Indeed, the use of wet air in a fog form is an old idea that was applied successfully in the steel

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doi:10.1016/j.ijthermalsci.2011.06.004

Nomenclature

B_M, B_T	mass or thermal Spalding number (–)
C_D	drag coefficient (–)
C_P	heat capacity (J kg^{-1} K^{-1})
D	diffusion coefficient (m^2 s^{-1})
d_P	droplet diameter (m)
g	gravitational acceleration (m s^{-2})
Le	Lewis number (–)
Lv	latent heat of vaporization (J kg^{-1})
m	mass (kg)
$\dot{m}$	vaporization rate (kg s^{-1})
Nu	Nusselt number (–)
Pr	Prandtl number (–)
Re_p	particle Reynolds number (–)
Sc	Schmidt number (–)
Sh	Sherwood number (–)
t	time (s)
T	temperature (K)
V	velocity (m s^{-1})
X_p	particle position (m)
Y	absolute humidity (g$_{water}$/kg$_{air}$)
Λ	thermal conductivity (W m^{-1} K^{-1})
μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Subscripts

f	continuous phase property
m	mixture property
p	particle or droplet property
r	relative property
sat	saturation
v	water vapor property

industry and in food refrigeration (for the meat carcasses cooling after slaughtering [3], to foodstuffs in pallets [4] or also in display cabinets in supermarkets [5]). However, although it is industrially used, the sprayed air cooled condenser associated with a complete refrigerating system is poorly highlighted in the literature [6,7].

But recently, some numerical [8,9] and experimental [9,10] studies investigate this kind of solution to improve the performance of air cooled condensers: lowering the temperature of outside air due to the evaporation of water helps to improve the exchange at the condenser causing a consistent drop in condensing temperature. This decrease in condensing temperature will affect the whole cooling cycle: lower compression work coupled with an increase in cooling capacity delivered. The coefficient of performance of the machine raised up to, in the best cases, 40%. But until now, it is difficult to accurately determine the location and the characteristics of spray nozzles to optimize the system particularly in terms of water consumption.

The present work has been carried out as a cooperation between the Cemagref (research centre in Antony, France) and the LEMTA (research laboratory in Nancy, France), developing both a numerical study and an experimental one on a sprayed air cooled condenser. The present contribution is mainly focused on the numerical part as a preliminary step aimed at searching for the best experimental conditions before further validation and experimentations.

2. Modeling

2.1. Modeling approach

Regarding available experimentations on evaporating droplets in the literature some information can be found on individual droplets flowing in air [11,12]. Guella et al. [12] in particular studied experimentally the evaporation of a single droplet falling in the air at rest. They also presented a simplified model for the tracking of this droplet, validating their model in the case of droplets slightly larger than the droplets of interest in the present study (diameter of the order of one to several 100 µm). Such data can be used for the validation of our sub-models aimed at the description of the physical phenomena affecting a given droplet. Concerning the global behavior of a collection of droplets, Collin et al. [13] also studied evaporating droplets for the purpose of water curtains, tracking droplets in wet air applying an Eulerian–Lagrangian method for the simulation of the whole air-droplet flow. The

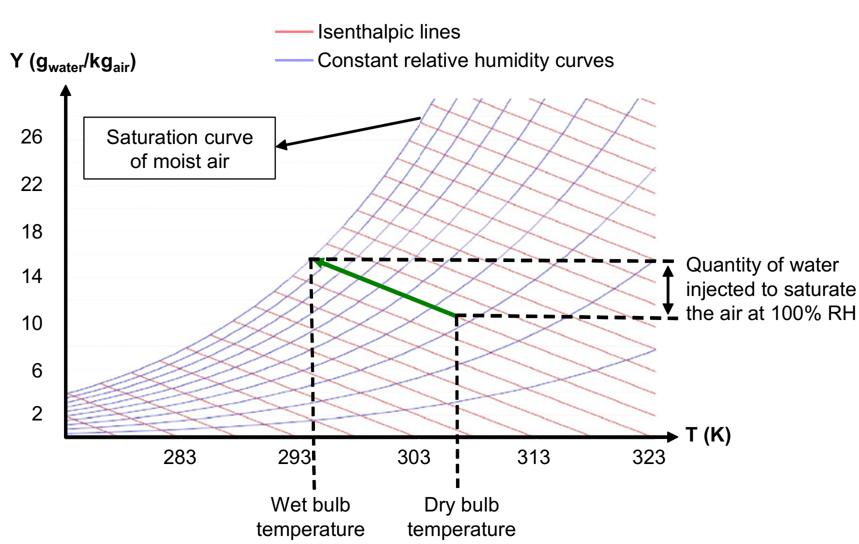

Fig. 1. Psychrometric chart: spraying effect on air properties.

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