Kufa Journal of Engineering
Vol. 11, No. 1, January 2020, P.P. 52-64
Received 26 August 2019, accepted 29 September 2019

THE EFFECT OF CURVATURE RATIO ON THE EVAPORATIVE COOLING OF AIR FLOW THROUGH BENT DUCT

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HTTP://DX.DOI.ORG/10.30572/2018/KJE/110104

ABSTRACT

This study investigates the effect of curvature ratio on the liquid-gas mixing in an air humidification process by choosing the optimum positioning of nozzles matrix fixed prior to a bent duct. The present study is considered as a simulation of the gas turbine compressor inlet air cooling by the fogging technique. The experiments were conducted using a wind tunnel with an average air velocity of (5 m/s) through a 50 cm square cross sectional duct. The study employs three curvature ratios of 0.25, 0.5 and 0.75. Also three nozzles tilt angles were tested at – 45°, 0° and 45° with respect to the axial air flow direction. The design and the configuration of the nozzles matrix is decided according to the flow structure extracted from numerical simulation using CFD analysis with RNG-k-ε turbulent model. The results indicate that a curvature ratio of 0.75 gives the best performance of the humidification system when the nozzles matrix installed as far as possible prior to the bent duct giving enough residence time for the injected droplets to evaporate. At nozzles tilt angle of 0°, the relative humidity increased about 53.63% and the corresponding reduction in air temperature was 17%. Therefore, the optimum position of the nozzles has been shown in this study is at 1.5 m prior to the curve and a tilt angle of 0° when using the largest curvature ratio of 0.75 due to the shrink in the separation zone accompany the weakening of centrifugal forces. This effect would widen the mixing area for the two streams to react and producing better cooling and humidification of the air.

Keywords: Curved Duct; Curvature Ratio; Compressor Inlet Air Cooling; Fogging System; Humidification System.

1. INTRODUCTION

Fluid flow in a bent duct or pipe bend is very common in engineering applications and has a significant importance for the designers of industrial equipment. Such equipment are heat exchangers, turbomachinery, aircraft intakes, fittings, HVAC appliances, turbine and blade passages, cooling and heating applications, and several other equipment.

Dean, (1928) was the first who proved mathematically the appearance of a pair of counter-rotating vortices (Secondary flow) for the fully developed in Newtonian viscous fluid in a bent duct. When fluid flows in a bend, a secondary flow is developed as a result of the outward driven fluid particles near the surface; this secondary flow is superimposed on its primary axial flow leading to a high velocity at the outer core of the bend, as explained by Dutta and Nand, (2015). Thereby, secondary flow enhancing the rates of heat and mass transfer over their straight-duct values, as was illustrated by Pratap, (1975).

Humidification systems are able to add water vapor to the air, and they fall into one of two distinct process categories, adiabatic and isothermal. In the adiabatic mode, all the heat energy for evaporation is taken from the air itself, leading to an increase in the humidity ratio of the air and a reduction in the dry bulb temperature. Most of the adiabatic processes are realized by evaporation from an atomizing water spray, a wetted medium, but in the isothermal mode (no cooling), the heat energy of evaporation water is supplied from a source other than the heat of the air as used in air steam injection causing increase humidity ratio and the temperature of the air is kept unchanged, as mentioned by Morton, (2015).

The generation of smaller diameter droplets increasing the interfacial area between water and air, and thus producing a higher rate of evaporation and humidification. The methods of sprays are also primary importance in determining the shape and penetration of the resulting spray, as described by Wang, (2001).

Sudo et al., (1998) conducted an experimental study on the turbulent flow through a smooth walls pipe with 90° bend has a curvature ratio of (δ=1.5). The technique used is the hot wire of rotating probe with an inclined wire. Results show that the presence of a pair of vortices due to the acceleration of the primary flow near the inner wall, which led to the generation of secondary flow moving from the outer to the inner wall of the bend occurs in the bend and remains even at L/D=10. A three-dimensional numerical study was carried out by Boutabaa et al., (2009) to simulate the developing of the secondary flow of the Newtonian viscous fluid passing through a square curved duct have a curvature ratio of (δ=15.1) when using a Dean number of (Dn = 125, 137 and 150). The result showed only two-vortex at Dn=125 due to weak centrifugal force. However, at Dn=137 the additional pair of vortices starts to appear at θ=90° and at Dn=150 the centrifugal forces become stronger and the additional pair of vortices starts form θ =80°. The result was compared with previous works and give acceptable convergence. Ahmed et al., (2012) studied experimentally the effect of the atomizer positions within a curved duct on the process of air humidification with Re = $4.16*10^5$ and Dn = $4.8*10^5$. The water atomizer rate of 0.24.ml/s was used in the study. The results showed that the lower half of the curved duct is less sensitive to the single point atomizer position for a range of tilt angles between 10̊ to 45̊ for radial locations between 0.05 to 0.20 m from the inner wall, and this region most suitable for using atomizing array injectors to give an acceptable performance of humidification. Nevertheless, the upper halve of curved duct introduces the optimum position of single-point spray at radial diameters (R_i/R_C=3.2) with tilt angles of -10° to the tangential flow. Dutta et al., (2014) investigated numerically the incompressible air turbulent flow through 0.104 m diameter pipe with a 90° bend, using two curvature ratios of δ= 0.5 ,δ=1.5 at Reynolds' number equal to 6×10^4. The velocity vector distributions appear that the resulting secondary motion is obviously caused by the fluid transition from the inner to the outer wall of the curvature leading to separation. In the case of δ= 1.5 no fluid separation occurs whilst in the strong curvature case of δ= 0.5 separating flow appears along the inner core. Kim et al., (2014) showed an assessment that is done to simulate the flow in a 90-degree- curved tube with a curvature ratio of δ=1.5 that the RNG k-ε turbulence model gives good results for primary streamwise velocity and secondary swirling velocity profiles compared to other turbulence models. It is found that the intensity of swirling secondary flow is a strong function of curvature ratio and a weak function of Reynolds number. Mohammed and Nasser-Allah, (2017) conducted an experimental study aiming to specify the optimum atomizer position on the air cooling by the fogging technique downstream a curved duct with (50×50 cm) cross sectional area at Re of 4.16×105 and Dn of 4.8×105 . The study showed that the maximum temperature reduction at a higher ambient temperature of 45.2 C° (DBT) was 26 % and an increase in the relative humidity ratio of 2.13 when using the ratio of air to water 1000 and the position of the atomizer in the central and tangential to the flow direction. The atomizer location shows less sensitivity to atomizer injection upward through the range of angles of 25° to -75° and this situation is most suitable for using matrix of atomizers across the duct. On the other hand, the central location with tangential spray gives the critical position for a single-point spray. The optimum atomizer place specified by a radius ratio of R_i/R_C=3 and tangential orientation to the direction of flow. Dutta and Nandi (2018) studied numerically the effect of curvature ratio and Reynold number on the separation and reattachment of the flow and the occurrence of the Dean vortices in 90-degree bend pipe at three pipes bend with curvature ratios of 0.25, 0.5 and 0.75. It has been observed that as curvature ratio decreases leads to increase the spatially separation zone. The formation of separation zone is largely dependent on the value of curvature ratio and it is less dependent on Reynolds number.

Evaporative air cooling is a simple and effective method of cooling the hot dry air, such a system provides an inexpensive, energy efficient, environment friendly (not causing ozone-damaging by used CFC compounds) (Maurya et al., 2017).

The power output and fuel consumption of the gas turbine are highly dependent upon the mass flow rate, quality, and the ambient temperature of the air drawn into the unit. Hence, there is a need to boost the gas turbine power output during the peak load periods during hot summer because the high temperature causes the air density to be less, reducing the mass flow of compressor intake air.

The motivation of the present work is to improve the compressor inlet air cooling of a gas turbine generating unit using fogging technique by changing the curvature ratio of the bent portions of the inlet air ducting system of the unit. This can be done by specifying the optimum position of the nozzles matrix including best curvature ratio, as well as, the nozzle tilt angle and effective axial distance prior to the bent portion.

2. EXPERIMENTAL SETUP

The test rig used in this study is mainly a subsonic wind tunnel having a square cross section with 50 cm sides. The layout of the wind tunnel schematically is displayed in Fig. 1. The air enters the wind tunnel through a bell mouth shaped duct that aims to reduce the effects of inlet turbulence and produce steadily flowing air. The bell mouth is connected to the first 3 m straight duct to accommodate the presence of inlet air preheaters and humidifier. The bent portion is connected to the end of the first straight duct to generate the secondary flow needed to help mixing the injected water with the air stream. In the present work, three bent ducts were used with curvature ratios of 0.25, 0.5 and 0.75 as shown schematically in Fig. 2. These curvature ratios ($\delta = R_c/D_h$) are chosen according to the regulations of ASHRAE, (2000). The downstream end of the bent duct is connected to another 3 m straight duct leading the air to the axial fan running at 1500 (rev/min) which is responsible for the induction of air through the wind tunnel. The airflow is adjusted by double butterfly gates built into the fan outlet. The air mean velocity at fully opened gates is about 5 m/s, (Re = $1.43*10^5$). The air inlet condition is kept fixed throughout all tests at 45 °C dry bulb temperature and 15% relative humidity. The air temperature is adjusted using eight electric preheaters with total capacity of 24.5 kW controlled by using 6250 W variac and four steps on/off buttons, the heater is shown in Fig. 3-A . On the other hand, a steam humidifier is used to fix the relative humidity of the air leaving the heaters to the desired value (15%). The steam humidifier consists of two heaters with total capacity of 15 KW arranged in two steps. The steam is delivered to the wind tunnel by a steam distributor, as shown in Fig. 3-B.

The properties of the humid air are measured using a DHT22 ARDUINO system containing 25 DHTD22 sensors measuring the humidity and temperature at the main test section installed at the fan entrance. The data from ARDUINO system are sent to a PC to be saved and analyzed, as shown in Fig. 4 A and B. There also four sensors are installed after the air treatment system to ensure that the simulated ambient condition is at the desired values. The nozzles matrix containing nine nozzles with a 0.1mm diameter nozzles placed in the first straight duct with the ability to be moved axially in advance to the bent duct inlet. The matrix is connected to the fog machine supplying water under a pressure of 70 bar, as shown in Figs. 5 and 6. The nozzles are capable to rotate from – 90o to 90o with the axial flow direction. The character Z is the nozzles matrix axial location prior to the bent duct and ϕ is the nozzles tilt angle relative to the axial flow, as shown in Fig. 7. The water flow rate was measured by Rotameter-1100. Measuring the air velocity is done using standard elliptical nosed Pitot-static tube installed in the first straight duct. The average air velocity of the whole section is determined by equation (1) below:

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

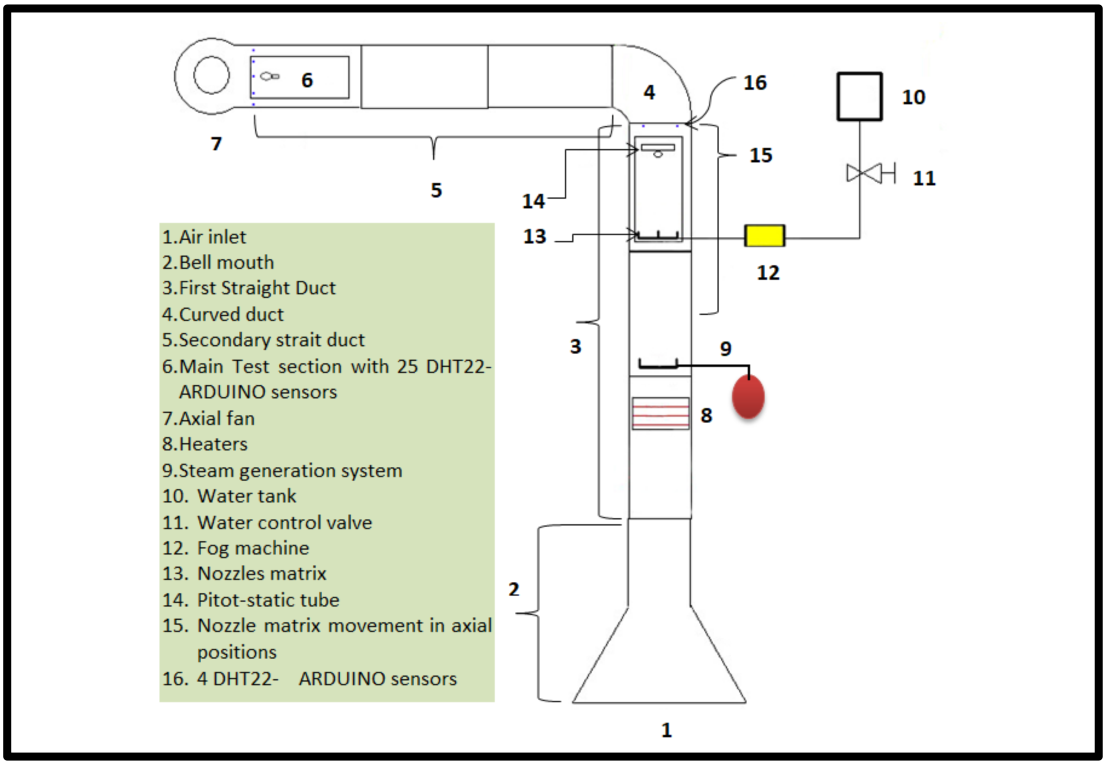

Fig. 1. Top view of the Test Rig with installation of fog machine, air heating systems, steam generation systems, steam distributor, and all other component.

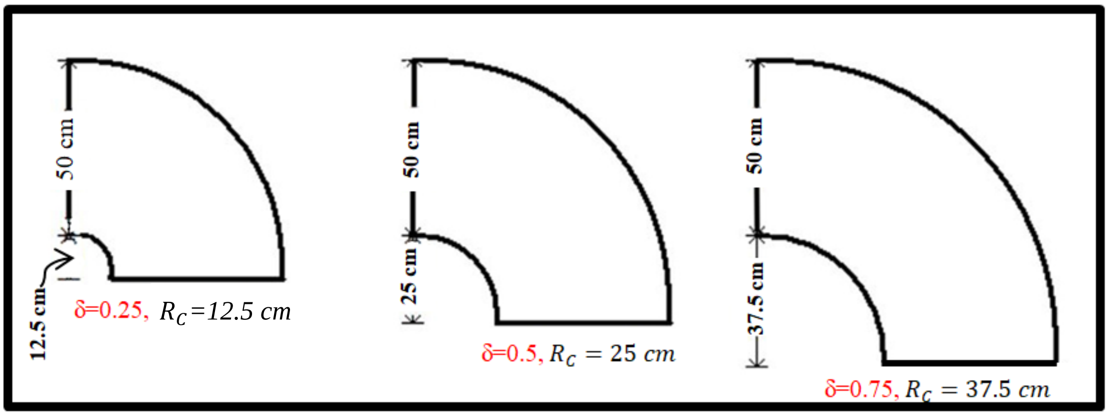

Fig. 2. Three bent duct with curvature ratio (δ=0.25, δ=0.5, δ=0.75) with (50*50) cm square cross section.

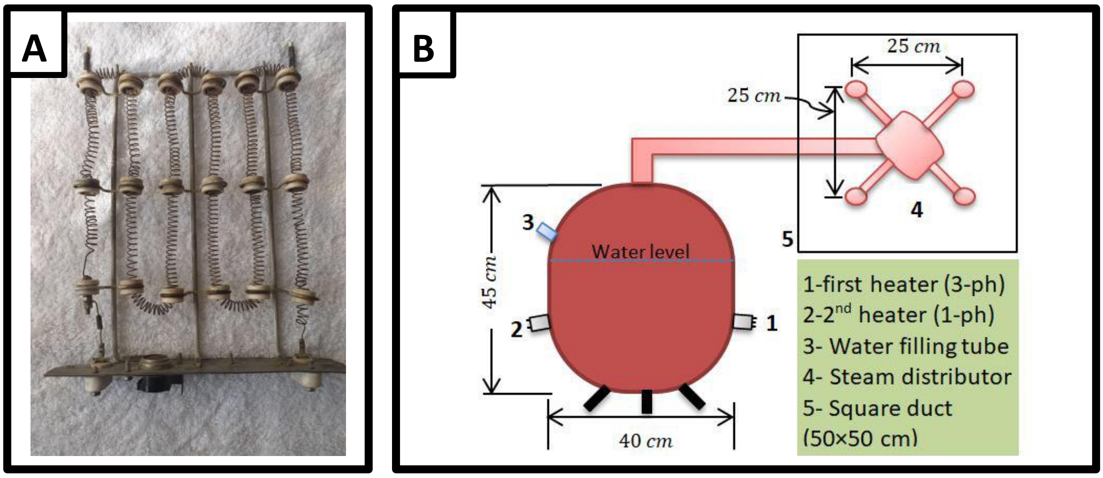

Fig. 3. (A) Air heater; (B) steam generation systems.

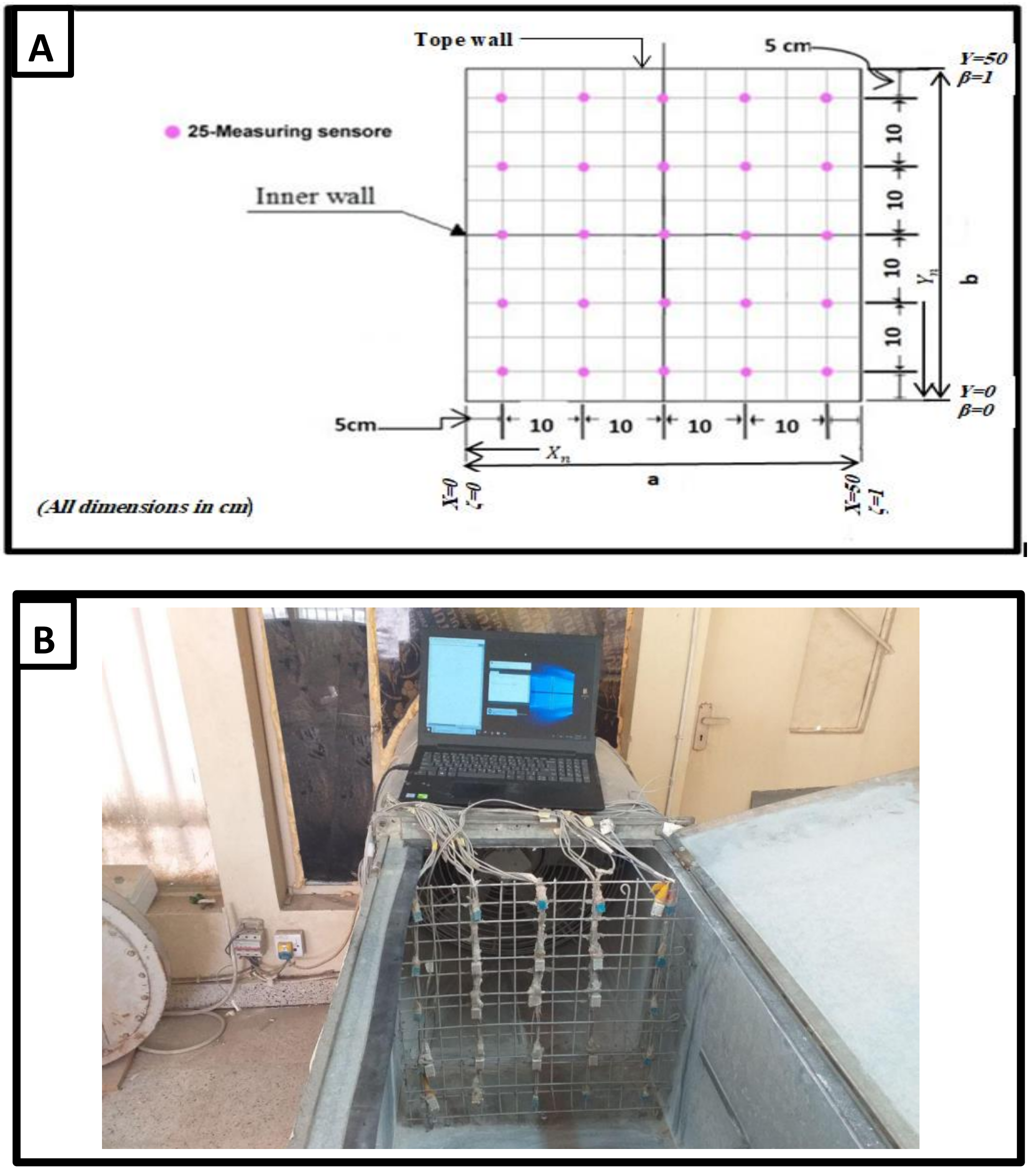

Fig. 4. (A) and (B) the measuring sensors distribution in cross sectional area of main test section.

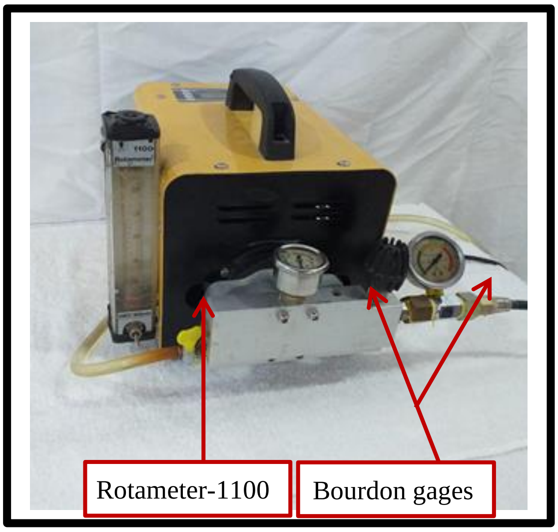

Fig. 5. Rotameter-1100 and Bulb Water Flow Meter.

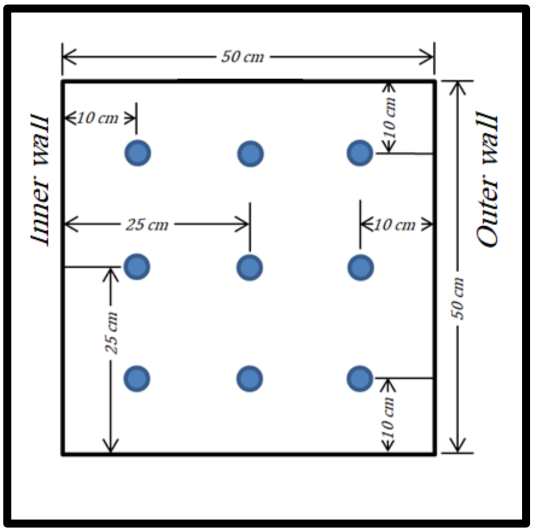

Fig. 6. The nozzles matrix with illustration the distances between the nozzles.

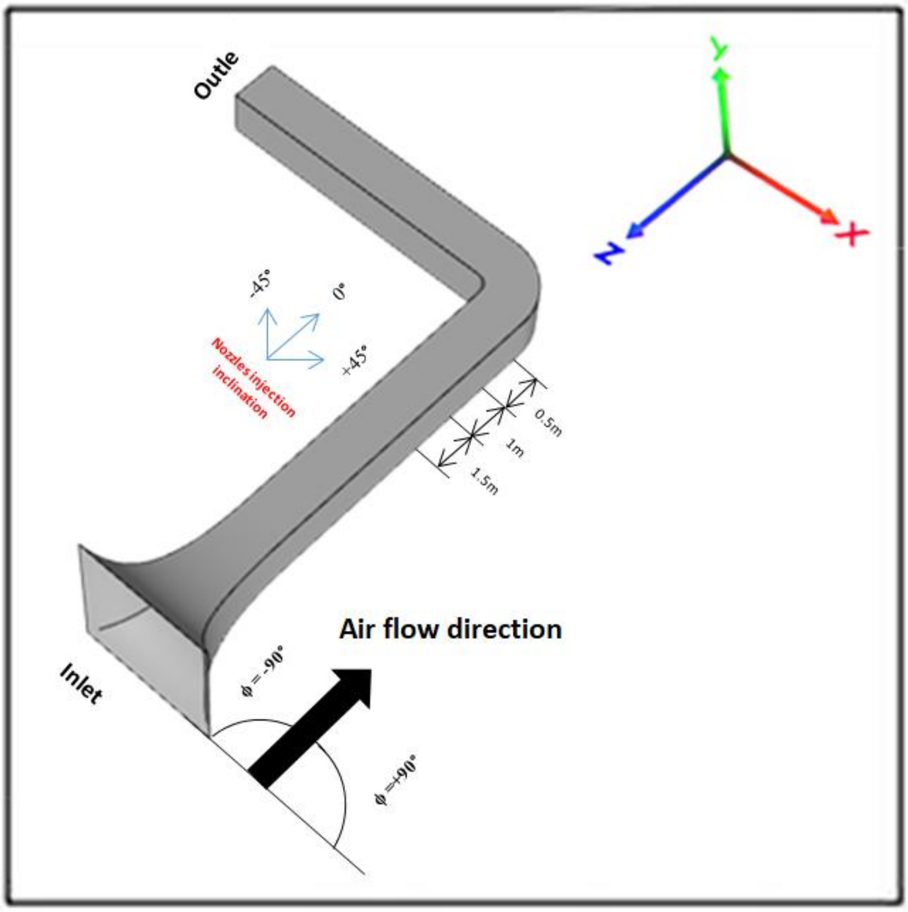

Fig. 7. The schematic of wind tunnel illustrating the movement of the axial nozzles matrix and the nozzles tilt angle relative to the axial direction.

3. RESULTS AND DISCUSSION

Advancing the injection spot relative to the bent duct entry will improve the humidification and cooling of the air as shown in Fig. 8. When the nozzles matrix is moved 1.5 m backward, the average decrease in air temperature is about 19%, while the humidity raised about 29% compared to that when matrix installed just at the bend entry. This improvement is attributed to the longer distance the droplets travel down to the test section. In other words, more time is available for the droplet to complete evaporation and mix with the surrounding air, i.e., the residence time for water droplets to exchange heat and mass with the carrying air.

The angle at which water spray is directed has a noticeable effect on the humidification of the air stream. Directing the spray axially with the air flow, i.e. at angle 0o gives a good cooling extent of about 17% since most of the cross section is exposed almost evenly to the water droplets which their fallout on duct walls is less possible, see Fig. 9. Nevertheless, if the spray is tilted towered the inner wall of the duct, i.e. with angle – 45o, the improvement is nearly the same because at this direction the droplets are drifted to the center of the flow due to the centrifugal forces created by the secondary flow within the bent duct. In that manner, the mixing between water and air is enhanced as the mixture travelling down to the end of the wind tunnel. Yet, directing the spray towered the outer wall of the duct at 45o makes the cooling to weaken due to the drift of water droplets to the outer region of the flow field. As the centrifugal forces taking the droplets outward with less possibility to return back to the center of the duct, more droplets will fallout on the outer wall and miss the opportunity to meet air and mix to give the desired cooling and humidification.

Fig. 10 depicts the variation in air temperature and humidity with a curvature ratio of the bent duct. It is obvious that as the curvature ratio is increased, the air temperature is reduced representing better cooling extent. This caused by the shrinking in the separation zone due to the weakness of centrifugal forces. As a result, a pair of vortices is pushed close to the inner wall and enhancing the mixing rates in that half of the duct while mixture travelling down to the end of the duct. On the other hand, as shown in Fig. 10, the outer half of the duct seems less sensitive to the variation in curvature ratio whatever the direction of spray will be.

Fig. 11 gives the contour view of the air temperature distribution across the duct at the test section. It can be easily realized that the coolest area of the flow is mostly concentrated in the lower right half of the duct due to both the centrifugal drift and gravity effects of denser water droplets. Nevertheless, the situation in which most of the duct is cold is that when the spray is directed axially with the flow. That is due to better distribution of water droplets within the air stream.

The decision of the optimum positioning of the nozzles with respect to the flow direction can be drawn out Fig. 12 which showing the average improvement in air cooling and humidification with the variable tilt angle at different curvature ratio. Fig. 12 revealed that the best performance of the spray system is obtained with a duct has a curvature ratio of 0.75 when directing the spray axially with the flow. i.e. at 0o nozzles tilt angle. This realization accompanies the fact that the water injection should start as earlier as possible prior to the bent duct such that droplets will have enough time to evaporate and mix with the air stream.

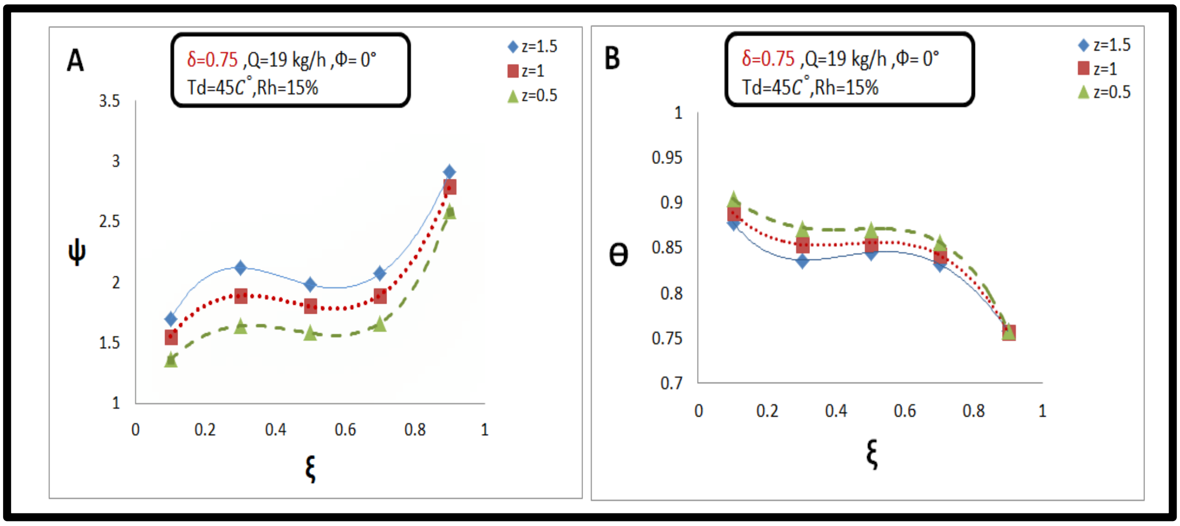

Fig. 8. The effect of nozzles matrix axial location on the air properties; (A) Relative humidity distribution, (B) Temperature distribution.

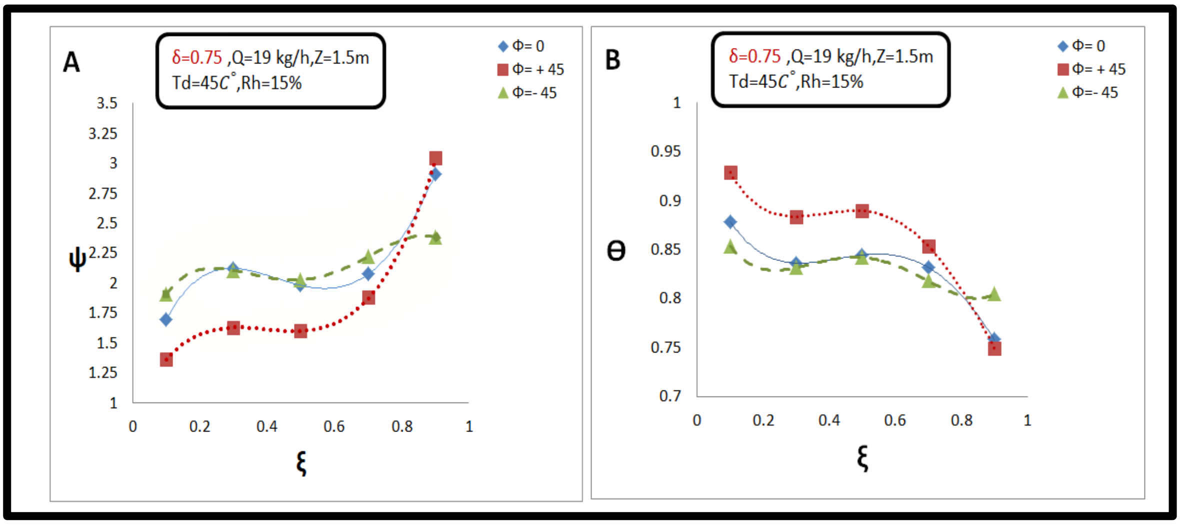

Fig. 9. The effects of nozzles tilt angles on the air properties for bent duct with δ=0.75; (A) Relative humidity distribution, (B) Temperature distribution, at z =1.5m.

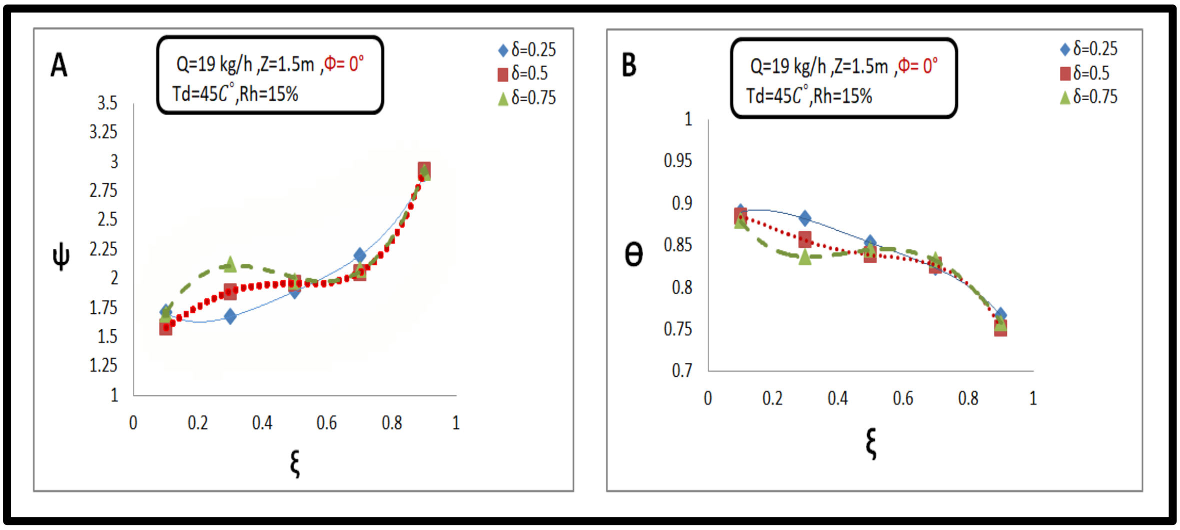

Fig. 10. The effect of curvature ratio on the air properties; (A) Relative humidity distribution, (B) Temperature distribution.

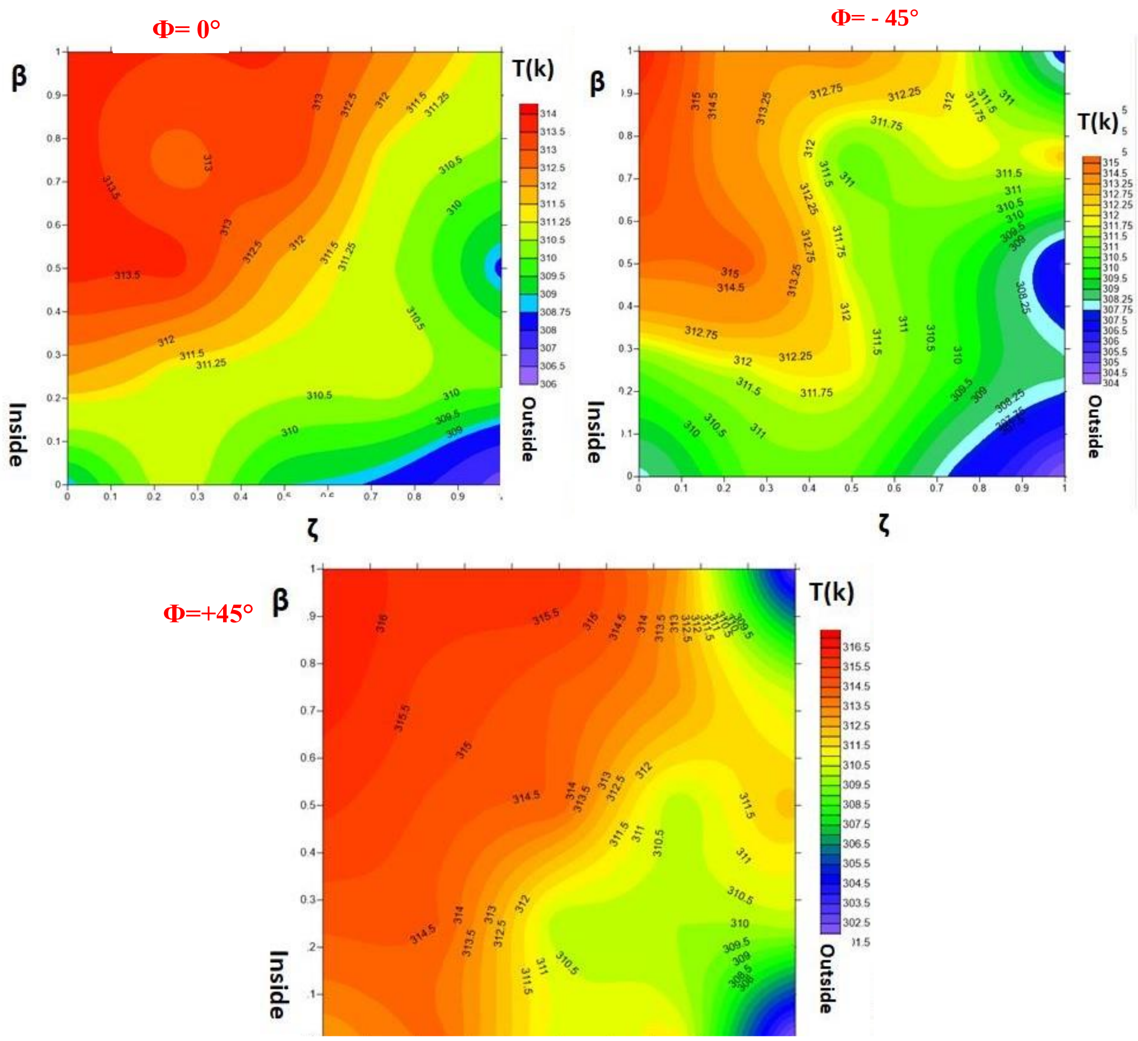

Fig. 11. Temperature contours of the humidified air for different nozzles tilt angles, at δ=0.25 and at axial location z=1.5m.

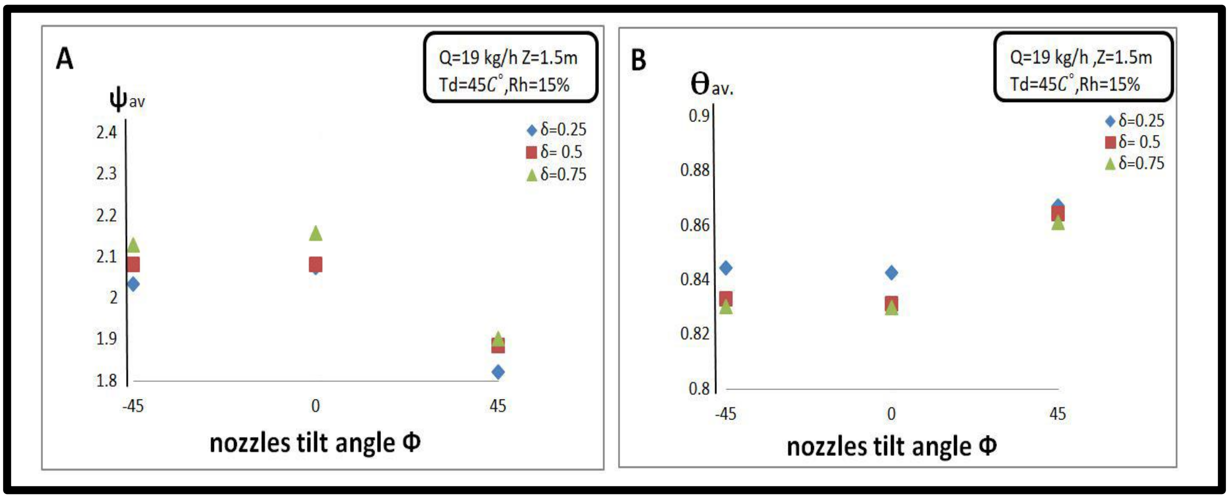

Fig. 12. The general chart of combined curvature ratio and tilt angle; (A) Average relative humidity distribution, (B) Average temperature distribution.

4. CONCLUSION

- The earlier the injection starts, the better cooling and humidification results due to longer residence time the droplets have while travelling downstream the curve duct.
- Directing the spray axially with the flow make most of the flow field exposed to the water droplets, with less possibility to fallout on the walls. Hence, this will enhance the mixing and cooling of the air stream.
- Increasing the curvature ratio leads the separation zone to shrink and thus the mixing area is widening as the mixture travel downstream.
- Optimum performance of the spray system is obtained with a bent duct having a curvature ratio of 0.75 with the nozzles directed axially with the flow, i.e. at 0^o tilt angle.

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