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Experimental Investigation of Natural Draft Wet Cooling Tower Performance

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Abstract

This study is deals with the performance of natural draft wet cooling tower, using a suitable technique. This technique takes into account the effects of fill type, nozzle hole and hot water flow rate on the performance of cooling tower. The model dimensions were: top outlet diameter (370 mm), bottom diameter (680 mm) and height (850 mm). (210) test experiments were done in three parts, (48) for different water flow rate, (108) for different fill types and (56 tests) for different nozzle holes. Three cases were studied for film and splash fills, where for film the heights were (60, 90 and 120mm) and for splash fill (30, 45 and 60mm) heights were studied. The performance parameter of the tower such as range, approach, effectiveness and Merkel number were studied. Eighteenth new experimental relation was proposed for Merkel number and water to air mass flow rate ratio. And compared with previous works.

Keywords

Cooling Tower, Natural Draft, Film Fill, Splash Fill

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1. Introduction

A cooling tower cools water by a combination of heat and mass transfer. The hot water to be cooled is distributed in the tower by spray nozzles, splash bars, or film- type fill, which exposes a very large water surface area to atmospheric air. A portion of the water absorbs heat and it is changed to a vapour at constant pressure. This latent heat of vaporization has long been used to transfer heat from the water to the atmosphere. Additional heat is taken away by the air by virtue of its temperature increase but this sensible heat exchange is minor compared to the latent component provided by the water's phase change, El-Wakil, [1988].

Cooling towers of interest play an important role in the cool-end system of power plant, and its cooling capacity can affect the total power generation capacity directly. The cooling efficient is highly sensitive to environmental conditions, particularly for most cases under the cross-wind conditions that may reduce dry-cooling towers up to (40%) of the total power generation capacity. However, for the conventional design of cooling towers, the impact of cross-wind, which actually exists in most cases, has not been paid more attention, Gao et al., [2007].

2. Natural Draft Cooling Tower

The natural draft wet cooling tower (NDWCT) or hyperbolic cooling tower, Figure 1 makes use of the difference in temperature between the ambient air and the hotter air inside the tower. As hot air moves up wards through the tower (because hot air rises), fresh cool air is drawn into the tower through an air inlet at the bottom. Due to the layout of the tower, no fan is required and there is almost no circulation of hot air that could affect the performance. Concrete is used for the tower shell with a

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height of up to (200 m). These cooling towers are mostly only for large heat duties because large concrete structures are expensive.

Wet cooling towers have a water basin with a cold water outlet at the base. These are both large engineered structures, able to handle up to of water circulation, as indicated in Figure 1. The fill construction inside the tower is a conventional frame structure, always prefabricated as illustrated in Figure 2. It carries the water distribution, a large piping system, the spray nozzles, and the fill-package. Often dripping traps are applied on the upper surfaces of the fill to keep water losses through the uplift stream under 1%. Finally, noise protection elements around the inlet decrease the noise caused by the continuously dripping water, Hooman, [2010].

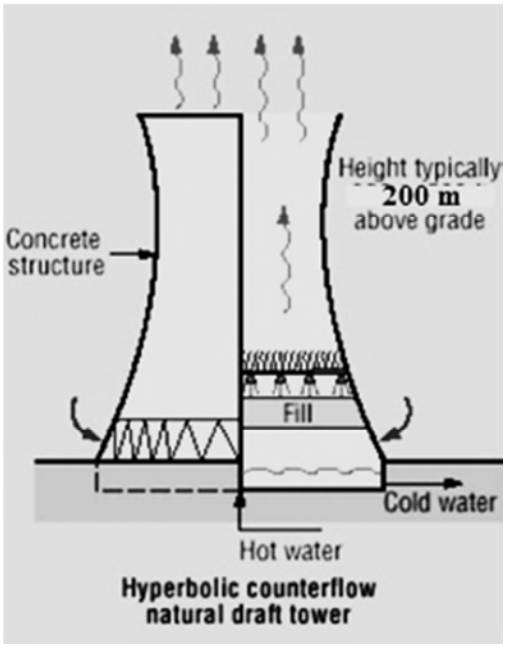

Figure 1. Types of cooling towers, ASHRE, [2008].

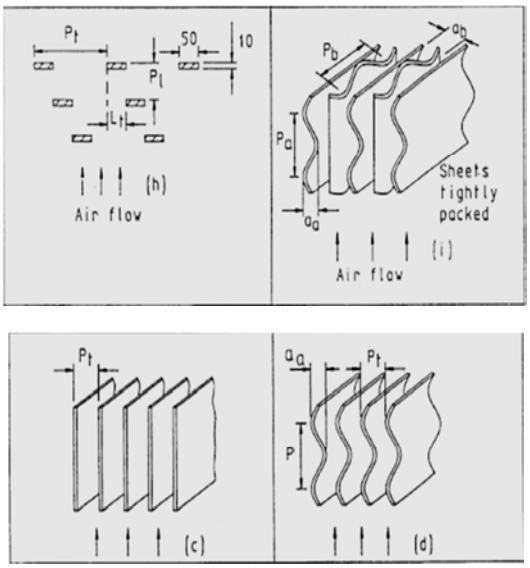

Figure 2. Types of fill in counter flow cooling tower, Hooman, [2010].

3. Similarity Criterion

The model test must satisfy the following similarity criteria, including the geometric, kinematic, dynamic and thermal similarity. Model for (NDWCT) used with a scale of (1:100) to the prototype tower. Height of the tower inlet is (50 mm), as shown in Figure 3. The water distribution system consists of two main pipes and many branch pipes. According to the kinematic similarity, the air velocity ratio of the model tower must be equal to that of the prototype that is,

$$(\frac{V_{to}}{V_{cw}})p = (\frac{V_{to}}{V_{cw}})m \qquad (1)$$

Where V_{to} is the air velocity at the tower top outlet, V_{cw} is the crosswind velocity at the height of the tower outlet, (P) and (m) represent the prototype and model tower respectively. The velocity in the Reynolds number varies inversely with the model scale while the velocity in the (Froude number) varies directly with the square root of the model scale, so the (Reynolds) and (Froude number) similarity cannot be satisfied simultaneously in one model test. In this model test, the driving force of buoyancy and the inertial force of crosswinds are the main factors to be concerned, while the viscous force is less important. Therefore, it is not the Reynolds number but the density Froude number similarity to be satisfied.

$$\Delta Fr = \left(\frac{v_{to}}{\sqrt{\frac{\Delta \rho_a}{\rho_i} * g * L}} \right)_p = \left(\frac{v_{to}}{\sqrt{\frac{\Delta \rho_a}{\rho_i} * g * L}} \right)_m \qquad (2)$$

In this experimental study, water to air mass flow ratio and water temperature drop were kept in the same order of magnitude for the prototype and model. Therefore, the water flow rate was set as (6 and 8 l/min) which correspond to (10 and 13.33) for the prototype, and the inlet water temperature was set as (40, 45, 50 and 55) to obtain a larger water temperature drop which is close to the actual conditions. To simulate the crosswinds. According to the dynamic similarity, the crosswind velocity in this hot model test should be (1/10) of the actual crosswind velocity. Six crosswind velocities are given by the lower fan, including (0.0, 0.2, 0.4, 0.6, 0.8 and 1.0 m/s), and the crosswind velocities provided by the upper fan should be determined according to the following equation, Gao, [2007]

$$\frac{V_{cw}}{V_{cwref}} = (\frac{Z}{Z_{ref}})^{0.2} \qquad (3)$$

Therefore, the crosswind velocity from the upper fan is about two times of that from the lower fan, which is (0.0, 0.4, 0.8, 1.2, 1.6 and 2.0 m/s) respectively. Crosswind velocities mentioned below are all from the lower fan.

The effectiveness of a cooling tower is defined as the ratio between the range and the ideal range, (i.e. difference between cooling water inlet temperature and ambient wet bulb temperature). The higher this ratio means higher cooling tower effectiveness.

$$\text{Effectiveness}(\%) = \frac{[\text{water inlet temp.} - \text{water outlet temp.}]}{[\text{water inlet temp.} - \text{air inletwetbulb temp.}]} \quad (4)$$

4. Experimental Apparatus Layout

The whole experimental simulates the actual working process of cooling tower in power plant. Before operating experiments, the pure water, that is circulating, and heated up to required temperature by several heaters, then the circulating pump feeds the water to the overhead water tank. During the experiments, circulating water enters into the model tower and goes through the fills from top to bottom, while the dry air flows through the fills from bottom to top. Heat and mass transfer are finished in the course of flow. A schematic diagram of the equipment used in the experimental study is shown in Figure 3. The cooling tower has been designed to meet the demand for compact cooling tower which clearly demonstrates all the processes found in model for natural draft wet cooling tower and behaves in a representative manner supplied with standard column. Water distribution troughs and pressure tapping with (0.5,1.0 and 1.5 kW) heaters and float level control, make up tank, bronze circulating pump, air fan, electrical control panel.

Figure 3. Test rig for NDWCT model.

5. Results and Discussions

5.1. Cooling Tower Range

For film fill, the effect of water flow rate on cooling tower range at different values of inlet water temperature is illustrated in Figure 4. For each value of water inlet temperature, as the water flow rate is increased, the cooling tower range is decreased. For instance, as water inlet temperature (40, 55°C) and water flow rate is (2, 14 L/min), the cooling tower range is (2.49, 10.47°C) and (1.5, 3.89°C) respectively. Splash fill behave same as film fill as shown in Figure 5, where in splash fill, the range is slightly more than film fill. As water inlet temperature (40, 55°C) and water flow rate is (2, 14 L/min) the cooling tower range is (4.59, 12.4°C) and (4.3, 6.7°C) respectively. This can be explained as the water mass flow rate increases, cooling tower range must be decrease due to the cooling load is constant. Cooling tower range decreases the at water mass flow rate increases, due to the increasing of heat and mass transfer coefficients.

The effects of air flow rate on cooling tower range, for different values of the water flow rate are illustrated in figs. 6, 7 and 8. For each value of water flow rate, as the air flow rate is increased, the cooling tower range is increased. For instance, as water flow rate of (5 L/min) and air flow rate of ($46.8m^3$/hr and $169.2m^3$/hr), the cooling tower range is (9.5°C and 18.4°C) respectively. For film fill at height (120 mm) is the best range for all types of fills as shown in Figure 6. This result can be explained as the air flow rate increases, the evaporated water per unit of air increases and when fill height increase due to an increase in air travelling and to break up droplets of water into films, and finally falling to the next element below. Figs. 7 and 8 show the variation of range with air flow rate after increasing water flow rate (10 L/min) and (15 L/min) respectively. It can show that increasing water flow rate cause a decreasing in range due to decreasing heat transfer which arise from no time enough of heat transfer exchange.

The variation of cooling water range with water to air mass flow rate ratio ($m\bullet_w/m\bullet_a$), for different values of air flow rate is illustrated in figs. 9, 10 and 11. As shown in Figure 9, at lowest values of ($m\bullet_w/m\bullet_a$), the best cooling water range is achieved. When the water flow rate increases ($m\bullet_w/m\bullet_a$ increases), cooling water range decreases. This decrease is seen clearly at the lowest value of air flow rate, which means at the highest ($m\bullet_w/m\bullet_a$) ratio as shown in Figure 9. For instance, as water flow rate of (5 L/min) and water to air mass flow rate ratio of (5.34) and (1.477), the cooling tower range is (9.5°C and 18.4°C) respectively for film fill at height (120 mm) which is the best range for all types of fills as shown in Figure 9. Therefore, the mass flow rate of air and water has a direct effect on cooling tower range. Figs. 10 and 11 show the variation of range with water to air mass flow rate ratio after increasing water flow rate (10 L/min) and (15 L/min) respectively. It can see that increasing water flow rate cause increasing in mass flow rate ratio and decreasing in range.

5.2. Cooling Tower Effectiveness

The influence of air and water mass flow rate on cooling tower effectiveness is analysed. Since the cooling tower effectiveness (ε) is defined as the ratio of the actual energy transfer to the maximum possible energy transfer. Therefore, the tower effectiveness is determined from eqn.(4). Variation of cooling tower effectiveness with water flow rate for different values of water inlet temperature for film fill is illustrated in the Figure 12. For each value of water inlet temperature, as the water flow rate is increased, the cooling tower effectiveness is decreased. For instance, as water inlet temperature (40, 55°C) and water flow rate is (2, 14 L/min) the cooling tower effectiveness is (12.39%, 27.99%) and (6.9%, 10.9%) respectively. Splash fill behave same as film fill as shown in Figure 13, while for splash fill, the effectiveness value is more than the effectiveness value film fill. Also, for splash fill as water inlet temperature (40°C, 55°C) and water flow rate is (2,14 l/min), the cooling tower effectiveness are (16.9%, 33.7%) and (12.4%, 22.06%) respectively.

Therefore, as the water to air mass flow rate ratio ($m\bullet_w/m\bullet_a$) is decreased, the cooling tower effectiveness is increased. as shown in Figure 14 for water flow rate (5L/min). For instance, as ($m\bullet_w/m\bullet_a$) ratio of (5.43); the effectiveness is calculated as (35.29%.) Where, as water mass flow rate is constant and air mass flow rate is decreased, which means ($m\bullet_w/m\bullet_a$) ratio of (1.47), the effectiveness is calculated as (69.9%). The best effectiveness for film fill at height (120mm) as shown in Figure 14. This means for each value of water mass flow rate, as ($m\bullet_w/m\bullet_a$) ratio decreases, effectiveness increases. Therefore, at constant mass flow rate of water, the mass flow rate of air is very important factor which affects the cooling tower effectiveness. The variation of cooling tower effectiveness with water to air mass flow rate ratio for different values of air mass flow rate is illustrated in figs. 14, 15 and 16. As shown in these figures as the ratio ($m\bullet_w/m\bullet_a$) value increases, cooling tower effectiveness decreases. Where for water flow rate (10 L/min) effectiveness reach to (58.1%) at mass flow rate ratio ($m\bullet_w/m\bullet_a$) is (2.59) for film fill at height (120mm) as shown in Figure 15. From Figure 16 best effectiveness is (46.6%) at mass flow rate ratio ($m\bullet_w/m\bullet_a$) is (4.08), water flow rate (15 L/min) for same fill type. That means when water flow rate increase effectiveness decrease at same type of fill, at the lowest values of ($m\bullet_w/m\bullet_a$) ratio the best cooling tower effectiveness is achieved.

Figure 17 and Figure 18 show the variation of effectiveness with circulating water flow rate for different nozzle hole for both cases heating air input and without heating. Figures show that effectiveness increase with increasing water flow rate.

5.3. Cooling Tower Approach

The relationship between approach and water flow rates with different water inlet temperature for film fill are illustrated in the Figure 19. As shown in this figure, the outlet water temperature approach to wet bulb temperature with increasing water flow rates. The increase of the outlet water temperatures caused by the increase of water flow rate. These results are obtained because increasing in hot water lead approach to increase. Splash fill as shown in Figure 20 show the approach increase slightly less than form film fill because heat transfer in splash boards serve two functions. The first is to break the large water droplets into smaller ones, thus increasing the air-water contact area. The second function is to slow the fall of the water droplets, and increase the water resident time in the tower.

For the best performance, water should be cooled to the entering air wet bulb temperature. Theoretically, this is possible when the packing heights approaching to infinity.

5.4. Pressure Drop Across Packing

The pressure drop across packing through a natural draft wet cooling tower depends on the geometry of the packing as well as the water and air flow rates along the tower. Therefore, if the velocity of air flow is decreased in the cooling tower, the air side pressure tends to drop. Where the pressure losses of air occur in the natural draft wet cooling tower, are; at air inlet (entrance losses), in the fill passages, pressure losses due to water distribution system.

The variation of pressure drop with respect to air velocities for different inlet water temperature for two types of fill are shown in the Figure 21 and Figure 22 respectively. Pressure drop across the packing increases with increasing air velocity at constant height of film fill and constant fill space for splash fill. The higher the pressure drop occur at higher water temperature inlet (55°C), as illustrated in Figure 21, for film fill. For splash fill pressure drop is decrease with decrease air velocity, the higher pressure drop occur at (45°C) as shown in Figure 22.

5.5. Variation of Outlet Water Temperature

Variation of outlet water temperature with water flow rate for different values of water inlet temperature for film fill at height (60mm) are illustrated in Figure 23. For each value of water inlet temperature outlet water temperature increase with increasing water flow rate because heat and mass transfer in tower.

Splash fill at fill spacing (30mm) behave differ from film fill for different inlet water temperature as shown in Figure 24, where outlet water temperature increase with increasing water flow rate. But the outlet water temperature increase with

increasing mass flow rate ratio for different water temperature as shown in Figure 25 for film fill at height (60 mm) and for splash fill at space (30 mm) as shown in Figure 26.

5.6. Merkel Number

The heat transfer capability of the cooling tower is measured by Merkel number (Me) to analyse the cooling tower performance. Figure 27- Figure 29 show the variation of Merkel number with mass flow rate ratio for different fill type, at water flow rate (5L/min,10L/min and 15L/min) respectively, where Merkel number decrease with increasing mass flow rate ratio. As shown in these figures, film fill at (120 mm)is the highest Merkel number for all the types of fills. The empirical relations were summarized at table (1).

Therefore, tower characteristic increases with an increase in air mass flow rate and a decrease in water mass flow rate. This value starts to decrease as the water flows towards the tower bottom until it reaches its lowest value as the water leaves the tower. This is due to evaporation process that takes its necessary heat of evaporation from the remaining water that leads to cooling the remaining water and decreasing its enthalpy.

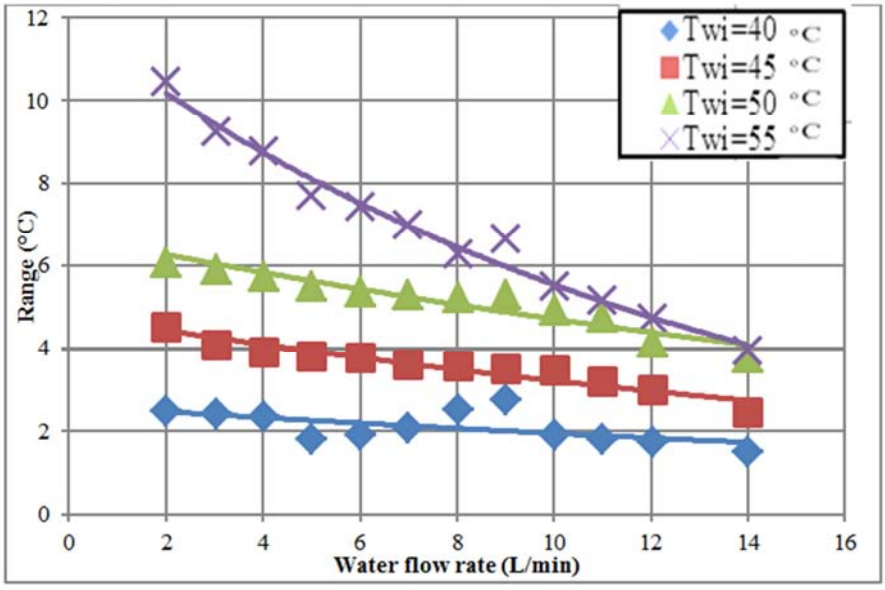

Figure 4. Variation curve of range with circulating water flow rate for different inlet temperatures.

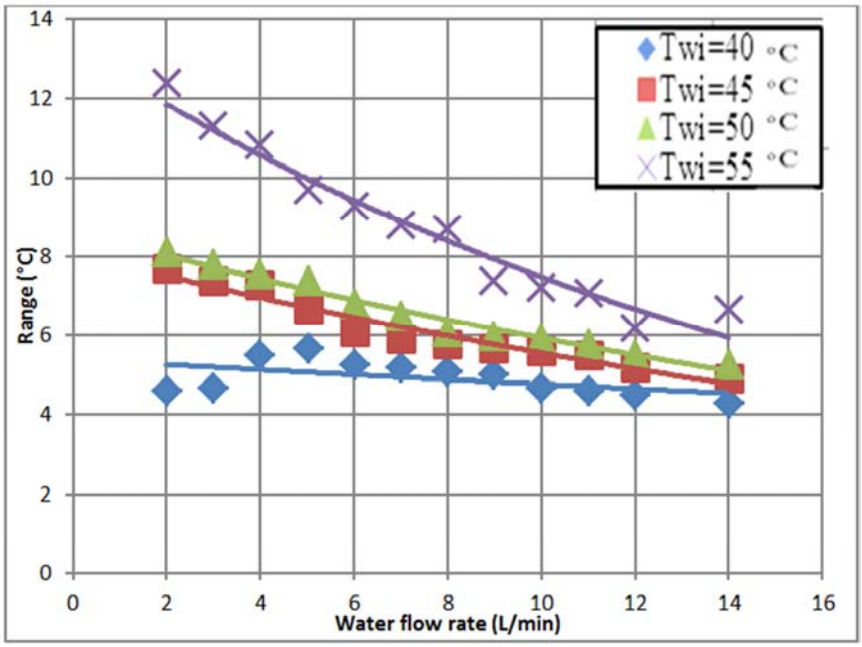

Figure 5. Variation curve of range with circulating water flow rate for different inlet temperatures.

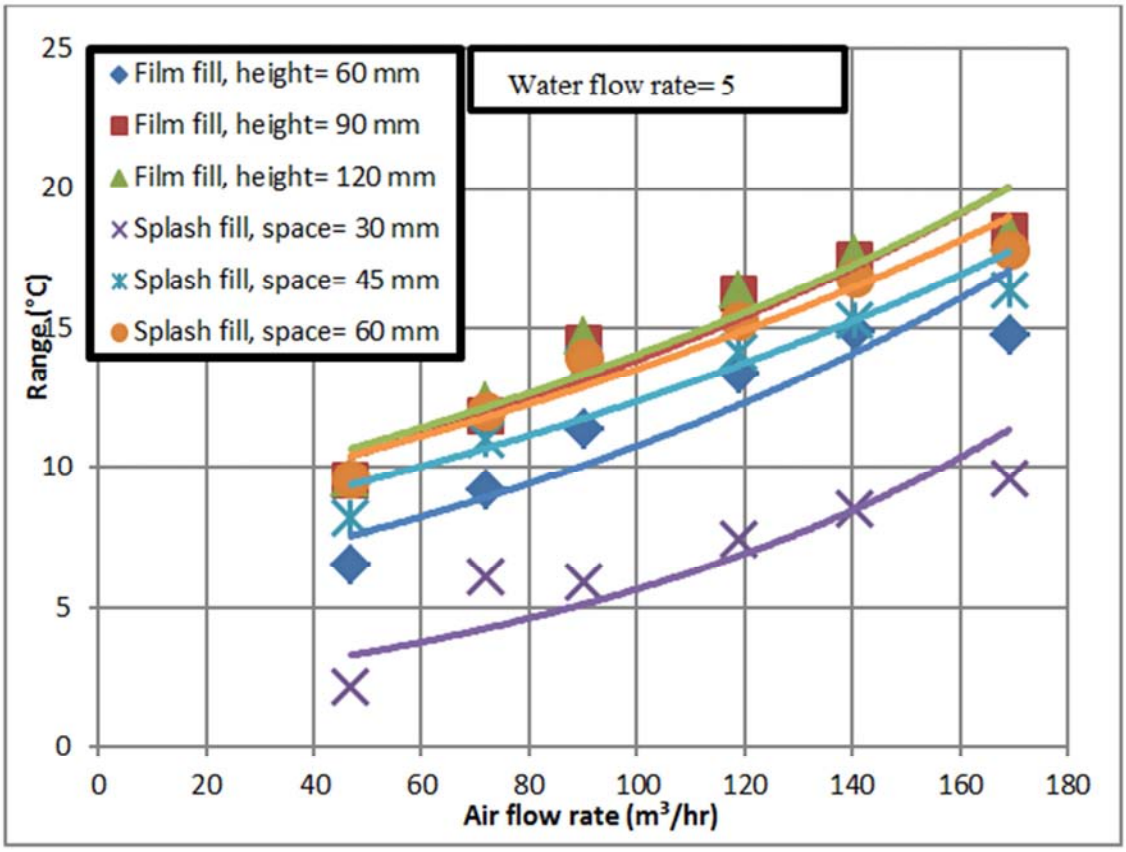

Figure 6. Variation curve of range with air flow rate for different fill types.

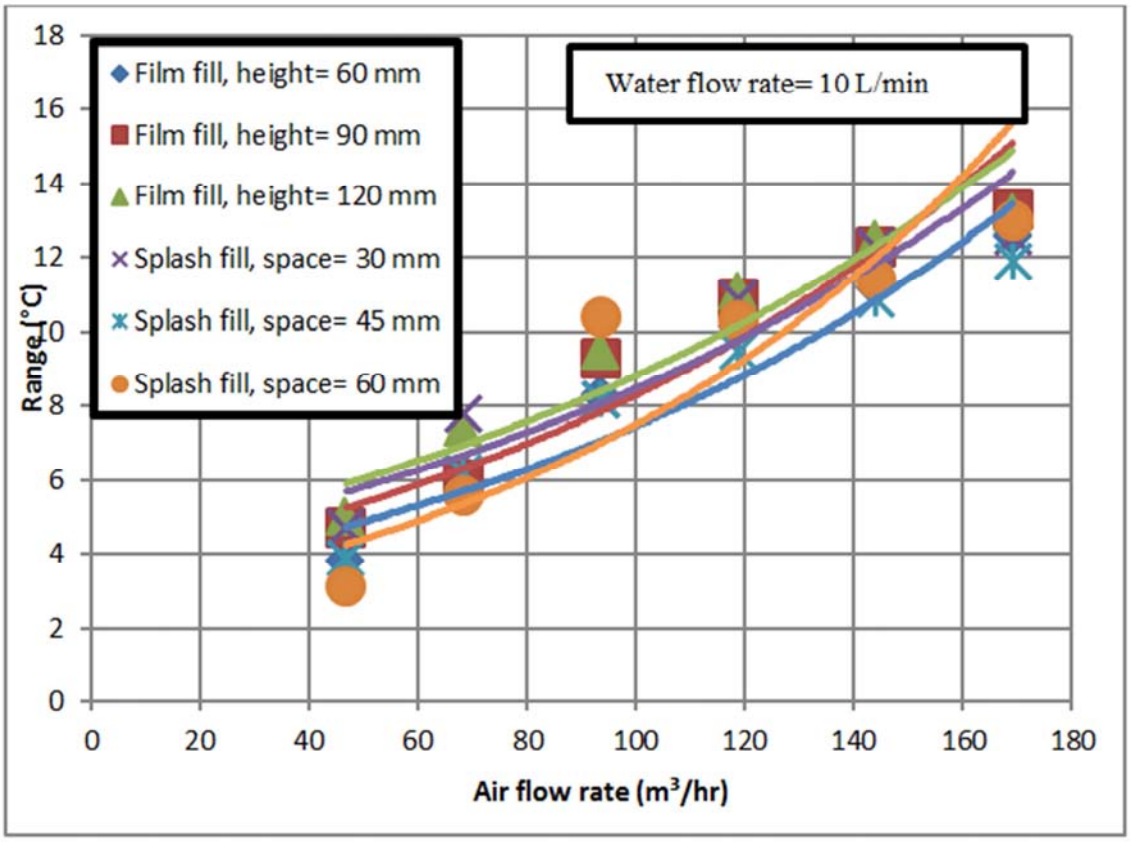

Figure 7. Variation curve of range with air flow rate for different fill types.

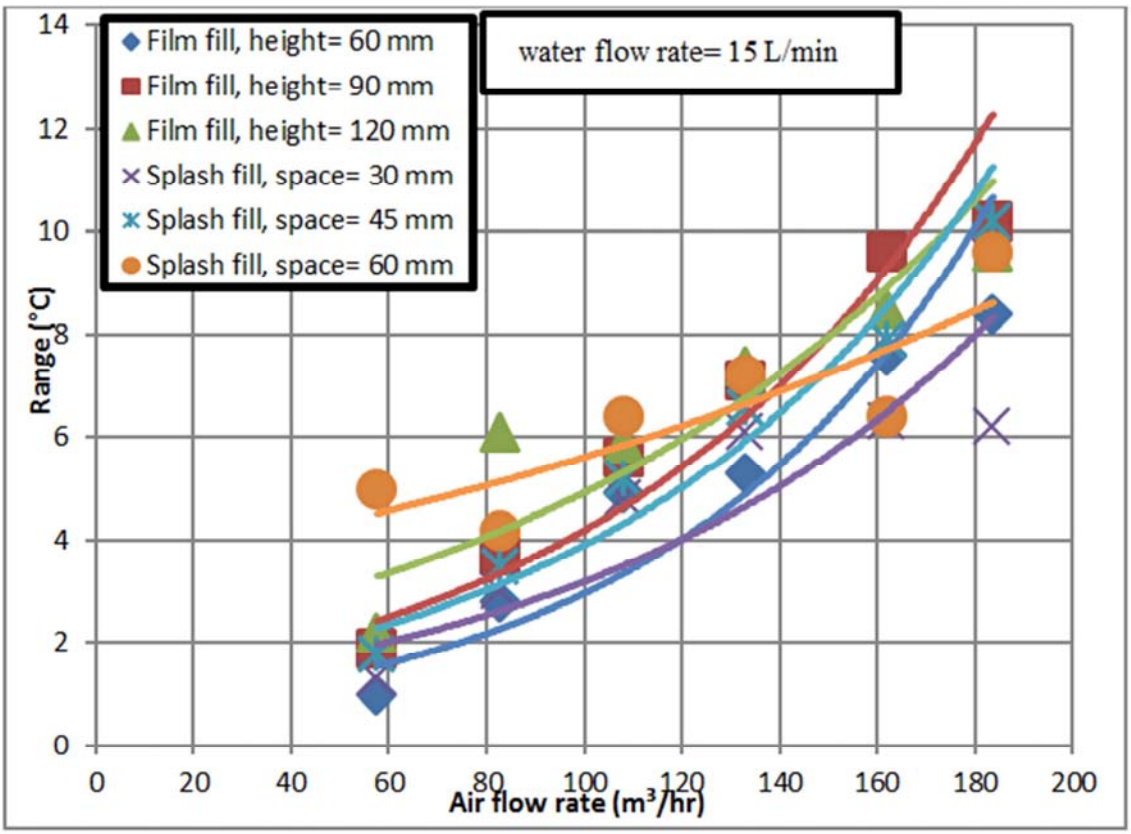

Figure 8. Variation curve of range with air flow rate for different fill types.

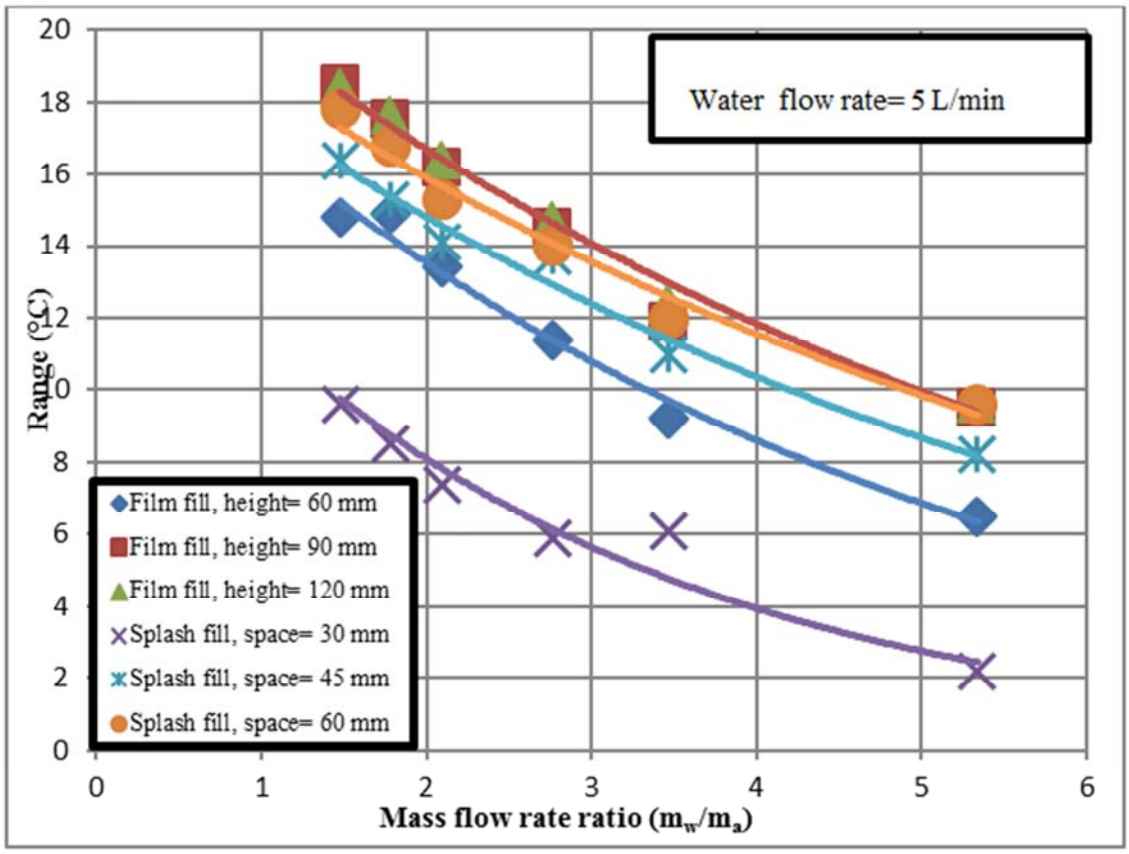

Figure 9. Variation curve of range with mass flow rate ratio for different fill types.

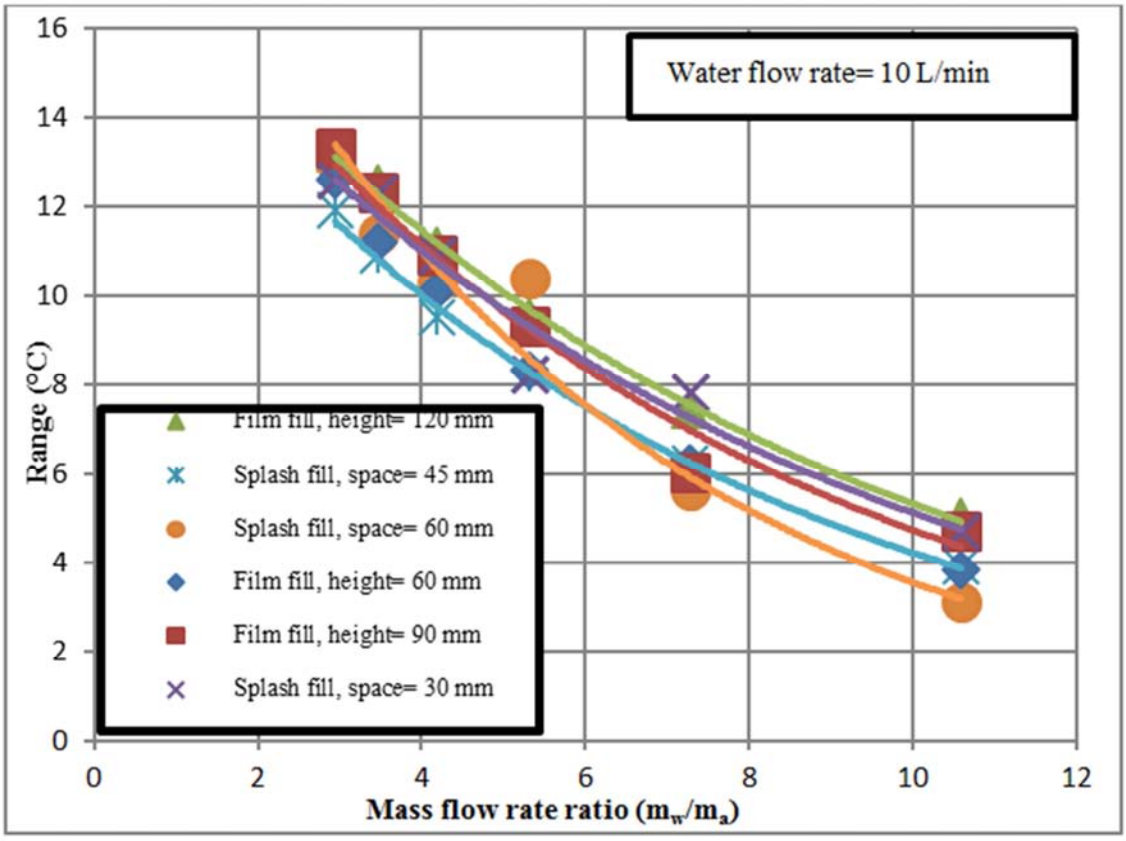

Figure 10. Variation curve of range with mass flow rate ratio for different fill types.

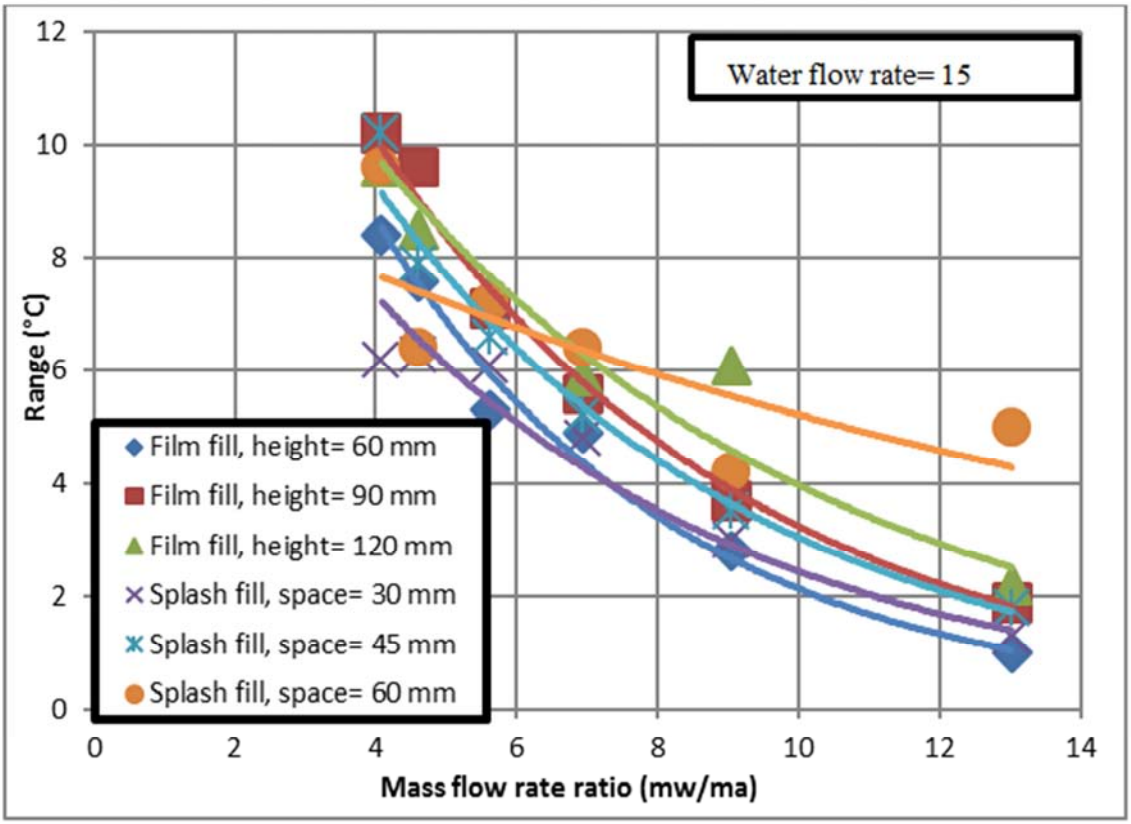

Figure 11. Variation curve of range with mass flow rate ratio for different fill types.

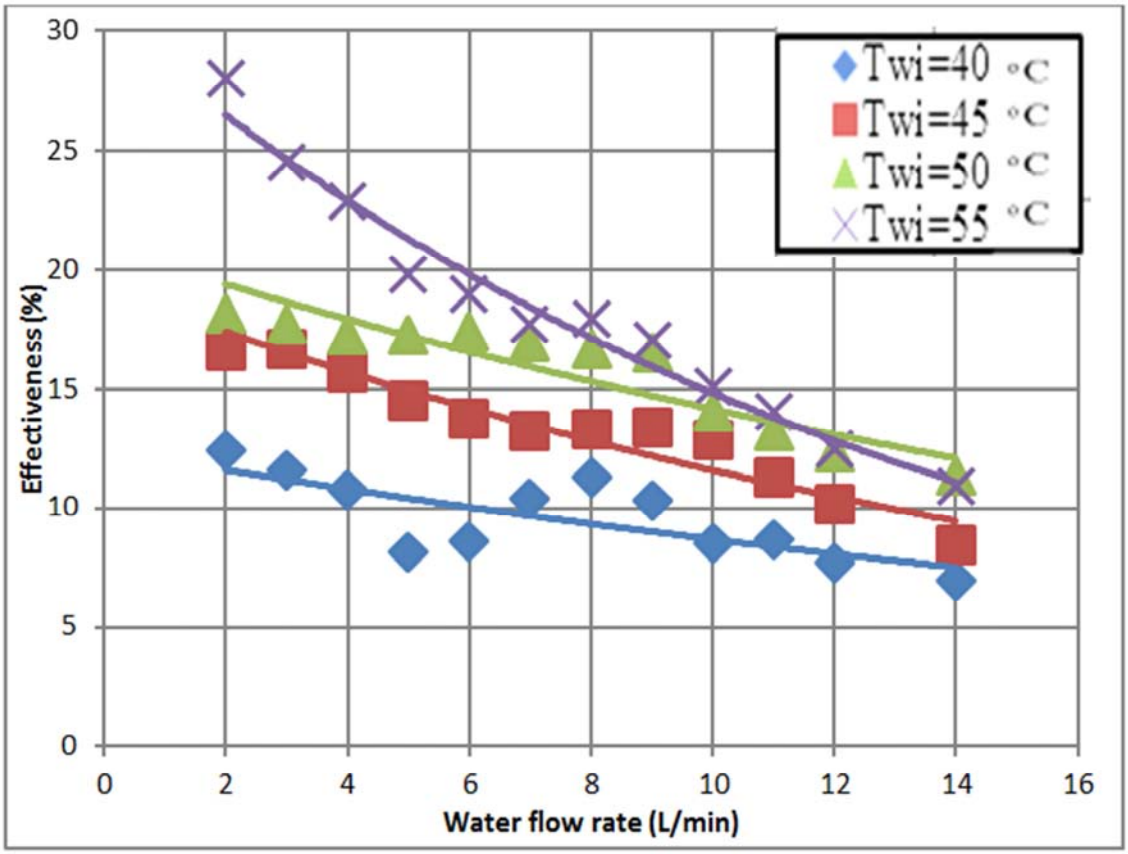

Figure 12. Variation curve of effectiveness with circulating water flow rate for different inlet temperatures of film fill.

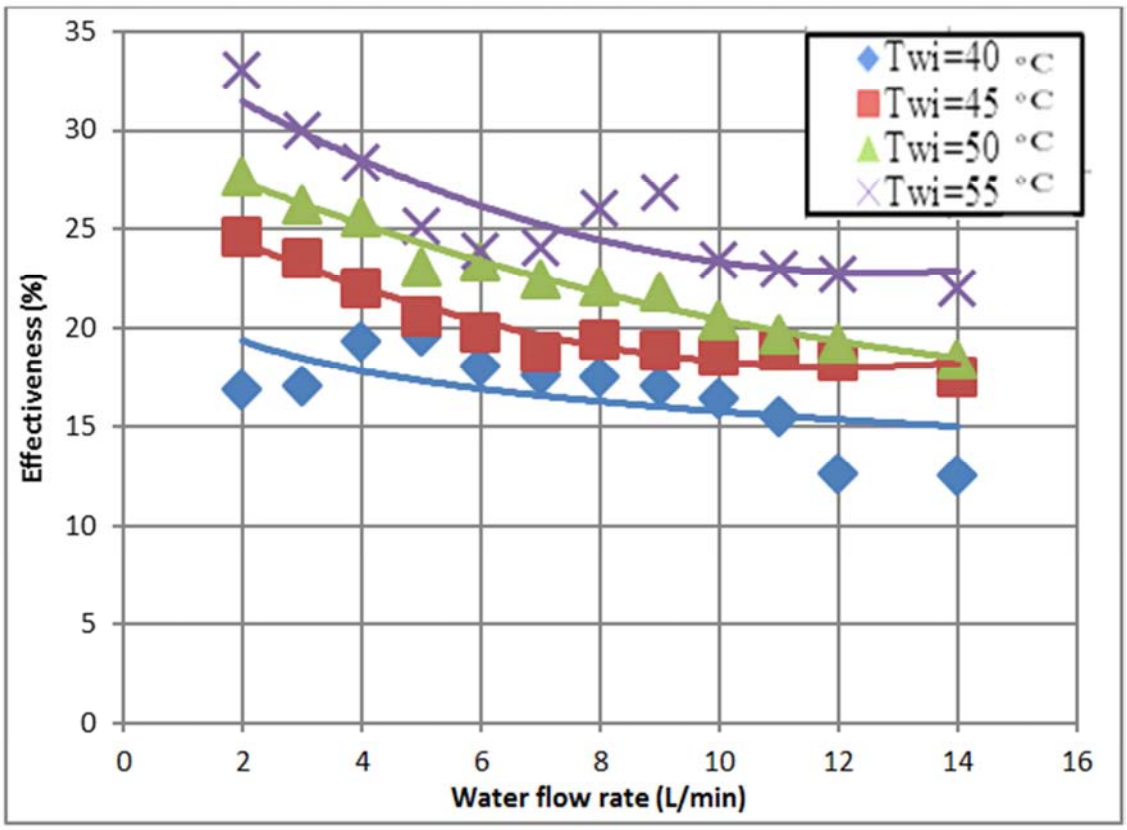

Figure 13. Variation curve of effectiveness with circulating water flow rate for different inlet temperatures for splash fill.

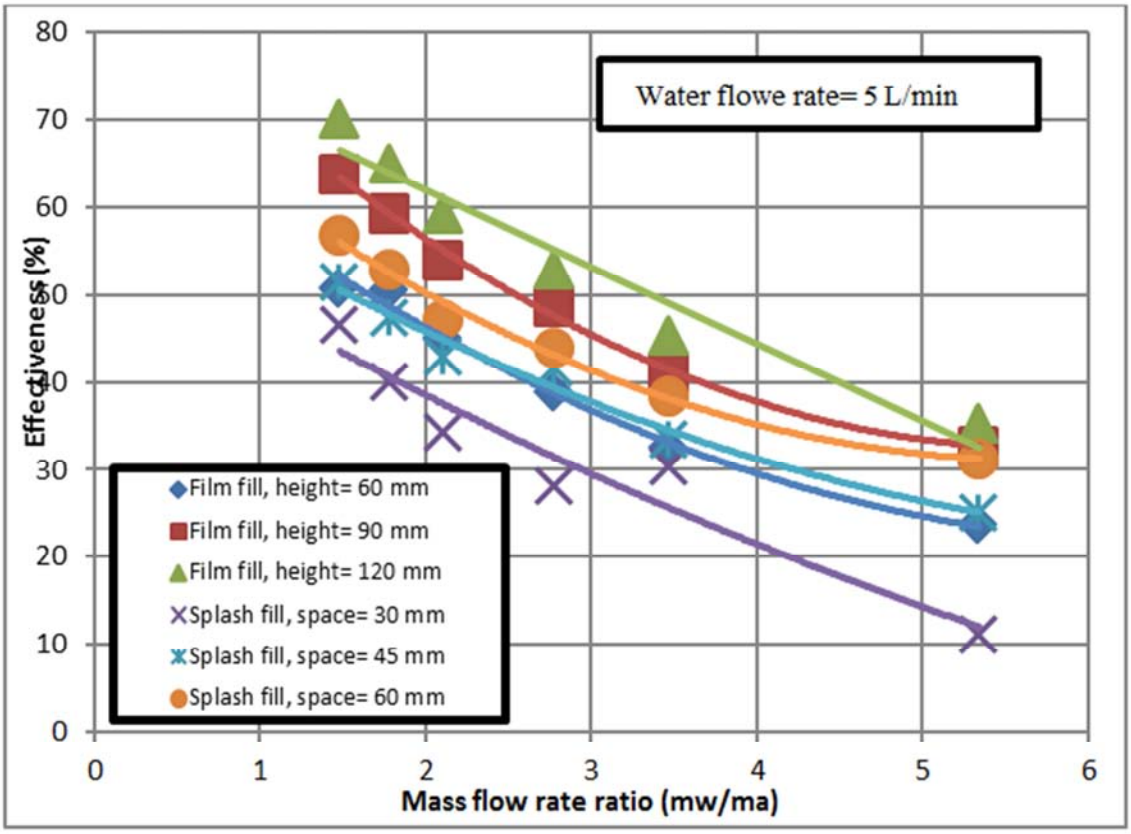

Figure 14. Variation curve of effectiveness with mass flow rate ratio for different fill types.

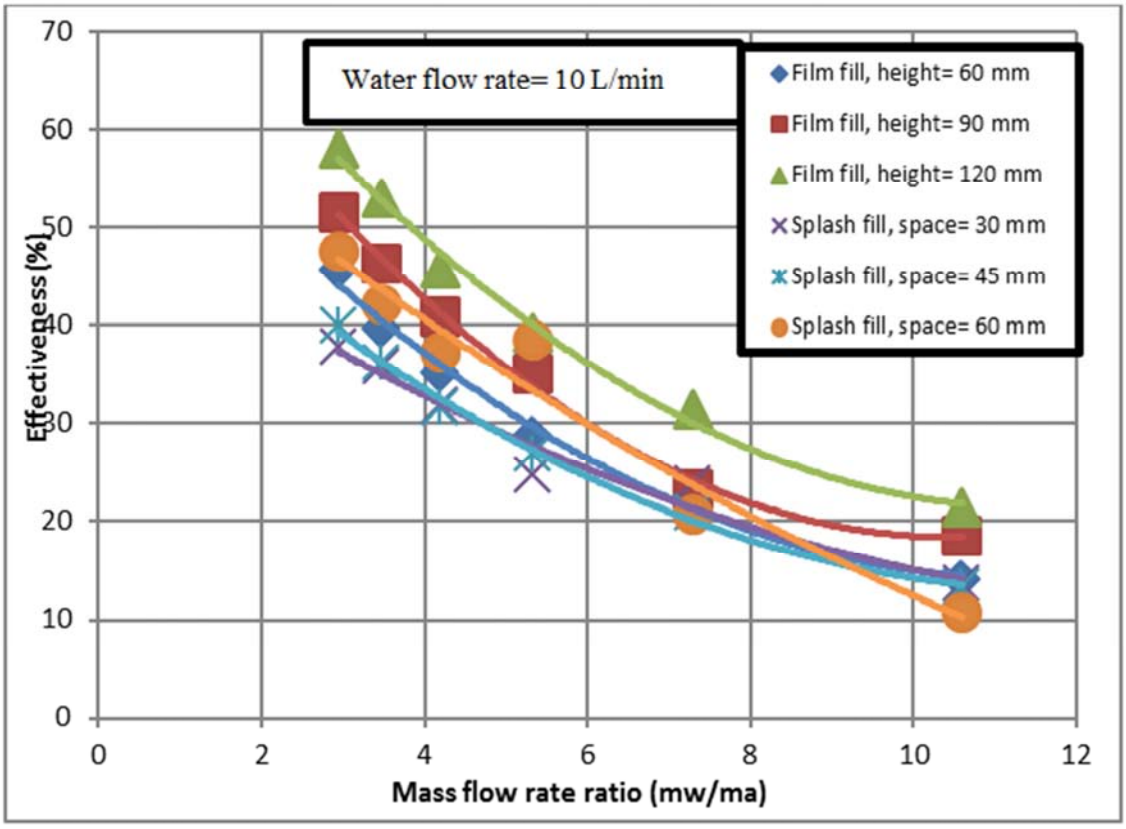

Figure 15. Variation curve of effectiveness with mass flow rate ratio for different fill types.

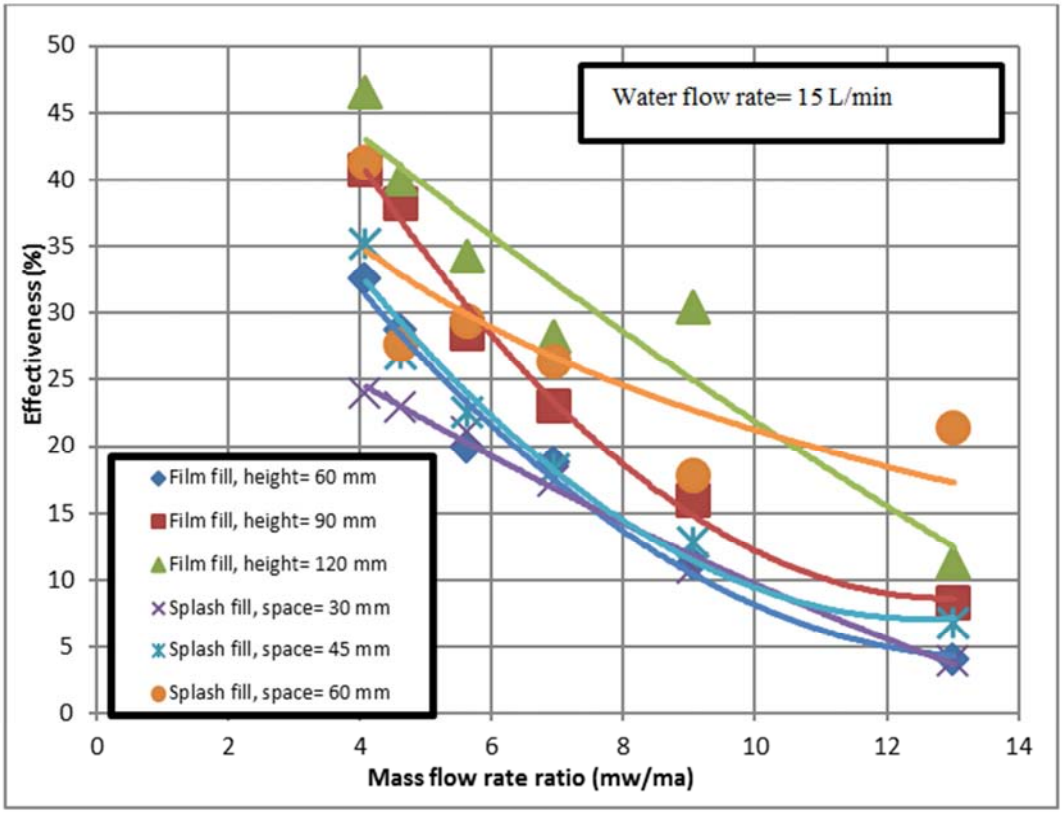

Figure 16. Variation curve of effectiveness with mass flow rate ratio for different fill types.

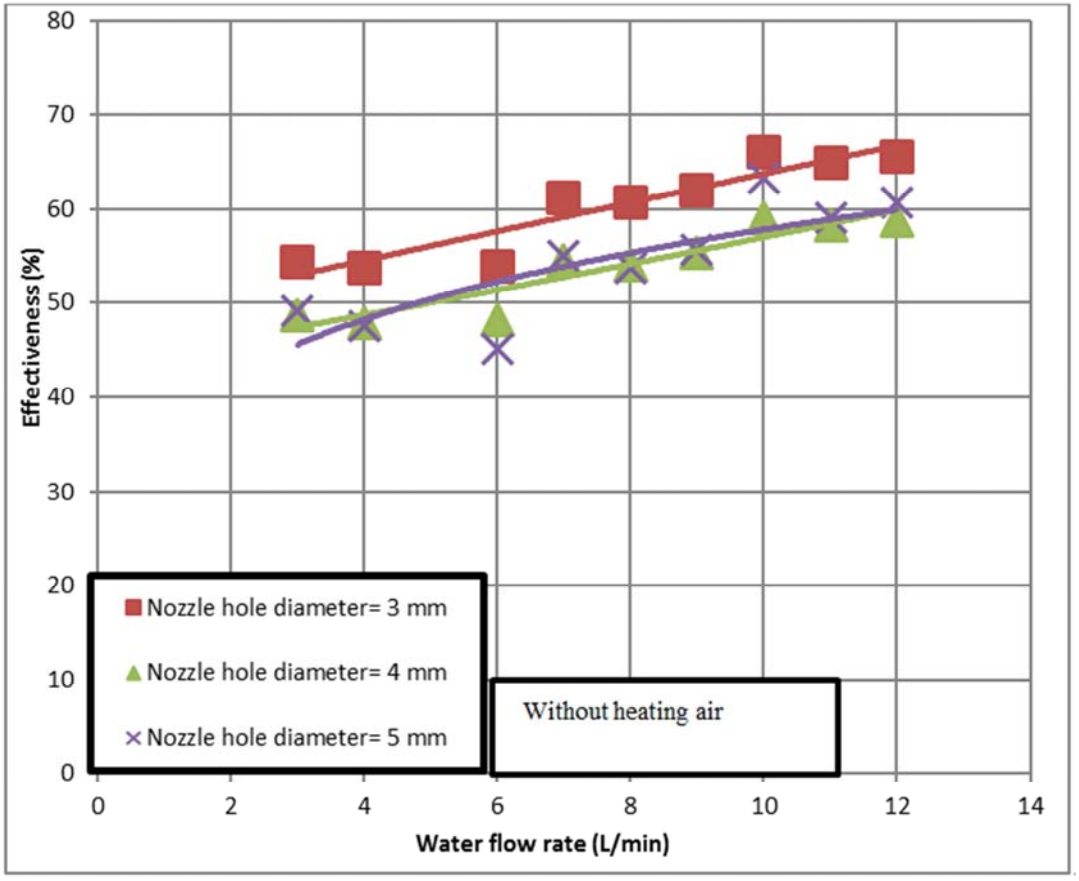

Figure 17. Variation curve of effectiveness with circulating water flow rate for different nozzle hole.

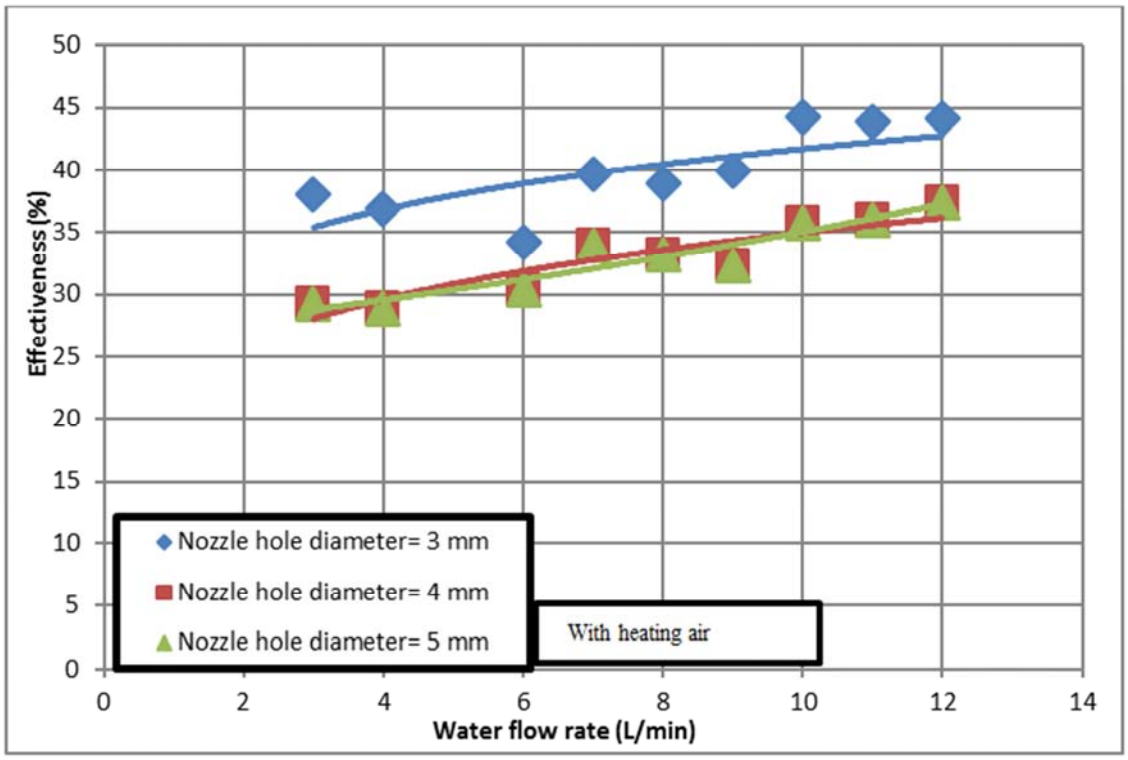

Figure 18. Variation curve of effectiveness with circulating water flow rate for different nozzle hole.

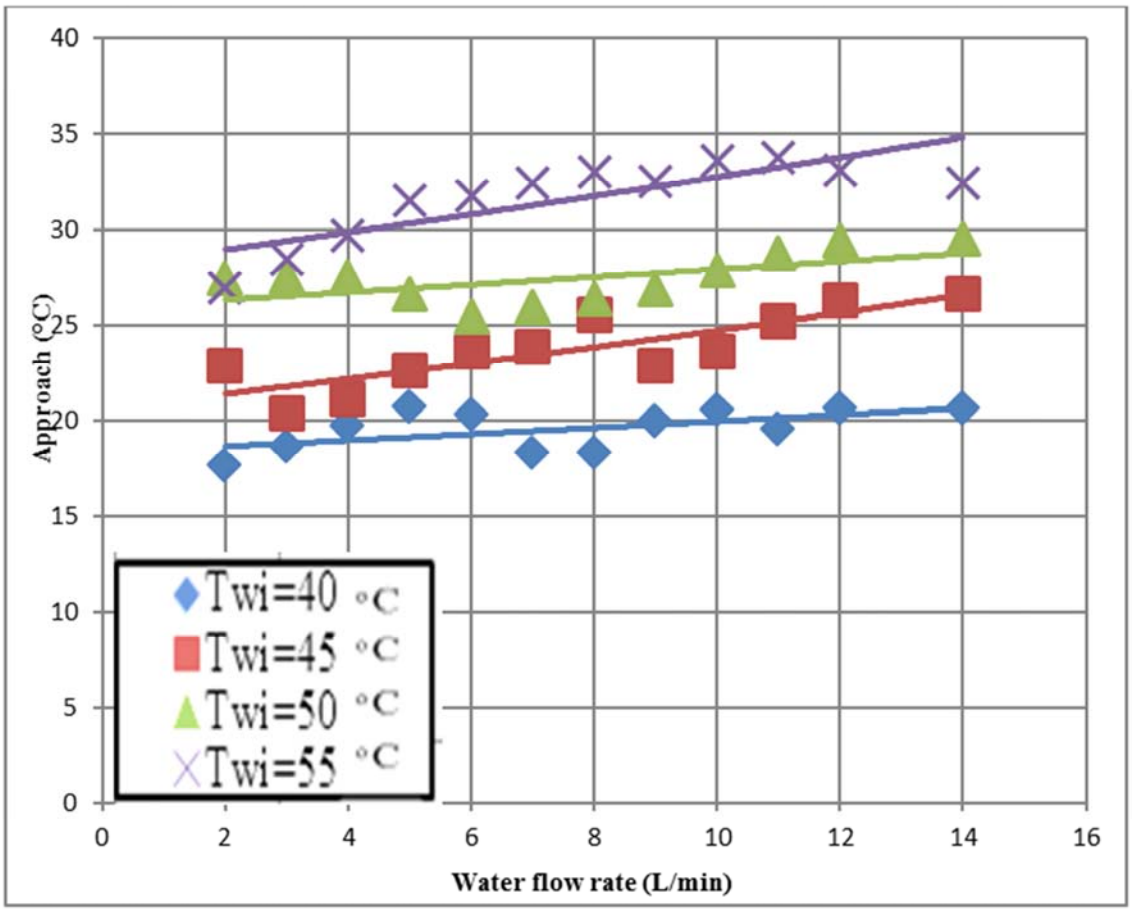

Figure 19. Variation curve of approach with circulating water flow rate for different inlet temperatures.(film fill=60mm).

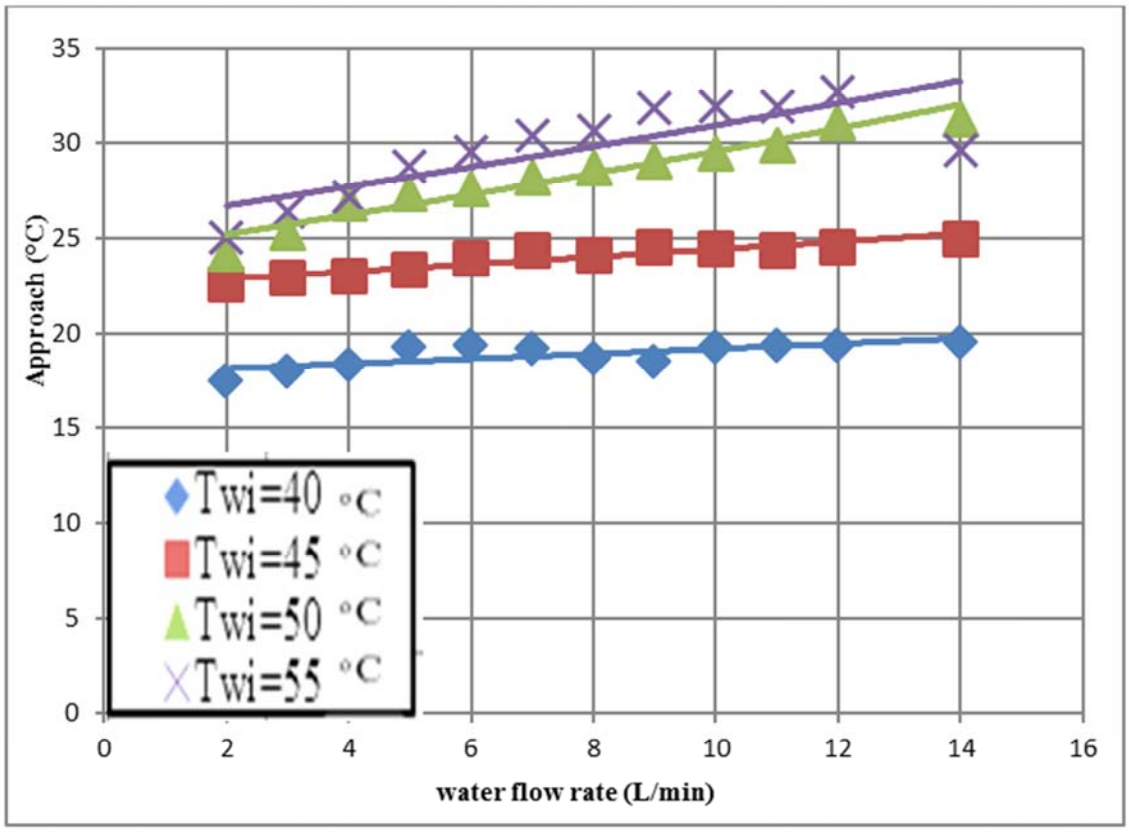

Figure 20. Variation curve of approach with circulating water flow rate for different inlet temperatures. (splash fill= 30 mm).

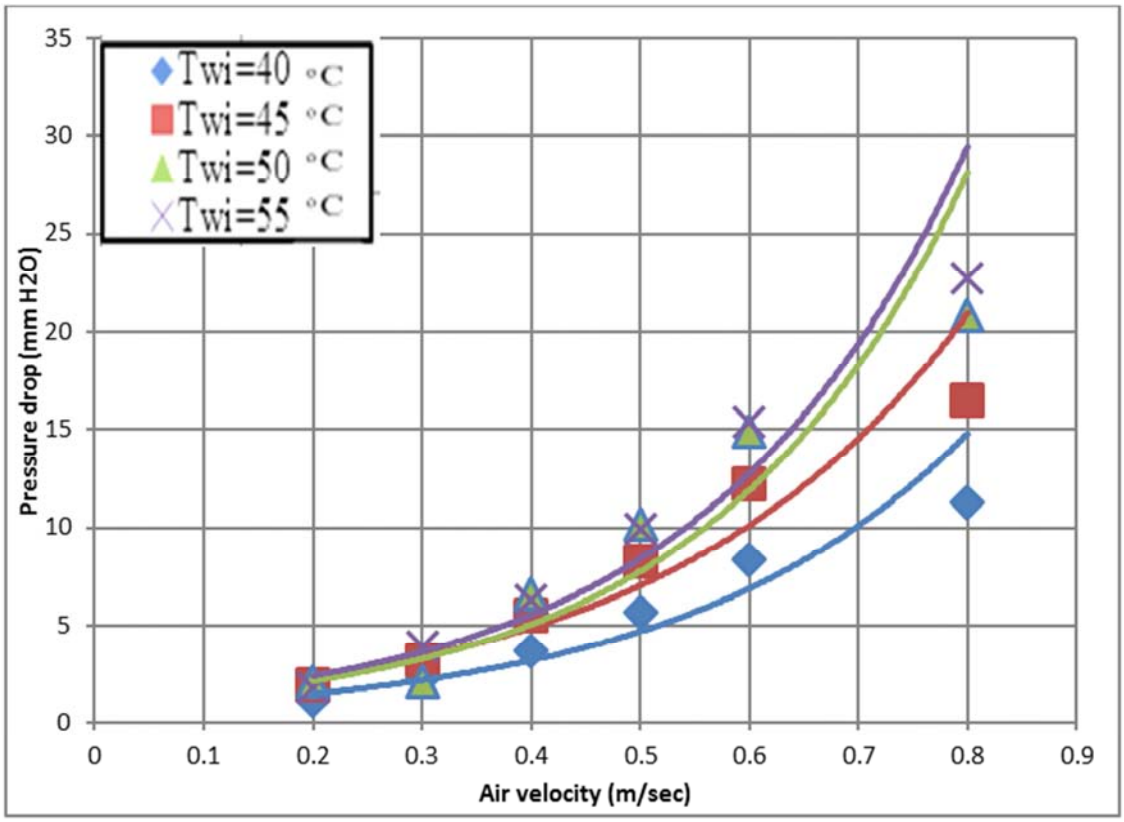

Figure 21. Variation curve of pressure drop with air velocity for different inlet water temperatures for film fill at height (60 mm).

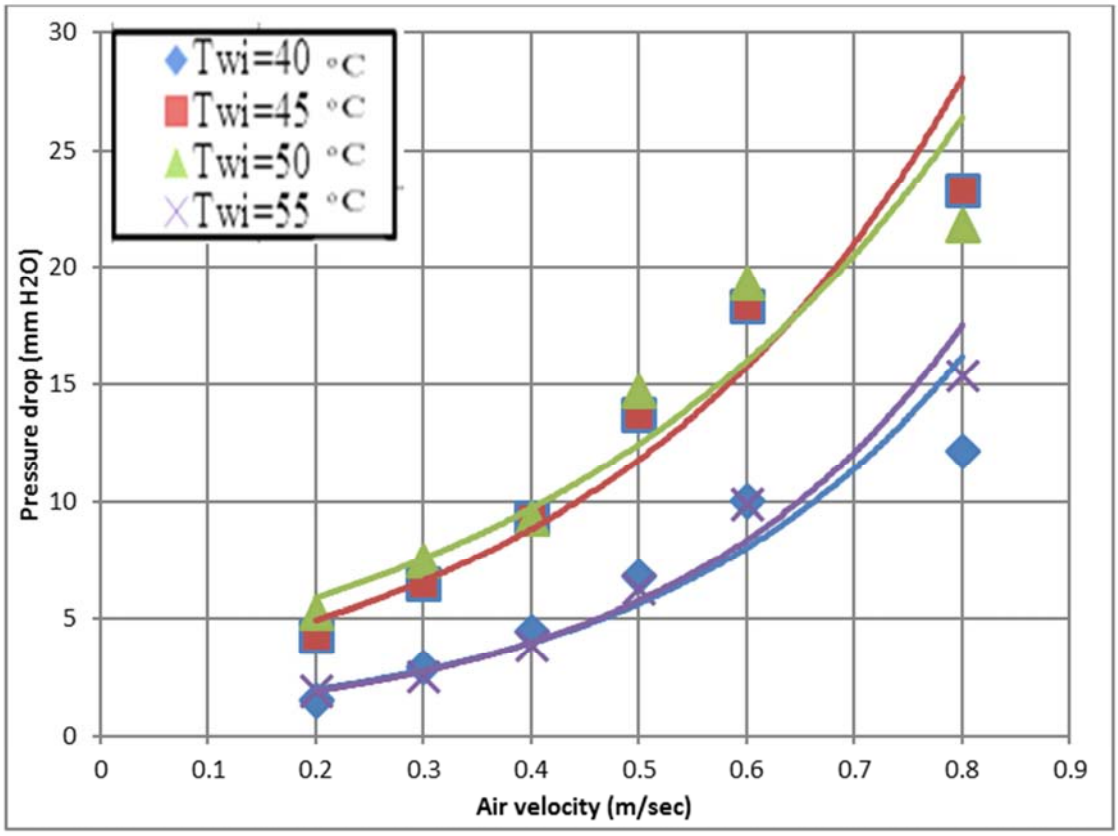

Figure 22. Variation curve of pressure drop with air velocity for different inlet water temperatures for splash fill at space (30 mm).

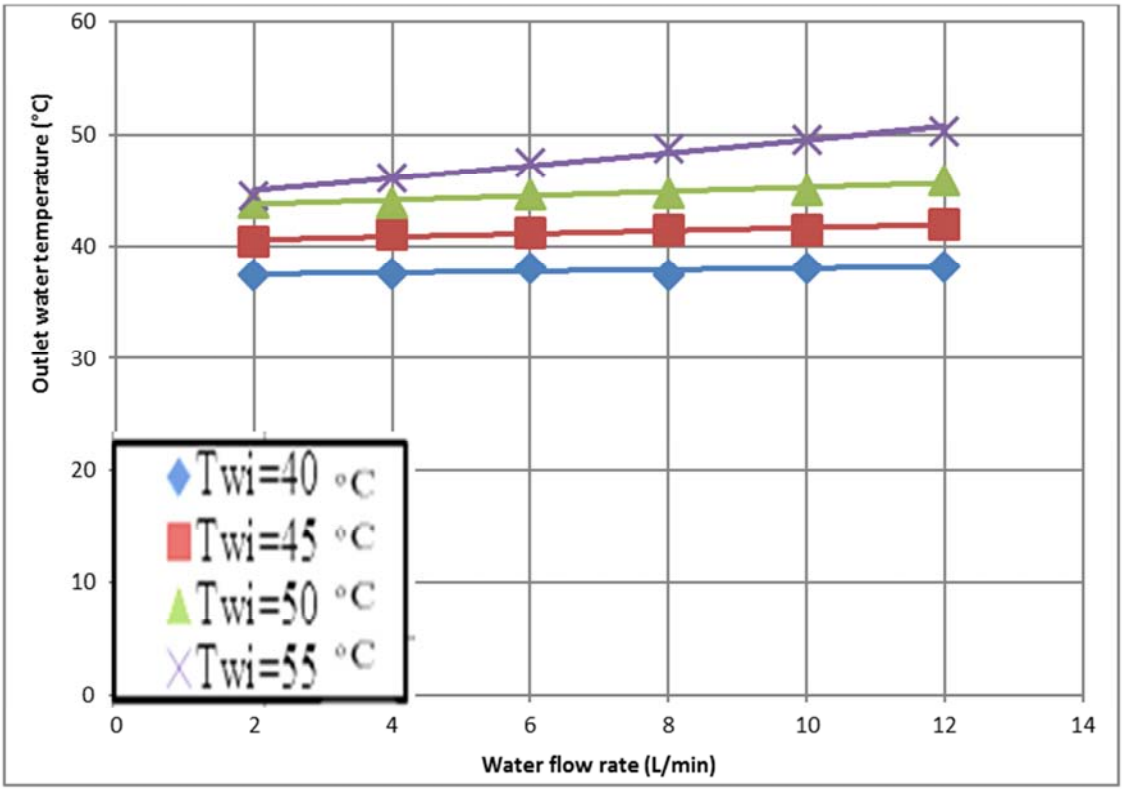

Figure 23. Variation curve of outlet water temperature with water flow rate for different inlet temperatures for film fill at height (60 mm).

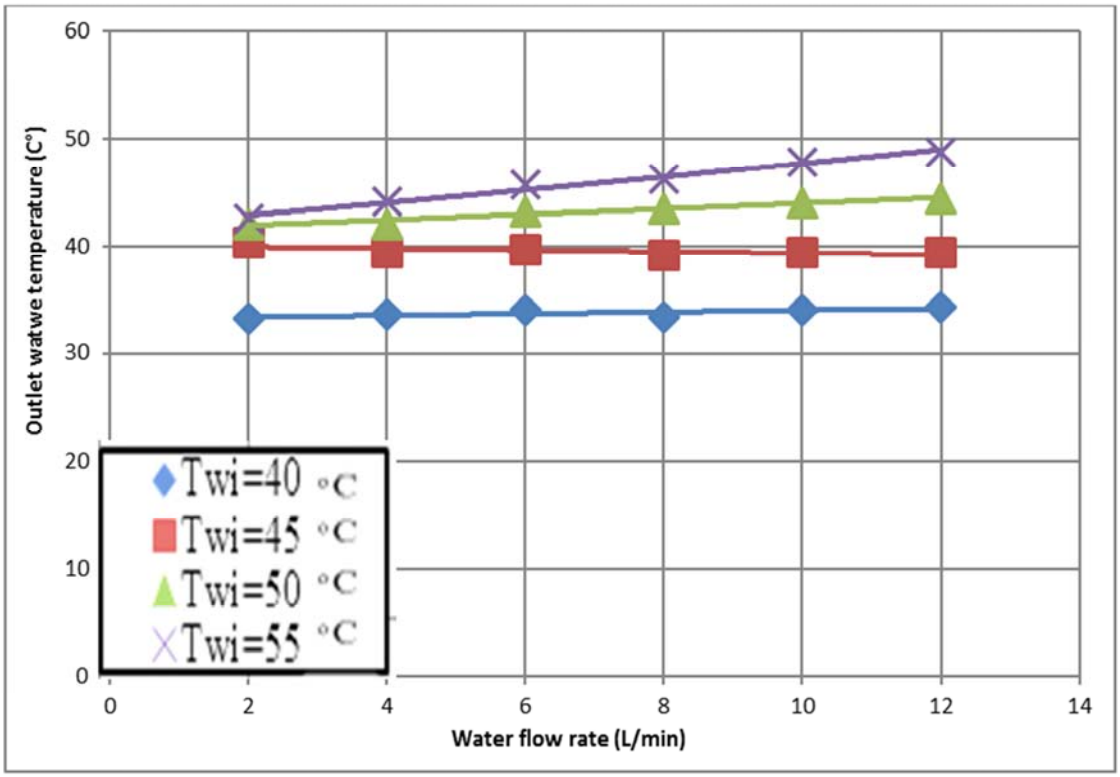

Figure 24. Variation curve of outlet water temperature with water flowrate for different inlet temperatures for splash fill at space (30 mm).

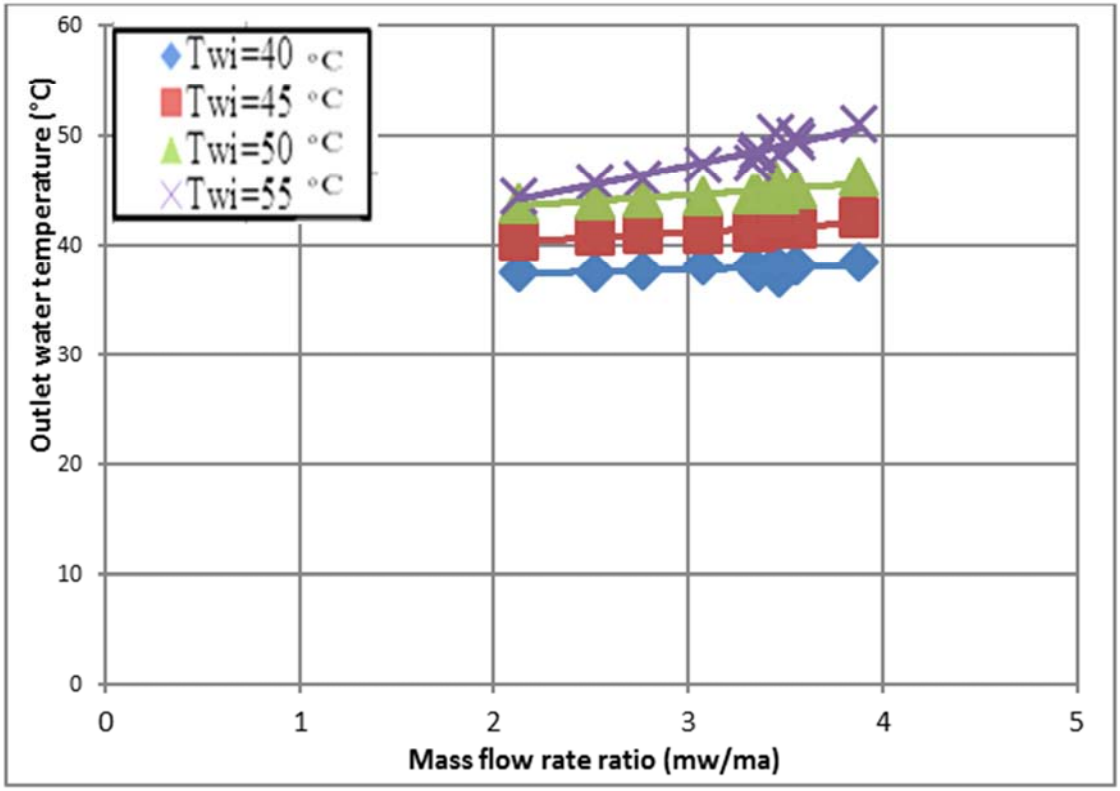

Figure 25. Variation curve of outlet water temperature with mass flowrate ratio for different water temperature for film fill at height (60 mm).

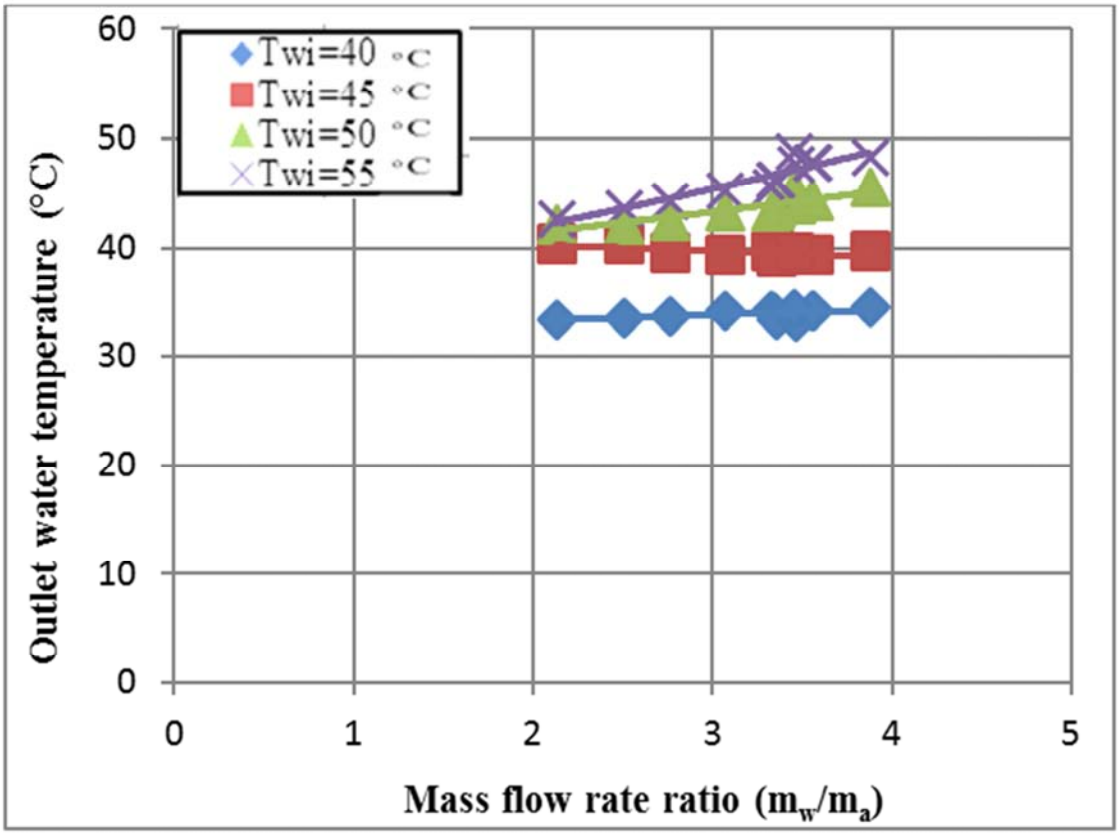

Figure 26. Variation curve of outlet water temperature with mass flow rate ratio for different water temperature for splash fill at space (30 mm).

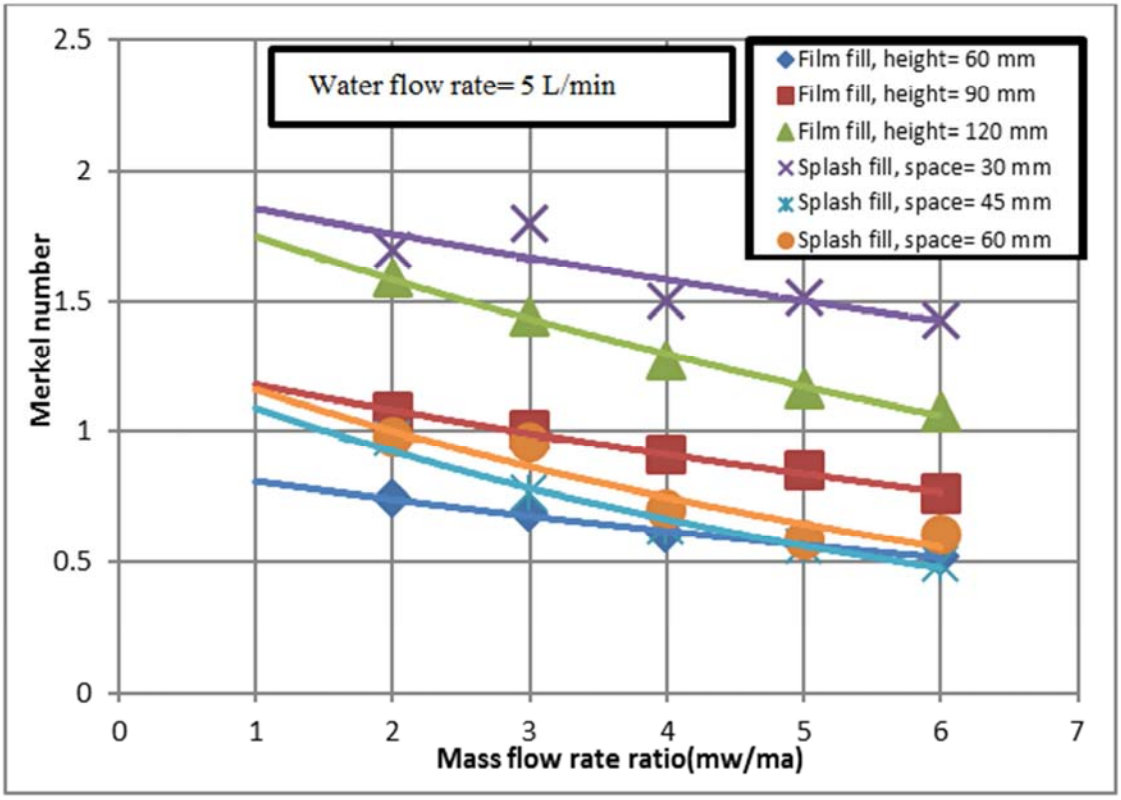

Figure 27. Variation curve of Merkel number with mass flow rate ratio for different fill type.

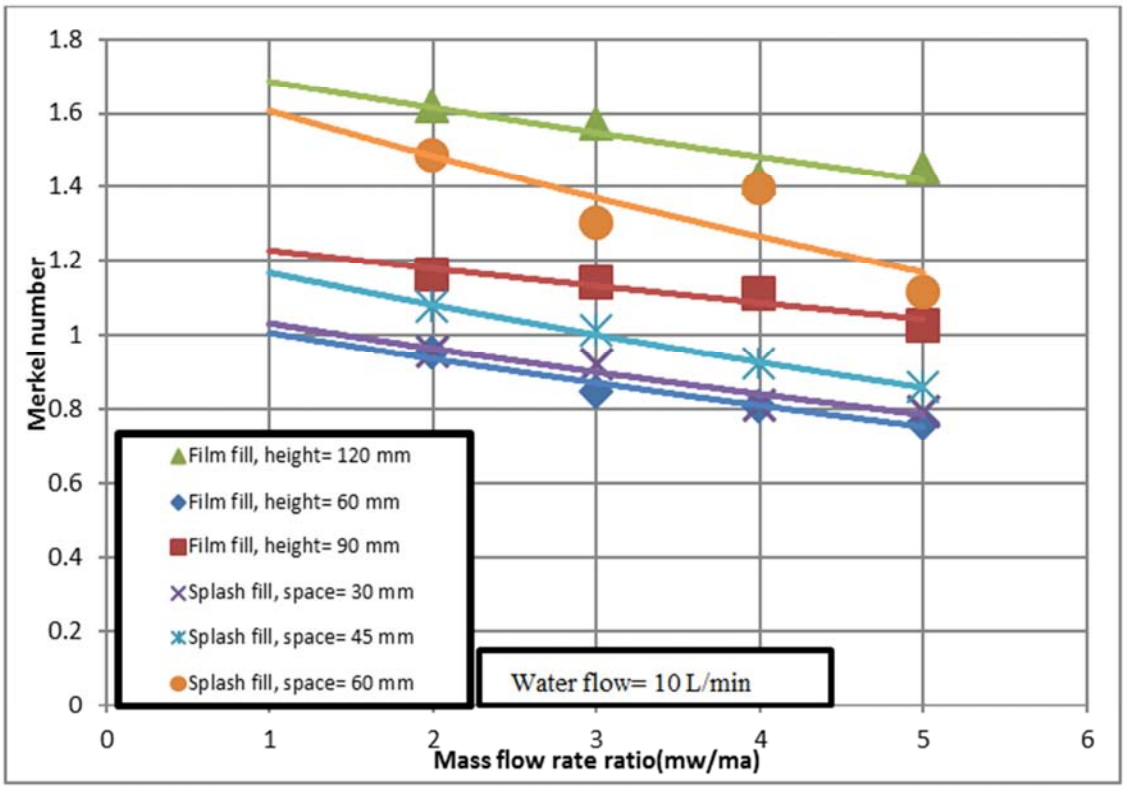

Figure 28. Variation curve of Merkel number with mass flow rate ratio for different fill type.

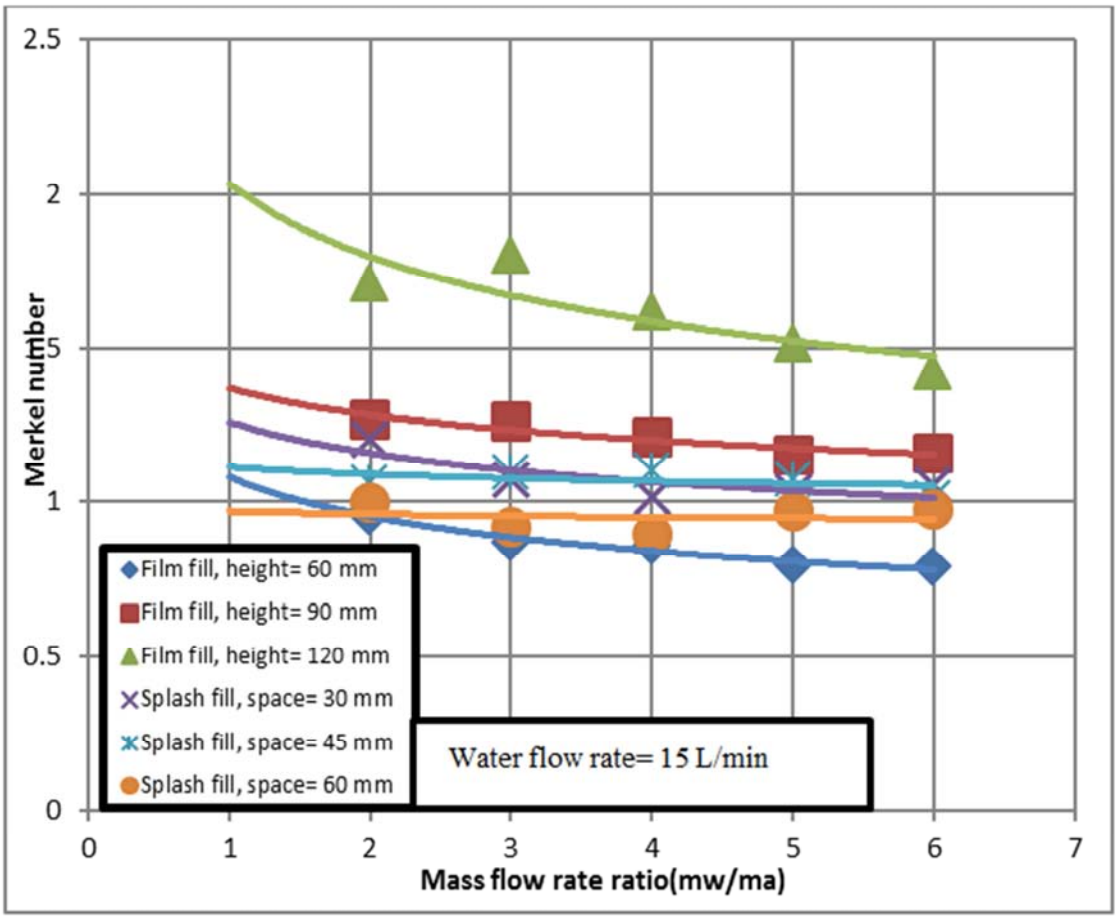

Figure 29. Variation curve of Merkel number with mass flow rate ratio for different fill type.

6. Conclusions

The conclusions drawn from the experimental and theoretical analysis are given as follows:

1. Laboratory experiments show that (Me) is decreased with the increment of $(\dot{m}_w / \dot{m}_a)$ value under different packing heights. The empirical relations between (Me) and $(\dot{m}_w / \dot{m}_a)$ for different fill type as shown in table (1).
2. The tower characteristic is improved when the cooling range is decreased and the tower approach is increased at constant tower volume.
3. Increasing the air mass flow rate ($\dot{m}_a$) causes decrease in the temperature of the outlet water, while increasing the water mass flow rate ($\dot{m}_w$) causes increase in the temperature of the outlet water.
4. Increasing the air mass flow rate ($\dot{m}_a$) causes decrease in the wet bulb temperature of the outlet air, while increasing the water mass flow rate ($\dot{m}_w$) causes increase in the wet bulb temperature of the outlet air.

Table 1. Empirical relation for the transfer characteristic of fills.

Fill type	Empirical relations	Correlation R^2
Film, height=60mm	$Me = 0.9455 (\dot{m}_w / \dot{m}_a)^{-0.323}$	0.968
Film, height=90mm	$Me = 1.3618 (\dot{m}_w / \dot{m}_a)^{-0.305}$	0.9485
Film, height=120mm	$Me = 2.0941 (\dot{m}_w / \dot{m}_a)^{-0.365}$	0.9867
Splash, space= 30mm	$Me = 2.0229 (\dot{m}_w / \dot{m}_a)^{-0.186}$	0.6953
Splash space= 45mm	$Me = 1.4811 (\dot{m}_w / \dot{m}_a)^{-0.61}$	0.9998
Splash, space= 60mm	$Me = 1.5058 (\dot{m}_w / \dot{m}_a)^{-0.533}$	0.8614
Film, height=60mm	$Me = 1.12 (\dot{m}_w / \dot{m}_a)^{-0.241}$	0.9861
Film, height=90mm	$Me = 1.2894 (\dot{m}_w / \dot{m}_a)^{-0.126}$	0.7942
Film, height=120mm	$Me = 1.796((\dot{m}_w / \dot{m}_a)^{-0.143}$	0.8158
Splash, space= 30mm	$Me = 1.1333 (\dot{m}_w / \dot{m}_a)^{-0.221}$	0.9073
Splash, space= 45mm	$Me = 1.2946 (\dot{m}_w / \dot{m}_a)^{-0.247}$	0.9647
Splash, space= 60mm	$Me = 1.7786 (\dot{m}_w / \dot{m}_a)^{-0.251}$	0.6439

5. The maximum rate of mass and heat transfer occurs at the top stage of the tower. The rate of mass and heat transfer between the water and the bulk air is increased when the inlet water temperature is increased, while the rate is decreased when the inlet air wet bulb temperature is increased. The same conclusion is drawn from the relation between the rate of mass and heat transfer.

References

[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE System and Equipment Handbook (SI), Ch.36, 2000.

[2] Australian Institute of Air Conditioning Refrigeration and Heating (AIRAH), "Types of Cooling Towers. I: Selecting a Cooling Tower Level 1 – Participant Guide", Version 1.0,2000.

[3] Bureau of Energy Efficiency, Ministry of Power, India. Cooling Towers. In: Energy Efficiency in Electrical Utilities. Chapter 7, pp. 135-151, 2004.

[4] Hooman K., School of Mechanical and Mining Engineering, The University of Queensland, Qld4072, Australia 2010.

[5] Perry. Perry's Chemical Engineers Handbook. pp. 12-17, 2000.

[6] United Nations Environment Programme (UNEP), 2006.

[7] El-Wakil M. M., "Power Plant Technology", McGraw-Hill Book Company, 1988.

[8] Ding E., "Air Cooling Techniques in Power Plants, Water and Electric Power Press, Beijing, 1992.

[9] Kloppers J. C., and Kroger D. G., "The Lewis Factor and Its Influence on the Performance Prediction of Wet-Cooling Towers", International Journal of Thermal Sciences, vol.44, pp.879–884, 2005.

[10] Fisenko S. P., Petruchik A. I. and Solodukhin A. D., "Evaporative Cooling of Water in a Natural Draft Cooling Tower", International Journal of Heat and Mass Transfer, vol. 45, pp. 4683–4694, 2002.

[11] Fisenko S. P., Brin A. A. and Petruchik A. I., "Evaporative Cooling of Water in a mechanical Draft Cooling Tower", International Journal of Heat and Mass Transfer, vol. 47, pp. 165–177, 2004.