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HYDRAULICS OF SURFACE POLLUTED WATER - JET IN OPEN CHANNEL FLOW

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Presented in this paper are the results of an intensive experimental program for studying the influence of jet inclination, velocity ratio, pollutant type and initial concentration on hydraulic characteristics of polluted surface water jet in open channel flow. Polluted jet is injected from a sided polluted source with different angles of inclination to mainstream direction. The polluted water is prepared by adding two types of chemicals (sodium chloride and pfennig) with different concentrations to fresh water. The initial jet velocity is varied to cover a range of velocity ratio R from 2.73 to 10.0. For each velocity ratio, the solute concentration is changed to take 800, 1050, 1382.23, 1440, 1780 and 2320 p.p.m .The centerline jet trajectory, velocity decay, pollutant dilution and the width of polluted area are measured. The velocity is measured by a calibrated current meter while the jet coordinates and water depths are measured using point gages. Samples are taken from jet centerline to measure the jet concentration. The concentrations are measured using Conductance /Total Dissolved Solids Model 76.

The factors influencing the problem are normalized with the help of dimensional analysis theory. The analysis of the results revealed that the characteristics of a polluted water jet in cross-flow depend mainly on jet to main stream velocity ratio and jet inclination to the main stream. Also, the decay of the velocity and dilution of pollution concentration are mainly depending on the studied parameters. The type of pollution does not affect these characteristics. Equations have been developed for the correlation of the experimental results. A comparison between the results of present study and those from previous studies are carried out. These comparisons give a reasonable agreement.

KEYWORDS: *Open channels, Surface discharging jets, Pollutant concentration and type.*

1. INTRODUCTION

Turbulent jets discharging from circular outlets held inclined to a moving stream (as free jet) have received an attention in the past few decades [1,4,8-19]. Abozeid [1] presented a laboratory study on the factors influencing the characteristics of surface discharge of heated water jet in an open channel. Chassaing et al. [4] investigated the physical characteristics of jets in a cross-stream. Jirka [8] reported that, the jet penetration depends mainly on the velocity ratio R. One effective way of achieving proper mixing and dilution is to discharge the effluent near the river-bed as a turbulent free jet perpendicular to the river flow [6,9,17]. Another way of achieving this dilution could be to discharge the effluent from the river bank as a surface jet, tangentially to the river bed and directed perpendicular to the river flow [15]. Keffer and Baines [10] and Moussa et al. [13] observed that the jet velocity and temperature trajectories were mainly governed by the momentum ratio, while McGuirk and Rodi [11] used a two-dimensional depth averaged calculation method utilizing the k- ε model to predict the flow in the near field of a jet discharging from the side of a straight channel. Wright [18] presented a model of a round buoyant jet discharges normally to an ambient crossflow. The behavior was analyzed by considering it to be a source of kinematic momentum and buoyancy flux. Mohamed [12] presented the results if an experimental investigation on heated wall jets in a cross-flow and stated that the diffusion of heated wall jets discharged at right angles into a cross flow depends mainly on the velocity ratio and the shape of the nozzle. Ibrahim and Gutmark [7] conducted their experiments in a subsonic closed loop wind tunnel, and studied the effect of velocity ratio on the trajectory of the jet and compared his results with Yuan et al. [19] to confirm that jet trajectories rise and penetrate deep with increasing the velocity ratio.

Present study is performed experimentally to investigate the influence of pollutant type, velocity ratio and angle of inclination of the jet to main stream direction on the flow characteristics of the polluted surface discharging jet in a cross flow.

NOMENCLATURE

B	Flume bed width	S	Distance along the jet centerline
b	Width of the outlet	U_o	Mainstream mean velocity
C	Jet concentration along the centerline	V_j	Initial velocity of the jet
C_j	Initial concentration of the jet	V_m	Maximum jet velocity along C.L.
C_o	Mainstream concentration	x, y & s	Distances along the jet
D	Channel depth	X & Y	Cartesian coordinates in the horizontal plane of jet C.L.
D	Outlet diameter	W_y	Jet width
d_m	Maximum depth at which the jet will reach if it is not restricted by the bed	λ	Aspect ratio = b/h
		θ	Inclination angle of the outlet
F_d	Densimetric Froud number	μ	Dynamic viscosity of ambient fluid
G	Gravitational acceleration	ρ_j	Initial density of polluted jet
H	Outlet depth	ρ_o	Ambient fluid density
R	Velocity ratio = V_j / U_o	$\Delta\rho$	Initial density difference

EXPERIMENTAL SET-UP

The experiments were conducted in a tilting flume located in the hydraulics Laboratory of Civil Engineering Department, Assuit University. A schematic representation of the experimental set-up is shown in Fig. 1. A rectangular open flume having 600 mm wide, 250 mm deep 3.00 m long was used as a main open stream. The mainstream flow was supplied from an elevated constant head tank through a pipeline and was regulated and measured by means of a gate valve and orifice-meter located on the delivery pipeline, respectively. The water depths were controlled using a downstream tailgate. A circular nozzle issuing the side surface flow jet is located at 1.50 m from the flume inlet section. The nozzle set to take 45^o and 90^o to the direction of mainstream. The lateral emanating polluted water-jet was supplied from an elevated constant-head tank containing polluted water. The polluted water was regulated and measured using a valve and orifice meter located at the supply pipe respectively (see Fig. 1). A current-meter with 5 mm diameter was used to measure the velocities. The measurements of mean concentration of the pollutant along the jet trajectory in the mainstream were made using Conductance/Total_Dissolved Solids Model 76 which measure the concentration for a range from 0 to 10^4 mg/L. Compacted digital camera was used to take vertical photos for determination the co-ordinates of the polluted wall jet centerline and its spreading in the mainstream by using Auto-cade software program. The measurements were taken at a depth corresponding to the level of the outlet centerline. The trajectory bent as a result of the cross flow was determined by adding a dye to the polluted water. The x-y coordinates of the jet centerline were measured by using point gages and scales.

Procedures: The experiments are achieved to study the influence of jet inclination, velocity ratio pollutant type and initial concentration excess on the mean flow characteristics of the surface discharging polluted jet in a cross flow. The following procedures are followed in performing the experiments:

1. The nozzle of the polluted water supply was fixed and its angle of inclination was set to be 90^o with mainstream direction.
2. The mainstream flow rate and its water depth were regulated to be 13.73 L/s. and 9.6 cm respectively.
3. The control valve of polluted water (solute of sodium chloride) was adjusted to give a certain discharge and the concentration was measured. The concentration was changed to be 800, 1050, 1382.23, 1440, 1780 and 2320 p.p.m.
4. Co-ordinates (x, y), velocity, concentration and width of polluted water jet along the jet centerline were measured and a photo by digital camera was taken.
5. The polluted water jet velocity was changed several times to change the velocity ratio ($R= V_{j}/U_o$) from 2.73 to 10.00, and step (4) was repeated.
6. The concentration of the polluted water jet was changed and steps from 3-5 were repeated.
7. The angle on inclination was changed to be 45^o and steps from 1-6 were repeated.
8. The type of chemical pollution was changed to be pfennig and steps from 1 - 6 were repeated.

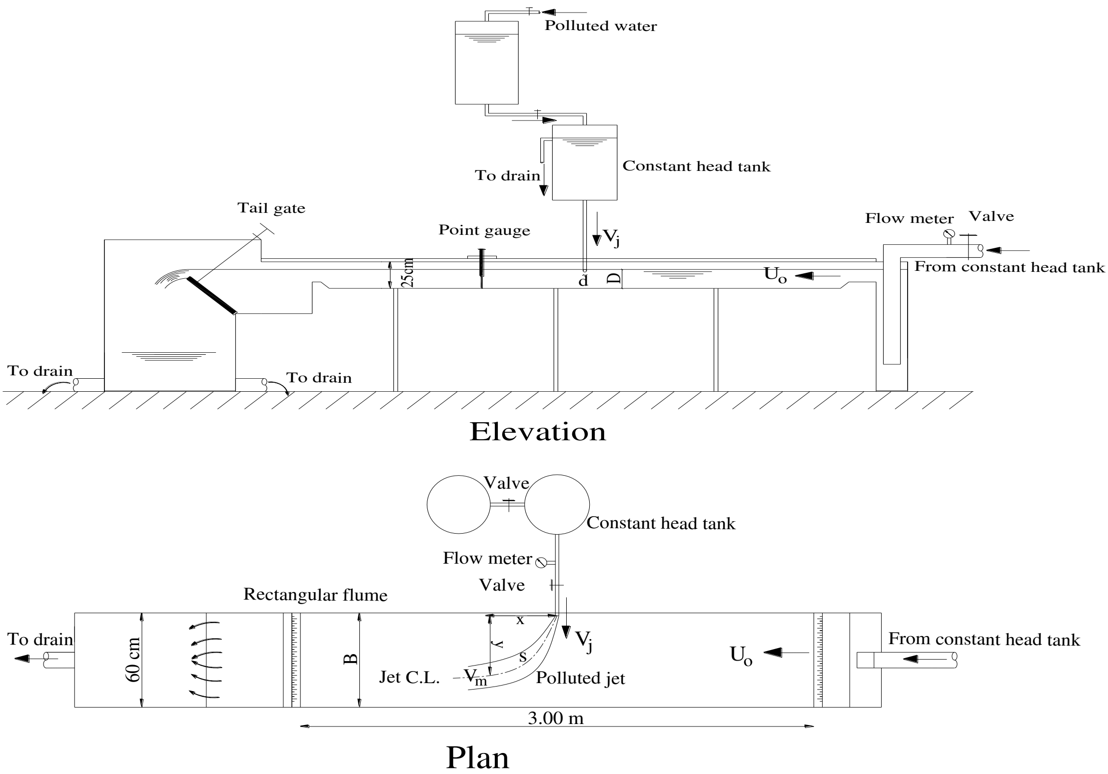

Fig.1: Schematic representation of the experimental set-up.

THEORETICAL APPROACHE

Theoretical formulation of the characterizing parameters of mean flow behavior of a surface side-discharging jet in a mainstream may be reached by dimensional reasoning. These parameters can have the following functional relationships;

$$\Phi_1 (B, D, d, \theta, U, V_j, V_m, C, C_o, C_j, x, y, s, g, W_y, \rho_o, \rho_j, \mu) = 0 \qquad (1)$$

If $\Delta\rho = \rho_j - \rho_o$ and applying the Backingham's "π" theory, in which d, U_o, and ρ_o are selected as repeated variables representing the geometrical dimensions, flow characteristics and fluid properties respectively, one can have:

$$\Phi_2 \left(\theta, C/C_j, C_j/C_o, V_j/U_o, V_m/V_j, x/d, y/d, s/d, W_y/d, U_o.\rho_o.D/\mu, V_j \Big/ \sqrt{gd\frac{\Delta\rho}{\rho_o}}\right) = 0 \quad (2)$$

in which $V_j \Big/ \sqrt{gd\frac{\Delta\rho}{\rho_o}}$ = densimetric Froud number, F_d (its effect is included in the effect of R). So, it may be dropped from equation (2). $U_o.\rho_o.D/\mu$ is the Reynolds number (R_e). In open channel flow R_e has insignificant effect; so it may be dropped from Eq. (2) [2 and 5]. Applying the properties of dimensional analysis and using the method of synthesis [3] one can get:

$$C/C_j,\ W_y/d \text{ and } y/d = \Phi_3 (x/d, \theta, R) \qquad (3)$$

$V_m/V_j = \Phi_4$ (s/d, θ, R) (4)

RESULTS AND DISCUSSIONS

Surface side discharge of polluted jet in a cross flow in shallow or deep water. It is considered to be shallow if $d_m / h \rangle 0.75$, while it can be deep if $d_m / h \langle 0.75$. The values of d_m can be calculated from the following equation [16].

$$d_m = 0.353hF_d(\lambda)^{-0.25} \tag{5}$$

in which λ is aspect ratio = b/h, where b is outlet width and h is outlet depth.

In the present investigation, the mainstream is considered to be shallow, where $d_m / h \rangle 0.75$ for all the studied cases. From his laboratory measurements, Abozeid [1] developed the following equation for the jet trajectory in shallow water;

$$\frac{y}{b} = 0.9\sqrt{R}\lambda^{-0.2}(x/b)^{\beta} \tag{6}$$

In which β is a constant depending on the angle of jet inclination to the mainstream, θ. For θ=90^o and θ = 30^o, β equals to 0.5 and 0.3 respectively. Also, Mohamed [12] and Mowad [14] developed the following equations for both the jet trajectory and mean jet width in shallow water respectively;

$$\frac{y}{b} = 1.55R^{0.65}\lambda^{-0.25}\left(\frac{x}{b}\right)^{0.35} \tag{7}$$

$$\frac{W_y}{Rd} = 0.93\left(\frac{x}{Rd}\right)^{0.49} \tag{8}$$

in which W_y is the jet width. The results of Eqs. (6-8) are compared with the results of the present study. The influence of velocity ratio, angle of inclination of the jet to mainstream, type and initial concentration on flow characteristics such as the jet trajectory, the growth of the jet width and the decay of velocity and the dilution of concentration-excess along the jet trajectory are investigated in this search.

Jet Trajectory: Figure 2 shows a typical plot of y/d values against x/d ones for velocity ratio 2.73 and θ = 90^o as an example. Also, the results of Eq. (6) and Eq. (7) are included. Also, the figure includes the estimated coordinates from photos by using Auto-cade software. From the figure, it is evident that the jet penetrates fast with the increase of x/d till a certain value of x/d, the jet moves with the mainstream flow. Agreements between the results of Abozied [1] and Mohamed [12] and also from the photos with the measured ones could be observed.

Shown in Fig. 3 is a comparison between jet trajectories for R = 10 at θ = 45^o and 90^o. It is clear that for θ = 90^o the jet penetrates deeper than that for θ = 45^o. This may be due to a higher momentum of the penetrated jet associated with θ = 90^o.

Results of y/d versus x/d for θ = 45^o with different values of velocity ratios, R are presented in Fig. 4. It is noticed that, the penetration of the emanating jet depends on velocity ratio, R. Where jet penetrates deeper with the high values of R than that with small ones. This may be due to the motion carrying the jet further in the transverse y direction is strongly dependent on the momentum of the jet with respect to the momentum of the cross flow, which is controlled by the velocity ratio (R). The best-fit relationship between y/d and x/d for different velocity ratios may be given in the following form:

$$\frac{y}{d} = aR^{c}(x/d)^{e} \tag{9}$$

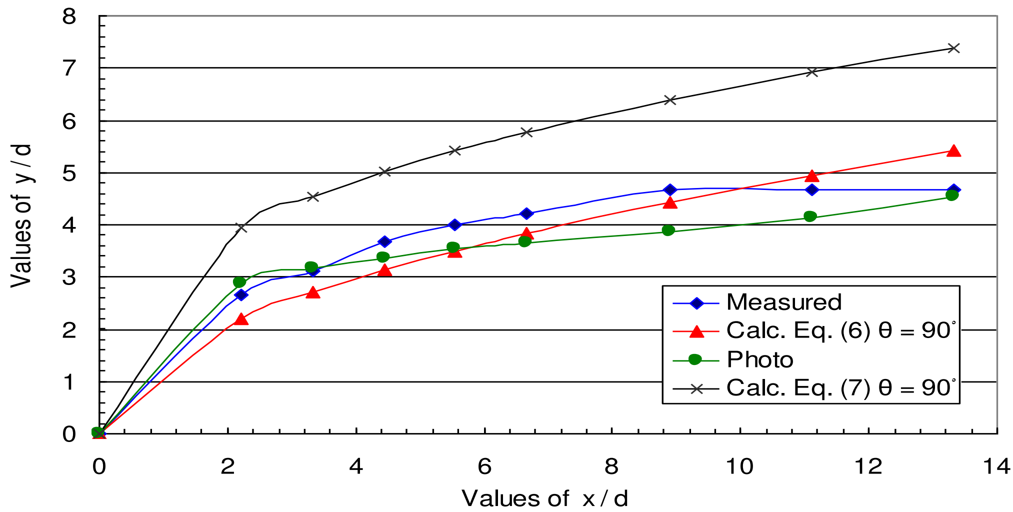

Fig. 2: Relationship between (y/d) and (x/d) for R = 2.73, and θ = 90°.

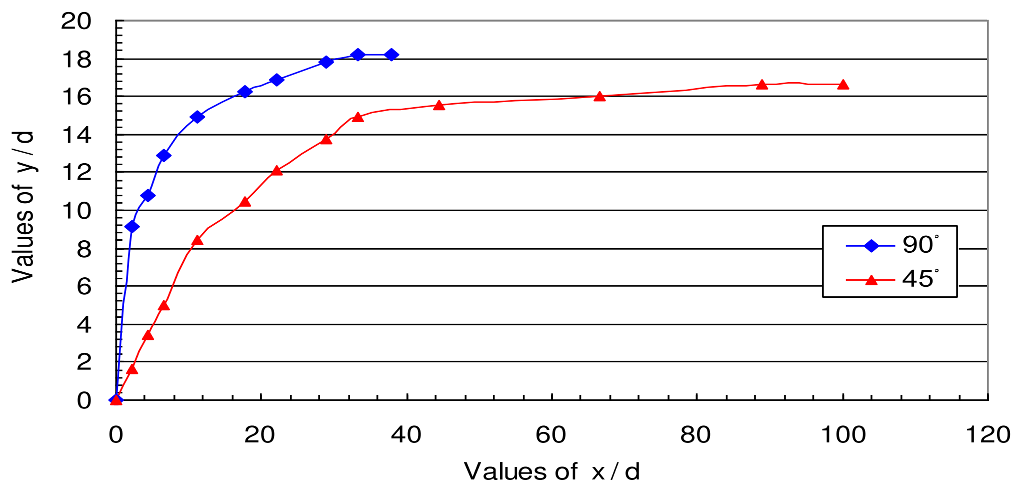

Fig. 3: Influence of jet inclination to the mainstream on jet trajectory for R = 10.00.

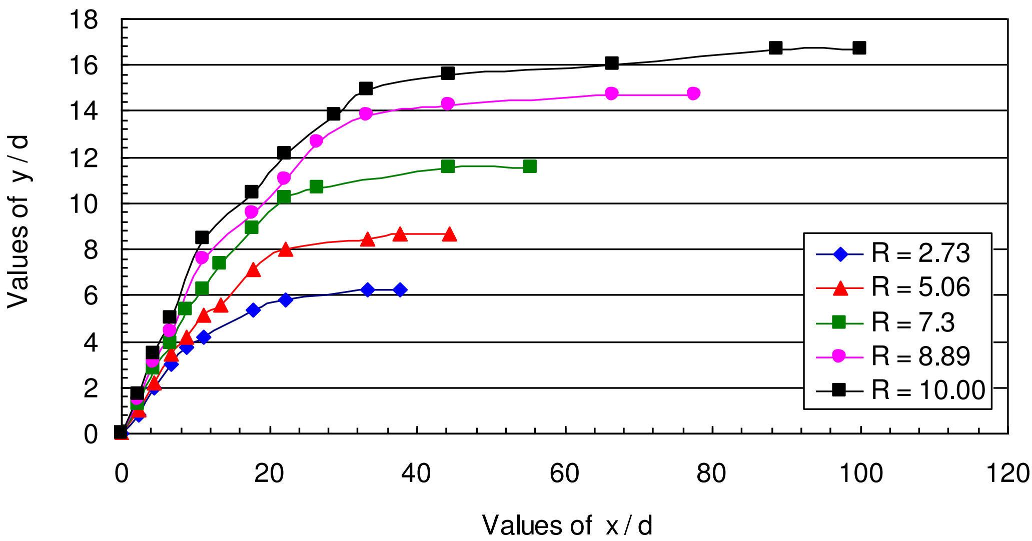

Fig. 4: Relationship between (y/d) and (x/d) for different values of R at $\theta = 45^o$.

where a, c and e are parameters depending on the jet inclination to mainstream flow direction, θ. Values from this research are shown in Table (1).

Table (1) Coefficients a, c and e in Eq. (9).

θ^o	a	c	e
90	0.92	0.84	0.35
45	0.78	0.6	0.35

Centerline Velocity Decay: The centerline velocities were measured at a depth corresponding to the outlet centerline from mainstream water surface. The jet velocity is normalized as V_m/V_j. Shown in Fig. 5 are the plots of the values V_m/V_j against s/d ratios for different velocity ratios at $\theta = 90^o$. It is seen from the figure that for all velocity ratios, V_m/V_j decreases sharply with increasing of the normalized distance s/d in the region of maximum deflection of the jet due to the presence of a re-circulation zone in the wake immediately downstream the outlet and this indicating a high rate of entrainment of the ambient fluid in this region. After that the decay becoming slow until V_m approaches the free stream average velocity, U_o. The value of V_m reaches to U_o for R = 2.73; s = 10d, for R = 5.06; s = 18d, for R = 7.30; s = 36d, for R = 8.89; s = 41d and for R = 10.00; s = 45d or according to the following form with a correlation coefficient of 0.98:

$$\frac{s}{d} = 2.84(R)^{1.21} \tag{10}$$

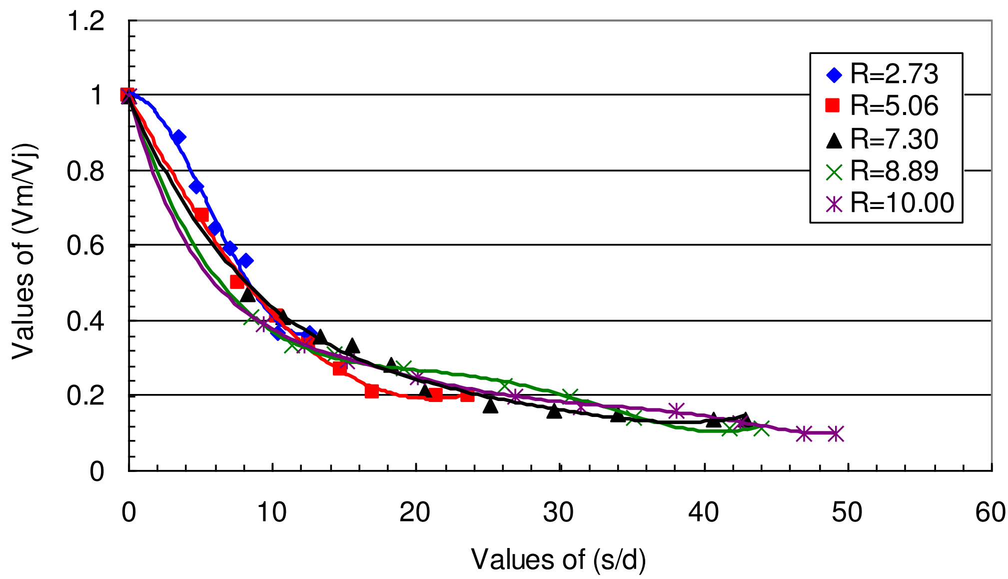

Fig. 5: Decay of centerline velocity-excess for different velocity ratios at $\theta = 90^o$.

Longitudinal and transverse concentrations were measured at a depth corresponding to the level of the jet centerline at several locations of the deflected jet. Pollutant concentration decay is investigated at five different velocity ratios.

Effect of Pollutant Type on Concentration Decay: To show the influence of pollutant type on concentration decay, two types of pollutants are used. These two types are Sodium Chloride and pfennig. The values of C/C_j with x/d for the two pollutants at $C_j/C_o = 2.94$, $R = 7.30$ and $\theta = 90^o$ are shown plotting as in Fig. 6. It is observed that the concentration decay has the same values and trend for both the two studied types.

Effect of Velocity Ratio on the Concentration Decay: The variation of C/C_j with x/d are shown drawing in Fig. 7 for different values of R at $\theta = 45^o$ and $C_j/C_o = 4.34$. For $\theta = 45^o$ and $C_j/C_o = 4.34$, about 75% of the concentration-excess is rapidly decayed with the increase of x/d from 0.0 to 25.0 from the outlet. After that, the decay of concentration-excess slightly decreases with the increase of x/d values. Rapid decay of the concentration-excess in the zone of maximum deflection may due to the volume of fluid entrained is large due to the secondary flow in the wake of the jet, after that, the decay becoming slow. Also, velocity ratios does not have any significant effect on the rate of this decay. Result for $\theta = 90^o$ (not shown here) show that the decay is faster for $\theta = 90^o$ than that for $\theta = 45^o$. This may due to the rapid mix for $\theta = 90^o$.

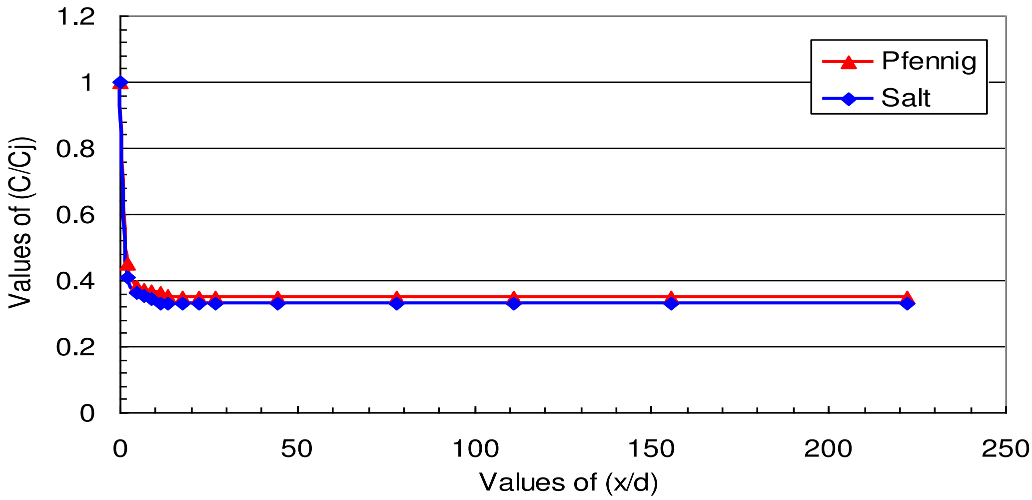

Fig. 6: Relationship between C/C_j and x/d for different types of pollutants at $\theta = 90^o$, $C_j/C_o = 2.94$ and R = 7.30.

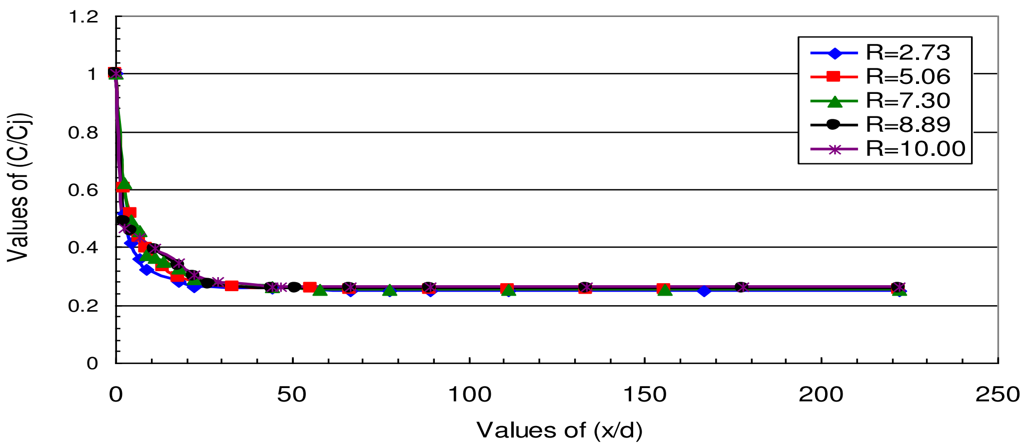

Fig. 7: Relationship between C/C_j and x/d for different velocity ratios at $\theta = 45^o$ and $C_j/C_o = 4.34$.

Effect of Initial Concentration on Concentration Decay: Typical values of C/C_j are plotted against these of x/d as shown in Fig. 8 for different values of initial concentration-excess (C_j/C_o) at R = 2.73 and $\theta = 90^o$ as an example. A sharp decay in the zone of maximum deflection is seen, after that the rate of decay becoming slow till the concentration reaches to 5% higher than the ambient concentration. The decay is faster with the initial concentration-excess. About 75% of the concentration-excess is rapidly decayed with the increase of x/d from 0.0 to 11.0 from the outlet. This is because by increasing the initial concentration-excess, the buoyancy effect tends to make the polluted surface layer spread further away from the discharging outlet. The best fit relationship between C/C_j and x/d for different values of (C_j/C_o) may be drawn as follows;

$$\frac{C}{C_j} = f(x/d)^{-0.02(C_j/C_o)^k} \tag{11}$$

The values of the parameters f and k depend on the angle of inclination as shown in the following table.

Table (2) Coefficients f and k in Eq. (11).

θ^o	f	k
90	0.45	1.66
45	0.61	1.53

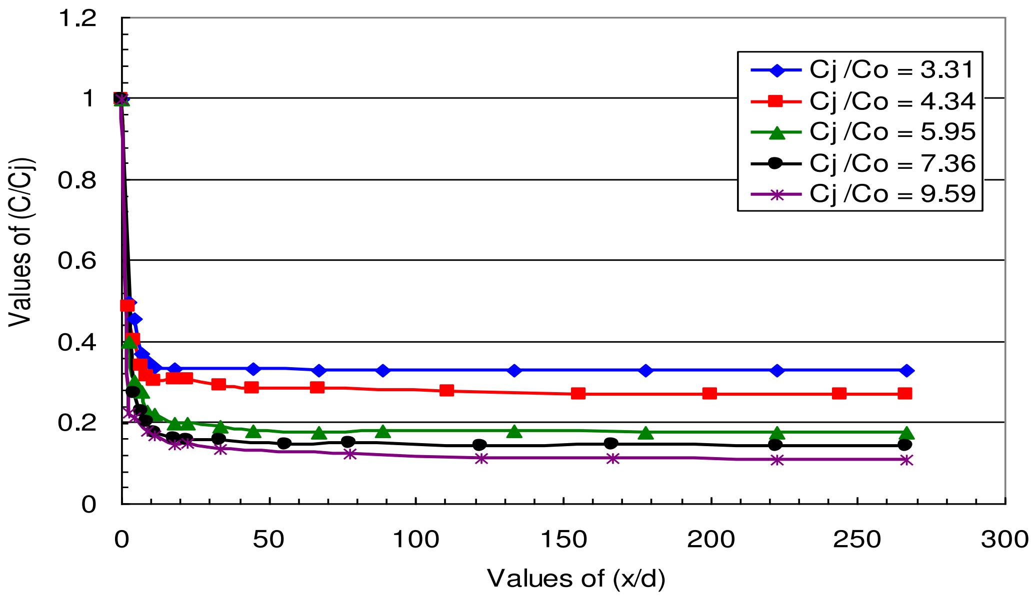

Fig. 8: Relationship between C/C_j and x/d for different values of C_j/C_o at $\theta=90^o$ and R=2.73.

Jet Width: The importance of studying the growth of jet width W_y in transverse direction is to predict the polluted area in the main stream. Figure 9 shows the variation of jet width normalized by jet diameter W_y/d with normalized distance x/d for R=8.89 and $\theta=90^o$ and 45^o. The results of Eq. (9) are also included. It is seen from the figure that the width of the jet increases rapidly with increasing the longitudinal distance along the jet trajectory near the source, then the increasing rate becoming slow with the increase of the distance from the source. Jet width at $\theta= 90^o$ is greater than that at $\theta= 45^o$, which is due to the higher mix at $\theta= 90^o$. A good agreement with results of Eq.(9) is noticed.

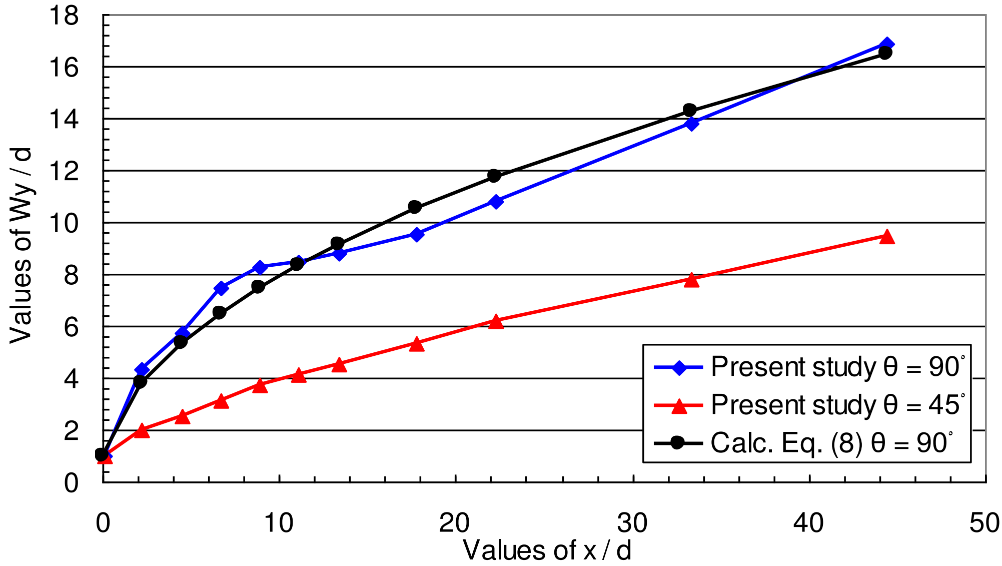

Fig. 9: Influence of jet inclination to the mainstream on growth of jet width for R = 7.30.

To study the effect of velocity ratio on the jet width, the values of W_y/d are plotted against x/d for different velocity ratios and $\theta = 45^o$ as shown in Fig. 10. It is observed that, jet width increases with the increase of the velocity ratio and traveling distance. This is may be due to the increase of momentum flux from the nozzle with the increase of velocity ratio. Then leads to an increase of the entrainment with the cross flow. The variation of the normalized width W_y/d with x/d for jets in cross stream can be described by the following equation:

$$\frac{W_y}{d} = \alpha[x/d]^{\varepsilon(R)^{\omega}} \tag{12}$$

where α, ε and ω are parameters depending on jet inclination to mainstream flow direction, θ. Their values are given in Table (3) based on the present data.

Table (3) Coefficients α, ε and ω in Eq. (12).

θ^o	α	ε	ω
90	3	0.15	0.53
45	2	0.14	0.42

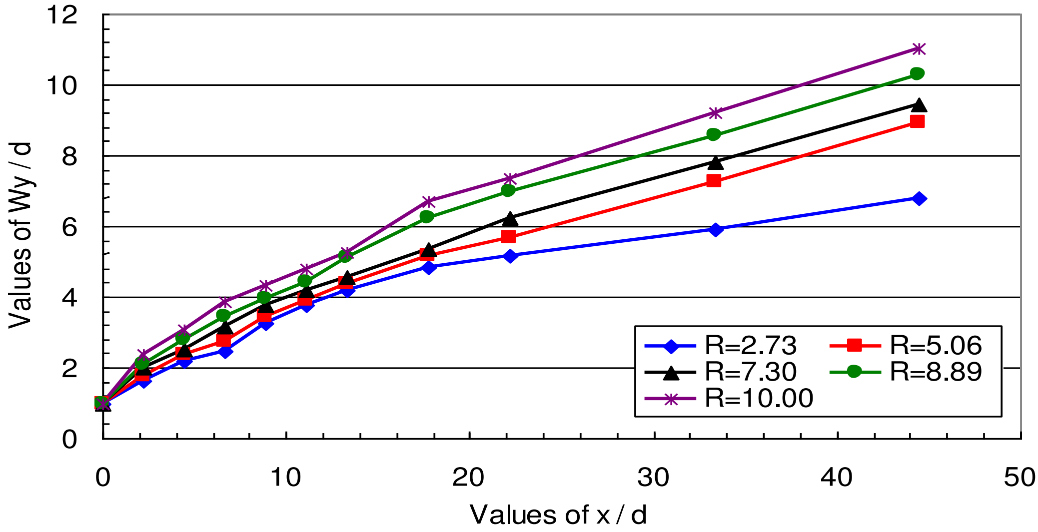

Fig. 10: Relationship between W_y/d and x/d for different velocity ratios and $\theta = 45^o$.

CONCLUSIONS

Based on experimental results on studying the hydraulics of surface polluted wall jets discharged at different angles into a cross flow with circular nozzle, it is found that:

1. The trajectory of the jet centerline is dependent on the velocity ratio, angle of inclination to main stream, where a deep penetration is associated with $\theta = 90^o$ and high values of R.
2. The decay of velocity-excess along the jet trajectory depends mainly on traveling distance from the nozzle.
3. Concentration-excess decay is not influenced by the velocity ratio, while it increases with the increase of initial concentrations.
4. The distances at which the concentration reached to 5% higher than that of the ambient flow is dependent on the angle of inclination, θ.
5. The growth of jet width along the jet trajectory increases with the increase of R, θ and traveling distance.
6. Empirical equations are awarded for estimating the jet trajectories, the concentration decay and the jet width.

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"السلوك الهيدروليكي لتدفق مائي ملوث خلال السريان بالقنوات المكشوفة"

يقدم هذا البحث دراسة معملية على بعض العوامل التي تؤثر في الخصائص الهيدروليكية والبيئية لمصب من المياه الملوثة كيميائيا في مجرى مائي مكشوف لما لها من أهمية عند التصميم الهيدروليكي لكل من المصب والمجرى المائي المكشوف، كذلك لما لها من تأثير بيئي على الأحياء المائية وكذلك صحة الإنسان والحيوان. أجريت الدراسة بغرض التعرف على الخصائص الهيدروليكية للسريان بالقنوات المكشوفة عند مصب مصدر مائي ملوث كيميائيا من معدل هبوط للسرعات خلال مسار التدفق المائي الملوث ومعدل خفض لتركيز الملوث في الاتجاهين الطولي والعرضي، وكذلك أبعاد اختراق التدفق الملوث للمجرى المكشوف وذلك:-

1- بدراسة بعض العوامل المؤثرة في خصائص هذا السريان مثل تعير نسبة سرعة اندفاع الملوث الابتدائية إلى سرعة المجرى المائي (R)، زاوية دخول التدفق المائي الملوث إلى المجرى المائي (θ)، نوع مادة الملوث وكذلك التركيز الابتدائي للملوث.

2- في محاولة للتعرف على حدود المنطقة الملوثة داخل المجرى المائي وذالك عند الوصول إلى أقل تركيز ممكن للملوث أو الوصول إلى نفس تركيز المجرى المكشوف قبل التلوث.

أجريت الدراسة بمعمل الهيدروليكا بقسم الهندسة المدنية، كلية الهندسة جامعة أسيوط على نموذج معملي مكون من قناة مكشوفة بطول 3 متر وعرض 0.6 متر وعمق 0.25 متر حيث تم عمل مصب جانبي أفقي من المياه الملوثة عند سطح المياه بالقناة المكشوفة. يأخذ المصب الشكل الدائري. تم تغير زاوية ميله على الاتجاه الطولي للسريان بالقناة المكشوفة لتأخذ 90°، 45°، كذلك تم تغير التركيز الابتدائي للملوث عدة مرات وأيضا تم تغير نسبة السرعة الابتدائية للتدفق الملوث إلى سرعة المياه بالمجرى المكشوف خمسة مرات. ولمعرفة تأثير نوع مادة الملوث على هذه الخصائص تم استخدام نوعين من الملوثات على التوالي هما كلوريد الصوديوم والفنيك. استخدمت نظرية الأبعاد في إيجاد بعض العوامل الغير بعدية والمؤثرة في الخصائص الهيدروليكية لهذا المصب والتي بني على أساسها تحليل ومناقشة النتائج المعملية. كان من أهم النتائج المستخلصة من هذا البحث الاتى:

1- وجد أن خصائص التدفق المائى السطحى فى مجرى مكشوف من أبعاد هندسية وهبوط فى السرعات وخفض فى التركيز الكيميائى للملوث يعتمد على العوامل المدروسة (السرعة الابتدائية للتدفق – زاوية ميل مصدر التدفق – التركيز الابتدائى للملوث).

2- وجد أن نوع المادة الكيميائية للملوث لاتؤثر فى خصائص السريان المتدفق فى المجرى المكشوف.

3- تم استنتاج معادلات تجريبية يمكن بواسطتها التعرف على خصائص هذا التدفق المائى الملوث كيميائيا.