Experimental Study of Air Evaporative Cooling with a Downward Water Spray

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ملخص

عملية تبادل الفعل بين الهواء والماء تُرى في العديد من التطبيقات الهندسية .ففي المناخ الساخن الجاف، يتم تذرية الماء خلال الهواء لتبريد الهواء وذلك بتحويل جزء من الحمل المحسوس به إلى حمل كامن .التغير في درجة حرارة الهواء نتيجة تداخل رذاذ ماء منحدر لأسفل معه تم بحثه تجريبيا داخل محوي رأسي .في هذا البحث، تم الأخذ في الاعتبار تأثير عوامل تشغيل مختلفة مثل درجة حرارة الهواء الداخل، درجة حرارة الماء المُذرَّي، نسبة كتلة الماء إلى الهواء، سرعة دخول الهواء، وطريقة دخول الهواء إلى الوسط ذو الأهمية .

لقد أظهرت النتائج فرقا واضحا عندما تم تذرية الماء فوق سطح به مادة حشو يمر من خلالها الهواء عما لو تم تذرية الماء في الهواء مباشرة .هذا الوسط المسامي المبتل يؤدى إلى زيادة مساحة السطح ويؤخر سريان الهواء مما يسمح بوقت كاف لتلاحم الهواء مع قطرات الماء .فعند استخدام حشو ذو تخانة 100 مم أدى ذلك إلى زيادة محتوى الرطوبة في الهواء بنسبة 30% مقارنة بعدم وجود الحشو .فضلا عن ذلك، لوحظ تناقص ذو دلالة في درجة حرارة الهواء فى النصف السفلي من المحوي، حيث دخول الهواء، مقارنة بالنصف العلوي .هذا التناقص يصبح مماسا في النصف العلوي .هذا بالتالي ممكن أن يساعد في الوصول للارتفاع الأمثل للمحوي.

Abstract

The process of air-water interaction is seen in many engineering applications. In hot dry climates, water is sprayed through air to cool the air down by replacing part of its sensible load by a latent load. The air temperature variation inside a vertical enclosure as a result of an interaction with downward water spray was experimentally investigated. In this investigation, different operating conditions such as air inlet temperature, water spray temperature, air-water mass ratio, air inlet velocity, and the way air is introduced to the interested domain were considered.

The results showed a distinct difference when water droplets are sprayed over a porous medium (pad), through which air passes, from being directly sprayed into the upward flow of air. This wet porous medium increases the surface area and retards the air flow allowing an enough time of contact with the water droplets. When using a 100 mm pad, a 30% increase in the air moisture content was noticed rather than the no-pad case. Further, a significant decrease in the air axial temperature was noticed in the lower half of the tower, where air enters, compared to the upper half. This decay would become almost asymptotic in the upper half. Accordingly, this might help optimizing the tower height.

Keywords: Evaporative cooling, humidifiers, spray nozzle, pad material

Nomenclature

H	enclosure interested height, mm
mr	water-air mass flow rate ratio (m_w/m_a)
P	pressure, kPa.
T	temperature, ^oC
z	elevation, m
NZ	number of spray nozzles

Subscripts

a	air
dis	discharge
in	inlet
ex	exit
w	water

Greek Letters

θ	Air dimensionless temperature ratio $(T_{in} - T(z))/(T_{in} - T_{ex})$

Introduction

The process of water –air interaction arises in many engineering applications. Cooling towers, evaporative humidifiers, air washers, and evaporation coolers are some examples. The driving force during the interaction is the temperature and density difference between both streams. Macroscopically, air cooling process takes place on the expense of water droplets vaporization. Therefore, the process involves both heat and mass transfer. The main feature of this process is to substitute the air high sensible load by a latent load. In an adiabatic process, the total energy of air before and after moisture addition to air remains constant. Therefore, the wet-bulb temperature also remains constant [1]. The water to air mass flow rate ratio is a crucial parameter that controls the process of heat and mass transfer. Under a steady state condition, the amount of vapor leaving the water by evaporation equals the gained humidity by air [2]. This agrees with the assumption of unity Lewis number.

Packing material is used as an intermediate porous media splashes the falling water spray into droplets forming a wet film region on the surface facing the falling water and a rainy downward flow region against the upward air flow. The existence of this porous material would enhance the heat and mass transfer. The enhancement is due to increasing the contact surface area and retarding the flow. The packing material breaks up the falling drops, thereby reducing the average water velocity and drop diameter. In [3] a comparative study between spray and pad types humidifiers showed that the evaporation rate was almost similar for 100 mm pad thickness and mass ratio ranges from 0.8 to 5.6. However, in the same study, the authors reported that the pad type gave substantially higher evaporation rates than the spray type for a 300 mm pad and higher mass ratios.

The spray nozzles diameter and arrangement have a direct effect on the evaporative cooling process. Hence, care is required in determining the layout of the nozzles to insure as little as possible of the water spray migration to the wall allowing almost one percent of the total water flow to be carried up to the eliminator [4]. The air dry-bulb temperature change (ΔT_{db}) decreased with increasing the spray nozzle(s) diameter. The pump discharge pressure had a strong effect on spray water flow rate change for a 4.8 mm nozzle diameter than for a 3.2 mm nozzle diameter. Therefore, the water to air mass flow rate ratio, at a given water discharge pressure, increased with increasing the nozzle diameter [5]. Dreyer and Ernes [6] mentioned that reducing the water droplet diameter and velocity increases the interface area and the residence time. They also added that any reduction in the surface tension of the circulating water results in increasing the cooling capacity and pressure drop across the packing material due to reducing the drop sizes.

The available previous literatures are concerning with the effect of packing material and water spray characteristics on the evaporation process. The temperature distribution due to heat and mass transfer during the interaction was briefly handled. There is a belief that the enclosure height, in which air and water-spray interact, would play an important role in the air axial temperature variation. Therefore, the present study focuses on studying the effect of air inlet temperature, pad thickness, spray water temperature, and number of spray nozzles on air axial temperature variation and accordingly its moisture content change.

Experimental Set-up

The experimental setup focusing on the interested domain is shown in Figure (1). As shown in the figure, there is a pump 0.55 kW (0.75 hp) circulates the water from a tank, made of a galvanized sheet painted with anti-rust material, to the spray nozzle(s) near the top of the tower. A thermostatic electrical heater, to control the water temperature, is mounted inside the tank. The air enters the tower from two symmetric side inlets. The section where measurements take place is transparent. Two valves are mounted in the pump discharge pipe to control the water flow-rate to the spray nozzle(s). A pressure gauge indicator (up to 5 bar) is connected to the pump discharge pipe. An eliminator made of corrugated plates is fixed near the tower exit to prevent water droplets from escaping with the exit air.

The used spray nozzle geometry is shown in Figure (2). The shown internal tangential passage increases the swirl action of water and consequently, increases the spray cone angle enhancing the spray atomization. Fine droplets and larger cone angles provide larger surface area of contact leading to effective heat and mass transfer process. The water spray constitutes a conical shape that would cover the upper tray area. The cone angle depends upon the pump discharge pressure, nozzle diameter, water flow rate, and water passage shape inside the spray nozzle. A certain pipe arrangement was designed to allow using more than one nozzle. In case of having a bank of nozzles, an overlap would occur among water spray cones. Corrugated plastic sheets, formed in a certain deck, with 50 mm or 100 mm thickness are used as packing material.

The air dry-bulb temperature measurements inside the spray humidifier required a particular arrangement and precaution to isolate the thermocouple junctions from being exposed to the falling water droplets. The isolation is achieved by using a shield around the thermocouple junction. The shield was made of small plastic tubes (10 mm diameter and 70 mm length). The thermocouple junction was fixed at the center of the tube. Internal baffles were properly placed to prevent water droplets from reaching the thermocouple junction. Figure (3) illustrates the thermocouple distributions and an enlarged view of the used shield. Upward air and downward water flow across these shields. While air is moving up, it enters the small cavity, formed by the plastic tube, through its both open ends, reaching the thermocouple junction.

Results and discussion

The temperature measurements inside the domain of interest were taken at two planes. Nine points were measured at each plane, then the average axial temperature was calculated. In addition, the air inlet and exit dry and wet bulb temperatures were also measured. The domain height, H, was considered as shown in Figure (1), and an assumption was made that the air temperature right at the spray nozzle axis equals that at the exit plane neglecting any losses in section above the nozzles.

Figure (4) shows the variation of the dimensionless air temperature, $\theta(z)$, at different air inlet dry-bulb temperatures. The figure illustrates that the dimensionless temperature ratio increases as air moves upward, meaning that the air average temperature decreases or the air gets cooler. The heat of evaporation of water spray would offset the air sensible heat causing the air dry-bulb temperature to decrease. It is observed from the overall trend that the dimensionless temperature profiles are nearly steeper at the lower half of the test section than at the upper half where the profile approaches asymptotic trend. This observation is similar to that mentioned and presented by Kachhwaha, S. S. et al. [5]. The figure illustrates further that if air receives some heat before entering the spray chamber and interacting with the water spray, the local axial air temperature would be quantitatively higher, keeping the spray water temperature constant. Heating the air leads to increasing its enthalpy potential.

To study the effect of placing pad material inside the spray chamber on the air axial temperature variation, a comparison was held and presented with the no-pad case, Figure (5). The figure illustrates that using a pad of 100-mm thickness, located at almost z/H = 0.5, lead to a reduction in the air temperature by almost 40%, while this percentage was nearly, 15% for the case of using a 50 mm-pad, compared with the no-pad case. This means that the axial air temperature decreases as the pad thickness increases, noticing that increasing the pad thickness would add more flow resistance on the air-handling unit. The thicker the pad, the more flow-retardation and longer contact time between upward air and water spray. Definitely, there should be an optimization for the pad thickness and shape.

In order to study the effect of varying the number of spray nozzles, with a certain arrangement, on the axial air dry-bulb temperature inside the chamber, one, two, and four nozzles were tested at the same pump discharge pressure. As shown in Figure (6), the trends are similar and the differences are close. The figure shows that the one nozzle case yielded a lower axial temperature compared to the four nozzles, which seems illogic. This behavior might be explained as; for the same discharge pressure, the flow rate passing through one nozzle is higher than that through two and four nozzles. This would create a larger cone angle and accordingly a larger contact area.

The water inlet temperature is an important parameter that would affect the heat and mass transfer process between the air and water spray. Three different water temperatures were considered. General speaking, changing the water phase from liquid droplets to vapor would enhance the mass transfer to the air, leading to an increase in the air moisture content. When water receives some heat before spraying into the air, this results in heating the air. Figure (7) indicates that increasing the water temperature resulted in increasing the air local temperature, as the shown dimensionless temperature ration decreases. Increasing the water temperature closer to or slightly higher than the air temperature would decrease the availability for heat transfer due to decreasing the temperature difference. The figure indicates that increasing the water temperature to 45^{o}C decreases the overall temperature by almost 15% while further heating of water (65^{o}C) decreased the overall temperature difference by nearly 37%.

In this study, air was supplied to the test section through either a single or dual duct. The objective was to investigate the effect of inlet flow pattern on the evaporative cooling process. Therefore, the inlet air direction effect on moisture content change is shown in Figures (8). The experimental results showed that supplying the air from two symmetric side ports enhances the mixing process compared to the one side port. The two side ports resulted in improving the mass transfer of vapor to the air, increasing its moisture content by nearly 10% compared to the one side port for a water-air mass flow rate ratio of 0.93. This percentage decreased by increasing the water-air mass ratio. Air supply from the two side ports resulted in more homogenous flow pattern and less-fluctuating flow structure. Ramadan [7] mentioned that a symmetrical flow pattern with small regions of secondary losses would be existed for flow from dual inlets to a non-circular vertical enclosure. He reported that a high rate of turbulence production and accordingly dissipation was reported in case of the one port inlet compared to the dual symmetric inlets.

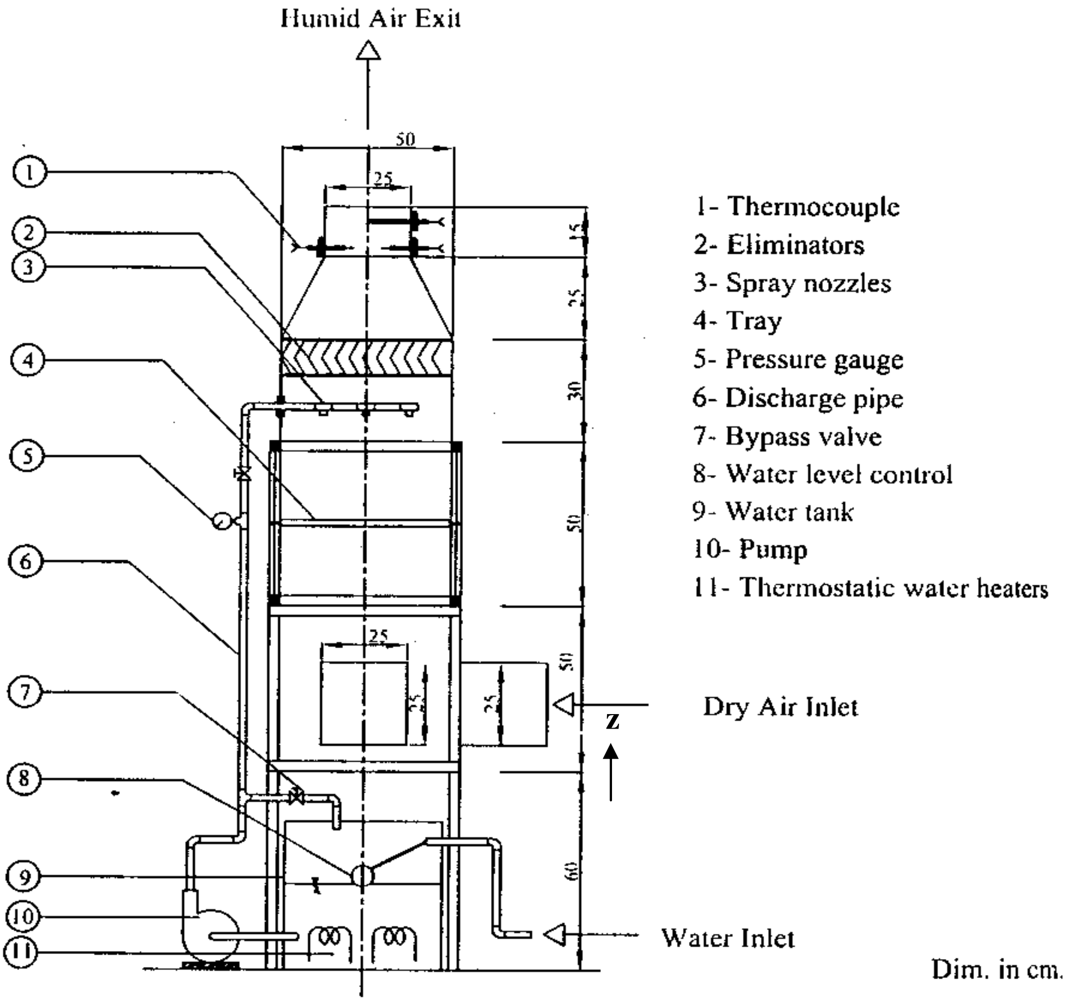
Increasing the air inlet velocity greatly affects the air-water spray interaction process. The effect of air inlet velocity on its moisture content change is presented in Figures (9). Air inlet velocity varied for constant airflow rate by changing the hydraulic diameter. Increasing the air inlet velocity would lead to speeding up the air flow inside the space allowing inadequate time of contact with water spray droplets for the no-pad case. This agreed well with the results presented by Kachhwaha, S. S. et al. [4].

Conclusions

The present study has focused on investigating some of the parameters that are expected to affect the air–spray water interaction in an air evaporative cooling process. The study showed that the major part of air evaporative cooling rate, and accordingly heat and mass transfer processes occurred in the lower half of the enclosure, where air enters, compared to the upper half, near the spray nozzle (or nozzles). This, as a result, would help optimizing the enclosure height, as in the case of cooling towers and spray humidifiers. In addition, inlet airflow direction has a noticeable effect on the evaporative cooling process. The experimental results showed that supplying air from two symmetric side ports enhances the evaporative process compared to the one side port. This is attributed to the more homogenous structure of air pattern with small regions of secondary losses in case of the dual inlets. Under constant airflow rate, decreasing the air inlet velocity resulted in improving the mixing process between water spray and air, and hence the evaporative cooling improves. This, accordingly, allows a more air residence time to effectively transfer its load to the spray water.

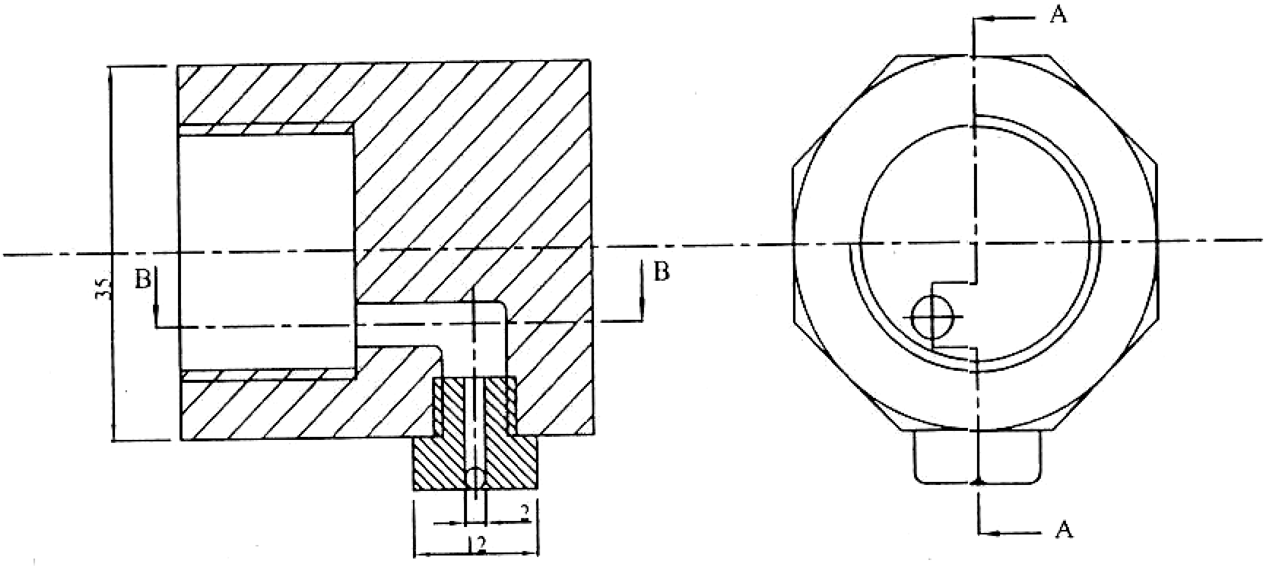
References

1. Arora, S. C., and Domkundwar. S. " Refrigeration and Air Conditioning" 1992, 3 rd edition, Chapter 24 pp.24.17-24.30
2. Baker, D. R. and Shryock, H. A., "A Comprehensive Approach to the Analysis of Cooling Tower Performance," Journal of Heat Transfer, Trans. ASME, 1961, pp. 339-350.
3. Yanniotis, S., and Xerodemas, K.," Air Humidification for Seawater Desalination", Desalination Journal, Vol. 158, 2003, pp. 313-319.
4. Hollands, K. G.T.," An Analysis of Counter Flow Spray Cooling Towers", Intl J Heat Mass Transfer, Vol. 17, 1974, pp. 1227-1239.
5. Kachhwaha, S. S., Dher, P. l., and Kale, S. R., "Experimental Studies and Numerical Simulation of Evaporative Cooling of Air With a Water Spray (Horizontal Parallel Flow)," International. Journal. of Heat Mass Transfer, Vol. 41, No. 2, .1998, pp. 447 - 464.
6. Dreyer, A. A., and Ernes, P. J., "Modeling of Cooling Tower Splash Pack," International. Journal of. Heat Mass Transfer, Vol. 39, 1996, pp. 109-123.
7. Ramadan Bassiouny," A Numerical Prediction of 3D Air Turbulent Flow through a Non-Circular, Variable Cross-Section, Vertical Enclosure", International Mechanical Engineering Conference and Expo, December 5-8, 2004 Kuwait.

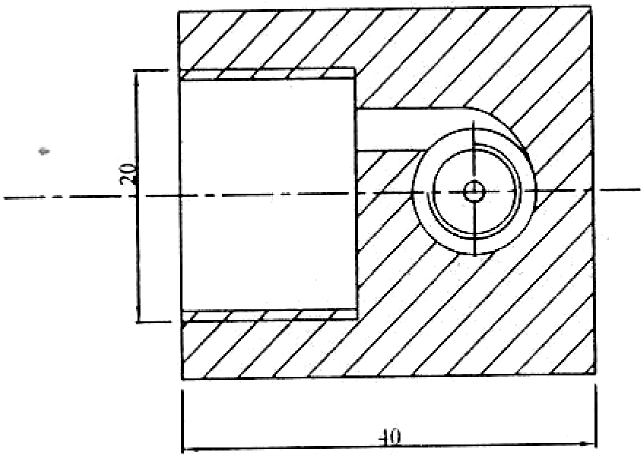


H = 90 Cm measured from the centerline of the air inlet duct to the centerline of the spray nozzles pipe.

Figure 1: Spray Chamber and Test Set-Up Arrangement



SEC. A-A



SEC. B-B

Dim. in mm.

Figure 2: Swirl Spray Nozzle

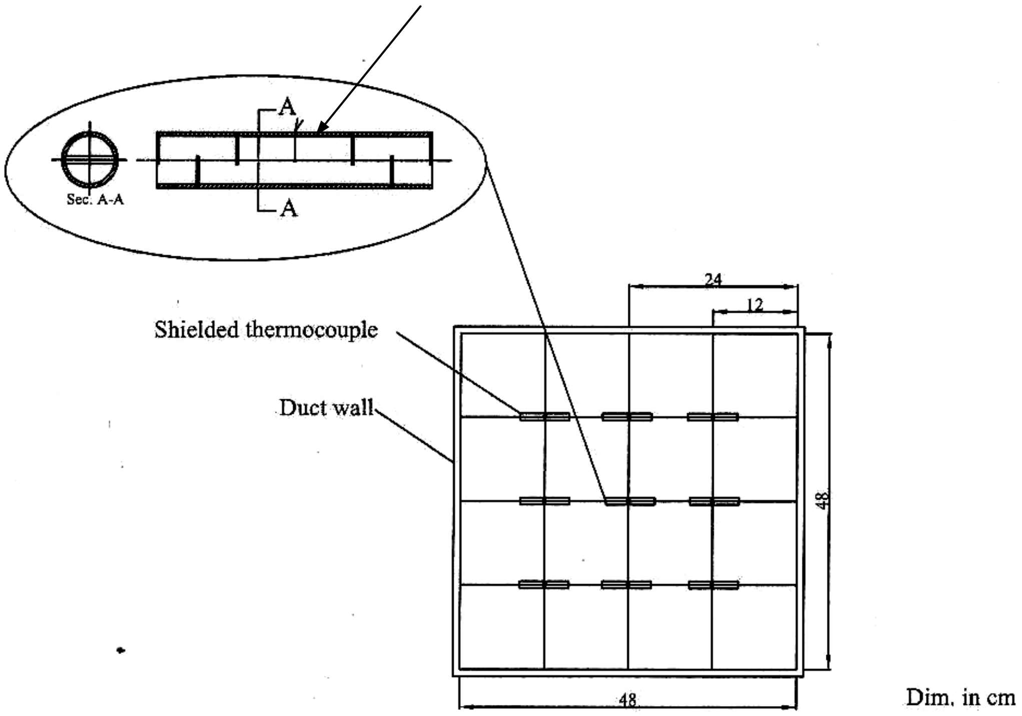

Plastic Tube D = 10 mm, L = 70 mm

Figure 3: Thermocouples Arrangement

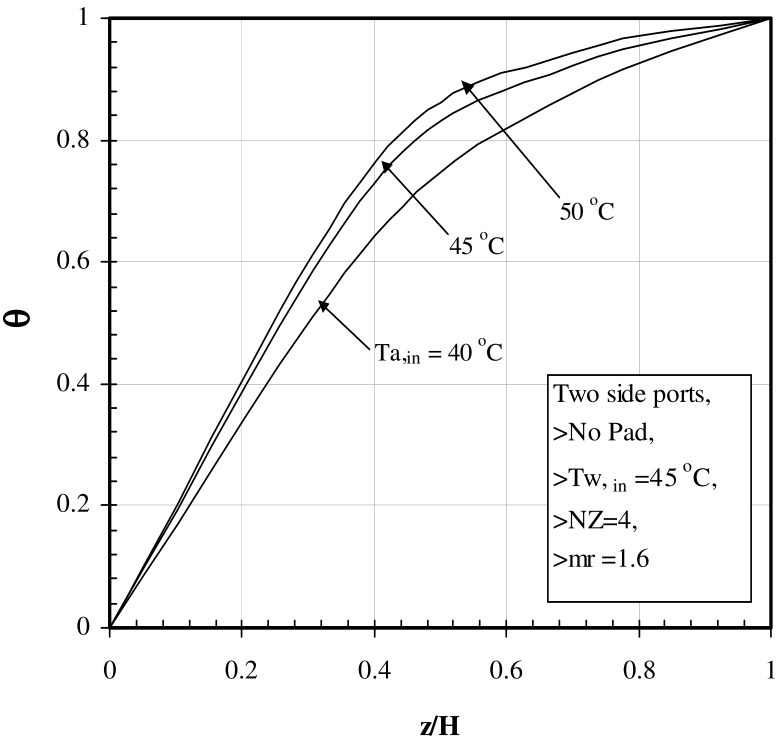


Figure 4: Axial Temperature Variation Inside the Enclosure for Different Air Inlet Dry-bulb Temperatures.

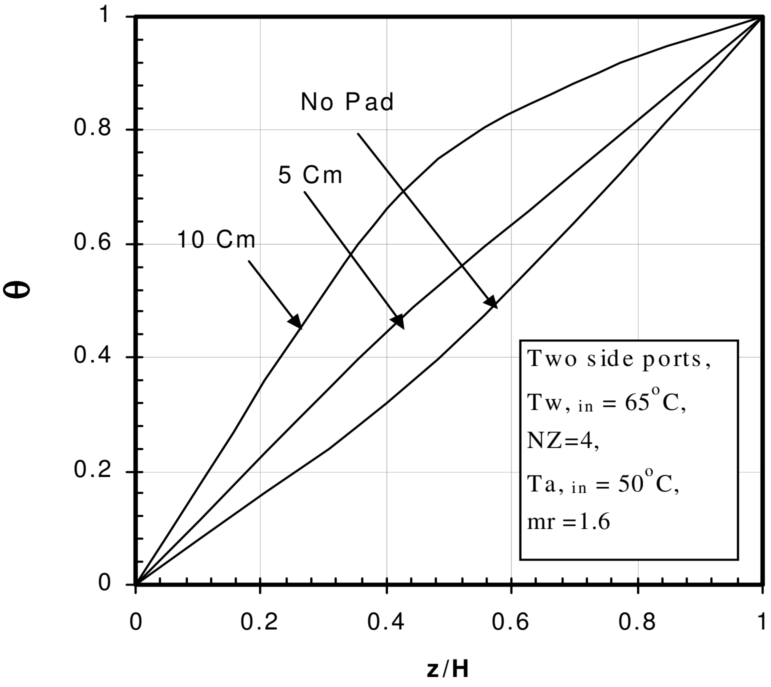


Figure 5: Effect of Packing Material on Axial Temperature Variation Inside the Enclosure.

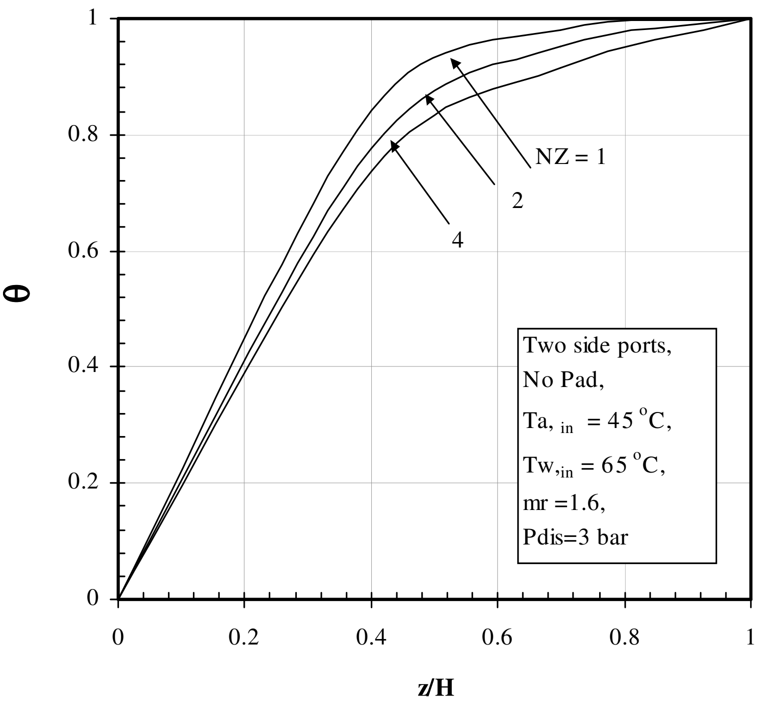


Figure 6: Air Axial Temperature Variation as a Result of Varying the Number of Spray Nozzles.

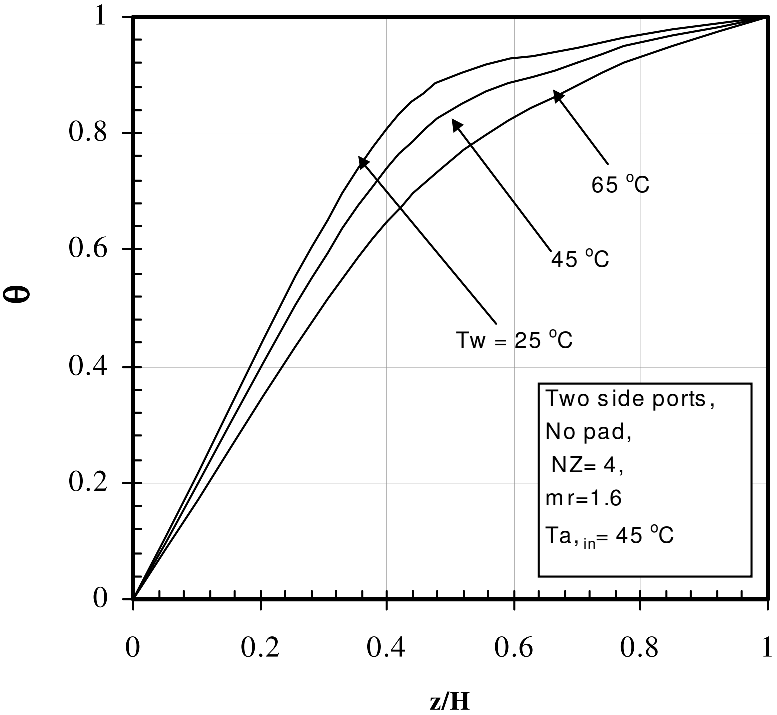


Figure 7: Effect of Water Inlet Temperature Variation on the Air Temperature Inside the Enclosure.

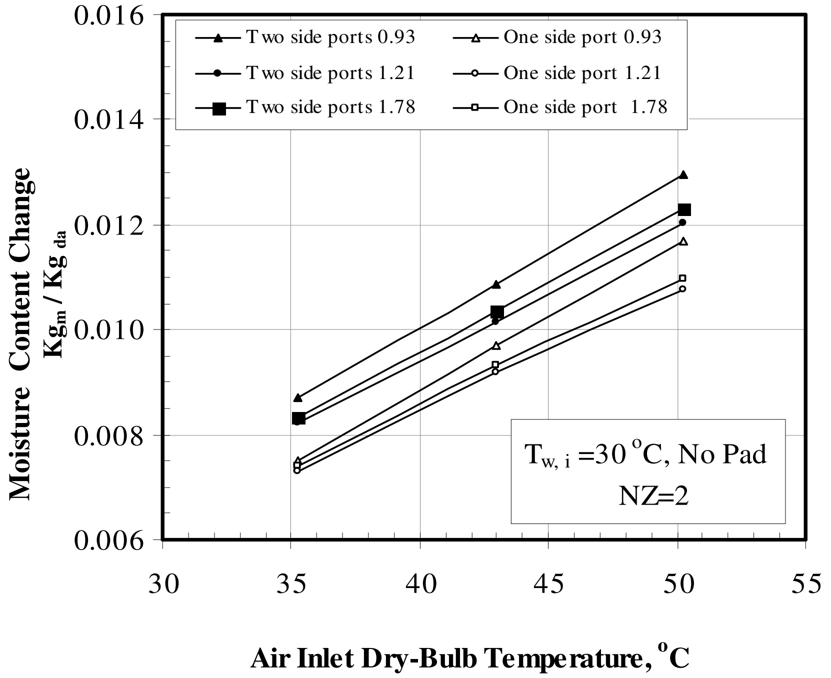


Figure 8: Effect of Varying the Way Air is Supplied to the enclosure on Air Moisture Content Change.

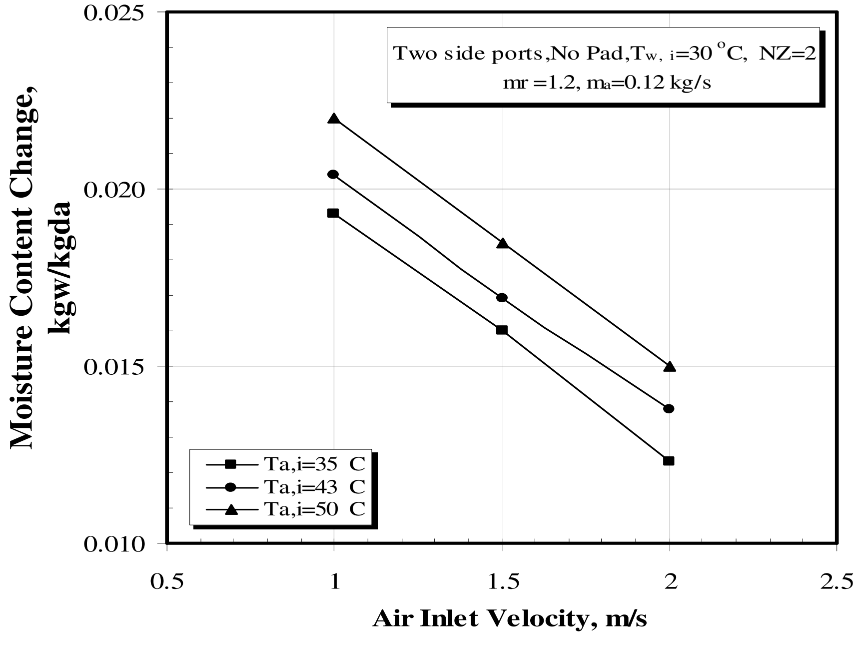


Figure 9: Moisture Content Change as a Result of Varying the Air Inlet Velocity for Different Air Inlet Dry-bulb Temperatures.