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Experimental investigation of spray dehumidification process in moist air

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ABSTRACT

This study represents an experimental investigation of spray dehumidification process of hot and moist air in turbulent flow. An experimental setup is constructed in order to produce hot and humid air flow in a circular tube. Sub-cooled water at a temperature below the dew point is injected into air stream. The effects of spray water flow rate, water temperature, spray injection direction (parallel/counter flow), nozzle type (hydraulic/air atomization) and air inlet conditions on dehumidification performance are investigated. The results of the present study show that improved dehumidification performance is obtained for highly humid air.

1. Introduction

Air or water cooled condensers are frequently used in order to enhance cooling capacity and reduce moisture content of air in various industrial processes and household appliances. Well known disadvantages of moisture condensers are long process times, high energy and/or water consumption. Thus developing new drying techniques and systems with superior dehumidification performance has been a continuous effort. One proposed technique is the spray dehumidification. In the spray dehumidification process direct contact condensation phenomenon takes place between sprayed water and moist air. The direct contact condensation is utilized in various industrial applications such as emergency cooling systems of nuclear reactors, desalination and air-conditioning [1]. Since indirect contact processes lead to a resistance to heat transfer, in general direct contact condensation systems are known to be more effective in dehumidifying.

In one application of spray dehumidification system, sub-cooled water is injected into hot and moist air [2]. As long as the water temperature stays below the dew point temperature of mixture, condensation occurs; otherwise water spray leads to increase of mixture humidity. When the water spray contact with the mixture, sensible heat of the mixture starts to decrease and condensation induces latent heat release. Brown [3] experimentally studied the vapor condensation on sub-cooled water droplets. The study revealed that decreasing droplet diameter results an enhancement in heat transfer. Ford and Lekic [4] obtained a correlation which shows the growth of the droplet diameter in the direct contact condensation of steam on water droplets. The correlation results were in good agreement with the experiments. Kulic and Rhodes [5] developed a model to determine the temperature distribution during direct contact condensation of air-vapor mixture on a droplet. It is found that heat and mass transfer model estimations are in good agreement with experimental data. Crowe et al. [6] analyzed the velocity and temperature fields in a spray cooling application for a vertical channel flow. The inlet temperature of air and water was 20°C and 60°C, respectively. The relative humidity was 30% and the mass flow rate of water droplets was ten times that of air. Lee and Tankin [7] developed a model to investigate the behavior of water spray in a steam environment. They found that average droplet diameter is greater in vapor compared to air environment, due to the condensation of vapor on water droplets. Sundararajan and Ayyaswamy [8] investigated the heat and mass transfer mechanism of vapor condensation on droplets, numerically. It was concluded that droplet bulk temperature increases with time and results were in good agreement with experiments. Celata et al. [9, 10] investigated the direct contact condensation of saturated steam on subcooled water droplets, experimentally. The condensation efficiency and local heat transfer coefficients were reported as functions of droplet diameter and velocity. Mayinger and Chavez [11] experimentally investigated the growth of a sub-cooled spray droplet in a saturated vapor with pulsed laser holography technique. Increasing mass flow rate of water spray led to the decrease of droplet diameter. It is also found that as spray velocity increases, heat transfer enhances asymptotically and reaches a maximum value. Akira et al. [12] analyzed direct contact condensation phenomena in vapor-subcooled water interface using three different models. Reindl [13] investigated the heat and mass transfer to chilled water sprays in parallel, counter and cross flow configurations. The inlet temperature of air and water was 35°C and 0.6°C, respectively. The relative humidity was 40%. The ratio of mass flow rate of air to water varied from 0.2 to 0.95. Kachhwaha et al.

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[14] carried out experiments in order to investigate the heat and mass transfer in hollow cone water sprays in parallel and counter air flow configurations. Air and water temperatures were varied between 35°C – 42°C and 26°C–33°C, respectively. The maximum relative humidity of air was 60%.

Takahashi and Nayak [15] analytically and experimentally studied the direct contact heat transfer between vapor and subcooled water spray. It is found that heat transfer in liquid sheet region is underestimated with pure conduction model. El-Morsi [16] investigated the optimum performance parameters of spray cooling and dehumidification process by employing experimental and analytical techniques. The inlet temperature of air and water was 30°C and 2°C, respectively. The relative humidity was 25%. The ratio of the mass flow rate of air to water was 0.85. The results showed that increasing mass flow rate of water spray results in enhancement of spray dehumidification performance. Malet and Lemaitre [17] analyzed water spray and air-vapor mixture interaction with a heat and mass transfer model. Experimental results showed that after water - spray interaction, humidity and temperature of air decreases. It is noted that experimental results are lower than the numerical data since the droplet evaporation in the numerical study was neglected.

The aforementioned review reveals that there have been very few experimental studies on spray dehumidification of moist air. Mostly the air conditioning applications with moderate air temperature and relative humidity values were studied. The focus of the present work is a hot and moist air dehumidification system with an attached water spray injection nozzle. Relatively higher temperature (65°C – 75°C) and relative humidity (80%) values, compared to conventional air conditioning applications, were considered. To the authors' best knowledge, no experimental investigation was performed for the air temperature and relative humidity range considered in this study. In the experimental investigation the parameters affecting the performance of the spray dehumidification process are explored. The parameters under investigation are the water mass flow rate, the water temperature, the spray injection direction, the spray cone angle and the moist air inlet conditions (temperature and relative humidity). Air to water mass flow rate ratio values of the present investigation also significantly differ from the experiments reported in the literature. In the previous study [5] the air – water ratio varied from 0.1 to 1. In the present experiments relatively lower water flow rates were considered and the air – water mass flow rate ratio varied from 0.7 to 7.4.

Preliminary results of the present research was presented by Gumruk and Aktas [18]. Unlike the present manuscript, the performance of the spray dehumidification system in parallel and counter flow configurations at different air temperature and humidity values were reported for limited number of cases. The present manuscript considers wider range of temperature and humidity values along with additional critical spray parameters (water temperature, water flow rate, nozzle type and spray cone angle) in order to fully characterize the system performance.

2. Material and method

An experimental setup is designed and constructed in order to generate hot and moist air-vapor mixture stream in a closed loop. A schematic drawing of the experimental setup is presented in Fig. 1. Air is circulated by using a fan in the loop at a constant flow rate of 20 l/s. Overall length and height of the setup are 1.5 m and 1.35 m, respectively. The air circulation loop is made of circular stainless steel pipe. The inner diameter of the pipe is 65 mm. The average air velocity in the pipe reaches 6 m/s and corresponding Reynolds number is nearly 20,000. The air temperature is controlled by resistance heaters.

The setup consists a custom made water boiler that serves as humidifier. An air cooled condenser is utilized in order to evaluate the combined effect of the spray dehumidifier and conventional condenser on dehumidification process. The condenser and spray dehumidifier assembly can be run simultaneously or separately.

Table 1 summarizes the measurement instrumentation of the experimental apparatus. The temperature and the relative humidity (RH) of air are measured by five probes (Rotronic Hygroflex4-HF4-Universal Transmitter) located at critical sections of the air circulation loop.

The probes are inserted into the air channel in cross flow configuration. Due to relatively large diameter (15 mm) and length (20 mm) of the probes, the temperature and RH readings are assumed as cross-sectional average measurements.

The experimental setup is shown in Fig. 2. The air circulation loop is thermally insulated against heat losses. Five measurement probes are numbered as; Probe 1: spray inlet, Probe 2: spray outlet, Probe 3: condenser inlet, Probe 4: condenser outlet and Probe 5: cooling air inlet/outlet for condenser. The spray dehumidification module is attached by removable mechanism (see the red circle in Fig. 2).

In order to avoid water interaction waterproof filters (Rotronic NSP-POM-FD2) are used in the probes. A dosing pump (Grundfos DDE 15–4) supplies filtered water to the spray nozzle at a constant flow rate. The water is provided from a container. Ice cubes and an immersion thermometer are used in order to adjust the container temperature within the range of ± 1 °C.

A SCADA system (Fig. 3) was designed in order to control the system and collect data. The SCADA system measures the temperature and the relative humidity at spray inlet by one second intervals and brings the system to desired setting by adjusting the water heater power.

The detachable spray dehumidification apparatus supplies water spray by a nozzle in to the air loop in parallel or counter flow configuration (Fig. 4). The nozzle exit is located on the pipe centerline.

3. Results

Table 2 lists the operation parameters of the dehumidification system. The dry bulb air temperatures and relative humidity values were measured during the experiments. In a typical experiment, sufficient amount of time is given to overcome the initial transient of the setup. A sample temperature data at four different locations is shown in Fig. 5.

During the first 40 min of the experiment rather strong temperature variations were observed. At this time the humidifier is turned on and experiment starts when the temperature values stabilize. Around 140 min from the start of the experiment nearly steady-state behavior is achieved. By this time the target air temperature and relative humidity value at the inlet (Point 1 in Fig. 2) is obtained. At this time the spray nozzle is opened and the effect of water droplets in air flow is studied. With the injection of the water droplets into the air stream, a sudden decrease in the air temperature is measured. This is due to the sensible heat transfer from air to water spray. The decrease is more pronounced right after the spray nozzle (Probe 2).

Fig. 6 depicts the temporal variation of the relative humidity at Probe locations 1, 2, 3 and 4 in the air circulation pipe. The initialization of vapor release from the humidifier near 40 min is obvious. The relative humidity values reach steady-state behavior in nearly 140 min. With spray nozzle opening the relative humidity significantly increases due to increase of the moisture content and air temperature decrease.

Table 3 presents the results of the experiments. The results also demonstrate the repeatability of the experiments. In experiments 1 and 2 the inlet conditions (Probe 1) of air are 65°C and % 80 relative humidity (RH). The volumetric flow rate of sprayed water is 10 l/h. The water spray is provided by a hydraulic nozzle which atomizes water by using water line pressure. The water spray injection is opposite to the air flow (counter flow configuration). The experiments were performed with water at 15°C.

The air humidity ratio (ω) is calculated based on measured relative humidity and temperature values by using Eqs. (1)–(2).