Experimental Study of Direct Contact Condensation of Steam on Water Droplets

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Abstract—**Air or water cooled condensers are used to reduce the moisture content of the air in some devices. Because of disadvantages of these systems such as long drying time, high energy and water consumption, it is required to find a new system for dehumidifying air. This paper represents an experimental study of drying air by injecting water spray into hot and humid air. Spray water is injected into the moist air, in the meantime interaction of subcooled water droplets with air direct contact condensation occurs. As a result of this phenomenon steam condenses on the surface of the droplets due to temperature of water droplets less than the dew point of air. As a consequence of condensation latent heat is released and it increases the water temperature. Experiments were carried out to investigate the effect of different parameters on the dehumidification process i.e., spray droplet diameter, spray water flow rate and spray nozzle configuration (parallel-counter). In this investigation maximum dehumidification performance was obtained when air is supplied with higher relative humidity. It was observed that for a given spray configuration, increasing flow rate of water spray leads to higher reduction in humidity ratio of moist air. The effect of spray configuration was also analyzed and maximum decrease in humidity ratio was observed in counter-flow arrangement.**

Index Terms—**Direct contact condensation, droplet, dehumidification, water spray.**

I. INTRODUCTION

Direct contact condensation of steam on subcooled water droplets has been widely used in several industrial applications such as nuclear reactor (emergency cooling system), desalination and direct contact heat exchanger (air conditioning). Due to advantage of high heat transfer capacity direct contact condensation has been conducted in many studies. Although there are numerous theoretical studies of direct contact condensation, it is required to performed experimental studies to understand the phenomenon in all aspects.

Mayinger and Chavez [1] performed experimentally growth of the subcooled spray droplet in the saturated vapor with pulsed laser holography. They concluded that there is a strong relationship between the vapor pressure and spray geometry. Ford [2] investigated numerically and experimentally the parameters which affect the condensation of vapor on the subcooled water droplets. They developed a mathematical model which includes heat transfer rate, drop size distribution and motion of drop. They concluded that droplet diameter is the most important parameter on the thermal utilization. Brown [3] studied experimentally vapor condensation on the subcooled water droplets. Ford and Lekic [4] obtained a correlation which shows the growth of the droplet diameter in the direct contact condensation of steam on the water droplets. Niroomand et al. [5] analytically investigated the performance parameters which affects the spray dehumidification process. They reported that droplet diameter and the droplet velocity are the most important parameters which affect rate of condensation. Takahashi et al. [6] studied analytically and experimentally direct contact heat transfer between vapor and subcooled water spray. They found that maximum heat transfer occurs on the liquid sheet part. Lee and Tankin [7] investigated the behavior of water spray in the steam environment. They observed that pressure drop in the liquid sheet area leads to decrease in spray angle. Celata et al. [8] studied experimentally direct contact condensation of saturated vapor on the water droplets and effects of droplet diameter and velocity on the heat transfer rate. Kulic and Rhodes [9] developed a model to obtain the temperature fields of direct contact condensation of air-vapor mixture on the droplets. El-Morsi [10] investigated experimentally and analytically the optimum performance parameter of spray cooling and dehumidification technique. Hasson et al. analyzed analytically heat transfer behavior of vapor and water jet in direct contact condensation.

The purpose of this study is to investigate the effects of thermodynamic conditions of air, water spray flow rate and spray configuration on the heat transfer between the air and subcooled water droplets. Spray flow rate was selected 5 and 11 l/h and experiments were carried out cross and parallel flow configuration. Also experiments were performed for three different set values, 75°C - 80 % , 65° C - 80 % , 65° C – 80% temperature and relative humidity respectively. In the first case the effect of water flow rate was determined for all experiments and in the second case the effect of spray configuration was analyzed.

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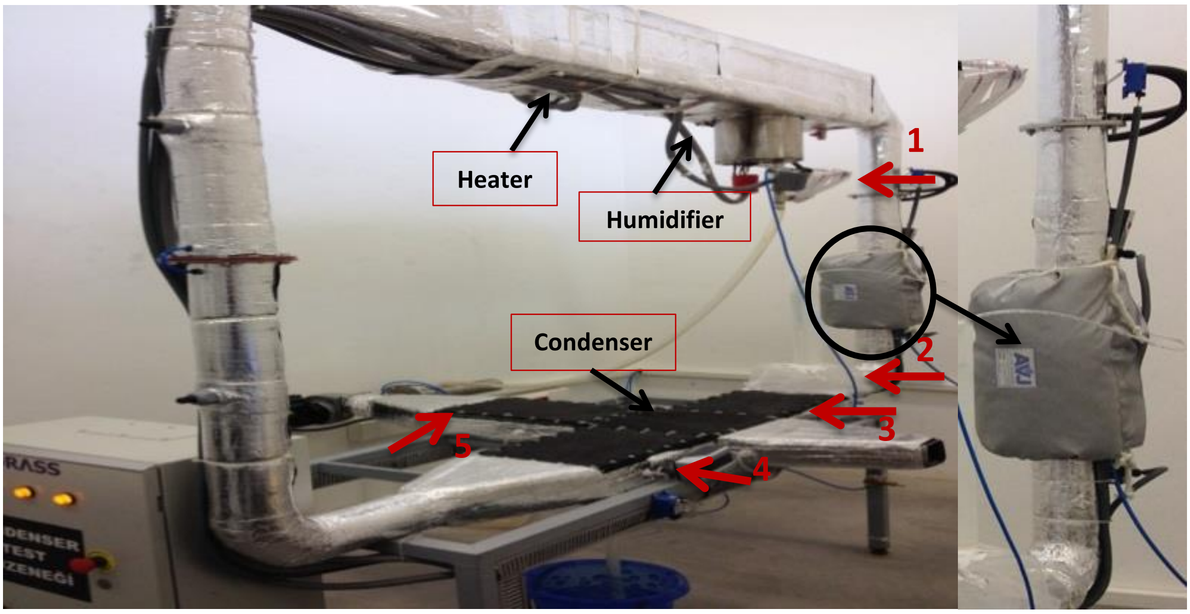

Fig.1. Schematic diagram of experimental system.

II. EXPERIMENTAL SYSTEM AND METHODS

Experimental setup is schematically presented in Fig 1. Setup mainly consists of a heater, a humidifier, an air cooled condenser and two fans. As seen in Fig 2, a removable part was located in vertical pipe in setup to try different nozzle configuration. The setup was made of stainless steel and insulated. Heater and humidifier were used to supply air at desired temperature and relative humidity. Air supply was controlled by a fan and maximum flow rate is 20 l/s. Filtered water was controlled by a valve manually and measured by a specific flow meter which provides instant and total flow rate and also water spray temperature. Water spray produced with a commercial hollow cone nozzle and it was located before the condenser.

The temperature and relative humidity of air were measured by temperature and humidity probe. Five measure points are located in setup to measure temperature and relative humidity simultaneously. In Fig 1 probe locations are given in terms of numbers which represents 1 air inlet, 2 spray outlet, 3 condenser inlet, 4 condenser outlet and 5 cooling air for condenser. An automatic control system and program was installed to provide air at test conditions continuously.

In this context the effect of spray on the dehumidification process was analyzed. The experimental setup was controlled by automatic control system to provide the necessary conditions. The hydraulic nozzle was positioned in removable apparatus and city water was used during the experiments. Spray dehumidification system and condenser were operated together and separately.

The probe at the air inlet measures the data and it connects with the program to set the system at desired temperature and relative humidity. To prevent the water interaction with sensor waterproof filter was used in probes.

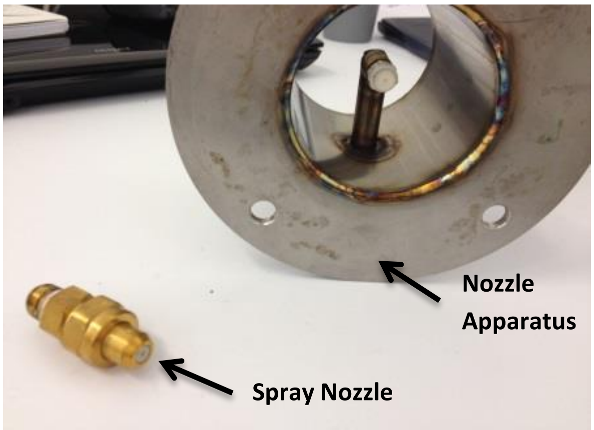

Fig. 2. Hydraulic nozzle and removable nozzle apparatus

There are two drainage points in test rig. The first drainage point was located at spray outlet to gather the condensate water and it provides to measure the water outlet temperature. Second drainage was located after the condenser for condensate water. To prevent water condensation on the plain surface after the condenser, an oblique plate was located on the horizontal wall. Table I shows experiment conditions and results are represented in the Table II.

The equation which is used to calculate humidity ratio using the temperature and relative humidity data, is showed below.

$$\omega = 0{,}622 * \frac{P_w}{P_B - P_w} \qquad (1)$$

In equation (1) P_w is the partial pressure of water vapor in moist air and P_B is the atmospheric pressure of moist air in Pa.

Table I. Test conditions in experiment

Exp.	**Temperature (°C)**	**Relative Humidity (%)**	**Flow configuration**	**Water Temperature (°C)**	**Water flow rate (l/h)**
1	75	80	Counter	21	11
2	65	80	Counter	18	10,90
3	65	50	Counter	20	10,3
4	75	80	Parallel	22	10,6
5	65	80	Parallel	23	9,6
6	65	50	Parallel	23	9,3
7	75	80	Counter	20	4,7
8	65	80	Counter	20	5,00
9	65	50	Counter	18	5,4

III. EXPERIMENTAL RESULTS AND DISCUSSION

When subcooled water spray is injected into the hot and humid air, steam condenses on the water droplets. As a result of the condensation, latent heat releases and it increases the water spray temperature. After the spray dehumidification process air temperature decreases and relative humidity of air increases.

Experiments were conducted when the experimental setup reaches steady-state condition. First experiment is counter flow arrangement study and water flow rate is constant at 11 l/h. Results of first experiment are depicted in Figure 3, Figure 4 and Figure 5. As can be seen in Figure 3 after water is injected, air temperature starts to decrease to dew point temperature.

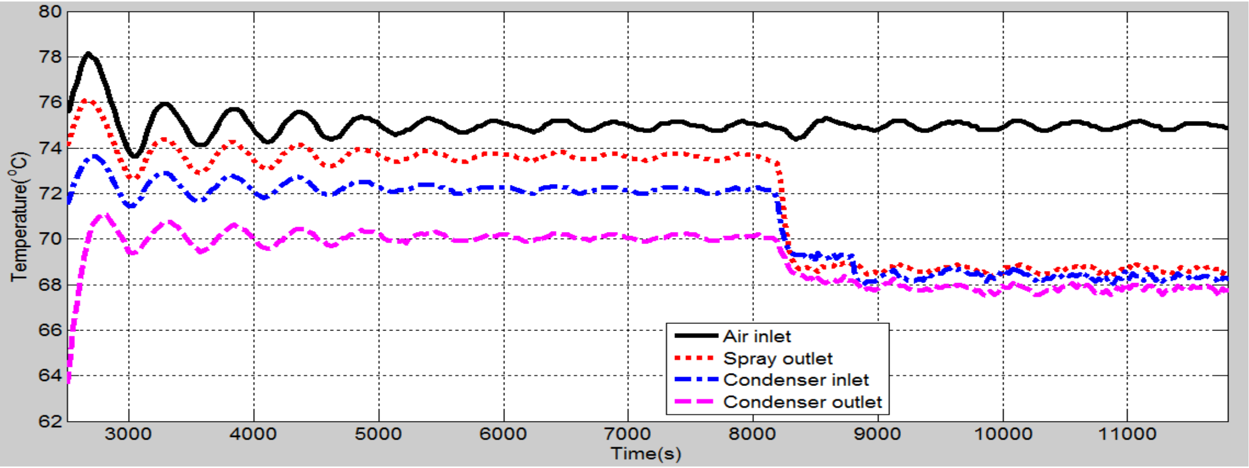

Fig.3. Effect of water spray on air temperature (75°C-80 % RH – Counter Flow)

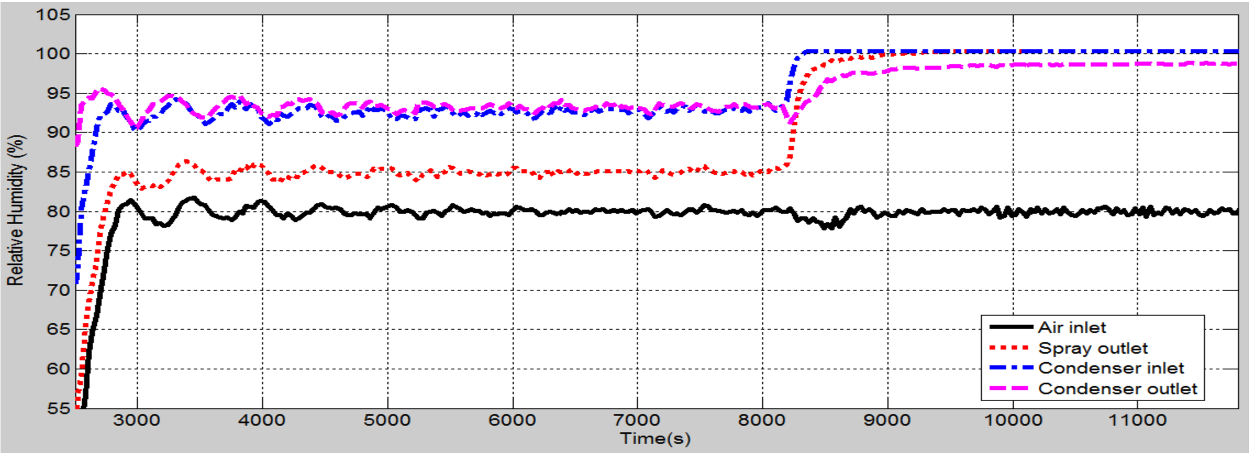

Fig.4. Effect of water spray on air relative humidity (75°C-80 % RH – Counter Flow)

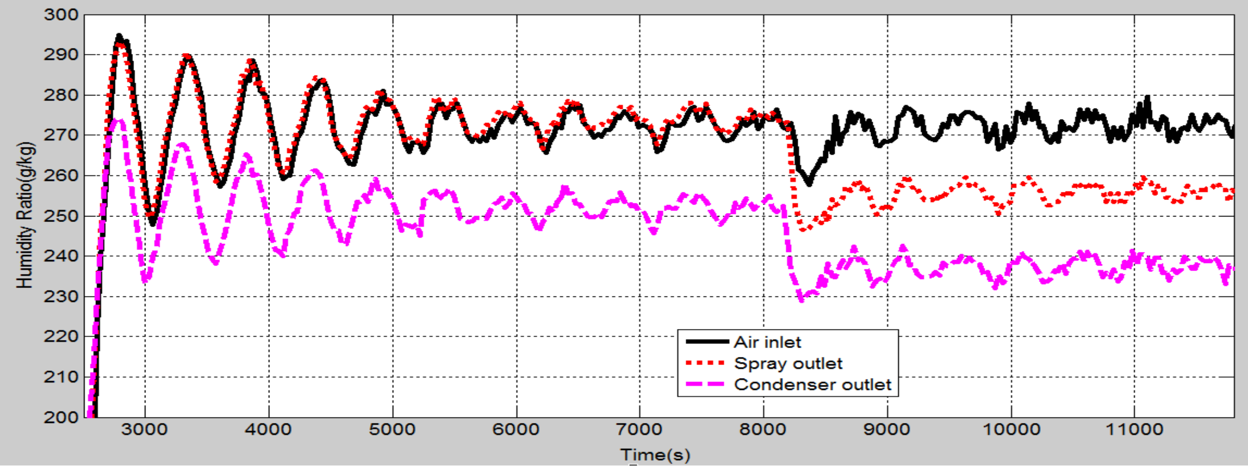

Fig.5. Effect of water spray on air humidity ratio (75°C-80 % RH – Counter Flow)

In the meantime, relative humidity starts to increase and it reaches saturation point (%100 RH) represented in Figure 4. If air cooled below the dew point, water vapor starts to condensed as droplets.

Figure 5 represents the effect of water injection on humidity ratio of air for spray outlet and condenser outlet.

This figure indicates that after water was released into hot and humid air, humidity ratio of air starts to decrease and this reduction is more when condenser and spray were used together.

Table II. Mean humidity ratio of air in different locations of experimental setup

	MEAN HUMIDITY RATIO (g/kg)						
Exp.	**Air inlet**	**Spray outlet**	**Condenser outlet**	**Difference (with spray)**	**Difference (with spray and condenser)**	**Percentage change (with spray)**	**Percentage change (with spray and condenser)**
1	272	255,4	237,1	16,6	34,9	6	13
2	153,1	143,5	132,9	9,6	20,2	6	13
3	87,48	85,47	77,82	2,01	9,66	2	11
4	273,1	260,9	241	12	32,1	4	12
5	153,1	149,0	136	4,1	17,5	3	11
6	87,50	87,28	79,01	0,22	8,49	0	10
7	272	267,6	249	4,5	23,1	2	8
8	153	149,9	138	3,2	15,1	2	10
9	87,59	86,91	80,62	0,68	6,97	1	8

Table III. Mean relative humidity of dehumidified air after reheat

	MEAN RELATIVE HUMIDITY (%)				
Exp.	**Air inlet**	**Spray outlet**	**Condenser outlet**	**Percentage change (with spray)**	**Percentage change (with spray and condenser)**
1.	80,00	76	72	5	10
2.	80,00	76	71	5	11
3.	50	49	45	2	10
4.	80,00	77	73	3	9
5.	80,00	78	72	2	10
6.	50	50	46	0	9
7.	80,00	79	75	1	6
8.	80,00	79	73	2	8
9.	50	50	46	1	7

For the second part of experiments dehumidified moist air was heated to their inlet temperature. Table III depicts mean relative humidity values after heating for each experiment.

IV. CONCLUSIONS

An experimental study was conducted to analyze the direct contact condensation of steam on subcooled water droplet. The effects of spray configuration and water spray flow rate on the dehumidification process were investigated. From the measured temperature and relative humidity values, humidity ratios were calculated on the different section of experimental setup.

It was observed that increasing the flow rate of water leads to higher reduction in humidity ratio of air. This is because of producing more drops, increases spray area and it leads to an increase in heat transfer. As a consequence of heat transfer enhancement humidity ratio decreases more.

Maximum decrease in humidity ratio was obtained with counter flow arrangement due to higher contact time with water spray.

It was also clarified that increasing relative humidity at constant temperature results more reduction in humidity ratio. This is resulted from increasing humidity ratio of air leads to an increase water vapor pressure in the air and it enhances mass transfer potential from air to water spray.

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