The Effect of Atomizer Position in a Curved Duct on the Humidification Process of Steadily Flowing Air

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ABSTRACT

An experimental study is conducted on the utilization of water atomization to evaluate its impact on the humidification of steadily flowing air travelling throughout a curved portion of a uniform cross sectional duct. One of the more interesting aspects of curved channel flows is the introduction of a secondary flow pattern in the duct cross-section. The naturally generated turbulences in air flow will certainly assist the mixing between the air and the injected water droplets and improve the heat and mass transfer process encountered in evaporative cooling of the incoming air drought.

The present study is considered as a simulation of the gas turbine inlet air cooling by the fogging technique. The drier the air, the better the humidification and cooling process. At higher ambient temperature of 43ºC, an increase in the relative humidity of 67.8% and a temperature reduction of 39.6% were recorded at higher water atomizer rate of 24.2ml/s. Generally, the lower half of the curved duct is shown to be less sensitive to the atomizer position for a range of inclination angles between 10º to 45º with radial locations between 5 to 20cm from the inner wall. This situation makes this region most suitable for using atomizing array across it in order to give acceptable performance for cooling system. Nevertheless, the upper half of the curved duct introduces a critical atomizer position suitable for single point spray. This position is considered as the optimum atomizer position defined by a radii ratio of (r/r_{in} = 3.2) and an orientation of -10º to the tangential flow.

Keywords: curved duct; atomizer; fogging system; inlet air cooling; humidification.

تأثير وضع المذري في مجرى منحني على عملية الترطيب لجريان هواء مستقر

الخلاصة

أجريت دراسة عملية لاستخدام تذرية الماء وتقييم أثرها على عملية ترطيب لهواء مستقر الجريان عبر مجرى منحني ذو مقطع منتظم.إحدى السماتِ الأكثرِ أهمية لجريان مائع في مجرى

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منحني هي ظهور نمط الجريانِ الثانوي في مجال الجريان. الإضطرابات الطبيعية المتولدة في مجرى الهواء تعزز عملية الخلط بينتيار الهواء وقطرات الماء المحقونة وتحسن من عمليات انتقال الحرارة والكتله المرافقة للتبريد التبخيري لتيار الهواء الداخل.
تعتبر الدراسة محاكاة لتَبريد المدخل لماكنة التوربين الغازي بإستخدام تقنية التوليد الضبابي. الهواءَ الاكثر جفافا يعطي أفضل عمليةَ تبريد و ترطيب, فعند درجةِ حرارة الجو العالية 43°C كانت الزيادة في الرطوبة النسبيةِ مقدارها 67.8% وأنخفاض درجةِ الحرارة بحدود 39.6%, وذلك لمعدل تذرية الماء الأعلى (24.2 ml/s). بشكل عام, لوحظ من خلال الدراسة ان النصف الاسفل من المجرى المنحني اقل حساسية لوضع المذّري لزوايا ميلان تتراوح بين 10° إلى 45° مَع موقع قطري يتراوح بين 5 إلى 20cm مِنْ الجدار الداخلي. لذا فإن هذا الجزء من المجرى المنحني سيكون مثالي لإستخدام صف من المذريات لإعْطاء أداء مقبول لمنظومة التبريد. أما بالنسبة للنِصْف الأعلى من المجرى المنحني فانه يُقدّمُ موضع حرج للمذّري سيكون اكثر مناسبة لموقع رش منفرد. هذا الموضع يعتبر الأمثل للمذّري كما تحدده نسبةِ أنصافِ الأقطار (r/r_i=3.2) وبالميلان (−10°) نسبةً للجريان المماسي.

NOMENCLATURE

Latin Symbols:

Symbol	Description	Unit
L	The duct width in the mean test section	M
P	Pressure	bar
Q	Water atomization rate	ml/s
R	Radius	cm
RH	Relative humidity	%
T	Temperature	°C
U	Velocity	m/s
X	Transverse position	cm
Z	Atomizer radial location	cm

Creak symbols:

Symbol	Description	Unit
Φ	Atomizer inclination angle	degree

Subscript:

Symbol	Description
A	Air
Amb	Ambient
Atom	Atomizer
Ave	Average
I	At any element
In	Inner
N	At any location
W	Water

Dimensionless parameters:

Symbol	Description	Expression
Dn	Dean number	$Dn= Re\sqrt{(L/r_{in})}$
Re	Reynold number	$Re = u.\rho.L / \mu$

ζ	Probe position	$\zeta = X_n / L$
Θ	temperature	$\Theta = T_n / T_{amb}$
Ψ	Relative humidity	$\Psi = RH_n / RH_{amb}$

INTRODUCTION

Atomizing is simply meant producing 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 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 of the air 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 from the flowing air [1].

Evaporative air cooling is an effective simple method of cooling hot, dry air as it uses no refrigerant gases or mechanical compression in producing the cooling effect. The decrease in electrical consumption and zero use of CFC compounds accompany the evaporative air cooling help to reduce greenhouse gas emissions and ozone depletion problems [2].

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: The media based evaporative cooler in which the air is forced through a wetted media (placed in the inlet duct) and the fogging that uses a spray system in the path of the incoming air [3].

Fogging system is one type of evaporative cooling in which the media has been eliminated and a mist of fine water droplets is introduced instead in the path of the incoming air. Demineralized water is injected via a series of distribution manifolds which contain multiple nozzles to distribute the water in the incoming air in small droplets. The greatest cooling benefit is realized when employed in warm, dry climate [4].

The power output and fuel consumption are highly dependent upon the mass flow, quality, and ambient temperature of the air drawn into the gas turbine unit. A land based gas turbine for power generation has the characteristics that the output falls on hot summer days when the electricity demand peaks. This is because the high temperature causes air density to be less, reducing the mass flow of compressor intake air.

One type of gas turbine inlet air cooling is the evaporative cooling by fogging technique in which a mist of fine water droplets is introduced in the path of the incoming air. Both, the nozzles performance and location are critical to the proper operation of the fogging system [5].

The inlet air duct of a gas turbine is usually has 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 totally different from that in the straight portions and it's certainly will show a clear effect on the ability to absorb humidity within the flowing air.

One of the more interesting aspects of curved channel flows is the introduction of a secondary flow pattern in the duct cross-section resulting from the imbalance developed between the centrifugal force and the radial pressure fields [6].

The centrifugal force driving the air stream which flowing near the outer wall of the curved duct to accelerate producing higher momentum to drag most of the injected droplets to penetrate the air flow there. On the other hand, the air flowing near the inner wall of the bend may have slower air stream which miss the opportunity to mix and penetrate the air flow. Nevertheless, if the deceleration is not that much, then it might be better for mixing process as more time is now available for the heat and mass transfer between droplets and the carrying air to occur. Therefore, a compromise must reach to make use of the naturally generated turbulences within the curved duct.

Zhang et al**.** [7] conducted a study in the fluid flowing in a rotating curved duct subjected to both the Coriolis force due to a rotation and the centrifugal force due to a curvature. Wang et al**.**[8] studied theoretically the curved duct by using fluent programming. They represented among various cooling schemes, fog cooling (a direct evaporative cooling) has gained increasing popularity due to its simplicity and low installation cost.Mossad et al**.** [9] investigated numerically and experimentally the turbulent air flows inside a sharp 90° elbow bend. The study was conducted in an open-circuit horizontal-to-vertical suction wind tunnel system.

The present work focuses on the water injection within the curved portion of square duct. The aim of this work is to obtain the most effective cooling and humidification of steadily flowing air draught, by specifying precisely the optimum position of the atomizer within the flow field in a curved duct.

THE EXPERIMENTAL WORK

Experimental work was performed in an open cycle, low speed wind tunnel (manufactured by Plint and Partners LTD.). The air enters the wind tunnel through a bell mouth shaped duct that gradually becomes a 50cm. The bell mouth aims to isolate any entrance effects and to produce steadily flowing air, where one of humidity meter device was fixed at the inlet of the wind tunnel. Tes-1367 professional temperature and humidity meter with LCD display has an operating temperature range from 0 to 60 ºC and relative humidity from 0% to 100% as shown in Figure (1). An additional straight100cm length of the 50cm 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 12.5cm inner radius, 62.5cm outer radius. The ratio of inner to outer radii is chosen according to the regulations of ASHRAE [10].

Figure (1) The humidity temperature meter.

The main test section was used to measure the temperature and the relative humidity profile of the treated air across the duct as illustrated in Figures (2), (3) and (4). It has a 50cm square cross section with 200cm length and has been thermally insulated to avoid the surrounding interaction to the cooling process.The probe of a humidity meter was mounted on a sliding plate that moves from wall to wall transversely as shown in Figure (2). The Lutron model, HT-3005HA professional humidity meter with LCD display has an operating temperature range from 0 to 50 ^{0}C and relative humidity from 10% to 95% as shown in Figure (3).

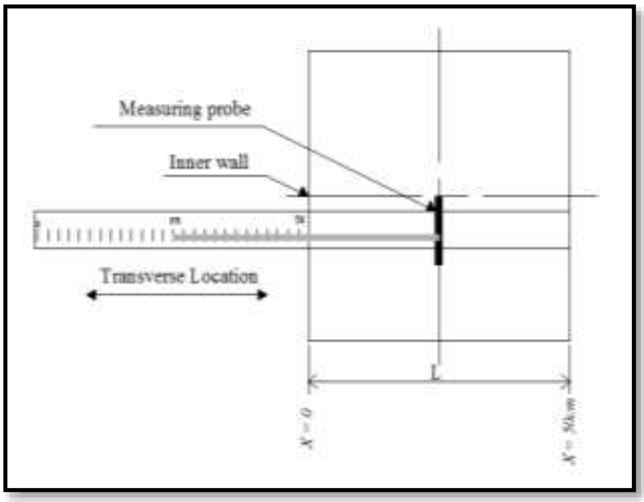


Figure (2). The probe travel.

Figure (3). The humidity meter.

The air drawn into the duct will be driven out by the axial fan of the wind tunnel.The operating velocity was adjusted from 4m/s to 38m/s and controlled by

Figure (3-16) The humidity temperature meter means of a double butterfly valve at the fan outlet. The fan discharges the treated air through a silencer.

The air mean velocity in the main test section was selected to be(14m/s) with(Re = 4.16*105), (turbulent flow) and (Dn = 8.32*105) according to the calculations carried out corresponding to technical information attached to the gas turbine unit (V94.3a) installed at Kirkuk gas turbine power plant. Considering air flow and dimension of the curved portion of the intake duct of that unit at peak loads, the air velocity and dimensions of the test section were adopted and have been applied [11]. The velocity was measured by using a standard Pitot-static tube. The layout of the wind tunnel is shown in Figure (4) shows the schematic drawing of the whole wind tunnel with both air and water systems attached to it.

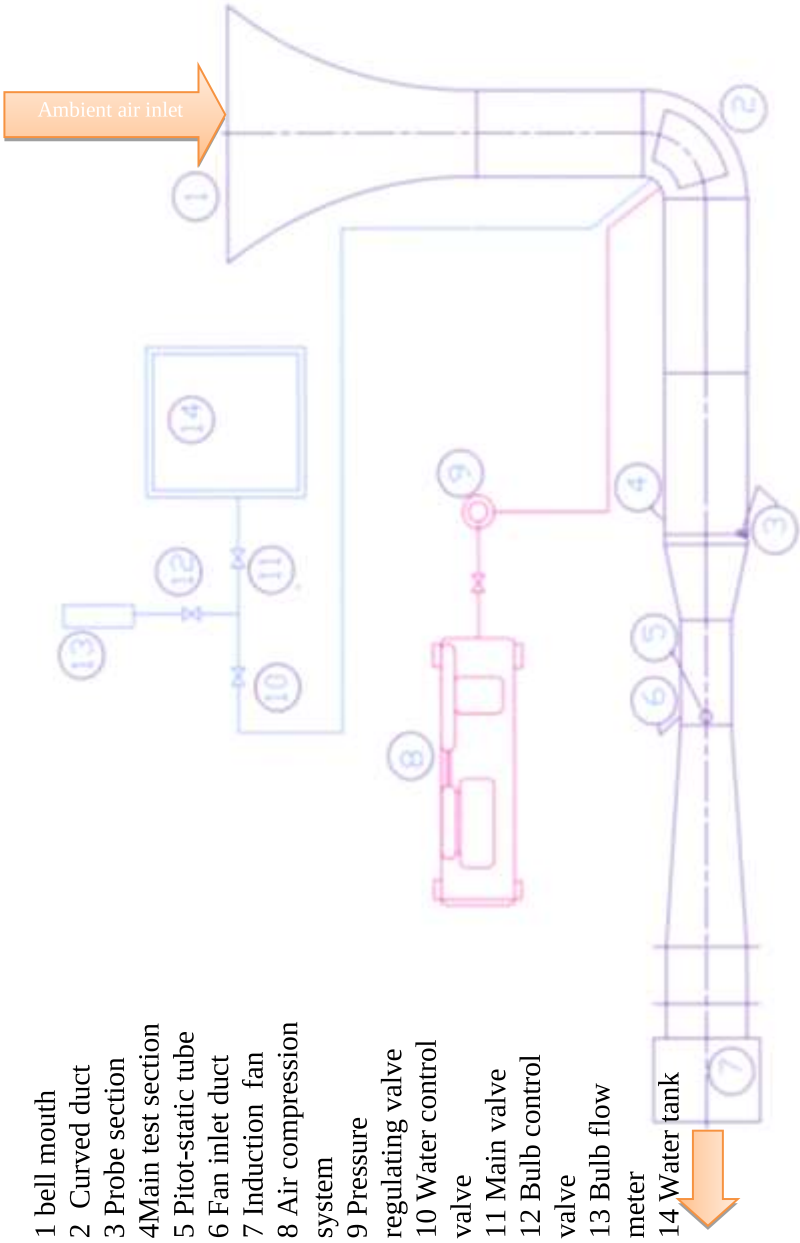


Figure (4) Top view of the Test Rig.

The atomizer used in this workhas a diameter of (2.5 mm), and working at a safe pressure of (3.8 bar). The atomizer is used to introduce water in the form of fine droplets. This atomizer slides radially between 5 to 45 cm from the inner wall of the curved duct and it is mounted on a bracket that has the ability to rotate from -90° to +90° to the tangential flow direction by a step of 5° as illustrated in Figure (5).

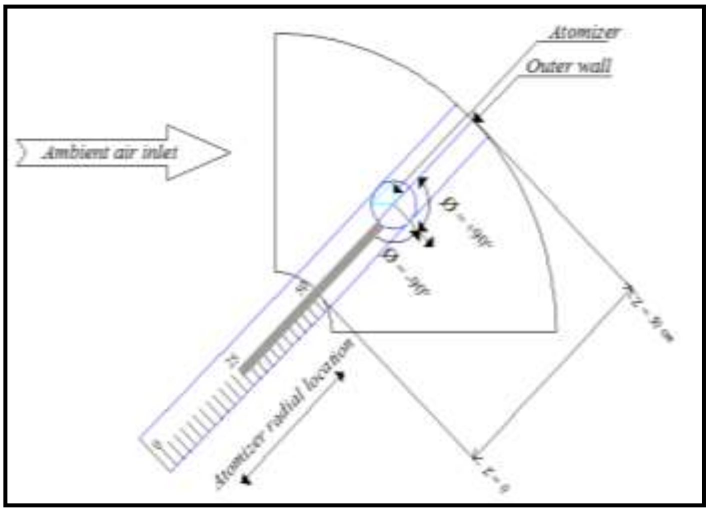


Figure (5) Details of atomizer movements in the curved duct.

To measure the dynamic pressure of the air stream in the wind tunnel, a Pitot - static tube is installed at the end of the fan inlet duct. A standard elliptical nosed Pitot - static tube with curved junction (N.P.L Standard) travels about (30cm) from the upper wall to the lower wall of the fan inlet duct section as shown in Figures (6) & (7).

Figure (6) Pitot - static tube with manometer at fan inlet duct.

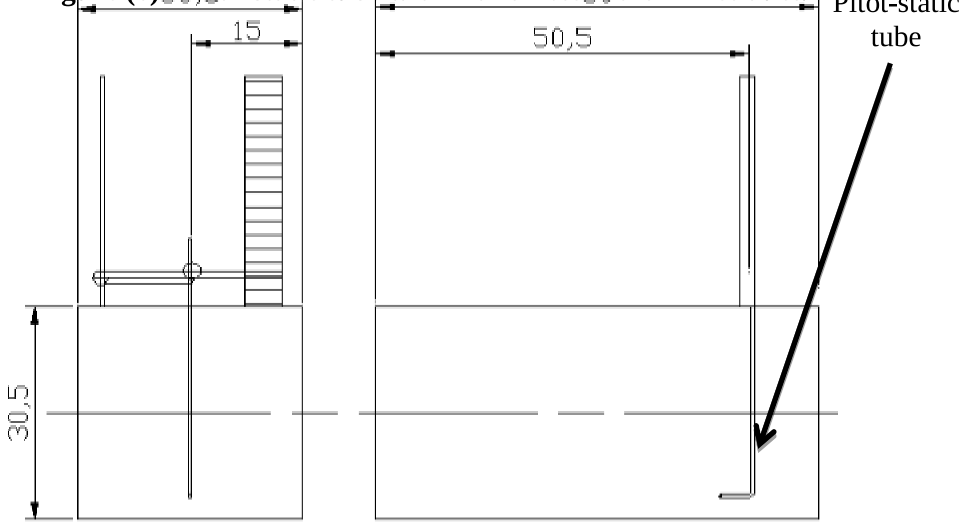


Figure (7).Pitot - static tube.

After converting the manometer reading into velocity [App.].We get air velocity distribution as illustrated in Figure (8).The average air velocity of the whole section is determined by equation (1).

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

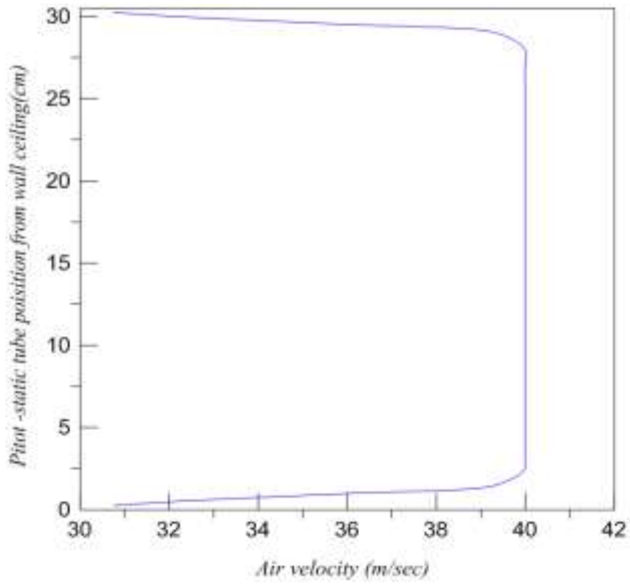


Figure (8) Air velocity distribution in the fan inlet duct.

RESULTS AND DISCUSSION

Increasing the atomization pressure leads to an increase in the water atomization rate and motivates an increase in the velocity of the injected fluid which leads more mass to be ejected out of the atomizer orifice [5].

The atomization rate increased from 4 to 30.7ml/s as the atomization pressure increases from 1 to 3bar as indicated in Figure (9). In the present work, the atomization pressure used was 2.5bar corresponding to 24.2 ml/s of water atomization rate. Increasing the atomization pressure over 2.5bar causes extra droplets to surround the measuring probe and to give inaccurate reading.

When increasing the ambient air temperature, the relative humidity is decreased leading to higher ability of the air stream to contain water vapor. This phenomenon assists the humidification and the attainable cooling [5].

Figure (10) shows clearly the same trend for both minimum and maximum water atomization rate at different ambient conditions. The drier the air is the better the humidification and cooling will be. It is obvious that increasing the water atomization rate ends in a higher increase in the relative humidity from (14.7%) at 7ml/s to (44.2%) at 24.2ml/s, this trend is also observed in a temperature drop as the higher cooling of (17ºC) occurs at the higher water atomization rate of 24.2ml/s, while it was only (9.6ºC) at 7ml/s. In the present work, a maximum ambient temperature of 43ºC was selected due to more improvement that had happened in the humidification and the resultant cooling.

Increasing the water atomization rate leads to improve the humidification of the air as more liquid is available for evaporation. This augmentation has a limit when the rate of increase reduces as the ability of the air to carry water droplet reduces due to the previous addition of water [12].

The higher water atomization rate of (24.2ml/s) shown in Figure (11) gives good improvement in the relative humidity of 44.1%, but at the lower flow rates of 7 and

12.1ml/s, the relative humidity difference was 14.7 and 28.9 % respectively. The reduction in the temperature was 10.6, 13.9 and 17.2^{o}C with the corresponding atomizing rates of 7, 12.1 and 24.2 ml/s respectively. In the present work, a volume flow rate of 24.2ml/s was selected as a compromise between the best possible humidification and the most accurate probe reading.

In Figure (12) for an inclination angle of (+90^o), the relative humidity shows an increase of about 64.3, 55 and 26.2% corresponding to the atomizer radial location of 5, 25 and 45cm respectively. At 5cm, the humidification is better than the other trends because no water droplets fall on the outer walls of the curved duct. Most regions in the cross section exposed to the spray gave low average temperature. The temperature reduced about 39, 23.1 and 3.4% corresponding to atomizer radial location of 5, 25 and 45cm respectively.

At an inclination angle of (+45^o), more uniform distribution of the relative humidity and temperature is clearly shown in Figure (13) compared to the previous inclination angle due to better mixing with air stream. An increase in the relative humidity of 65.6, 58.3 and 34% is observed at Atomizer radial location of 5, 25 and 45cm respectively. More uniform distribution is due to the injection that approaches the direction of flow. The cooling of air is about 41.5, 29.7 and 7.4% corresponding to the atomizer radial location of 5, 25, 45cm respectively.

Figure (14) represents the treated air properties for an inclination angle of (0^o). Better humidification is obtained at a location of 25cm when most of the duct is exposed to the water spray and droplets that to be entrained with the air. This makes the droplets to penetrate deeper into the air stream and enhance the mixing and evaporation, and hence, humidification. Figure (14) shows an improvement of 67.7% in the relative humidity accompanied with a 39.6% reduction in air temperature at 25cm. On the other hand, at 5cm, close to the inner wall, an increase in the relative humidity and temperature reduction had shown to be 56.5 and 27.9% respectively. The relative humidity increased at 45cm about 52.2% and the temperature reduced by 25.8%. At that location, major humidification occurs in the second half of the duct where most of the water droplets were drifted out towards the outer wall due to the acceleration caused by the centrifugal force.

For the inclination angle of (-45^o), the increase in the relative humidity and the temperature reduction at 45cm were 69.8 and 39.1% respectively as shown in Figure (15). This was due to the centrifugal force and the secondary flow that circulate the water droplets across the curved duct where the flow is more disturbed. The disturbances permit the water droplets to improve mixing with flowing air naturally, as well as, increase the cooling extent. For 5cm, the relative humidity increases by 49.5% due to the adhesion of water droplets on the inner wall. At the same time, the temperature reduction of 19% is obtained at that location. For 25cm, water is injected into the lower velocity region and some will entrained to the center of the flow field which results in slightly better humidification. For this location relative humidity increases by 65.4% while temperature reduces by 37.1%.

The relative humidity was improved by 67.9% at 45cm for an inclination angle (-90^o) as shown in Figure (16). This location has maximum reduction in temperature of 39%. The improvement in the humidification was achieved by the exposure of most of the cross section to the spray and by the penetration of the injected droplets into the most of the flow field away from the outer wall. At other locations of 5 and 25cm, the increase in the relative humidity was 31.8 and 63.3% respectively; as well as, a reduction in the temperature of 8.9 and 29% respectively, due to less exposure to the spray and more water droplets to adhere on the inner wall.

ATOMIZER OPTIMUMPOSITION

Investigating all the graphs have been previously explored showing that at any location across the curved duct; the best performance of the spray system was obtained when directing the spray towards the centre 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 curved duct.

For clear presentation of the above discovery, the humidity and the temperature profiles of the treated air is drawn at different inclination angles with varying radial locations. Figure (17) have shown the average values of the non-dimensional humidity and temperature that been obtained for the range studied. Figure (17) indicates that the lower half of the curved duct gives a stable performance for humidification and the cooling process, especially for angles in the range of +10 to +45° as they show very close uniform trends across that region. The mean values for these angles gave an average relative humidity improvement of 67.6% and average temperature reduction rate of 42.3%. This indicates less directional sensitivity and promising steadily and efficient operation of the spray system at any location across that half of the curved duct. Nevertheless, the upper half of the curved duct shows a clear difference in the relative humidity and the temperature distribution throughout indicating high sensitivity of position for the spray system. This would limit the possibility to utilize that region efficiently in producing good cooling of air stream.

In spite of high velocity in the upper half that help the injected droplets to penetrate deeper, the centrifugal forces will bring a large portion of them to fall out on the outer wall of the duct and reduce the possibility of evaporation and heat exchanging with air stream. This action would expose most of the duct section to the higher temperature air as many droplets are entrained with the outer layers of the flowing air. The situation in the lower half seems better for humidification process as the moderate air velocity and vortices give longer time for heat exchanging and penetrating into air stream. This circumstance is suitable to make most of the duct section exposed to water spray and to lead the injected droplets outward which certainly aid the rates of cooling and humidification.

Re-examining Figure (17) shows that the high sensitivity of the upper half introduces a location that to be considered as the optimum for the atomizer since it gives the higher humidity and lower temperature obtainable throughout. This critical position was observed at Z=27.5 cm and an angle of -10°. The atomizer when being in that position gives a typical path for the injected droplets along the flow field and makes use of air turning around the curved duct to carry and diffuse the droplets across the entire section. This position utilizes both effects of the centrifugal forces with less falling out on the outer wall, and the secondary flow for penetrating and heat exchanging between the injected droplets and the air layers that go around the spraying spot to diffuse across the entire lower half of the duct. Higher average relative humidity of (79.4%) and larger temperature reduction rate of (49.1%) were recorded at this critical position.

At this stage of analysis, it is essential to introduce two important realizations. First; the less sensitivity of the lower half to the atomizer position considered suitable for the case of the multi-point spray by using atomizing array in the air stream which would give good performance at many acceptable positions. Second; for single-point spray, it seems that the best is to install the atomizer at the radial location of (r/r_{in} = 3.2) and at an angle of (-10°).

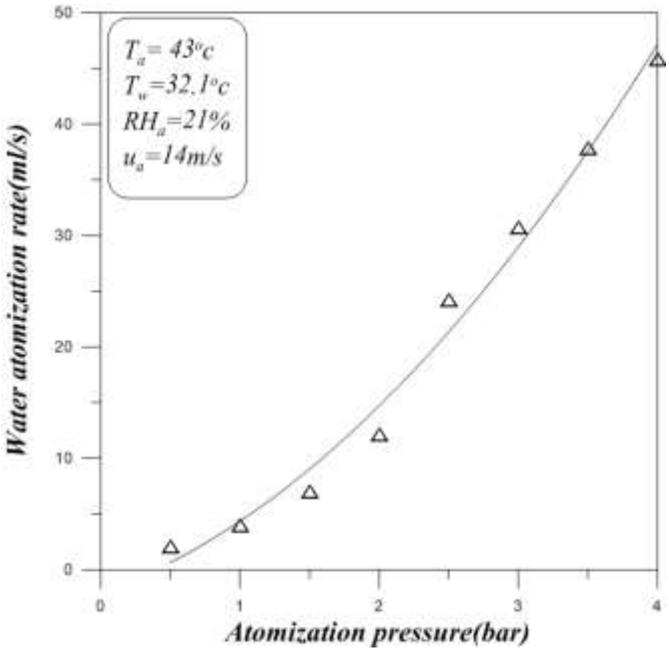
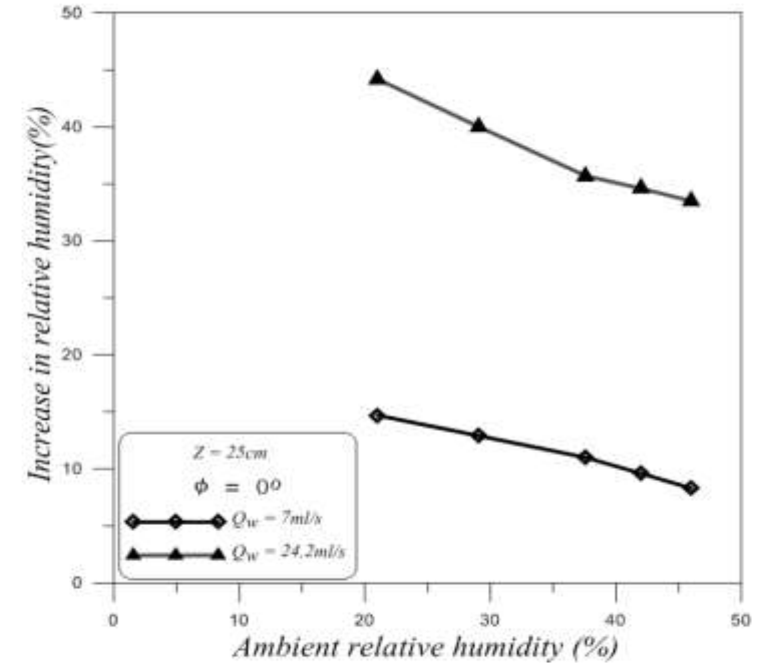
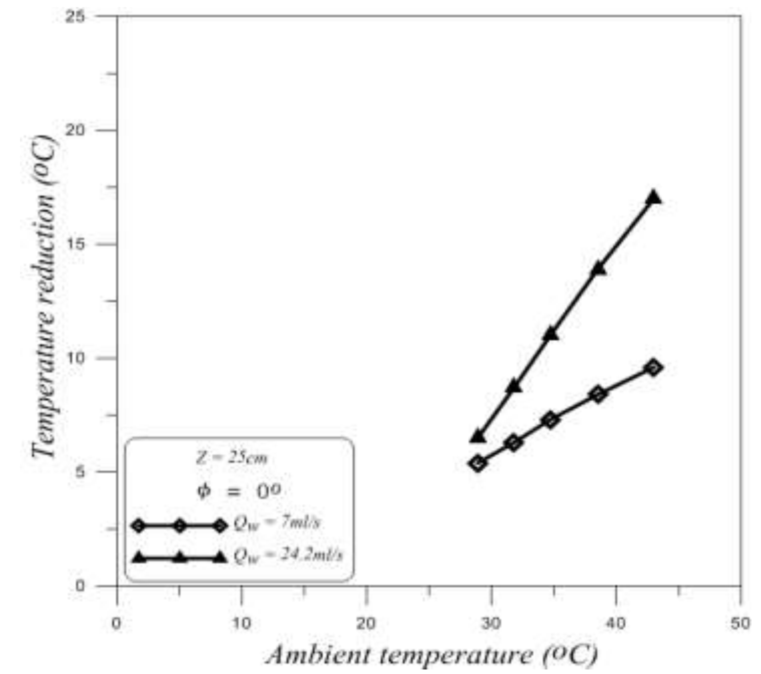


Figure (9) Relation between water atomization rate and atomization pressure.

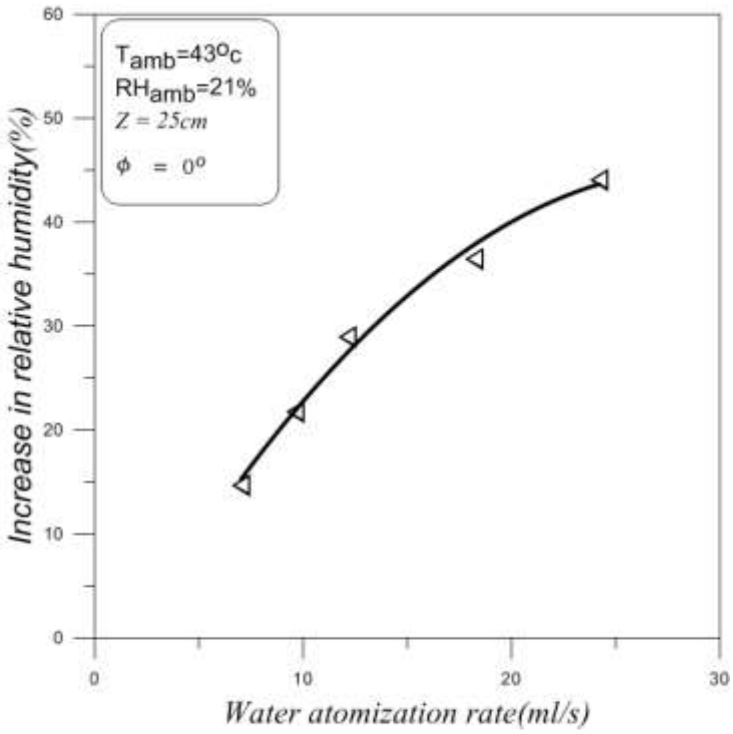


(A)



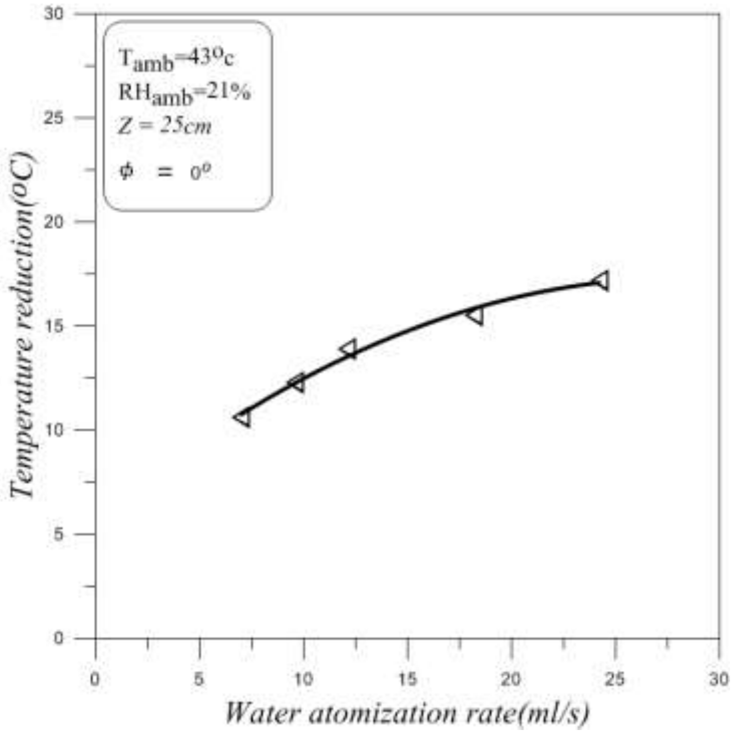
(B)

Figure (10) The resultant improvement in treated air properties due to ambient condition; (A) Relative humidity (B) temperature; at Q_w = 24.2ml/s.



T_{amb}=43^{o}c
RH_{amb}=21%
Z = 25cm
φ = 0^o
Increase in relative humidity(%)
Water atomization rate(ml/s)
0
10
20
30
40
50
60

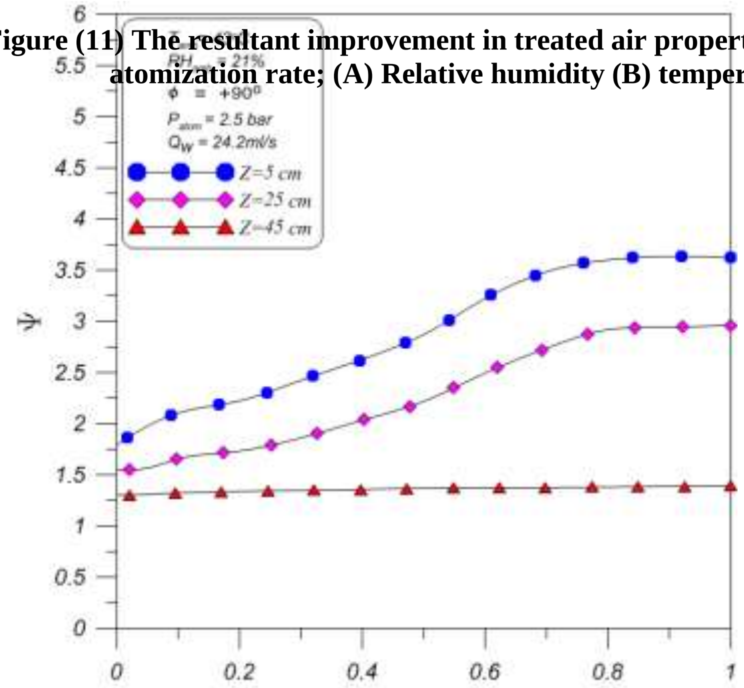
(A)



T_{amb}=43^{o}c
RH_{amb}=21%
Z = 25cm
φ = 0^o
Temperature reduction(^{o}C)
Water atomization rate(ml/s)
0
5
10
15
20
25
30

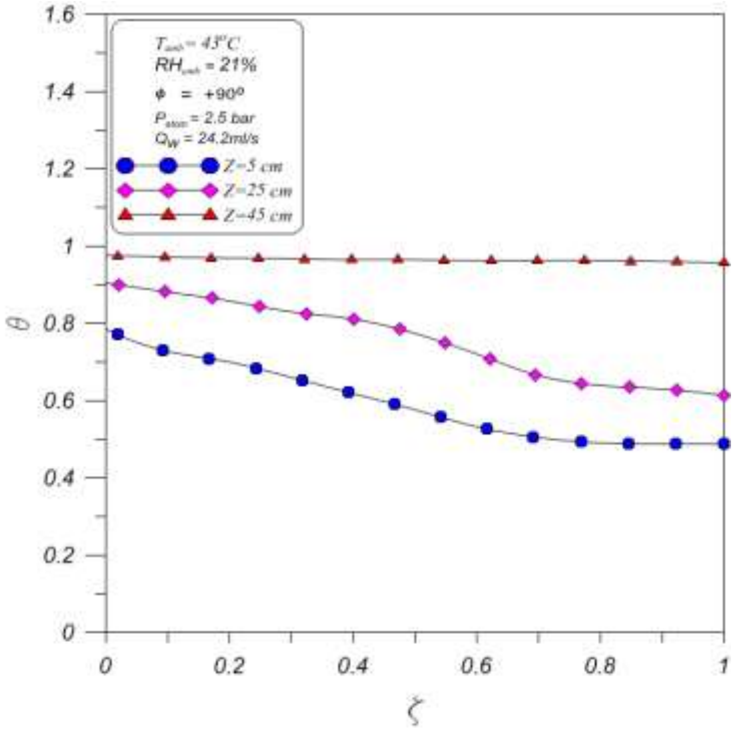
(B)

Figure (11) The resultant improvement in treated air properties due to water atomization rate; (A) Relative humidity (B) temperature.



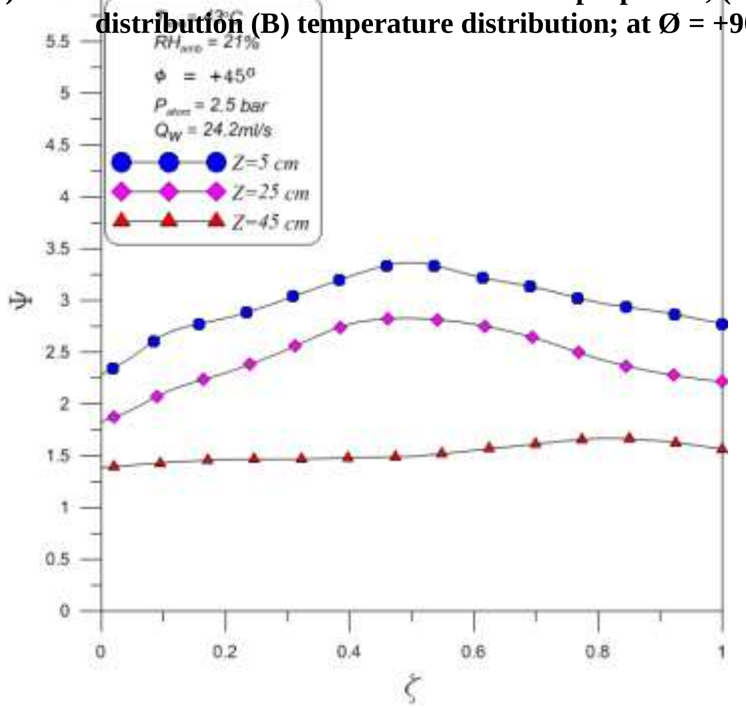
(B)

(A)

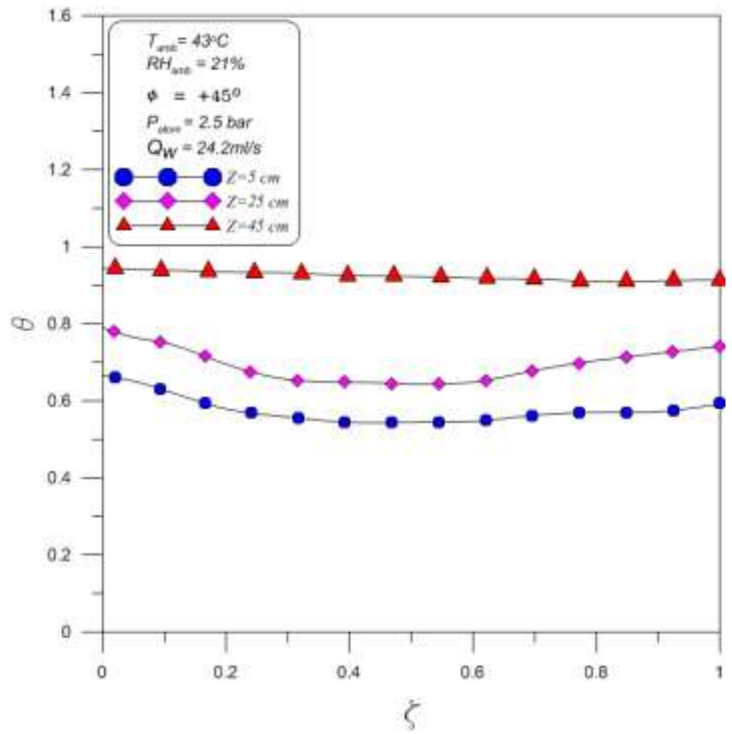


(B)

Figure (12) The effect of atomizer radial location on air properties; (A) Relative humidity distribution (B) temperature distribution; at Ø = +90º.

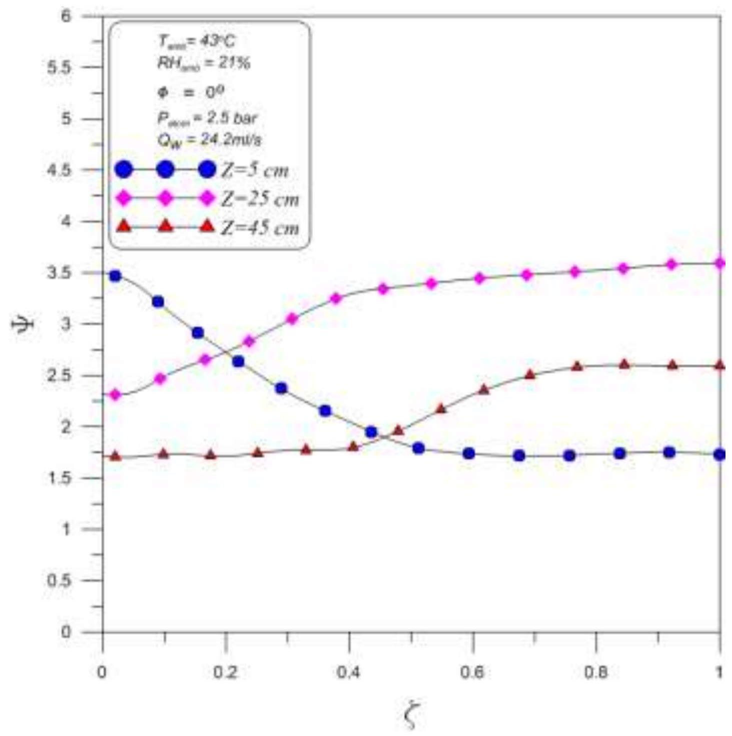


(A)

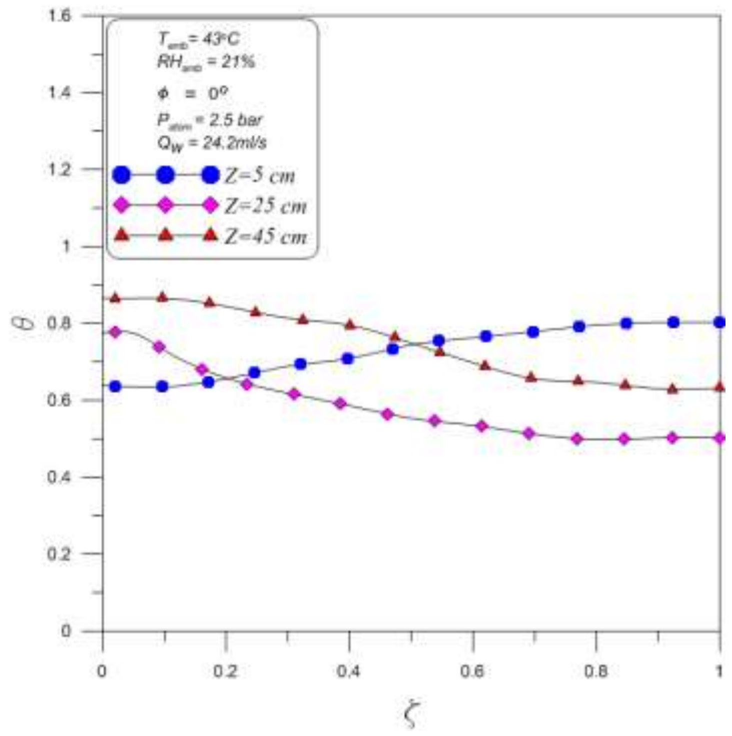


(B)

Figure (13) The effect of atomizer radial location on air properties; (A) Relative humidity distribution (B) temperature distribution; at Ø = +45º.

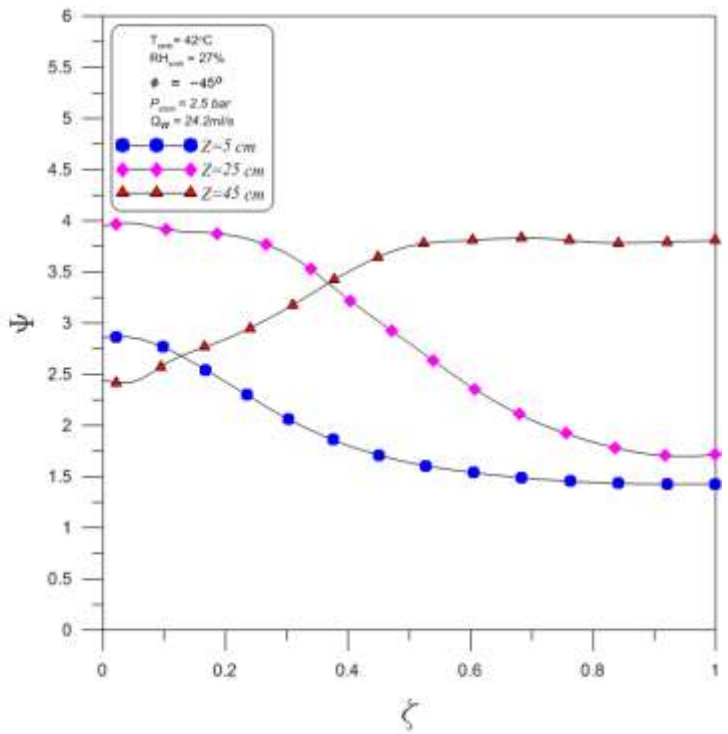


(A)

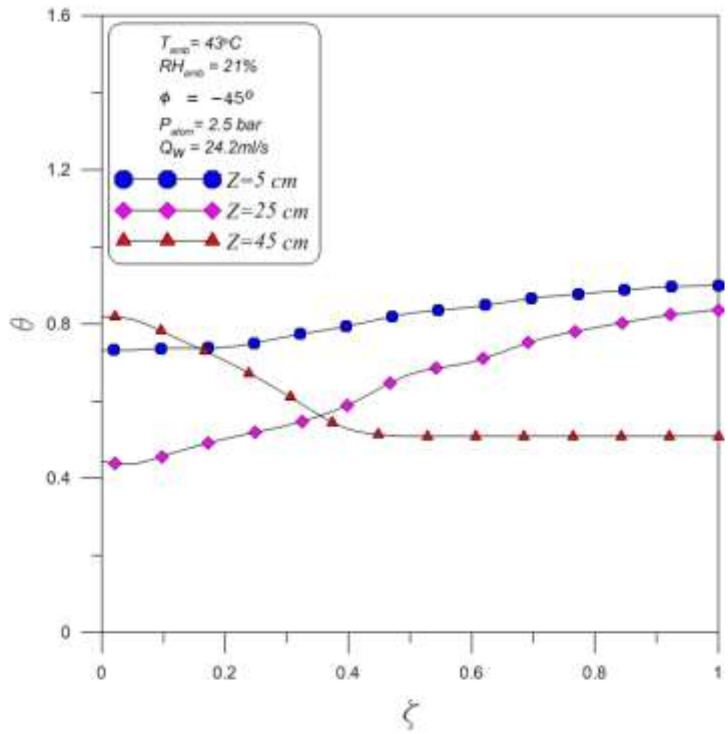


(B)

Figure (14) The effect of atomizer radial location on air properties; (A) Relative humidity distribution (B) temperature distribution; at Ø = 0°.

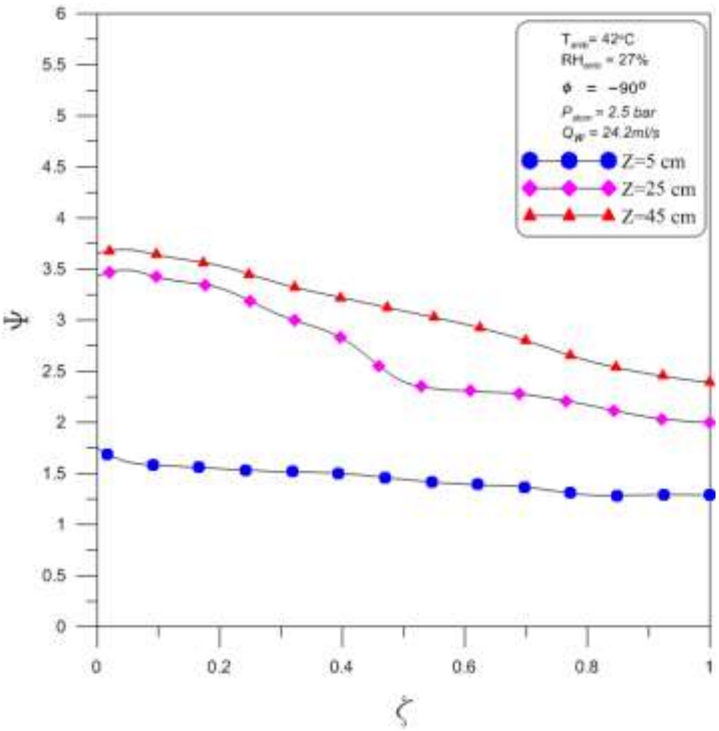


(A)

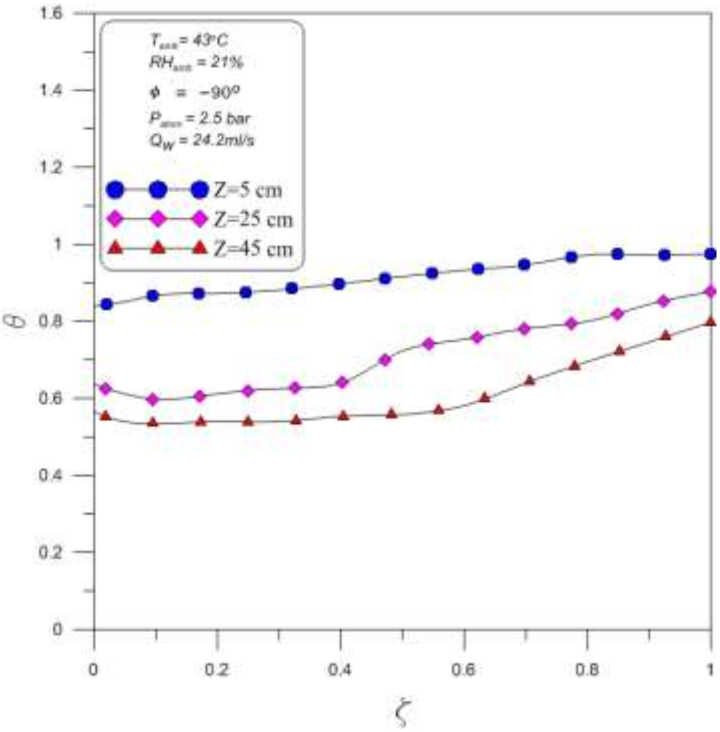


(B)

Figure (15) The effect of atomizer radial location on the air properties; (A) Relative humidity distribution (B) temperature distribution; at Ø = -45º.

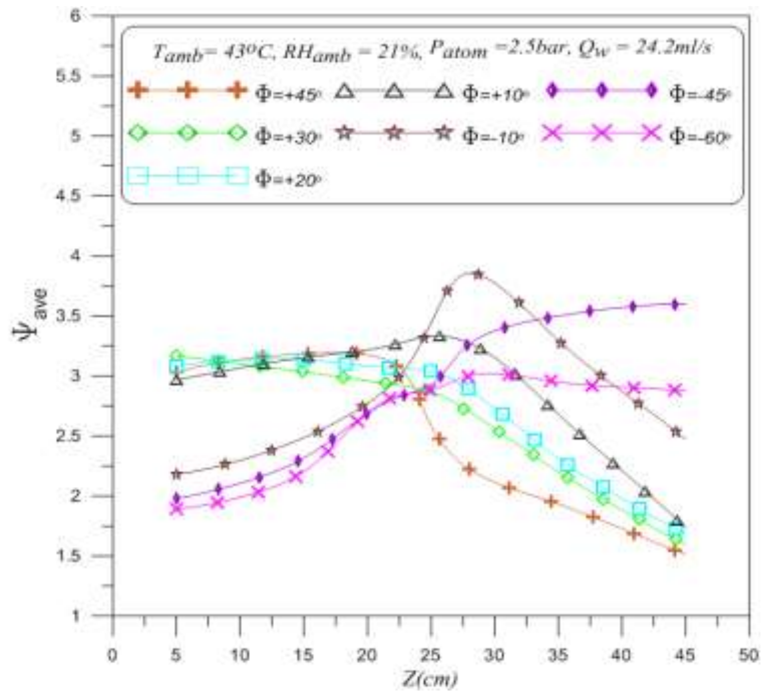


(A)

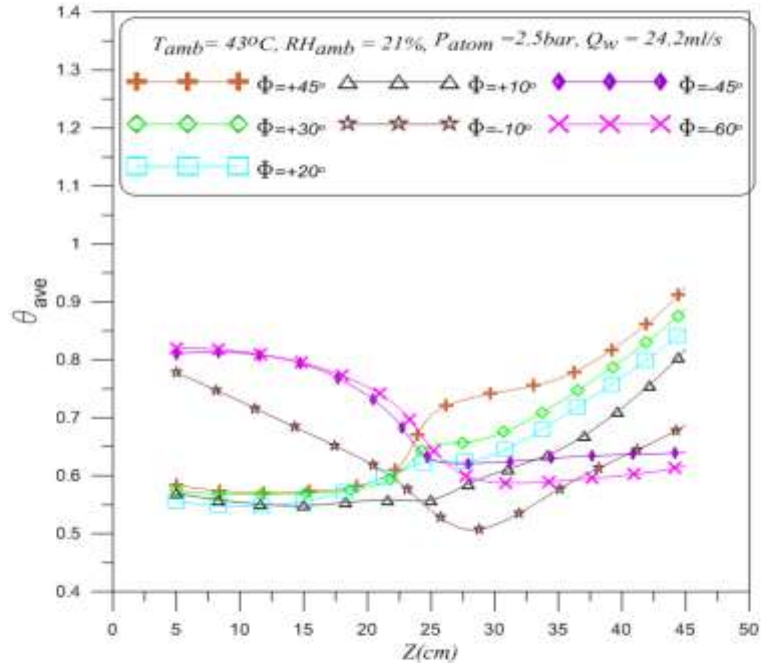


(B)

Figure (16) The effect of atomizer radial location on the air properties; (A) Relative humidity distribution (B) temperature distribution; at Ø = -90°.



(A)



(B)

Figure (17) Variation of treated air properties with atomizer position; (A) Average relative humidity distribution (B) Average temperature distribution.

CONCLUSIONS

1. The drier the air, the better the humidification and cooling process will be. At higher ambient temperature of 43ºC, an increase in relative humidity of44.2% and temperature reduction of 17ºC were recorded at higher water atomizer rate of 24.2ml/s.
2. Increasing water atomization rate brings more improvement in humidification process. When increasing water flow rate from 7 to 24.2ml/s, the improvement in relative humidity increases from 14.7 to 44.1% respectively. The corresponding reduction in the temperature is 10.6 to 17ºC.
3. Close to the inner wall of the curved duct, i.e., at 5cm, the best performance recorded was at +45º with the tangential flow as reaching an increase in humidity of 65.6% and reduction in temperature of 41.5%.
4. Close to the outer wall, i.e., at 45cm, the best performance recorded was at -45º to the tangential flow as reaching an increase in relative humidity of 69.8% and a reduction in temperature of 39.1%.
5. At the middle of the curved duct, i.e., at 25cm, the best performance that was recorded when the injection was arranged tangentially along the flow direction. Improvement in the relative humidity reaches 67.7%, while the temperature reduces by 39.6%.
6. The less sensitivity of the lower half to the atomizer position considered suitable for the case of the multi-point spray by using atomizing array in the air stream which would give good performance at many acceptable positions.
7. For single-point spray, it seems that the best is to install the atomizer at the radial location of (r/r_{in} = 3.2) and at an angle of (-10°).

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Appendix

The correction of Pitot-static tube for reading air velocity is determined according to the standards as in the following [13].

$P_{total} = P_{dynamic} + P_{static}$ (2)

$P_{dynamic} = P_{total} - P_{static} = \Delta P_{velocity} = \Delta H_w . \rho_w . g = \frac{1}{2} . C . \rho_a . {u_a}^2$ (3)

$$u_a = \sqrt{\frac{2.\Delta H_w.\rho_w.g}{C.\rho_a}} \quad (4)$$

$C = Co + \tau + \Omega$ (5)

Where:

Co: stem-static holes distance term, in this work used type is 0.9975.

τ : Viscosity term, (fully developed flow ($\tau = 0$)).

Ω: distance of the tube from the wall term may be determined from Figure (18).

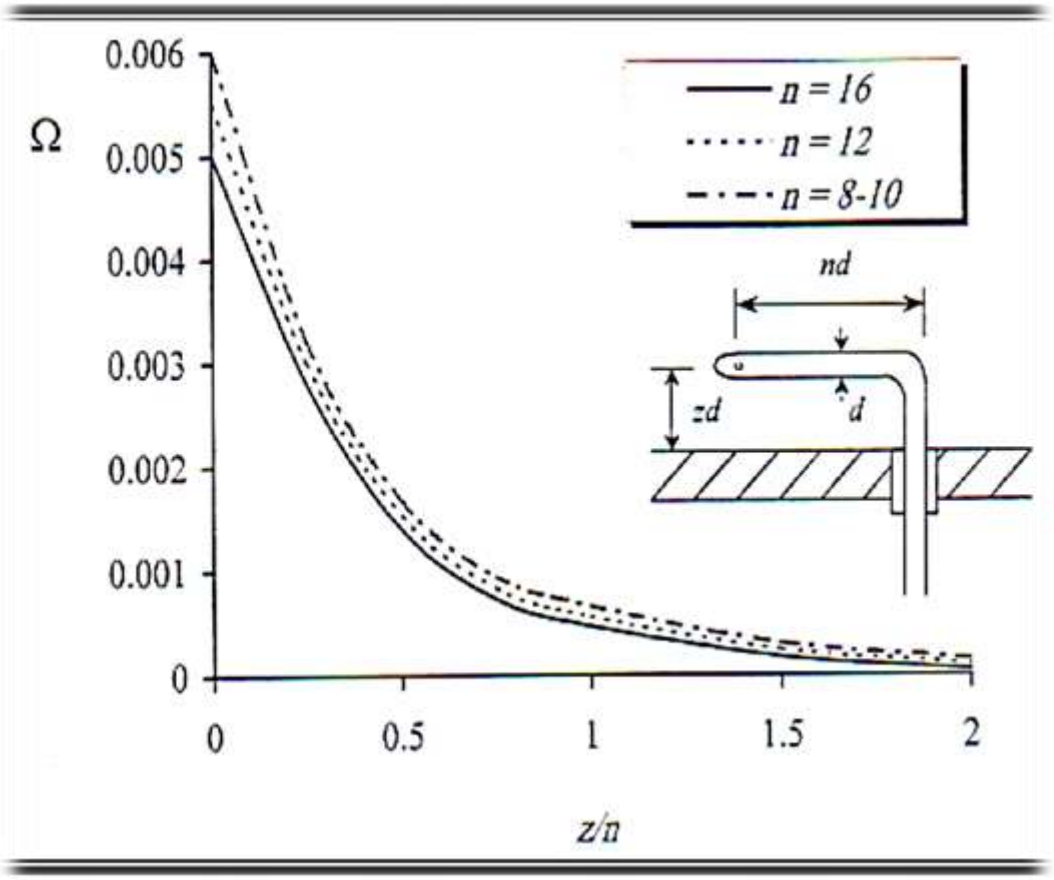

Figure (18) CorrectionPitot - static tube.