Thermal Performance of a Cross-flow Rotating Spray Bed

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Abstract. This work examined the thermal performance of evaporative cooling of water by an air stream in an equipment wherein the liquid phase is sprayed between two coaxial disks. The contact between the two phases was in a cross-current mode. The performance of the spray bed in terms of thermal efficiency and evaporation rate of liquid were calculated by varying operational parameters like air flow rate, water flow rate, and rotational speed. Both the thermal efficiency (minimum = 0.183, maximum = 0.34) and evaporation rate (minimum = 0.009 kg/min, maximum = 0.032 kg/min) increased with rotational speed and air flow rate. However, the thermal efficiency decreased with liquid flow rate.

1. Introduction
Massive amount of waste heat is generated in air conditioning, power generation units, petrochemical, chemical processing industries etc that must be released continuously for proper functioning of the units [1]. A proper coolant is required to reject this heat from the system. Water is considered as a suitable coolant due to its high heat capacity, easy availability, minimal cost and non degrading nature. Mass transfer devices like cooling towers are used to reuse the water. Cooling in this equipment is based on the principle of Evaporative cooling [2]. The process involves introduction of warm water at the top of the tower. In these towers, the air and the warm water are contacted directly. The liquid comes down under the action of terrestrial gravity through fills or packings. Transfer of sensible heat as well as the latent heat takes place between the two phases, the later because of the evaporation of water. The flow may be countercurrent or crosscurrent.

The thermal characteristics of countercurrent cooling tower and the impact of different filling materials had been studied by various researchers [3-6]. Gonzalez et al. [7] has optimized a mechanical draft countercurrent cooling tower for minimizing the cost. Grobbelaar et al. [8] studied the performance characteristics of a cross and countercurrent wet cooling tower using trickle fills. Spray cooling technique has been successfully utilized in various industries like Gas Turbine fogging, food refrigeration etc [9]. Sun et al. [9] has studied the effect of spray cooling in a naturally draft drying cooling tower. Tissot et al. [10] has performed an experimental study on air cooling by spray in a heat exchanger. Si et al. [11] has studies the effect of cross-flow on the structure of the spray, droplet diameter and velocity distributions in a gasoline engine.

In this study, gravitational force used in traditional cooling towers to drive the liquid is replaced by centrifugal force which is few hundred times to that of gravity. There is no previous literature to indicate the efficacy of this process. Therefore the objective of this work was to evaluate the thermal performance and cooling effectiveness in a cross current spray bed.
2. Materials and Methods

![Figure 1. Experimental Set Up](image)

The experimental set up is provided in a schematic form in figure 1. Warm water was contacted with the air inside the rotor under the action of centrifugal force. Two thin strips of metals were welded onto thin circular strips in both sides of the rotor. The rotor was connected to an AC motor through a shaft that rotated along the horizontal axis. The insulated casing has a diameter of 238mm and an axial length of 75mm. In order to minimize the bypassing of air within the rotor, circular baffles were attached to either sides of the casing wall.

Air was introduced inside the rotor by a blower. Water was heated to 50°C in a reservoir provided with heating equipment and a stirrer. It was pumped into the rotor through a stationary distributor (provided with 24 holes of 1mm each). The liquid get dispersed in form of jets from the distributor and strikes the wire mesh strip aligned perpendicular to the direction of flow. The liquid was thrown in the outward radial direction inside the rotor due to strong centrifugal force and was discharged at the bottom through an opening on the casing wall. The temperature of the water and air entering as well as leaving the contactor were measured using a thermocouple connected to a digital display. The humidity of the inlet and outlet air was measured using a digital humidity meter. Baffles were provided in each of the four air outlets to prevent the carryover of water.

3. Results and Discussions

Simultaneous heat and mass transfer performance of the contactor was estimated in terms of thermal efficiency (η) and rate of Evaporation (\( \dot{e} \)). The measurement of thermal efficiency inside the contactor is illustrated in Figures 2 and 3. Thermal efficiency (η) is defined as

\[
\eta = \frac{t_{wi} - t_{wo}}{t_{wi} - t_{wb,l}}
\]

where, \( t_{wi} \), \( t_{wo} \) represents the inlet and outlet temperature of water respectively, and \( t_{wb,l} \) is the wet bulb temperature of inlet air. It is the ratio of the experimentally determined cooling range, \( \Delta t_c \) \((= t_{wi} - t_{wo})\) and the cooling limit.
The effect of thermal efficiency with respect to rotational speed at different liquid flow rates and constant gas flow rate of 0.03 kg/s is shown in figure 2. It was observed as the rotational speed was increased from 300 to 1100 rpm, there is an increasing trend in the thermal efficiency. This is due to the fact that high rotational speed results in more shearing force that reduces the size of the droplets and enhances the gas-liquid interfacial area to a great extent [12]. The maximum thermal efficiency obtained was 0.31. With increase in the liquid flow rate from 0.0125 kg/s to 0.029 kg/s, there is a gradual decrease in the efficiency.

![Figure 2. Effect of rotational speed on thermal efficiency](image)

The influence of liquid to gas mass flow rate ratio and rotational speed on thermal efficiency in the spray bed contactor is illustrated in Figure 3 at constant liquid flow rate of 0.0125 kg/s. The thermal efficiency is noted to increase with rotational speed for all the operating conditions. η increased from 0.28 to 0.34 at a $\frac{L}{G}$ ratio of 0.31 in the spray bed as the rotational speed was increased from 300 to 900 rpm ($L = 0.0125$ kg/s).

![Figure 3. Effect of liquid to gas flow rate on thermal efficiency](image)

The effect of air flow rate on the thermal efficiency (shown in figure 4) was studied at constant flow rate of liquid (0.0125 kg/s) for different rotational speed. With the increase in the air flow rate from 0.0128 kg/s to 0.03 kg/s there was an increase in the efficiency from 0.18 to 0.31.
The evaporation rate of water ($\dot{e}$) was estimated from the difference in moisture content between the inlet and outlet air, and the air flow rate.

$$
\dot{e} = G (Y_{out} - Y_{in}) \tag{2}
$$

The variation of rotational speed with the evaporation rate is shown in figure 5. The evaporation rate increased with the rotor speed and liquid flow rate.

As the liquid flow rate was increased from 0.0125 to 0.029 kg/s with constant air flow rate 0.03 kg/s, there was an increase in the evaporation rate from 0.009 kg/min to 0.032 kg/min. Figure 6. depicts the effect of air flow rate on the evaporation rate at different rotational speed at constant liquid flow rate 0.0125 kg/s. With increase in the air flow rate from 0.0128 kg/s to 0.03 kg/s, increase in evaporation rate was observed from 0.009 kg/min to 0.028 kg/min.
Small water droplets or thinner ligaments are formed on increase of rotational speed [13]. This increases the gas-liquid surface area. Increase in liquid flow rate leads to better distribution of liquid over the rotor from the liquid distributor opening as more of the distributor openings become effective. This increase the surface area for evaporation of water and sensible heat transfer which results in high evaporation rate. The increase in air flow rate facilitates evaporative cooling by increasing sensible heat uptake capacity of the air particles in contact with the warm water.

The temperature change of water on account of only evaporation ($\Delta t_e$) can be calculated by

$$\Delta t_e = \frac{\dot{e} \lambda}{\rho C_w L}$$

where $\lambda$ is the latent heat of vaporization of water. The contribution of $\Delta t_e$ to the experimentally determined cooling range of water varied between 75% and 90% in these contactors. Thus, cooling of water is achieved primarily by latent heat supplied by liquid for evaporation.

4. Conclusion
The thermal performance of a rotating spray bed was evaluated in a cross current mode for observing the evaporative cooling in water. Cooling is primarily obtained by the evaporation of water. The efficiency and evaporation rate for the range of condition studied varied between 0.18 and 0.34, and 0.009 kg/min and 0.032 kg/min respectively.

5. Nomenclature
- $\dot{e}$: evaporation rate of water (kg/min)
- $G$: gas mass flow rate (kg/s)
- $L$: liquid mass flow rate (kg/s)
- $C_w$: heat capacity of water (KJ/kg °C)
- $t_w$: temperature of water (°C)
- $t_{wb}$: wet bulb temperature of air (°C)

Subscript
- $i$: inlet
- $o$: outlet

Greek letters
- $\lambda$: latent heat of vaporization of water (KJ/kg)
- $\eta$: thermal efficiency
\[ \Delta t_e \] temperature change in water due to evaporation (°C)

\[ \Delta t_c \] cooling range of water (°C)

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6. References

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