The Effect of Turbulences Flow on a Gas-Liquid Mixing Process Downstream of a Curved Duct

Abdul Satar Jawad Mohammed
Mechanical Engineering Department, University of Technology,Baghdad
asj_2006saraf@yahoo.com

Huda Ali Nasser-allah
Mechanical Engineering Department, University of Technology,Baghdad
huda.ali763@yahoo.com

Abstract

An experimental investigation is carried out on the use of water injection on the humidification process of air with a steady flow that travels during the curved part of a duct with a constant cross section. The naturally generated turbulences will surely aid the mixing process between the injected water droplets and the air to enhance both the mass and heat transfer. The current investigation is regarded as a simulation of the inlet air cooling of the gas turbine which aims to specify the optimum atomizer position on the air cooling by the fogging technique. The experiments were carried out on a (50×50 cm) wind tunnel with an average air velocity of (10 m/s). Experiments were conducted in a range of air to water flow ratio between 1000 and 2000, and an ambient temperature in a range of 30° to 50°C. At higher ambient temperature of 45.2°C (DBT), a temperature reduction of 26% and an increase in the relative humidity ratio of 2.13 were recorded at the flow ratio of 1000. Injecting water upward through the range of angles -25° to 75° showed less sensitivity to atomizer location regardless the radial position of the atomizer. This situation is most suitable for using atomizing array across the duct. The central location with tangential spray introduces the critical position for a single-point spray. Such position is promising the optimum atomizer place specified by a radii ratio of (r/r_{in}=3) and tangential orientation to the direction of flow.

Keywords:- Curved duct ; Inlet air cooling ; Fogging system ; Humidification ; Atomizer.

الخلاصة

أجريت دراسة عملية على استخدام حقن الماء على عملية ترطيب هواء ذو جريان مستقر ينتقل خلال الجزء المنحني لمجرى ذو مقطع ثابت. إن الاضطرابات الناتجة بشكل طبيعي تساعد بالتأكيد الخلط بين الهواء وقطرات الماء المحقن وتقليل الحرارة ونقل الكتلة. تعتبر الدراسة هي محاكاة لتوربينات الغاز مدخل الهواء التبريد يهدف الى تحديد موقع المذري الامثل على تبريد الهواء بإستخدام تقنية التوليد الضبابي. اجريت التجارب على جهاز النفق الهوائي لمقطع (50×50)، حيث كانت متوسط السرعة (10 m/s) في جزء الإختبارِ الرئيسيَ وبمعدلات نسب تدفق الهواء الى الماء بين 1000 و 2000 ومعدلات درجات الحرارة المحيطة بين 30 الى 50 مْ. عند درجةِ حرارة الجو العالية 45.2 م°لبصلة جافة كانت الأنخفاض في درجةِ الحرارة بحدود 26% والزيادة في الرطوبة النسبية مقدارها 2.13 ، وذلك لنسبة التدفق الاقل 1000 عندما يكون المذري في منتصف المجرى و موجهة بالتماس مع الجريان. لوحظ عبرالنتائج ان حقن المياه التصاعدي اقل حساسية لوضع المذّري خلال مجموعة من الزوايا 25°- إلى75°-. لذلك سيكون هذا الجزء من المجرى مثالي لمنح انجاز مقبول لمنظومة التبريد. أما بخصوص موقع المركز من المجرى فانه يعرض الموضع الحرج للمذّري المناسب لموقع رش منفرد بغض النظر عن الموقع القطري للمذري. يعتبرهذا الموضع الأمثل للمذّري المحدد بنسبة أنصافِ الأقطار(r/r_{in} = 3) نسبةً للجريان المماسي.

الكلمات المفتاحية: مجرى منحني ، تبريد مدخل الهواء ، نظام التوليد الضبابي ، الترطيب ، المذري.

Latin Symbols			Creak symbols		
Symbol	**Description**	**Unit**	**Symbol**	**Description**	**Unit**
F.R	**Flow ratio**	m°_a / m°_w	Φ	**Atomizer inclination angle**	**degree**
L	**The duct width in the mean test section**	**m**	ζ	**Probe position**	$\zeta = X_n / L$

p	**Pressure**	**bar**	**Θ**	**Temperature Reduction**	**$\Theta = T_n / T_{amb}$**
r	**Radius**	**cm**	**Ψ**	**Relative humidity**	**$\Psi = RH_n / RH_{amb}$**
RH	**Relative humidity**	**%**	**Subscript**		
t	**Time**	**s**	**Symbol**	**Description**	
T	**Temperature**	**^oC**	**a**	**Air**	
u	**Velocity**	**m/s**	**amb**	**Ambient**	
V	**Volumetric flow rate**	**ml/s**	**atomizer**	**Atomization**	
X	**Transverse position**	**cm**	**ave**	**Average**	
Z	**Atomizer location**	**cm**	**I**	**At any element**	
Dimensionless parameters			**In**	**Inner**	
Symbol	**Description**	**Expression**	**n**	**At any location**	
Dn	**Dean number**	**$Dn = Re\sqrt{(L/r_{in})}$**	**w**	**Water**	
Re	**Reynolds number**	**$Re = u.\rho.L / \mu$**			

1- Introduction

Moist air humidification is normally conducted by a steam injection, evaporation from a water spray, atomizing water, a wetted medium, or submerged heating elements **(Wang and Lavan , 1999).** Atomizing is simply meant to produce a fine spray of liquid in a gaseous environment. When liquid is atomized, the smaller the diameter of the liquid droplets, the greater the interfacial area is between liquid and gas and thus the higher the rate of evaporation. When air flows through an atomized water spray, the result is an increase in the humidity ratio due to the addition of evaporated water vapor, as well as, a drop in air temperature because of the absorption of required latent heat of vaporization of the flowing air. When the air is more drier, the humidification and cooling process will be better (**Shan , 2001).** There are two main strategies for inlet air cooling by evaporative cooling systems based on the basis of the method to put air and water in contact. First; the media based evaporative cooler in which the air is forced through a wetted media (placed in the inlet duct) and second; the fogging that uses a spray system in the path of the incoming air(**Dott, 2004**). Cooling by evaporation is most influential in the drier climates with a high potential of cooling. The wetted median is considered as one of the evaporative cooling technologies, in which the wetted median is able to cool the inlet air by 85% - 95% of the difference between the ambient dry-bulb and wet-bulb temperature. Also, it is regarded one of the lowest capital and operating cost choices. The original disadvantage of wetted median is that the scope of cooling is bounded by the wet-bulb temperature and, accordingly, it is weather dependent. Additionally, it needs a suitable chemistry control of the recirculated contaminated water and a proper monitoring of the degradation. It operates most effectively in hot and dry weather, less influential in the ambient with a higher humidity and also consumes great amounts of water **(Technology over view, 2006).** Air cooling by evaporation is an influential simple procedure of cooling hot, dry air as it utilizes no refrigerant gases or mechanical compression in yielding the effect of cooling. The electrical consumption reduction and zero utilization of CFC compounds accompany the evaporative air cooling help to minimize the problems of gas emissions of greenhouse and the depletion of ozone (**Jan , 2005).** Fogging is another means of adding water to an air flowing stream by spraying too fine water droplets. The systems of fogging can be constructed to yield variable droplets sizes, based upon the demanded time of evaporation and the ambient condition. The size of water droplet is, in general, lower than 40 microns and their average size is about 20 microns. The water utilized for fogging typically needs a demineralization process. The fogging system is able to cool the inlet air within 90 to 98% of the difference between ambient dry-bulb and wet-bulb temperature and, consequently, it is somewhat more influential than the wetted median. The capital cost of a fogging system is too comparable to that for a wetted median, and the fogging system has a similar limitation and disadvantages. Both, nozzle performance and location are critical to the proper operation of the fogging system **(Technology over view, 2006**). The main advantage of spraying the fog droplets in the gas turbine inlet airflow is to raise the density of the air that enters the turbine using the evaporative cooling in the stream of the inlet air. Owing to the small size of droplets employed in this application, the droplet temperature converges promptly to the wet bulb temperature, without taking into account the initial temperature of water. The speed at which this convergence takes place relies upon the initial size of droplet, temperature of water, ratio of the air mass flow to the injected water mass, and the ambient psychometric circumstances of the surrounding air (**Mustapha and Cyrus, 2013**). The inlet air duct of a gas turbine is usually has a varying cross section that containing many curved parts in it. The curved duct shape will affect significantly the humidity addition to the air stream that aims to boost the output power. The flow pattern around these curves is certainly will show a clear effect on the ability to absorb humidity within the flowing air. One of very important features of the flows in a curved channel is the introduction of a secondary flow pattern in the duct cross section arising from the imbalance induced between the centrifugal force and the radial pressure fields. **(Gyvesa *et.al.*, 1999;AL-Salman *et.al.*, 2007)** applied a fogging system in the compressor front in an open cycle gas turbine. The influences of relative humidity, ambient temperature, firing temperature, and pressure ratio on the performance of this turbine were investigated. The range of relative humidity was (10% - 90%), the range of ambient temperature was (10 - 60°C), the firing temperatures were 1100 K, 1200 K, 1400 K and 1600 K, and the range of pressure ratio was (3 - 23). The outputs of this investigation manifested that the resulted power and efficiency rise continuously with the rising of the firing temperature, and decrease with the rising of the ambient temperature. The efficiency first rises with the pressure ratio up to a maximum value and then starts to decrease. The increase of the relative humidity yields a reverse influence on the power and efficiency of this open cycle gas turbine. (**Mohammed, 2010)** focused experimentally on the determination of the feasible, effective position of the spray nozzle relevant to the gas turbine inlet matrix, and indicated that the effective entry length for the system used in the study was 1 m. A computational model was established to investigate the evaporation dynamics of the injected droplets into the inlet duct of the gas turbine. The model relies on the concept of discrete droplet in a separated flow based on the infinite conductivity formulation. The predicted and measured data were compared to validate the effective length obtained. The maximum deviation between them never exceeded 4.28%, for all operational ranges that studied. **(Sabah *et.al.*, 2013)** conducted an experimental study of the utilization of water atomization within a curved duct to evaluate its impact on the humidification process. At a higher than 43^{o}C ambient temperature, the rise in the relative humidity of 67.8% and the temperature decrease of 39.6% was registered at a higher rate of 24.2 ml/s of water atomizer. In general, the curved duct lower half is depicted to be less susceptible to

the position of atomizer for an inclination angles range of (10^o - 45^o) with 5 to 20 cm radial locations from the inner wall. However, the curved duct upper half introduces a critical atomizer position properly specified by a radii ratio of (r/r_{in} = 3.2) and -10^o orientation to the tangential flow. **(Mustapha *et.al.*,2013)** investigated experimentally and theoretically a detailed analysis of the water temperature influence on the overall fogging system efficiency. This investigation was conducted utilizing water temperatures between 1 °C and 60 °C. The results revealed that the temperature of water has no important influence on the size of the droplet. Nevertheless, throughout the range of droplet sizes that atomized from the nozzles, which installed in the fogging system, utilizing the cold water yields a limited advantage on the efficiency of cooling, while utilizing the hot water somewhat raises the efficiency of evaporation.
The present work focuses on the water injection at the downstream portion of square bent to obtain the most effective cooling and humidification of steadily flowing air draught and to specify precisely the optimum position of the atomizer at the downstream section.

2- The Experimental Work

The air enters the wind tunnel through a bell mouth shaped duct that gradually becomes 50 cm. The aims are to isolate any entrance effect and to produce a steadily flowing air. A digital relative humidity/temperature meter with RS232 interface was used. It has a working temperature range from 0° to 60° C and an operating relative humidity range from 0% tof 100%. An additional straight 100 cm length of the 50 cm side square duct was used in order to eliminate any turbulence in the air flow before entering the curved duct. The dimensions of the curved duct are 12.5 cm inner radius, 62.5 cm outer radius. The ratio of inner to outer radii is chosen according to the regulations of **(ASHRAE, 2000**). The main test section has a 50 cm square cross section with 200 cm length. In the first 100 cm of the duct, the atomizer was placed at the end of the curved duct, which represents the beginning of the main test section, which can be moved inside it in two directions, Figure (1). The second part of the duct was used to measure the temperature and the relative humidity of the treated air. These portions are equipped with two (50*100) cm hatches that provide access to the inside of the duct in order to adjust the positions of the atomizer and humidity/temperature meter. The temperature measurement was achieved by using a Lutron model; HT-3005HA professional humidity/temperature meter with LCD display having a working temperature range from 0° to 60° C and an operating relative humidity range from 0% to 100%. The air drawn into the duct will be driven out by the axial fan of the wind tunnel. The axial fan unit was driven by a (single Phase) AC motor. The air flow was controlled by two semi-circulars gates with **r =** 32.5 cm moved manually by linkages at the outlet side of the fan duct. The amount of air flow into the duct is reduced by reducing the gate openings using a serrated with ties lever that controls the size of the fan gate openings**.** The air mean velocity in the main test section at fully opened gates are about (10 m/s), (Re = 4.16×10^5) and (Dn = 8.32×10^5). The layout of the wind tunnel is displayed in Figure (2). Figure (3) depicts the schematic drawing of the whole wind tunnel with both air and water systems attached to it.

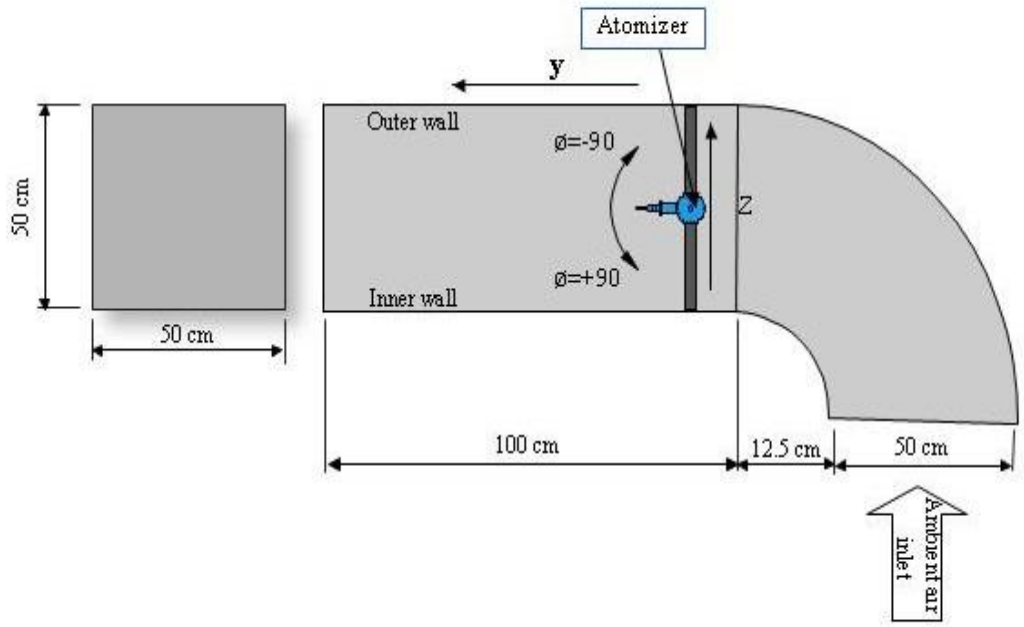


Figure (1): Details of atomizer movements in the duct

Figure (2): Outlet side of the wind tunnel

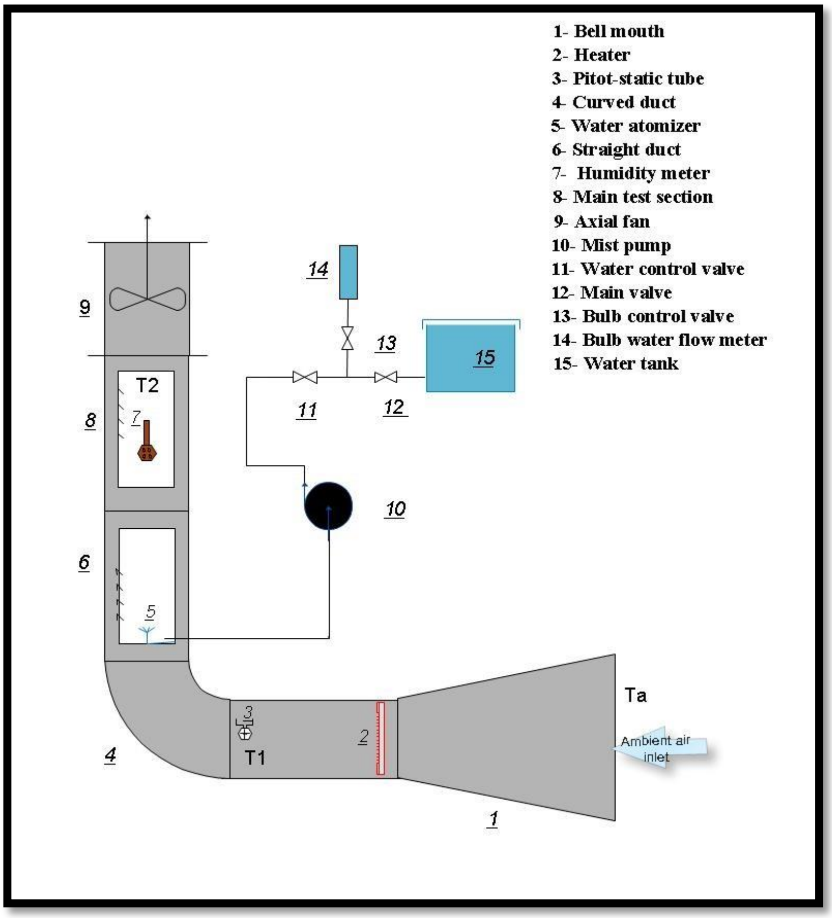


Figure (3): Top view of the Test Rig

The atomizer used in this work has a diameter of (0.1 mm). The atomizer is used to introduce water in the form of fine droplets. This atomizer has the ability to move in two-dimensions:

- The Z-axis (transverse) slides between 5 and 45 cm
- The ø-angle of the atomizer direction between 5° and 175°

To measure the dynamic pressure of the air stream in the wind tunnel, a Pitot - static tube was installed at the end of the straight duct. A standard elliptical nosed Pitot - static tube having a curved junction (N.P.L Standard) was used. After converting the manometer reading into velocity, the average air velocity of the whole section is determined by equation (1).

$$u_{ave} = \frac{\sum u_{ai} A_i}{\sum A_i} \qquad \ldots\ldots (1)$$

3- Results And Discussion

Figure (4) illustrates the effect of ambient conditions in the humidification process. If the air is too dry, the humidification and cooling will be better. The maximum reduction in temperature was 44.32% of the ambient temperature 45.2 °C. In the present work, a maximum ambient temperature of 45.2°C was selected due to more improvement that had happened in the humidification and the resultant cooling. The flow ratio represents the ratio of mass flow rate of air to mass of water, and it reflects the mass of water sprayed within the air stream. Better humidification and cooling are obtained at the minimum flow ratio of 1000. The lower flow ratio of

(1000) shown in Figure (5) gives a good reduction in the temperature of 45.6%. In the present work, a flow ratio of 1000 was selected as a compromise between the best possible humidification and the most accurate probe reading. The effect of the atomizer transverse position on the air humidification ability is shown in Figure (6) at an injection angle of +45°. The maximum humidity obtained at the position of 7 cm is of ratio 1.12 in the outer half of the duct, while the position 43 cm has the maximum humidification of ratio1.54 within the inner half. The corresponding maximum cooling for the positions of 7 and 43 cm is 12% and 17.4%, respectively. Therefore, the best position for the angle +45 ° was in the flower center where the droplets drifted with air streams giving the best spread of water through the air and thus best humidification of air. Also, the position of 25 cm achieves the better cooling with a 21% reduction in temperature at this angle, and the higher ratio of humidity increase was 2.5.

Figure (7) shows the result at an angle of -45° for different locations across the duct. The humidification was very effective in the outer half of the duct as the water droplets entrained with the faster streams of air flow, and this angle helps the droplets to spread and evaporate uniformly across the duct. The maximum humidity increases ratio at the center of 25 cm was 1.73, and the reduction in temperature was 15.3%. The maximum humidity increases ratio obtained at the position of 7 cm was 2.24, and the higher decrease in temperature was 20.5%, while an increase in humidity and a reduction in temperature at position of 43 cm were 1.48 and 12.1%, respectively. Hence, the best location at this angle is at 7 cm for the inner wall of the duct.

Figure (8) exhibits the effect of water injection in the tangential direction ø=0° with the flow at different atomizer locations. The best performance of the water injection system was realized at the central position of 25 cm where a maximum humidity increase ratio of about 2.6 was recorded. But, at positions 7 and 43 cm, the humidity increase ratios were only about 1.9 and 1.2, respectively. The corresponding maximum cooling at the central position 25 cm was 29%, while the cooling didn't exceed for the positions 7 and 43 cm 17 and 13%, respectively.

This figure also clarifies the sharp change of the humidity and temperature distributions for the central injection across the duct from the inner to the outer wall. While, this participation weakened with the two side cases of 7 and 43 cm. This is due to the better spread of the sprayed droplet and enhanced penetration into the air streams and along the duct width which improve the droplets evaporation and the air cooling process.

4- **Atomizer Optimumposition**

Investigating all the graphs that have been previously explored, showing that at any location across the duct, the best performance of the spray system was obtained when directing the spray towards the center of the flow field. This phenomenon is attributable to the better diffusion and deeper penetration of the injected droplets into the flowing air stream throughout the duct. For a clear presentation of the above discovery, the humidity and the temperature profiles of the treated air is drawn at different inclination angles with varying locations. Figure (9) shows the average values of the non-dimensional humidity and temperature that have been obtained in the range studied. When Figure (9) is examined, it indicates that directing the spray towards the outer half of the duct gives a stable performance for humidification and cooling process, as represented by the angles in the range of -25 to -75° as they show very close uniform trends throughout the entire duct.

The mean values for these angles gave an average relative humidity improvement of ratio 1.53 and the average temperature reduction rate of 7.5%. This indicates less directional sensitivity and promising steadily and efficient operation of the spray system at any location across the entire duct. Nevertheless, the injection towards the inner half of the duct shows a clear difference in the relative humidity, and the temperature distribution throughout indicates more sensitivity of the position of the spray system.

Re-examining Figure (9) reveals a distinct behaviour of the spray system at the central location with the tangential direction of water injection (Z=25 cm and ø=0°). It indicates the high sensitivity of the position and introducing a location that to be considered as the optimum for the atomizer since it gives the higher humidity and lower temperature obtainable throughout. This position utilizes the moderate air velocity crossing the injection spot to reserve enough time for droplets penetration and heat exchange with the carrying air. The maximum ratio of humidification was 1.54, while the maximum reduction in temperature of (21%) was recorded in that position.

Two important conclusions can now be realized. First: The less sensitivity of atomizer location with upward injection is considered suitable for multi-point injection by using an atomizing array in the air stream that would give a good performance at any position. Second: The superior position for atomizer installation is at the central location with tangential spray that seems suitable for single-point injection.

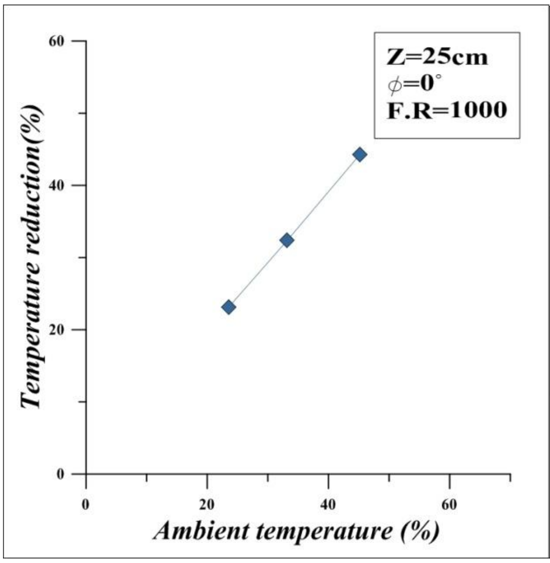


Figure (4): The effect of ambient temperature on the resultant evaporative cooling of air

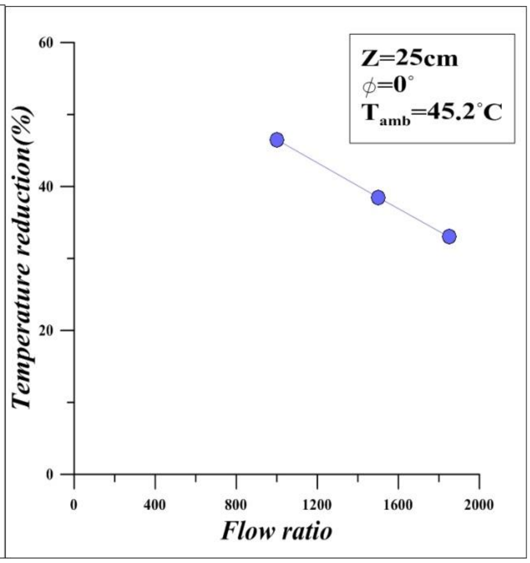
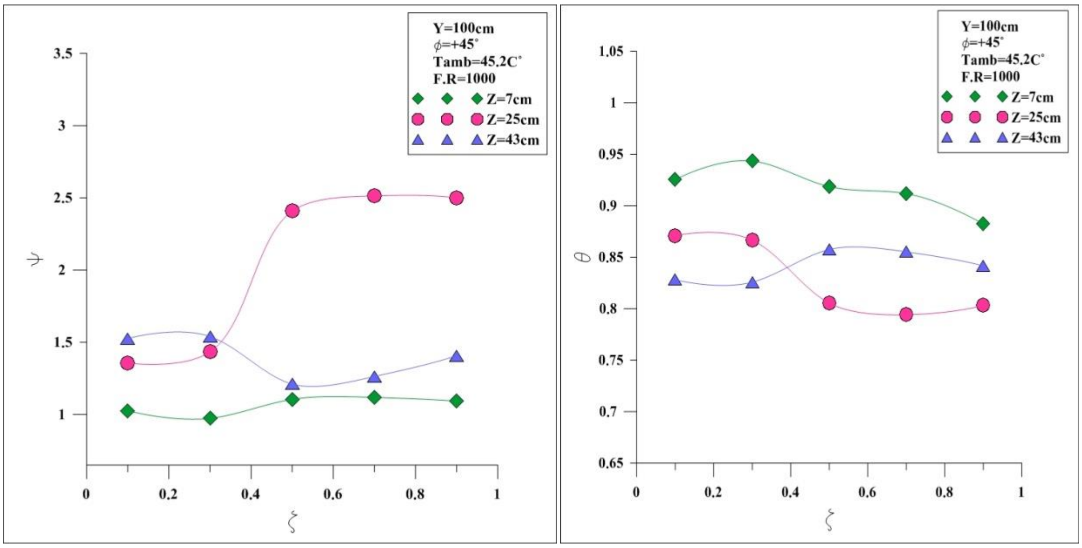
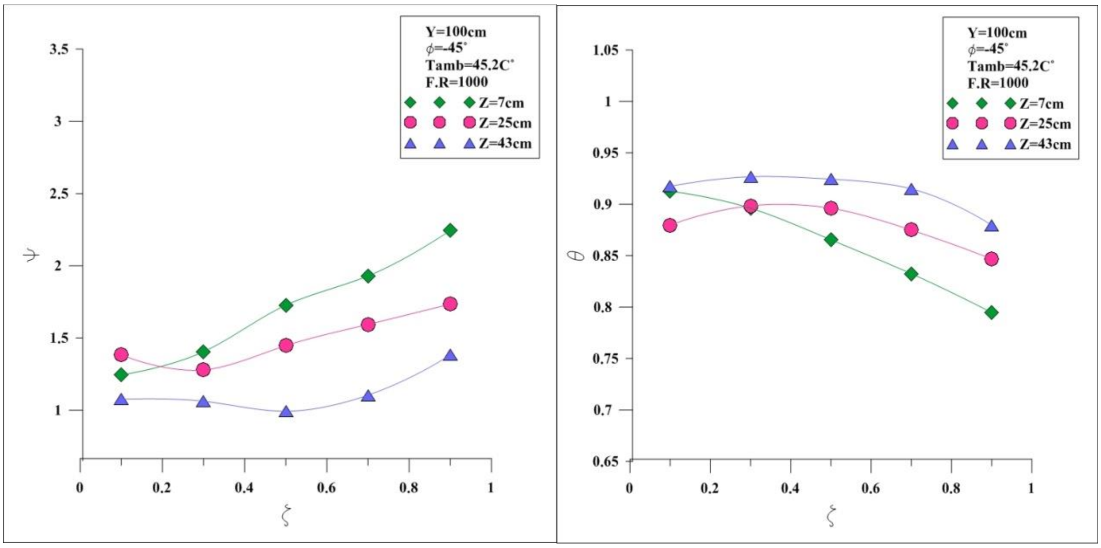


Figure (5): The effect of flow ratio on the resultant evaporative cooling of air



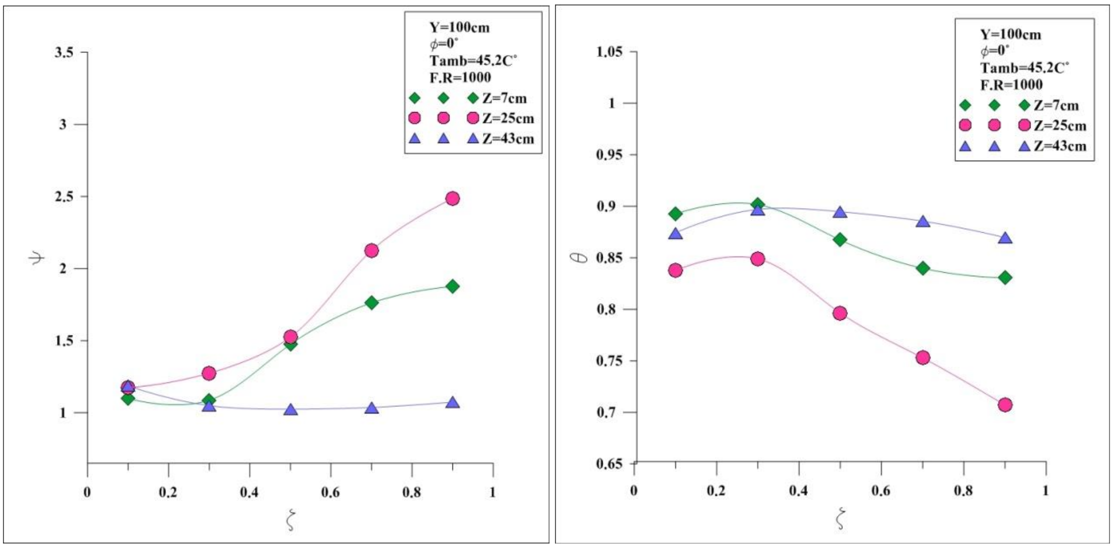
(A) **(B)**

Figure (6): The effect of atomizer location on air properties; (A) Relative humidity distribution (B) Temperature distribution; at Ø = +45^{o}



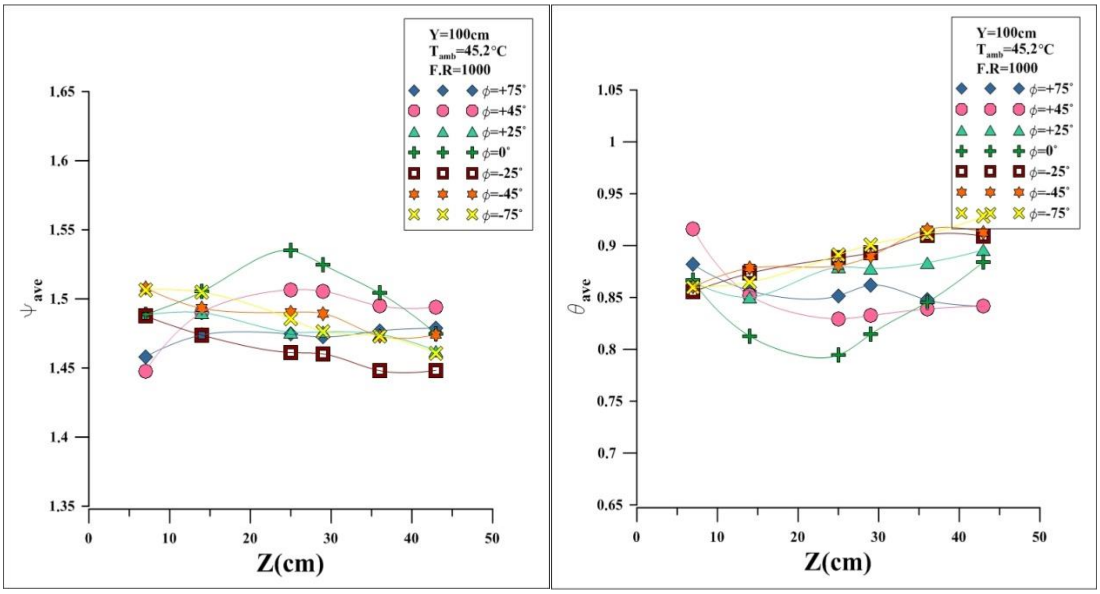
(A) **(B)**

Figure (7): The effect of atomizer location on the air properties; (A) Relative humidity distribution (B) Temperature distribution; at Ø = -45°



(A) **(B)**

Figure (8): The effect of atomizer location on air properties; (A) Relative humidity distribution (B) Temperature distribution; at Ø = 0°



(A) **(B)**

Figure (9): Variation of treated air properties with atomizer position; (A) Average relative humidity distribution (B) Average temperature distribution.

5- Conclusions

1. The drier the ambient air and higher the meter flow rate improving the humidification and cooling of air.
2. Close to the inner wall of the duct, i.e., at 7 cm, the best performance recorded was at angle -45° with the tangential flow, while close to the outer wall, i.e., at 43 cm, the best performance recorded was at an angle +45 □ to the tangential flow.
3. The best performance of the water injection system was realized at the central position of 25 cm with ø=0° where the maximum humidity increase ratio and maximum cooling were recorded.

4. Injecting water upward through the range of angles -25° to 75° showed less sensitivity to the atomizer location. This situation is most suitable for using atomizing array across the duct.
5. The central location with tangential spray introduces the critical position for single-point spray. Such position is promising the optimum atomizer position specified by a radii ratio of ($r/r_{in}=3$) and tangential orientation to the flow direction.

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