Journal of University of Babylon for Engineering Sciences, Vol. (26), No. (9): 2018.

The Effect of Optimum Injector Position on the Humidification Process of Steadily Flowing Air Stream in a Cross Varying Duct

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Submission date:- 16/8/2018	Acceptance date:- 29/8/2018	Publication date:- 14/10/2018

Abstract

Experimental and numerical investigations are carried out on the use of water injection in a humidification process of air traveling steadily through the divergent part of a wind tunnel. This work aims to study the optimum positioning of the water injector fixed at a divergent portion and to evaluate its impact on the liquid-gas mixing in an air humidification process. Experiments are conducted in a 50 cm square wind tunnel includes a gradually enlarged portion to 63 cm square having an air stream flowing at mean velocity of 5 m/s agrees with Reynolds number of $1.5X10^5$. This study adopts a mass flow ratio in a range of 300 to 600, and ambient temperatures between 30ºC and 45ºC. Experimental results showed that at any location within the divergent portion, the optimum position is realized when directing the spray towards the core of the flow which achieves the best humidification and cooling of the air. The optimum position for the single injection point is at the center of the duct with the axial direction of flow, i.e. at a yawing angle of 0^o. As the injector moves close to the wall, the cooling getting poorer. At the ambient temperature of 45ºC and flow ratio of 300, the maximum increase in relative humidity was 43.8%, corresponding to maximum cooling extent of 15.2% when the injector was fixed at 50 cm prior to the divergent portion. The study also implies a numerical analysis using ANSYS FLUENT 17.0 commercial CFD package, used to validate the conformity between experimental and numerical results obtained at the same operational conditions.

Keywords: Divergent duct; Inlet air cooling; Fogging system; Humidification system.

Nomenclature

Latin Symbols			Dimensionless parameters		
Symbol	Description	Unit	Symbol	Description	Unit
a	The duct width in the mean test section	m	Re	Reynold number	$Re = u.\rho.L / \mu$
b	The duct height in the mean test section	m	β	Vertical probe position	$\beta = Y_n / b$
F.R	Flow ratio	$\dot{m}_a / \dot{m}_w$	ζ	Horizontal probe position	$\zeta = X_n / a$
$\dot{m}$	Mass flow rate	kg/s	θ	Temperature	$\theta = T_n / T_{amb}$
p	Pressure	bar	Ψ	Relative humidity	$\Psi = RH_n / RH_{amb}$
Q	Water atomization rate	ml/s	Subscript		
r	Radius	cm	Symbol	Description	

RH	Relative humidity	%	*a*	Air
t	Time	s	amb	Ambient
T	Temperature	°C	atom	Atomization
u	Velocity	m/s	ave	Average
V	Volumetric flow rate	ml/s	dyn	Dynamic
X	Horizontal location	cm	i	At any element
Y	Vertical location	cm	in	Inner
Z	Axial location	cm	n	At any location
Creak symbols			stat	Static
Symbol	Description	Unit	tot	Total
Φ	Atomizer yawing angle	degree	w	Water

1- Introduction

Atomizing is meant producing a fine spray of liquid in a gaseous environment. A spray is a collection of moving droplets that are moving in a controlled shape and direction. Atomizers can be classified, according to their configuration and mechanism of atomizing, into pressure (airless) atomizers, air (air pressure assisted) atomizers, centrifugal atomizers, electrostatic atomizers, and ultrasonic atomizers. The atomization system used in this work is air-assisted, in which the fluid emerging from a nozzle at higher speed is surrounded by a lower speed air stream). The smaller the diameter of the liquid droplets, the higher the rate of evaporation will be. This is due to the greater interfacial area between the injected liquid and the carrying gas. 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 the air temperature due to the absorption of required latent heat of vaporization from the flowing air [1]. Evaporative cooling is most efficient during hot and dry weather and is less effective when the ambient humidity is high. Moisture can be added to the air stream until saturation with the extent of cooling limited to the wet-bulb temperature. The greatest cooling effectiveness is realized when employed in warm, dry climate [2]. The power output and fuel consumption of the gas turbine are highly dependent upon the mass flow rate, quality, and ambient temperature of the air drawn into the gas turbine unit. With increasing the demand for power and with shortages envisioned, especially during the peak load times during hot summer because the high temperature causes air density to be less, reducing the mass flow of compressor intake air. Hence, there is a need to boost gas turbine power output. Fogging system is one type of evaporative cooling eliminates the wet media and achieves adiabatic cooling by injecting demineralized water through special atomizing nozzles producing a fog of very fine droplets that evaporate almost instantaneously. The basic idea of the fogging system is to reduce the work for adiabatic compression by the injection and subsequent operation of water in the compressor. Both, the nozzles performance and location are critical to the proper operation of the fogging system [3]. The inlet air duct of a gas turbine is usually has varying cross sectional area parts. The flow pattern through gradually expanding duct is expected to give a clear effect on the ability to absorb humidity within the flowing air. One of the more interesting aspects of gradually expanding channel flows is the introduction of a secondary flow pattern in the duct cross-section resulting reverse flow near the inner wall of the divergent duct. Energy losses also arise from secondary flow. This phenomenon may most easily be explained by reference to a divergent duct of rectangular cross-section. Adjacent to the upper and lower walls, the velocity is reduced by the viscous action in the boundary layers there and, as a result, the increase in static pressure. The boundary layer in the divergent duct decelerates and thickens rapidly, and it can separate from the divergent duct walls causing reverse flow near the inner walls [4]. The air flowing near the walls of the divergent duct will decelerate and may have slow air stream which misses 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 the water droplets and the carrying air to occur. Therefore, a compromise must be reached to make use of the naturally generated turbulences within the divergent duct. **[5]** conducted experimental and theoretical studies that covered the important area of the fog plume pattern of impaction pin nozzles and examined the fog plume uniformity. The effect of ambient temperature and relative humidity, water evaporation rate, and the location of the fog injector with respect to the inlet duct was analytically and experimentally analyzed. An analytical model was used to study the evaporation dynamics of mist droplets injected in the straight uniform inlet ducts, and the model was validated experimentally in the air inlet duct. **[6]** conducted an experimental study on the using of water atomization to evaluate its effect on the humidification proses of steadily flowing air travelling throughout a curved duct. At higher ambient temperature of 43°C, an increase in the relative humidity of 67.8% and a temperature reduction of 39.6% were registered at a higher water atomizer rate of 24.2 ml/s. The lower half of the curved duct was shown to be less sensitive to the atomizer position for a range of yawing angles between 10° to 45° with radial locations among 5 to 20 cm from the inner wall. This situation makes this region most suitable for using atomizing array across the curved duct. 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 position of atomizer defined by a radii ratio of (r/rin = 3.2) and a direction of -10° to the tangential flow. **[7]** studied experimentally and theoretically the effect of water temperature on the overall efficiency of a fogging system. Due to the small size of the droplets used in this process, the temperature of the droplet approaches quickly to the wet bulb temperature, in any initial water temperature. This study was carried out using water temperatures between 1 °C and 60 °C and the initial ambient case of a DBT of 33.9°C and a WBT of 26.1°C. The results showed that the water temperature has no significant effect on the droplet size, on the other hand, using hot water, provides slightly increases the evaporation efficiency. **[8]** investigated experimentally the use of water injection at the downstream section of a curved duct with constant cross section on the humidification process of air with a steady flow that travels inside the curved duct. The experiments were conducted on a (50×50 cm) wind tunnel with an average air velocity of (10 m/s), a range of air to water flow ratio between 1000 and 2000, and an ambient temperature in a range of 30° to 50°C. A maximum temperature reduction of 26% and increasing in the relative humidity ratio of 2.13 were recorded at a higher ambient temperature of 45.2°C (DBT) and a flow ratio of 1000. The study showed less sensitivity to the atomizer location regardless the radial position of the atomizer at injecting water upward through the range of angles -25° to 75°. The central location with tangential spray gives the critical position for a single-point spray.

This work aims to study the optimum positioning of the water injector fixed at a divergent portion of a wind tunnel. The work is considered as a simulation of gas turbine inlet cooling by fogging technique. The divergent portion is to be designed in accordance to a compromise between lower pressure drop and higher temperature reduction of the air stream. The transvers locations of the injector vertically and horizontally will change, as well as, changing axial location by retarding the injection spot upstream of the divergent portion. The orientation of the spray will change on both sides of the duct axis to accommodate the enlargement of the section and to evaluate the impact of all these parameters on the liquid-gas mixing in an air humidification process.

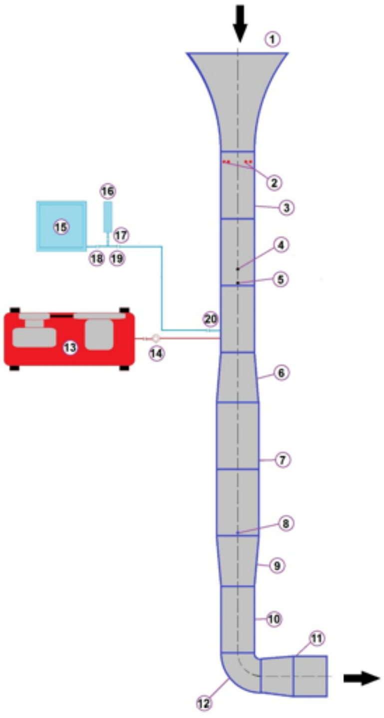
2- Experimental Work

The ambient air enters the wind tunnel through a bell mouth shaped duct that gradually becomes a 50 cm. The gradual converging of walls towards the center of the duct is to obtain a smooth entry and reduce the disturbances. An additional three parts with 100 cm length each are forming a straight duct with 50 cm square cross-section. This part is used to remove any turbulence in the air stream before divergent duct. A metallic mesh with 1 cm square cells located at the end of the first 100 cm part was attached to act as a straightener to minimize the lateral velocity components caused by the swirling motion in the air flow during the entry. A digital humidity/temperature meter with LUTRON HT-3005HA is used with a dual display showing the Relative humidity and temperature value at the same time on the screen. The atomizer was placed at the end of the straight duct. The section under study which diverges in the direction of flow has a cross-sectional area increases from (50*50) cm to (63*63) cm in the direction of air flow with 75 cm long. The dimensions of this part were carefully chosen using the commercial software package ANSYS Workbench (version 17.0) from Fluent, Inc. This divergent duct was used to investigate the effect of deceleration on the mist transport and cooling extent. Also, the optimized design meets the maximum cooling effectiveness and minimum pressure drop. The main test section is constructed of a uniform cross-sectional duct used to measure the temperature and the relative humidity of the cooled air. It has a 63 cm square cross section with 200 cm length. The second digital humidity/temperature meter YEHAI YH 2060 was fixed at the main test section. The probe is mounted on a sliding plate that moves from wall to wall transversely. The air drawn into the wind tunnel is driven through the blower of an axial fan, which is driven by a 850 W (1Ph) AC motor. Reducer duct, Secondary straight duct and curved duct are used to accommodate the inlet dimensions of the induction fan. The air mean velocity in the straight duct was selected to be (5 m/s), (Re = 1.594*105) according to the calculations carried out corresponding to technical information attached to the gas turbine unit (GE Frame 9E) installed at South Baghdad power plant. The layout of the wind tunnel is shown in Figure (1), while figure (2) shows the schematic drawing of the whole wind tunnel with both air and water systems attached to it. The atomizer used in this work has a diameter of (2 mm), working at a safe pressure of (4 bar). This atomizer slides in duct at multi positions. The atomizer was mounted on a bracket that has the ability to rotate from -90˚ to +90˚ to the axial direction. The character X refers to the atomizer horizontal location from the side wall of the duct, Y is the vertical location from the bottom wall of the duct, Z is the atomizer axial location prior to the divergent duct with the air flow direction, and ϕ is the atomizer Yawing angle relative to the axial flow, as illustrated in figures (3) and (4).

To measure the dynamic pressure of the air stream in the wind tunnel, as well as, the air velocity, a Pitot - static tube was installed at the primary straight duct. It is a standard elliptical nosed Pitot-static tube with curved junction (N.P.L Standard). The average air velocity of the whole section is determined by equation (1).

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

Figure (1): Wind tunnel



1. **Bell mouth**
2. **Heaters**
3. **Primary straight duct**
4. **Pitot-static tube**
5. **First Humidity measuring point**
6. **Divergent duct**
7. **Main test section**
8. **Second Humidity measuring point**
9. **Reducer duct**
10. **Secondary straight duct**
11. **Induction fan**
12. **Curved duct**
13. **Air compression system**
14. **Pressure regulating valve**
15. **Water tank**
16. **Bulb flow meter**
17. **Bulb control valve**
18. **Main water valve**
19. **Water valve**
20. **Water control valve**

Figure (2): Schematic drawing of the test rig

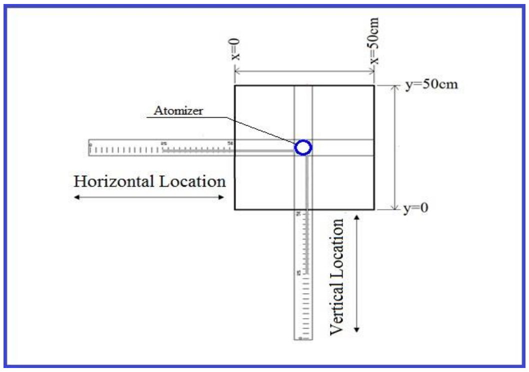


Figure (3): Details of atomizer movements in x-y plane

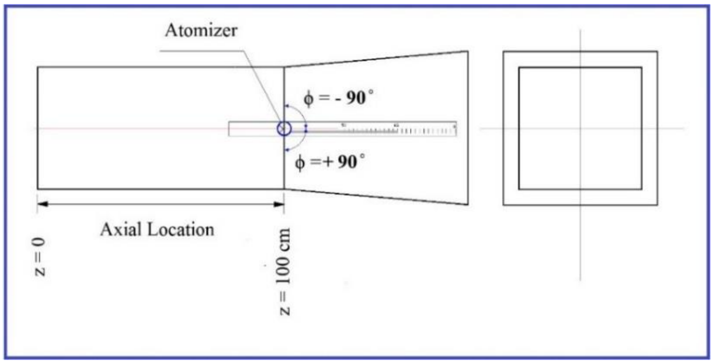


Figure (4): Details of atomizer movements in x-z plane.

3- Numerical Simulation

Computational Fluid Dynamics (CFD) is a technique, which uses numerical analysis and data structures to solve two-phase flow problems. CFD analysis gives a deep understanding of the process mechanisms and shows the source of problem. Analysis steps for FLUENT software package were used to develop the CFD model of cooling a hot air stream by water injection using species transport and discrete phase models of ANSYS FLUENT 17.0. CFD simulations used FLUENT software with solver strategy to create the geometry and grid and solving models (which include continuity, momentum and energy equations as well as turbulent flow model).

4- Results and Discussion

The increase in the ambient air temperature causes the relative humidity to decrease, leading to higher ability of the air stream to contain water vapor. This phenomenon assists the humidification and the attainable cooling. Figure (5) showing the effect of ambient conditions on the humidification of the air flowing through the divergent duct. It is clearly shown in figure, that as drier the air is, the better the humidification and cooling will be. In the present work, a maximum ambient temperature of 45˚C was selected due to more improvement achieved in the humidification and higher resultant cooling. The higher water atomization rate at the flow ratio of (325) shown in figure (6) gives the best improvement in the relative humidity of 33.8%, and the corresponding reduction in the temperature of 11.3 % compared to the lower flow ratios of 650 and 435. In figure (7), the effect of horizontal location of the injector on the treated air properties is shown for various yawing angles with the injector kept at the vertical location (Y=25cm). For both angles of +45o and 0o, the best performance for the humidification system is obtained at the central position where (X=25cm). This result is due to the better droplets distribution and mixing with the air stream, as well as, less falling out of droplets on the walls. This situation will lead to good evaporation as most of the duct section is exposed to the spray with droplets having higher rates of heat and mass transfer with the air. On the other hand, at the angle of -45o the best performance seems to be obtained at the horizontal position of (X=35cm) with more uniform distribution of temperature and humidity compared to other horizontal locations, where a higher humidification obtained near the walls leaving the rest of the duct more drier and hotter. At (X=35cm) with angle -45o, the uniformity is achieved because of the directing of the spray towards the core of the flow with less falling out of droplets on the walls. Therefore, the central position with axial directing injection gives the higher temperature reduction of 11.6% and corresponding raise in relative humidity of 31.5%.

The effect of the vertical location of the injector on the treated air properties is shown again for various yawing angles with the injector kept at the horizontal location (X=25cm) in figure (8). It is clear from the figure that at all angles the central location where (Y=25cm) gives the better performance of the humidification system. Directing the spray away from the core of the flow, as for angles +45o and -45o, leads to create a more wetter regions near the walls leaving the rest of the duct section drier and hotter. This attributed to the fact that these angles will bring the droplets to the slower streams of air decreasing the relative velocity responsible for the heat and mass exchanging rates. As a result, the reduction in air temperature and humidity increase is lower than those obtained at the central and axial positioning of the water injector. The central position provides the better droplets distribution which enhance the mixing and penetration of water within the carrying air, which in turn, raise the heat and mass transfer rates leading to higher evaporation rate.

Figure (9) showing the effect of yawing angle of the injector on the treated air properties for various horizontal and vertical locations of the water injector. The central location shows that the axial orientation of the spray with angle 0o gives the better humidification system performance compared to the other two angles. This is due to uniform distribution of water droplets across the entire duct section which enhances the evaporation rate of water. Therefore, the center of the flow is the coldest and most humid air across the flow field, as larger number of the injected droplets will gather and entrained downstream with the central air stream. On the other hand, moving diagonally towards the corners of the duct requires the spray to be directed to the core of the flow. Thus for the other two diagonal locations the best angle the spray directed to is -45o, otherwise more water droplets will fall out on the walls.

The effect of changing the axial location of the water injector with respect to the diverging portion of the duct is indicated in figure (10). As the central location where (X=25cm, Y=25cm) is shown the best location to inject water into the carrying air stream, figure (9) is dedicated to this location for various values of yawing angle. It is clearly demonstrated that at any angle, as the injection commences earlier, it is better for the humidification and cooling of the flowing air. Again it is obvious that the axial direction with angle 0o, gives the most efficient cooling of the air. Retarding the point of injection from (Z=100cm) at the beginning of the divergent duct, back to (Z=50cm) at middle distance from the divergent duct, gives a reduction in temperature of 15.2%, which is 31% greater than that obtained before. The corresponding increase in relative humidity is 43.8%, which is 39% greater than the increase obtained at 100 cm. This behavior is attributed to the longer distance the sprayed water travels before reaching the divergent portion. Longer distance means more time available for the mixing and heat transfer between the water and the air. Experiments show that beyond (Z=50cm), slight differences are attainable as the effect of the diverging in section that travel back upstream is weaken beyond that location, and the only remarkable influence was recorded at 50 cm prior to the divergent portion. It is then fair to conclude that the effective distance for the evaporation of injected water equals to the characteristic length of the geometry.

More realistic realization of the system performance can be obtained when expanding the work to the entire section of the duct by establishing contour drawing for the measured properties of the treated air. Such a drawing is shown in figure (11), where the temperature profiles of the humidified air are represented as contours indicated the isotherms around the whole cross section in the X-Y plane. The most interesting result is the appearance of the gravity effect of the sprayed water droplets as the contours shifted down toward the bottom wall of the duct. The results depicted are for the best orientation of the injector in axial direction, with the transvers location travelling diagonally toward the corners of the section. The same trends obtained before are appears here but with superior vision showing the overall impact of the intended position on the humidification process. The figure also compares the numerical analysis of the system at identical operating conditions with those obtained experimentally, in purpose of results validity. It is clear from the figure that both experimental and numerical are nearly identical, and this will encourage us to benefit from the fluent package to demonstrate the effect of the axial location of the injector on the process. This is achieved by establishing contours drawings in the X-Y and Y-Z planes for the three axial locations 100cm, 75cm and 50 cm in terms of temperature profiles see figure (12). It is clear that retarding the injection point axially upstream from the divergent portion, the sprayed water will travel a longer distance leading them to spread widely across the whole duct rising the opportunity of heat and mass exchange between droplets and the carrying air, hence better mixing and higher evaporation rate is obtainable. This improvement in evaporation will certainly improve the humidification and cooling of the air stream going through the diverging section.

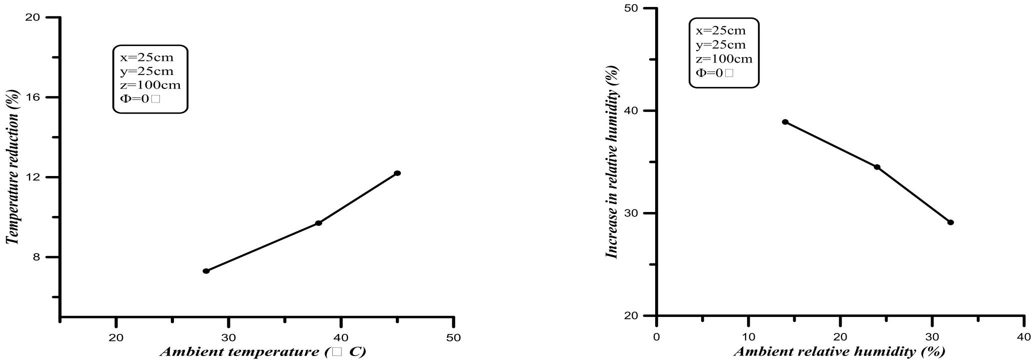


Figure (5): The resultant improvement due to ambient condition on; left: temperature, right: relative humidity; at flow ratio ma/mw=325.

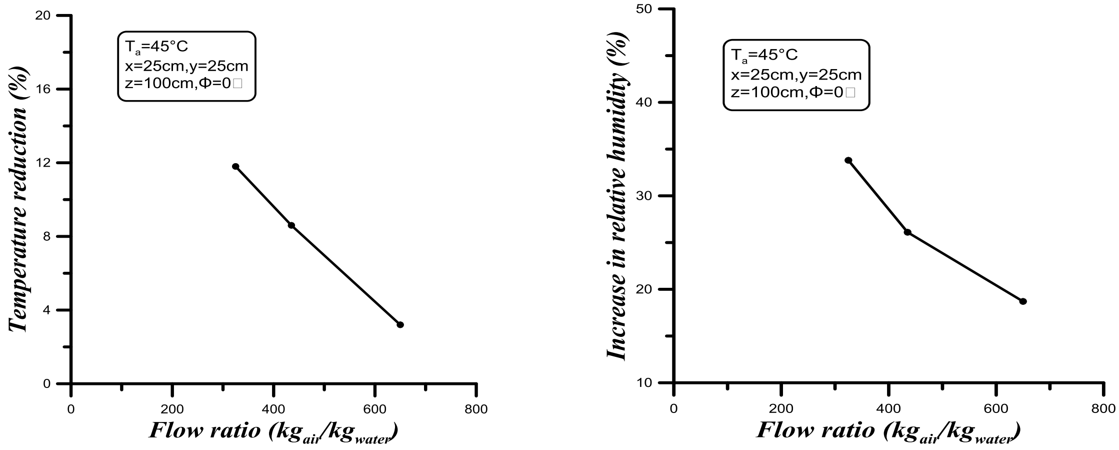
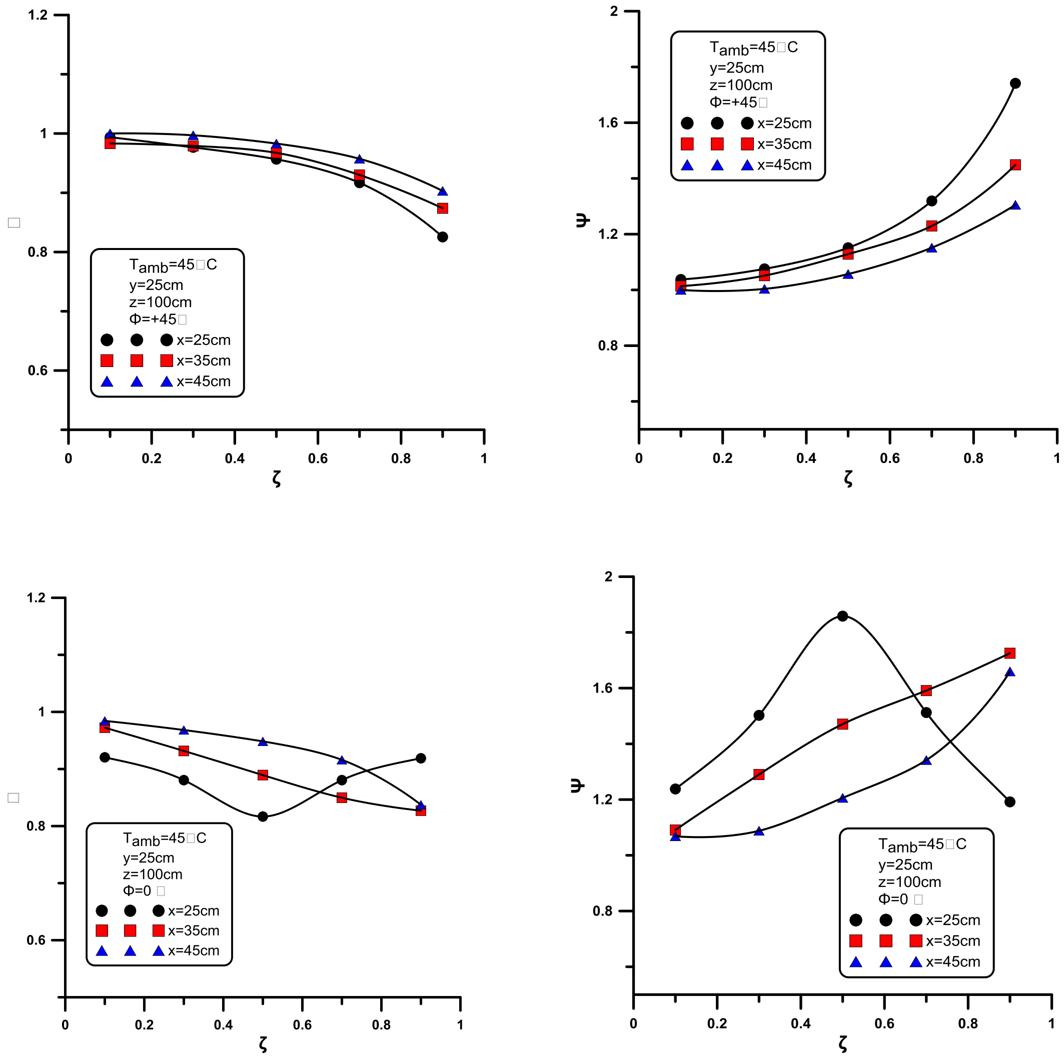


Figure (6): The resultant improvement in treated air properties due to water atomization rate; left: temperature, right: relative humidity.



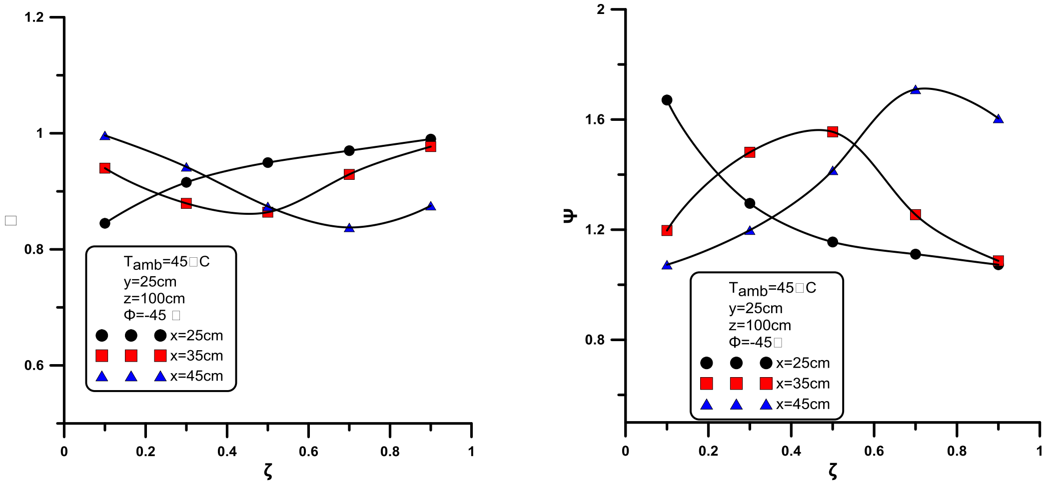
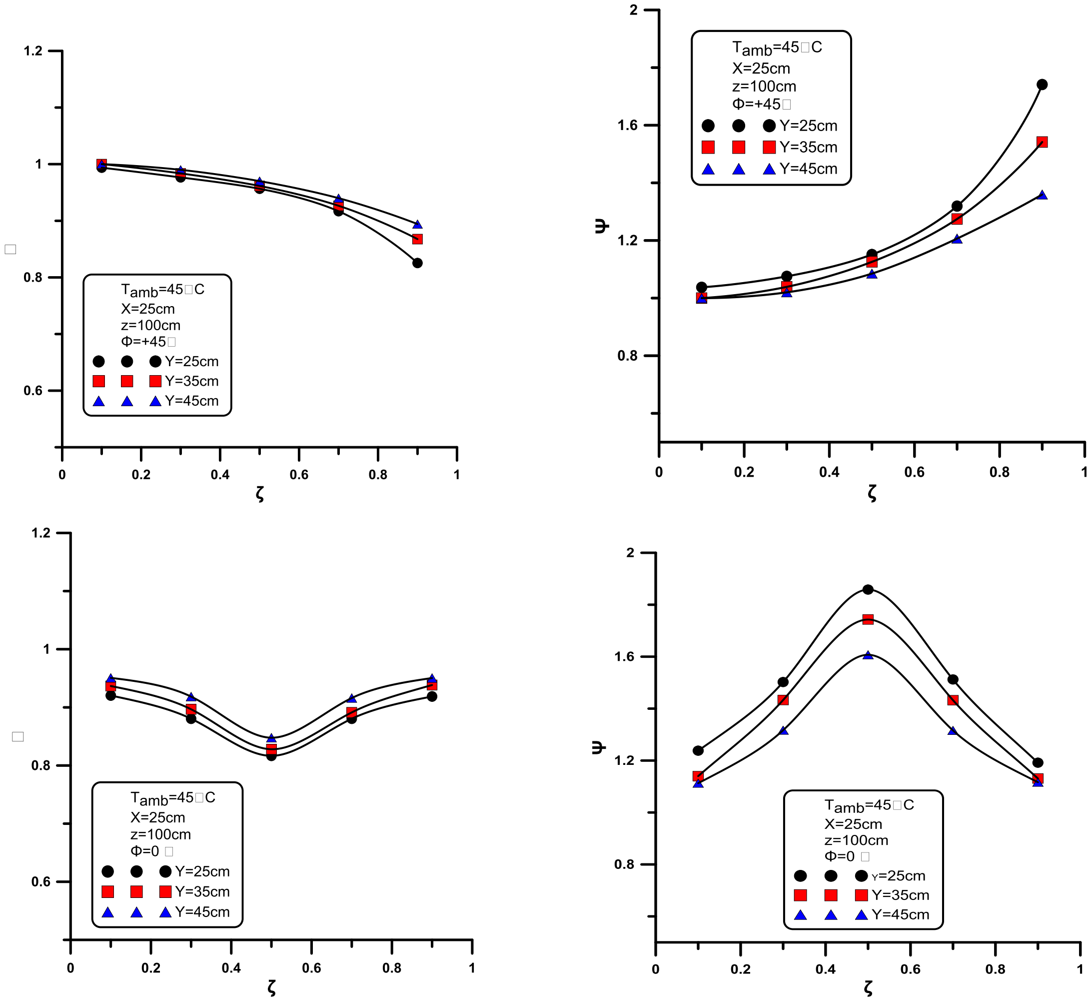


Figure (7): The effect of atomizer horizontal location on air properties; left: temperature distribution, right: relative humidity distribution; at flow ratio of 325.



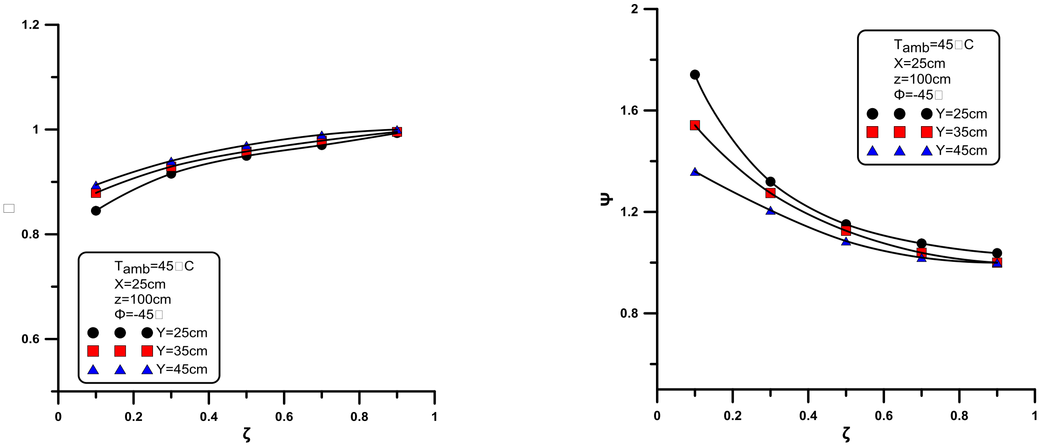
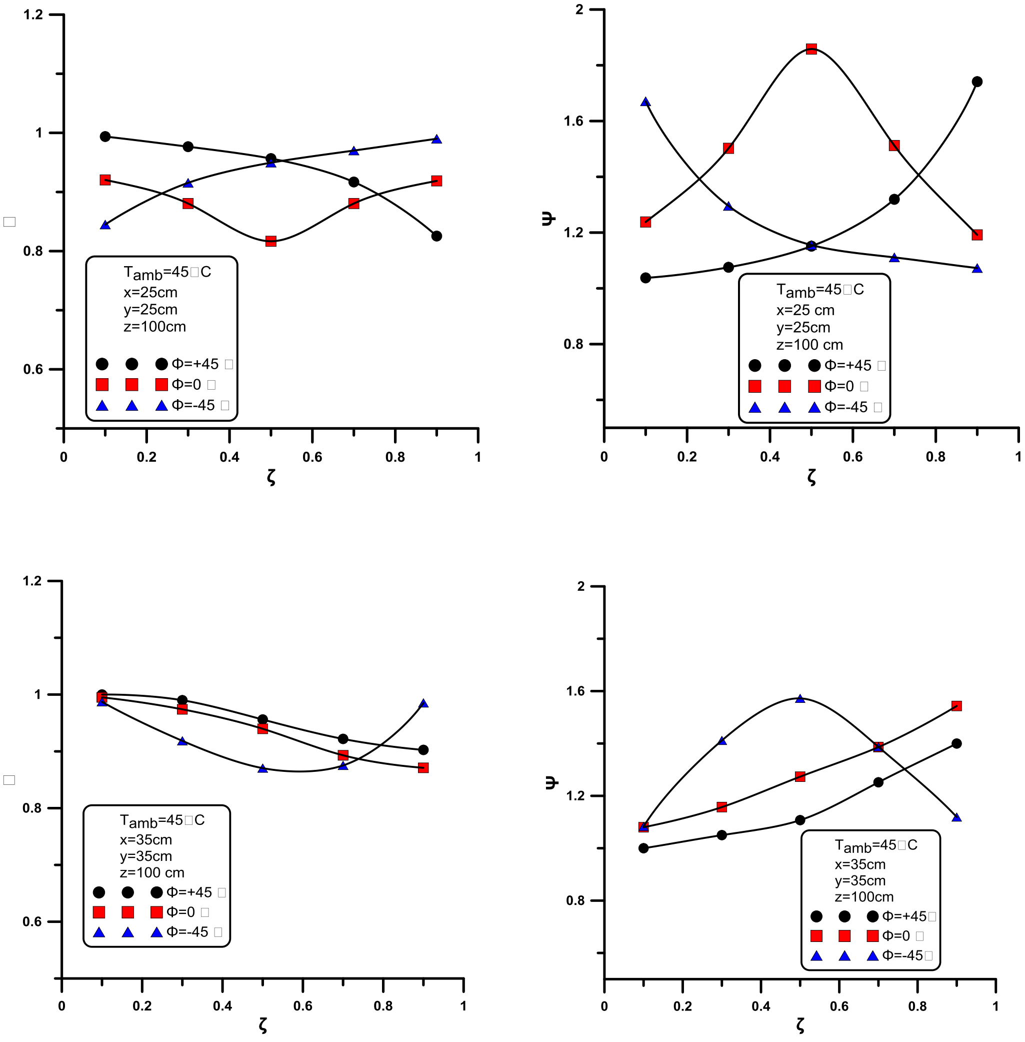


Figure (8): The effect of atomizer vertical location on air properties; left: temperature distribution, right: relative humidity distribution; at flow ratio of 325.



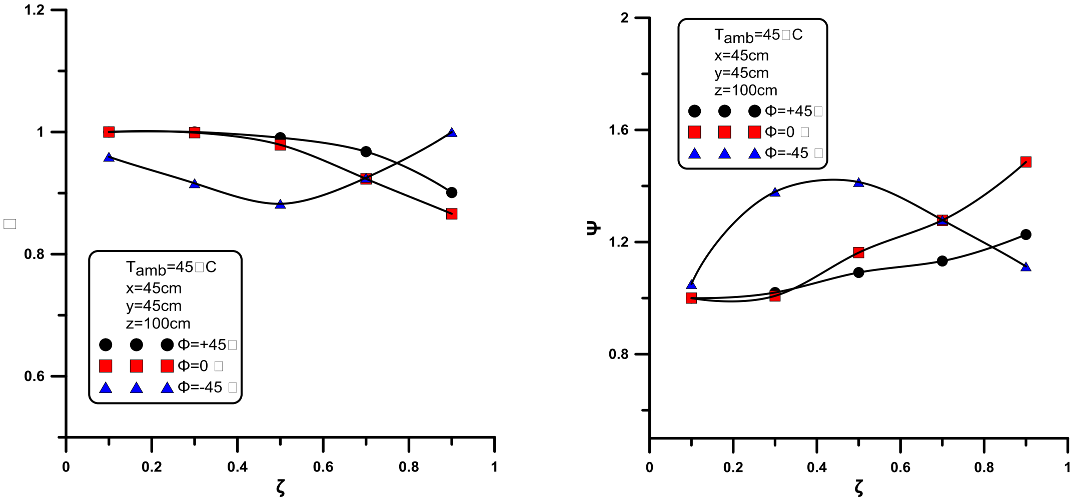
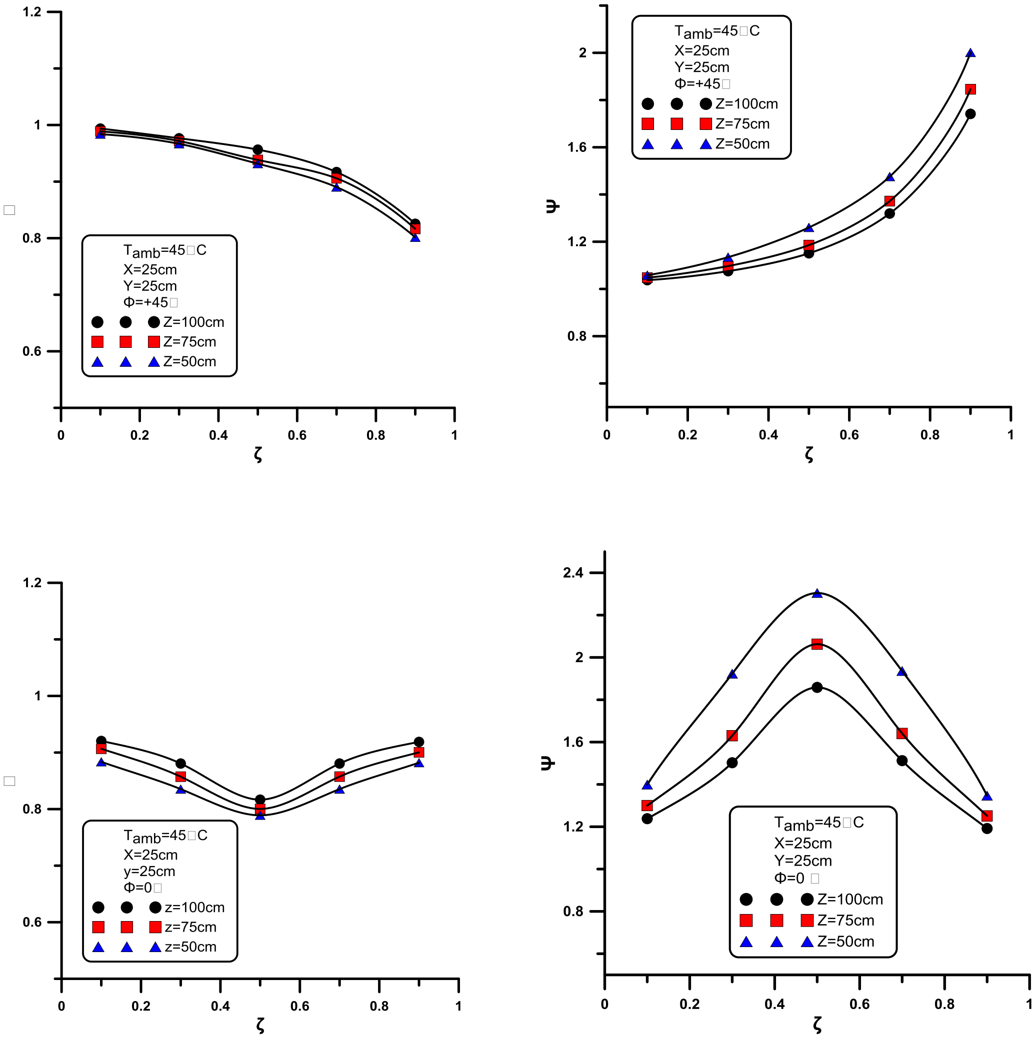


Figure (9): The effect of atomizer yawing angle on air properties; left: temperature distribution, right: relative humidity distribution; at flow ratio of 325.



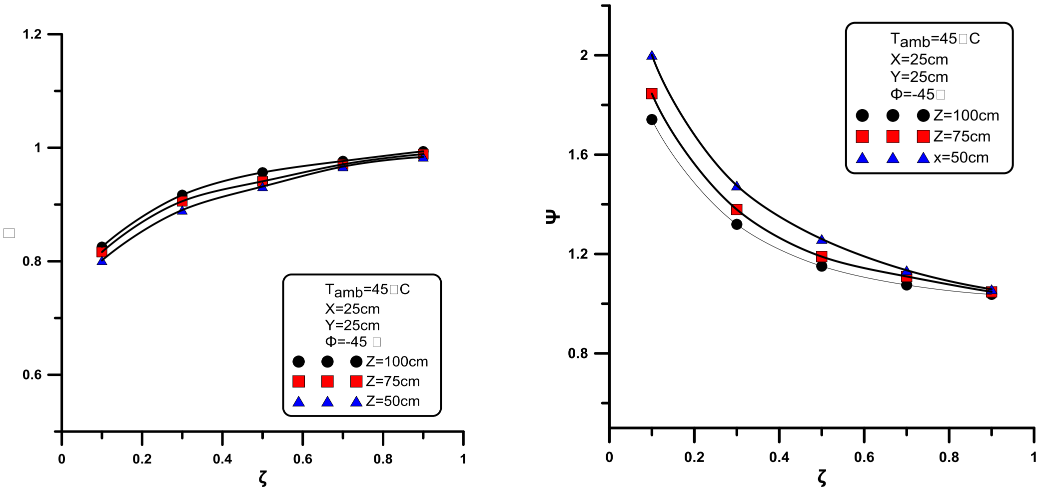


Figure (10): The effect of atomizer axial location on air properties; left: temperature distribution, right: relative humidity distribution; at flow ratio of 325.

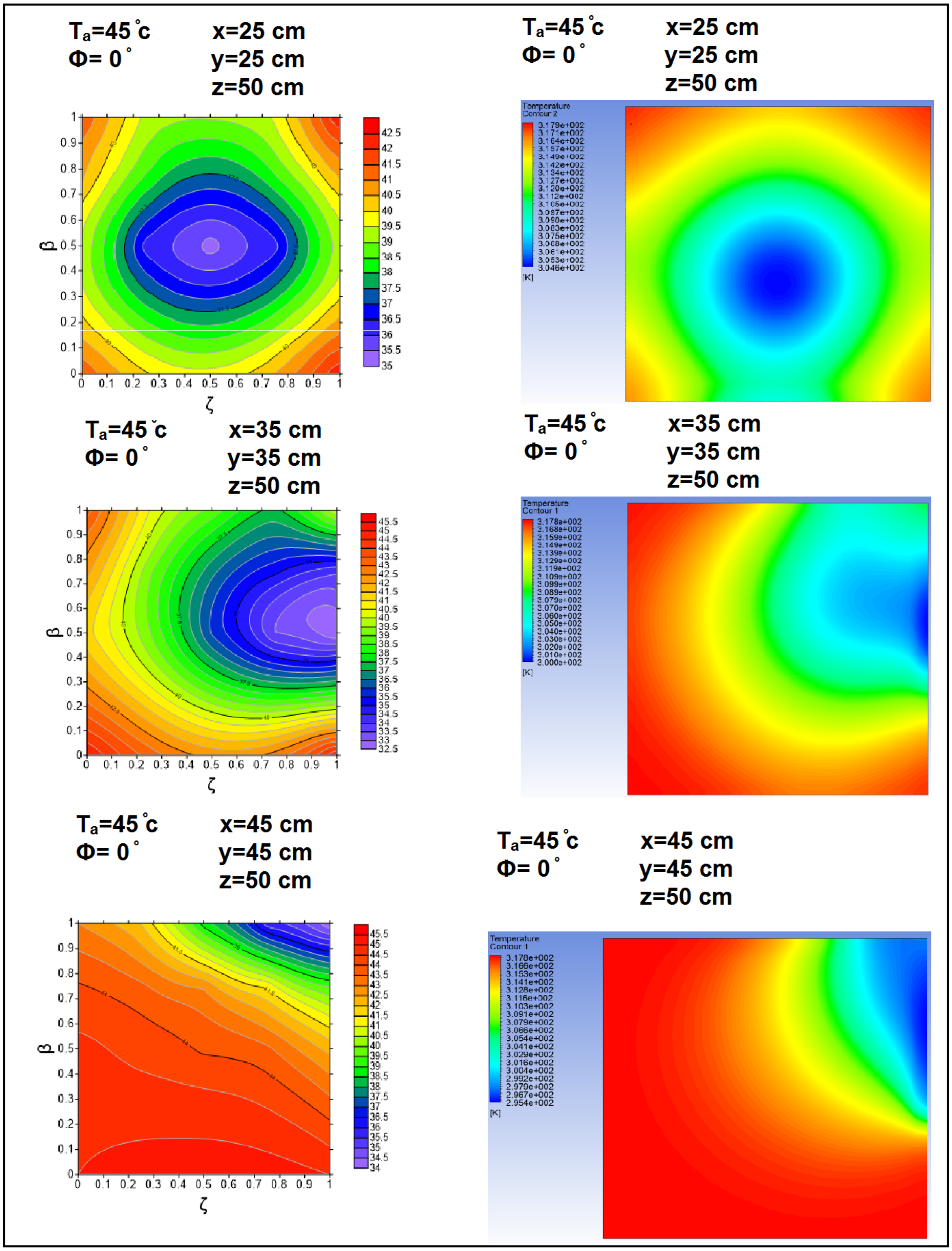
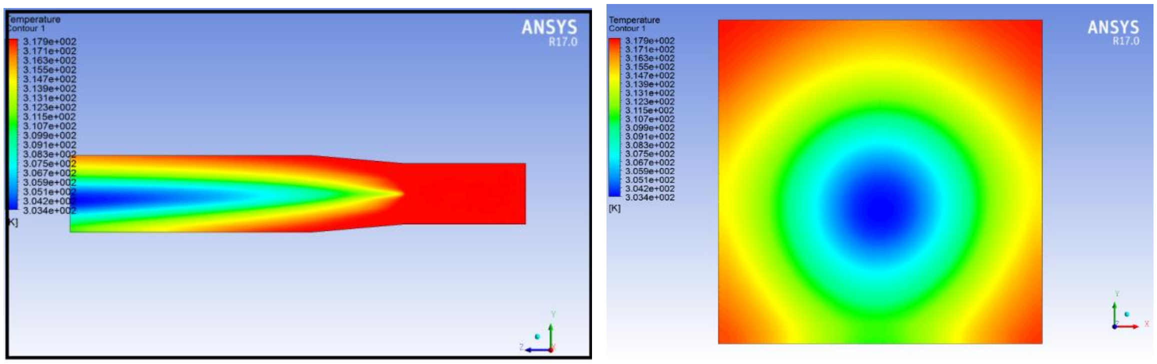
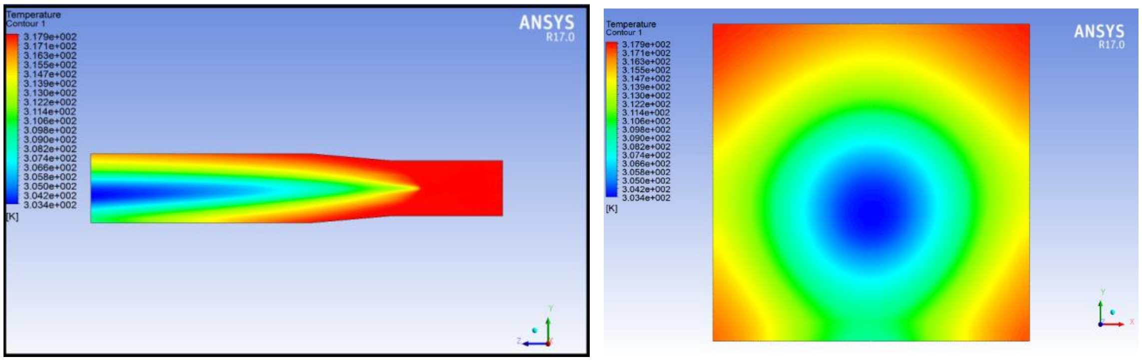


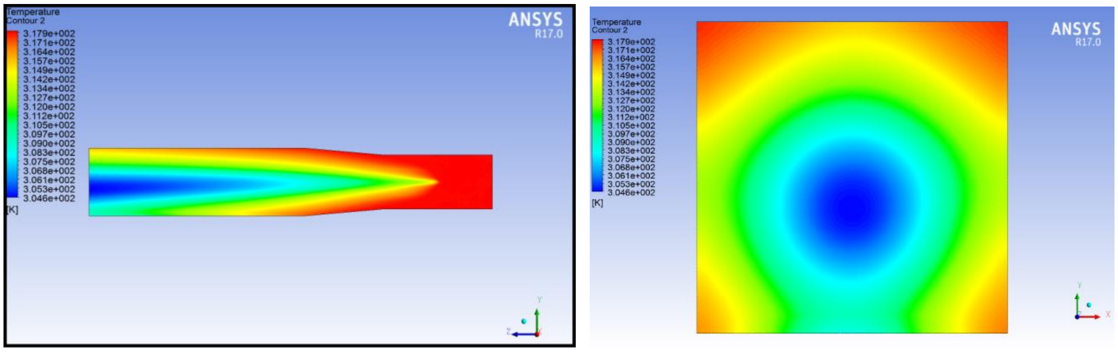
Figure (11): Temperature distribution in transverse section at different injection points, left experimental result, right: numerical simulation.



Z= 100 cm



Z= 75 cm



Z= 50 cm

Figure (12): The variation of the air temperature at injection in the centre of duct, at Φ=0° left: in the YZ planar side view, right: in the XY planar.

5- Conclusions

1. The drier the air, the better the humidification and cooling process will be. At the higher ambient temperature of 45°C corresponding to the relative humidity of 20%, the maximum temperature reduction was 12.2%. The corresponding increase in the relative humidity was 38.9%. This result is obtained at the flow ratio of 325 and with atomizer yawing angle of Φ=0°.

2. Increasing the water atomization rate brings more improvement in the humidification process. Reducing the flow ratio from 650 to 325, gives an improvement in the relative humidity of 82%, with corresponding improvement in the reduction in temperature of 72%.
3. Moving diagonally towards the corners causes the humidification and cooling of air to decline, yet, when directing the spray towards the core of the flow the process is significantly improved regardless the location of the injector.
4. The middle of the duct introduces the optimum atomizer position for single point spray defined by (X =25cm, Y=25 cm) and an orientation of 0° to the axial flow.
5. Better humidification and cooling of air is obtained as injection is advanced by 50 cm prior to the divergent section, representing the effective evaporation distance of sprayed water.

CONFLICT OF INTERESTS.

- There are no conflicts of interest.

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الخلاصة

أجريت دراسة عملية وتحليلية لاستخدام حقن الماء في عملية ترطيب لهواء مستقر الجريان عبر مجرى متباعد من نفق هوائي. تهدف هذا البحث لدراسة الوضعية الامثل لحاقنة ماء منصوبة في مجرى هوائي منفرج المقطع وتخمين انعكاس ذلك على عملية خلط السائل والغاز في عملية ترطيب هواء. التجارب العملية تم اجرائها في نفق هوائي مربع المقطع بضلع 50cm يشتمل على جزء يتحول بالانفراج التدريجي الى مقطع مربع بضلع 63 cm يجري فيه الهواء بمتوسط سرعة m/s5 بما يتوافق مع عدد رينولدز قدره 1.5 X 10^5. اعتمدت هذه الدراسة لنسب دفق كتلي بين 300 الى 600 ولمدى من درجات حرارة محيطية يقع بين 30^oC و 45^oC. اظهرت النتائج التجريبية انه عند اي موضع ضمن المقطع داخل المجرى المتباعد فأن الوضعية الامثل للحقن هي عند توجيه الرشة نحو قلب الجريان والتي تحقق أفضل ترطيب وتبريد للهواء. لقد كانت الوضعية الامثل للحقن المنفرد هي عند مركز المجرى مع اتجاه الجريان، اي عند زاوية تارجح 0^o. كلما تحركت الحاقنة نحو الجدار كلما ضعف التاثير التبريدي للرش. عند درجة حرارة محيطية 45^oC ونسبة دفق كتلي 300 كانت الزيادة القصوى للرطوبة 43.8% والتبريد الاقصى هو 15.2% عندما ثبتت الحاقنة عند مسافة 50 cm قبل المقطع المنفرج. اشتملت الدراسة ايضا تحليلا عدديا باستخدام الحزمة البرمجية ANSYS FLUENT 17.0 COMMERCIAL CFD، لتدقيق مطابقة معطيات الدراسة التحليلية مع النتائج التجريبية المستحصلة لنفس الظروف التشغيلية.

الكلمات الداله: مجرى متباعد، تبريد مدخل الهواء، نظام التبريد الضبابي، الترطيب.