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Experimental dropwise condensation of unsaturated humid air – Influence of humidity level on latent and convective heat transfer for fully developed turbulent flow

Sakay Danilo, Couton Dominique, Plourde Frédéric *

ENSMA, 1, avenue clément ader, 86961 Chasseneuil du Poitou, France

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ABSTRACT

Dropwise condensation is experimentally studied on the lower surface of a 0.03 m × 0.3 m rectangular test section. Turbulent flow develops along an isothermal horizontal 2 m-long section before single-sided condensation is initiated over a 0.1 m × 0.2 m cooled surface. The relative humidity level of unsaturated moist air is controlled by steam injection and ranges from 13% to 94%. Drop size and its distribution are followed from small droplets up to puddle formation just before the appearance of a liquid film. The latent contribution of condensation is determined from instantaneous condensed mass data. Comparison between latent and global heat flux demonstrates that drop growth has secondary effects on the condensation rate and that mass rises almost linearly for dropwise condensation. In addition, transition from droplets to large drops and puddles plays a direct role in global heat flux density and strongly influences convective heat transfer contribution.

1. Introduction

Condensation of water contained in humid air has many industrial applications, some are concentrated on air-drying while others on air-cooling, to enhance heat transfer efficiencies when compared to conventional forced convection of dry air. Two condensation processes are commonly addressed in the literature: dropwise condensation (DWC) on materials with low surface energies and filmwise condensation (FWC), liquid film formed on a surface with high free energy or arising from growth of condensed drops or puddles.

As regards condensation of steam, the heat transfer performance of DWC is superior to that of FWC [1]. Most recent experimental studies on condensation of water are focused on specific problems with direct industrial applications such as mini and micro channels [2], inclined surfaces [3] and specific surface treatments [4].

Though the condensation of humid air may have similar mechanics to that of pure steam, unsaturated humid air contains only a small amount of water when compared to the total volume of dry air. For example, if dry air is heated up to 28 °C, it will be able to hold no more than 2.4% of its own volume in water before becoming saturated; while the remaining 97.6% are composed of dry air and can be treated as a non-condensable gas (NCG).

The first experimental studies on the effects of non-condensable gas (NCG) were published in 1929 [5], noting a reduction of nearly 50% in the heat transfer coefficient for a NCG volume of 0.5%. It has been shown in many other studies that, for a small amount of NCG, heat transfer can be severely reduced when compared to pure steam condensation [6–8]. Even though the presence of NCG hinders condensation, these gases are often present in industrial processes. In other cases, as in this study, condensation involving non-saturated humid air is unavoidable. The poor thermal characteristics of the inert gas constituting most of the humid airflow severely reduce heat transfer coefficients when compared to that obtained for pure steam condensation [9,10].

Condensation of humid air can be unpredictable and sometimes undesirable in heat transfer processes with fluctuating humidity levels. It can be the source of unstable heat transfer performance, air outlet temperatures and humidity levels. The effects of condensation on air-cooling can be strongly influenced by condensed water formation over a surface. Numerous recent works [11–13] studied the positive effect of superhydrophobic coating on condensation heat transfer. Ölgçeroglu et al. [11] experimentally underlined the importance of nucleation site density, coalescence length and apparent wetted area ratio on overall heat transfer performance. Experiments involved almost spherical droplets because of contact angles greater than 170°. For contact angle greater than

* Corresponding author.
E-mail address: plourde@ensma.fr (P. Frédéric).

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150°, i.e. for hydrophobic and superhydrophobic conditions, Kim and Kim [12] proposed a mathematical model to predict the dropwise condensation phenomena and the heat transfer model is based through a single droplet heat balance with drop size distribution and even coalescence phenomenon. Such an approach was only possible because of the relative simple droplet geometry i.e. due to surface coating. Whatever the coating, drop formation may increase the heat transfer surface and produce significant turbulence levels near the surface, possibly enhancing mixing of the inert gas layer and favoring temperature gradients within the boundary layer. These phenomena are not yet fully understood, especially for developed turbulent boundary layers.

The present paper concerns an experimental analysis of condensation phenomenon arising along a flat horizontal plate for a fully developed turbulent non-saturated humid airflow along a horizontal flat surface. Coating studied corresponded to regular heat exchanger material (i.e. with contact angle close to 85°) for which, as far as we know, no specific studies have been carried out yet. Our main objective is to understand the contribution of condensation to overall heat transfer and its effects on convective heat transfer as drops grow without removal of condensate, due to the absence of favorable gravity. Under such conditions, condensation develops from initial droplets into larger drops, puddles and static film [14]. In this experimental work, we shall analyze convective and latent contributions separately and investigate the behavior of each of these mechanisms throughout the process of dropwise condensation. As humidity levels directly contribute to heat transfer augmentation [15], their role in DWC with regard to convective heat transfer shall be addressed as well. Second, despite condensation mechanisms have been extensively addressed mainly along vertical wall, condensation was studied along an horizontal plate with no gravity effect in order to focus on condensation mechanisms and forced turbulence convection flow with regard to heat transfer.

2. Materials and methods

2.1. Experimental set-up

The experimental setup, schematically displayed in Fig. 1, consists of a hot dry air inlet, two water vapor generators, a mixing chamber and a wind test section. Filtered air is provided by an oil-free compressor and passes through an air-dryer. Air mass-flow rate is measured by a Coriolis flowmeter (±0.01 g s^{-1}) located between two pressure regulators. A sonic nozzle equipped with two pressure gauges ensures control of the mass flow rate. An electric air heater connects the air inlet to the mixing chamber. Air temperature is controlled by an automatic system in which temperature is measured with a platinum resistance thermometer (100Ω *PT* 100 ± 0.1 °C) and type K thermocouples (chromel–alumel (±0.05 °C). The probes are placed at given locations in the mixing chamber. All the thermocouples are calibrated in a constant-temperature bath (±0.02 °C).

The two vapor generators work independently and production is modulated by controlling the power input of each device. Filtered desalinated water is pre-heated before entering the vapor generators. The water vapor produced is injected into the mixing chamber, thereby controlling airflow humidity levels. Relative humidity can be set, for air of 28 °C, at values ranging from 1.3% (considered as dry air) to 93.6% (close to saturation). A sample of humid air, extracted by suction at the entry of the converging section, is directed to a cold-mirror hygrometer *Optidew Vision* for humidity measurement.

The mixing chamber is 2.5 m long and has a square section 0.3 m wide and 0.3 m high. Dry air and water vapor inlet are localized before passage through a series of perforated plates with decreasing areas of passage; it ensures a uniform flow with low turbulence level and better mixing of air and vapor. The chamber is situated inside a temperature-controlled room with an air temperature of 28 °C ± 1 °C. A converging section connects the mixing chamber and the test section providing a uniform entry velocity profile. The test section is a rectangular duct 0.3 m wide, 0.3 m high and 0.2 m long. The effective test section represents the region where condensation takes place and is found at 2 m from the entrance to the wind tunnel.

The entire length of the test section is equipped with visualization windows and probe locations facilitating flow velocity acquisition by Particule Image Velocimetry (PIV) and air temperature measurement with intrusive thermocouples. Velocity measurements were measured in the mid-plane of the test channel ($Y = 0$). Fig. 2 displays the PIV equipment around the test section; a 70 mJ laser beam generator Nd:YAG was used delivering two pulses at 1 kHz while a 1024 × 1024 high frequency camera CCD (Photom Fast-Cam) recorded the images. Setting parameters was controlled by DaVis Software from LaVision. Flow was seeded by heated oil droplets and the CCD camera was neither overexposed nor underexposed to the seeding, using the generator, with injection oil time and quantity under control. Many interrogations

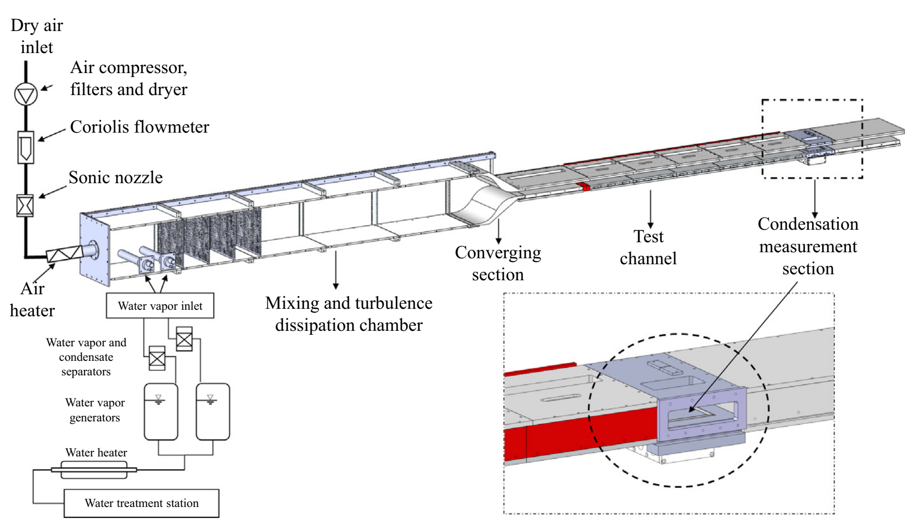

Fig. 1. Schematic view of the experimental setup: Air and vapor inlets, dissipation chamber and test channel.