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ANALYSIS OF SOME PARAMETERS AFFECTING THE CHARACTERISTICS OF POLLUTED WATER – JET IN OPEN CHANNEL

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Experiments were conducted to investigate the effect of jet shape, inclination, velocity ratio and initial concentration on the characteristics of side polluted surface water jet in open channel with two different angles of inclination to mainstream direction. The polluted water is prepared by adding sodium chloride with different concentrations to fresh water. The initial jet velocity is varied to cover a range of velocity ratio R from 3.30 to 10.30. For each velocity ratio, the solute concentration is changed to take values of 800, 1050, 1440, 1780 and 2320 ppm Centerline jet trajectory, velocity decay and dilution of polluted water are measured. Velocity is measured by a calibrated current meter while the jet coordinates and water depths are measured using point gages. Samples are taken from the jet centerline to measure the jet concentrations. The concentrations are measured using 4510 conductivity meter.

The factors influencing the problem are normalized with the help of dimensional analysis principle. The analysis of the results revealed that the geometrical characteristics of a polluted water jet in cross-flow, the decay of velocity and dilution of pollution concentration are mainly depending on the studied parameters. Equations have been developed from the correlation of the experimental results.

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

INTRODUCTION

Pollutant from industrial and municipal sewers and waste heat from thermal power plants are often discharged into rivers, estuaries, and coastal waters in the form of turbulent jet flows. The study of turbulent mixing of a surface jet provides useful information on the disposal and dilution of pollutants into rivers, lakes, coastal waters. Abdel Fattah [1], Prashant et al. [2] investigated, based on experimental studies, the trajectory of jet centerline. Abozeid [3] presented a laboratory study on the factors influencing the characteristics of surface discharge of heated water jet in an open channel. His findings were the trajectory of the jet centerline and temperature-excess decay are influenced by the change of the outlet shape, velocity ratio and angle of inclination to main stream and are rapidly in the zone of maximum deflection of the jet. Gutmark et al. [4] investigated experimentally both the initial profile of the cross flow boundary layer and the jets. They found the importance of determining the evolution of jets in cross flow in addition to the geometry of jet nozzle . Jirka [5] , Ching and Rong [6] reported that, the jet penetration depends mainly on the velocity ratio R. Abdel Fattah [1] and Abozeid [3] investigated that the decay of centerline velocity-excess along the jet trajectory depends mainly on the velocity ratio. Keffer and Baines [7] and Moussa et al. [8] observed that the jet velocity and the temperature trajectories were mainly governed by the momentum ratio. Mohamed [9] found 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. He considered that the jet to be a source of kinematic momentum and buoyancy flux, Wright [10] presented a model of a round buoyant jet discharges normally to an ambient crossflow.

The Present experimental study is conducted to investigate the effect of jet shape, inclination to the main stream, velocity ratio and initial concentration of a pollutant, on the characteristics of polluted surface water-jet in open channel.

NOMENCLATURE

Symbol	Definition	Symbol	Definition
B	Flume bed width	V	Maximum jet velocity along C.L.
b	Width or diameter of the outlet	V_j	Initial velocity of the jet
C	Jet concentration along the centerline	V_o	Mainstream mean velocity
		X and Y	Cartesian coordinates in the horizontal plane of jet C.L.
C_j	Initial concentration of the jet	x, y	Distances along the jet
C_o	Mainstream concentration	λ	Aspect ratio = b/h
d	Depth of channel	θ	Inclination angle of the outlet
d_m	Maximum depth at which the jet will reach if it is not restricted by the bed	μ	Dynamic viscosity of ambient fluid
F_d	Densimetric Froud number	ρ_j	Initial density of polluted jet
g	Gravitational acceleration	ρ_o	Ambient fluid density
h	Height of the outlet	$\Delta\rho$	Initial density difference
R	Velocity ratio = V_j / V_o		

EXPERIMENTAL SET-UP

The experiments were conducted in a tilting flume located in the hydraulics Laboratory of Civil Engineering Department, Assiut 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. Water depths were controlled using a downstream tailgate. A circular and rectangular nozzles of the same area are used to discharge the pollute water jet. The circular jet diameter is 4.5 mm and rectangular jet with dimension ratio b/h = 5.00 and 0.20. Side surface flow jet is located at 2.00 m from the flume inlet section. The nozzle set to take 30^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 taken by 4510 Conductivity meter which measure the concentration for a range from 0 to $2*10^5$ mg/L. Compacted digital camera was used to take vertical photos for determination of 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.

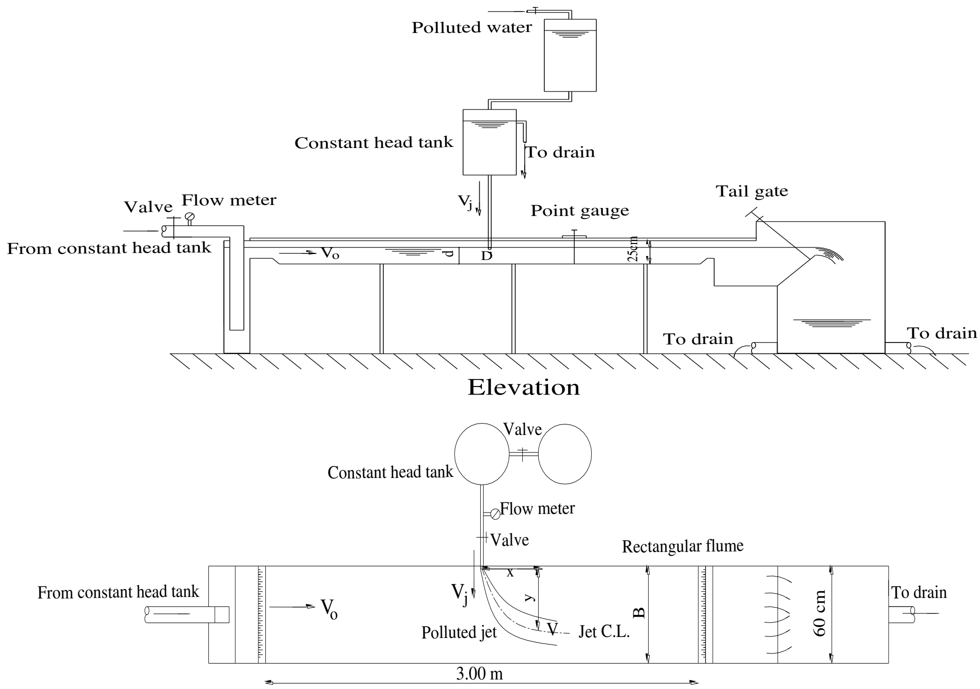

Fig.1: Schematic representation of the experimental set-up.

Experimental Procedures: The following procedures are followed in performing the experiments:

1. The nozzle of the polluted water supply was fixed with angle of inclination equals 90^o with mainstream direction .The circular nozzle is used.
2. The mainstream flow rate and its water depth were regulated to be 13.68 L/s. and 110 mm 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, 1440, 1780 and 2320 ppm.
4. Co-ordinates (x, y), velocity and concentration along the jet centerline were measured and photos by digital camera were taken.
5. The polluted water jet velocity was changed several times to have the velocity ratios ($R= V_j / V_o$) 3.30, 5.23, 7.30, 9.00, 10.30 and steps from 3 and 4 were repeated.
6. The concentration of the polluted water jet was changed and steps from 3 to 5 were repeated.
7. The angle of inclination was changed to be 30^o and steps from 1-6 were repeated.
8. Another jet shape was used and steps from 1- 7 were repeated.

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;

$$\Phi_1 (B, d, h, b, \theta, V_o, V_j, V, C, C_o, C_j, x, y, g, \rho_o, \rho_j, \mu) = 0 \quad (1)$$

If $\Delta\rho = \rho_j - \rho_o$ and applying the Backingham's "π" theory, one may obtain:

$$\Phi_2 \left(\theta, C/C_o, C_j/C_o, V_j/V_o, V/V_o, b/h, x/d, y/d, V_o.\rho_o.B/\mu, V_j \Big/ \sqrt{gh\frac{\Delta\rho}{\rho_o}}\right) = 0 \quad (2)$$

in which $V_j \Big/ \sqrt{gh\frac{\Delta\rho}{\rho_o}}$ = densimetric Froud number, F_d (its effect is included in the effect of R and aspect ratio). So, it may be dropped from equation (2). $V_o.\rho_o.B/\mu$ is the Reynolds number (R_e). In open channel flow R_e has insignificant effect; so it may be dropped from Eq. (2) [11 , 12]. Applying the properties of dimensional analysis and using the method of synthesis [13] one can get:

$$y/d , V/V_o = \Phi_3 (x/d, \theta, R, b/h) \quad (3)$$

$$C/C_o = \Phi_4 (x/d, \theta, R, b/h, Cj/C_o) \quad (4)$$

RESULTS AND DISCUSSIONS

Killiot and Harkness [14], considered surface side discharge of polluted jet in a cross flow in shallow and deep waters. 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 [15].

$$d_m = 0.353 F_d (\lambda)^{-0.25} \sqrt{bh} \quad (5)$$

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

In the present investigations, the mainstream is considered to be shallow, where $d_m / h \rangle 0.75$ for all the studied cases.

Jet Trajectory: Figure (2) shows a typical plot of y/d against x/d for a velocity ratio ranges from 3.30 to 10.30 for circular jet with λ = 1.00. The same in Figs.(3 and 4) for rectangular jet with λ = 0.20 and λ = 5.00 respectively. It is clear with increasing the velocity ratio R, the penetrations are deeper. 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). For all curves, one can observe that the jet penetrations is faster till a certain value of x/d (max.=0.5).This region is known as a mixing region. Figure (5) shows a typical plot of y/d against x/d for velocity ratio R= 9 and θ = 90^o as an example for different aspect ratio λ. It is obvious from the figure for θ = 90 ^{o} the circular jet penetrated deeper than the rectangular one. Figure (6) shows a typical plot of y/d against x/d for circular jet with R= 5.23 and angle of inclination, θ = 90^o and 30^o. It is clear that for θ = 90^o the jet penetrates deeper than that for θ = 30^o. This may be due to a higher y-component of the momentum of the penetrated jet with θ = 90^o.

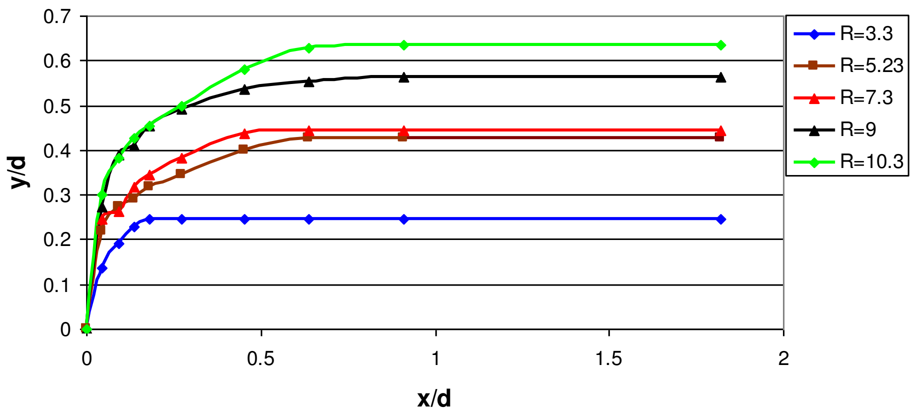

Fig. 2: Relationship between (y/d) and (x/d) for circular jet , and θ = 90^o

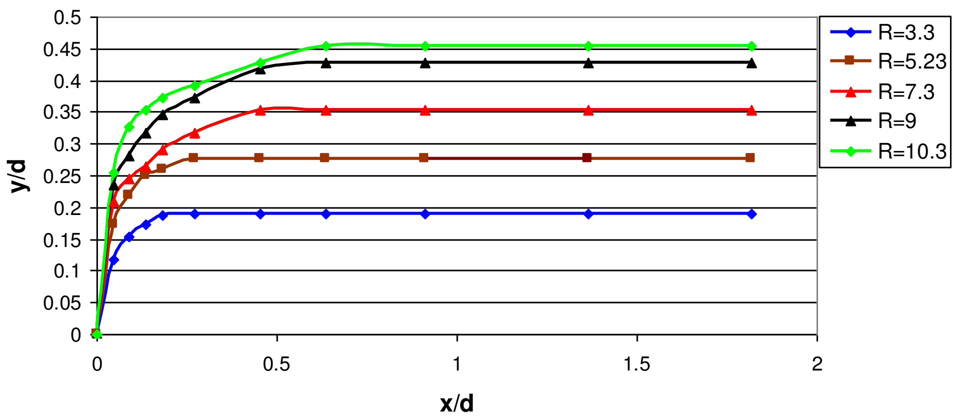

Fig. 3: Relationship between (y/d) and (x/d) for rectangular jet with λ = 0.2, and θ = 90^o

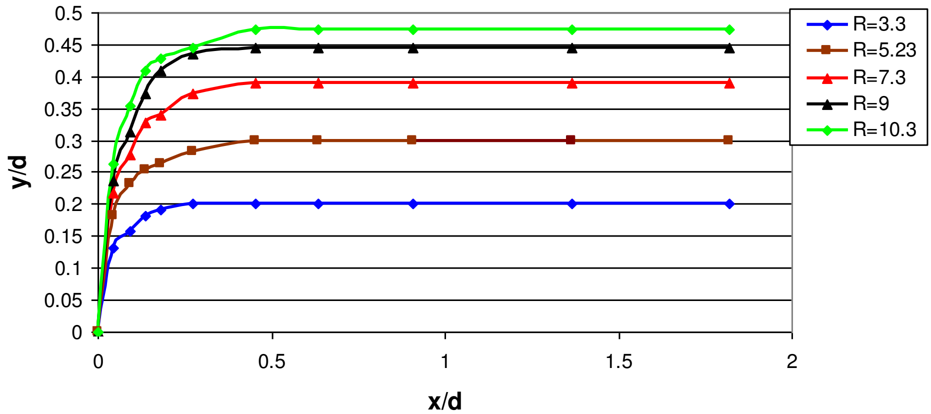

Fig. 4: Relationship between (y/d) and (x/d) for rectangular jet with $\lambda = 5.00$, and $\theta = 90^o$

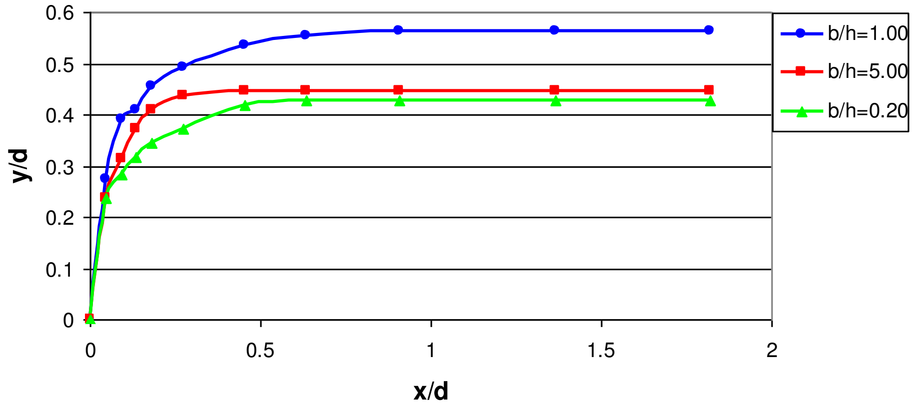

Fig. 5: Relationship between (y/d) and (x/d) for R= 9.00 and $\theta = 90^o$

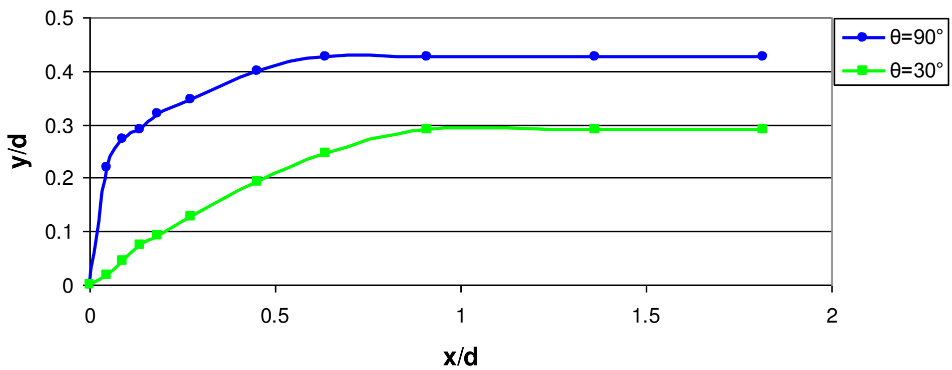

Fig. 6: Relationship between (y/d) and (x/d) for circular jet for R= 5.23

The correlation of y/d with x/d for different velocity ratios for circular and rectangular jets may be given by the following form :

$$y/d = a_1 R^{b_1} (x/d)^{c_1 R^{d_1}} \tag{6}$$

The values of constants a_1, b_1, c_1 and d_1 are listed in the following Table (1)

Table (1): values of constants a1, b1, c1 and d1 in equation (6)

Constants	Circular jet		Rectangular jet			
	λ=1.00		λ=5.00		λ=0.20	
	θ=90°	θ=30°	θ=90°	θ=30°	θ=90°	θ=30°
a_1	0.19	0.15	0.14	0.13	0.17	0.06
b_1	0.54	0.41	0.62	0.39	0.48	0.66
c_1	0.94	0.53	0.27	0.5	0.39	0.33
d_1	-0.65	0.2	-0.11	0.19	-0.25	0.39

Centerline Velocity Decay: The centerline velocities were measured at a depth corresponding to the outlet centerline from the mainstream water surface. The jet velocity is normalized as V/V_o. Shown in Fig. (7) are the plots of the values V/V_o against x/d ratios for b/h = 1.00 and for different velocity ratios at θ = 90°. It is seen from the figure that for all velocity ratios, V/V_o decreases sharply with the increasing of the normalized distance x/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. This indicating a high rate of entrainment of the ambient fluid in this region. After that, the decay becoming slow until V approaches the free stream average velocity, V_o. To compare between the effect of jet shape on velocity decay, plots of V/V_o against x/d for different aspect ratios are shown in Fig. (8). The plots are for θ=90° and R=5.23. It is seen that the circular jet velocities are diluted faster than those of rectangular ones. Same plots are shown in Figs. (9 and 10), but for angle of inclination = 90° and 30°. It is revealed from the figures that the dilution is faster for θ=90°. This may due to the high mix with deep penetration.

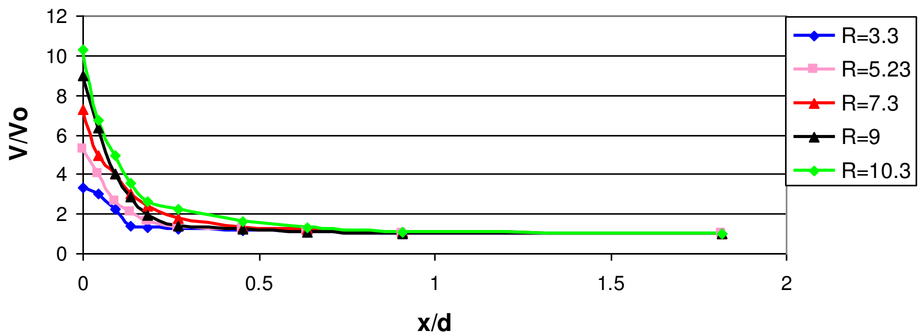

Fig. 7: Decay of centerline velocity-excess for different velocity ratios, θ = 90° and b/h = 1.00

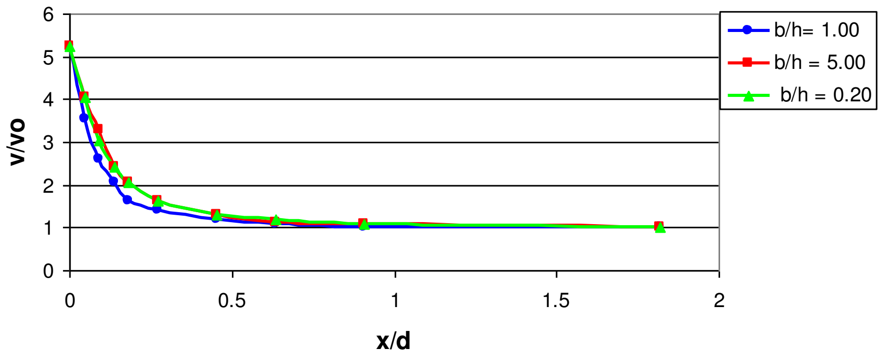

Fig. 8: Decay of centerline velocity-excess for R = 5.23, θ = 90 ° with different b/h.

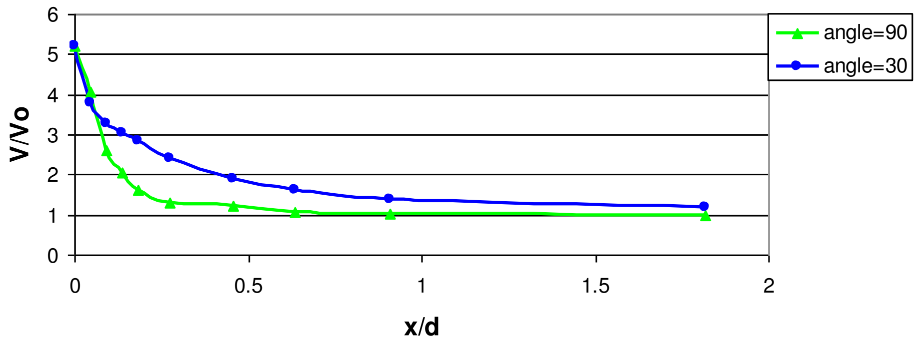

Fig. 9: Decay of centerline velocity-excess for b/h = 1.00 ,R = 5.23 with different angles of inclination.

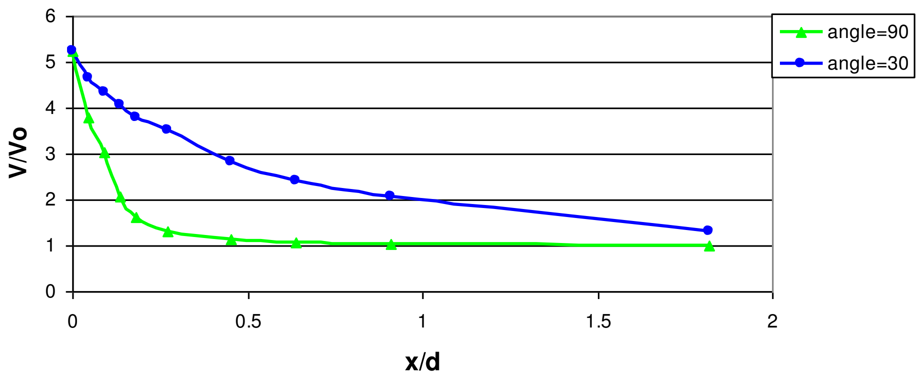

Fig. 10: Decay of centerline velocity-excess for b/h = 5.00 ,R = 5.23 with different angles of inclination.

The correlation of the experimental results on the decay of centerline velocities-excess may take the following form:

$$V / V_o = a_2 R^{b_2} (x / d)^{c_2 R^{d_2}} \tag{7}$$

The values of constants a_2, b_2, c_2 and d_2 are listed in Table. (2)

Table (2): values of constants a2, b2, c2 and d2 in equation (7)

Constants	Circular jet		Rectangular jet			
	λ=1.00		λ=5.00		λ=0.20	
	θ=90°	θ=30°	θ=90°	θ=30°	θ=90°	θ=30°
a_2	0.68	0.7	0.89	0.77	0.9	0.53
b_2	0.2	0.46	0.09	0.5	0.11	0.63
c_2	-0.24	-0.11	-0.15	-0.15	-0.18	-0.19
d_2	0.35	0.65	0.6	0.51	0.48	0.43

Centerline Concentration Decay: Pollutant concentration decay is investigated at five different velocity ratios and five initial concentrations. The variation of C/C_o with x/d are shown in Fig. (11) for different values of R at $\theta = 90^o$, b/h = 1.00 and $C_j/C_o = 5.25$ as an example, about 80% of the concentration-excess is rapidly decayed with the increase of x/d from 0.0 to 0.50 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 till the concentrations approximately reaches to mainstream concentration. Fig. (12) shows the same plots, but with different jet-angles of inclination to mainstream. Same trends of jet-velocity excess decay are seen due to the same reasons.

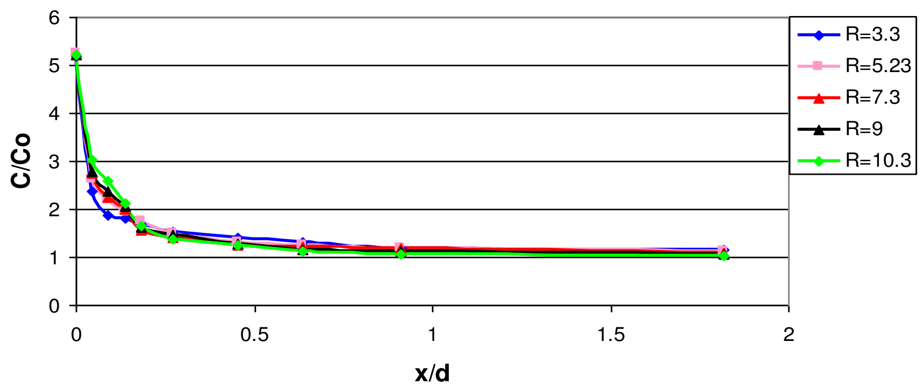

Fig.11: Relationship between C/C_0 and x/d for different R at $\theta=90^o$, b/h=1.00 and $C_j/C_o = 5.25$

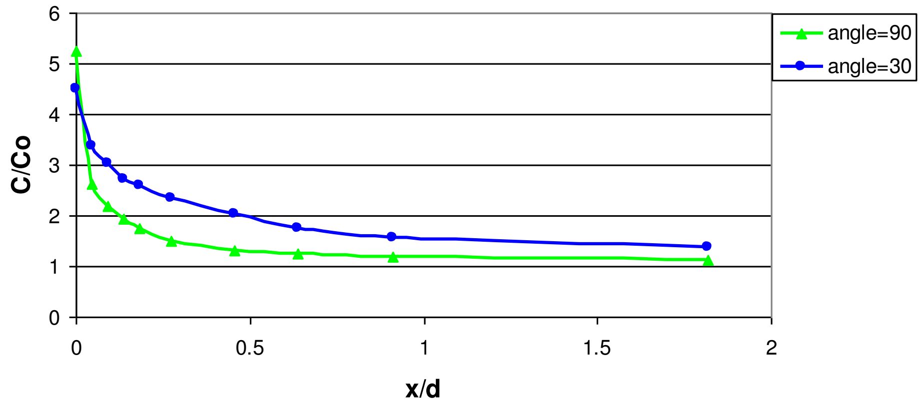

Fig.12: Relationship between C/C_0 and x/d for R = 5.23, C_j/C_o = 5.25 and b/h = 1.00 .

From the experimental results, one can get the following relationship for centerline concentration decay :

$$C/C_o = a_3 (C_j / C_o)^{b_3} (Rx/d)^{c_3 (C_j / C_o)^{d_3}} \tag{8}$$

The values of constants a_3, b_3, c_3 and d_3 are listed in Table. (3)

Table (3): values of constants a_3, b_3, c_3 and d_3 in equation (8)

Constants	Circular jet		Rectangular jet			
	λ=1.00		λ=5.00		λ=0.20	
	Θ=90°	θ=30°	θ=90°	θ=30°	θ=90°	θ=30°
a_3	0.89	0.87	0.73	1.00	0.85	1.03
b_3	0.58	0.57	0.38	0.68	0.52	0.74
c_3	-0.15	-0.18	-0.05	-0.18	-0.12	-0.26
d_3	0.48	0.32	0.84	0.29	0.47	0.22

CONCLUSIONS

Based on the analysis of experimental results of some parameters affecting the characteristics of surface polluted water jet in open channels, it may be conclude that:

1. The trajectory of the jet centerline is dependent on jet shape, velocity ratio and angle of inclination to mainstream, where a deep penetration is for circular jet with λ=1.00 then rectangular jet with λ=5.00 and λ=0.20 respectively.
2. The trajectory of the jet centerline is dependent on the velocity ratio where a deep penetration is for high velocity ratio values R.
3. The trajectory of the jet centerline is deeper for θ= 90 ° than for θ= 30 °
4. The decay of velocity-excess along the jet trajectory depends on jet shape, velocity ratio and angle of inclination. It is higher with circular jet and with θ=90°

5. Concentration-excess decay is influenced by the velocity ratio and the initial concentration. It is high with high velocity ratio, low initial concentration and with θ=90°
6. Empirical equations are awarded for estimating jet trajectories, velocity decay and concentration decay.

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"دراسة لبعض العوامل المؤثرة فى خصائص تدفق مائى ملوث فى قناه مكشوفة"

يقدم هذا البحث دراسة معملية على بعض العوامل التي تؤثر فى الخصائص الهيدروليكية والبيئية لمصب من المياه الملوثة كيميائيا في مجرى مائي مكشوف لما لها من أهمية بيئية وكذلك عند التصميم الهيدروليكي للمجرى المكشوف. أجريت الدراسة على مصب ملوث دائرى و مستطيل ذو ابعاد نسبيه مختلفه بغرض:

1. دراسة بعض العوامل المؤثرة فى الخصائص الهندسيه والبيئيه لهذا السريان مثل تغير شكل المصب وتغير نسبة سرعة اندفاع الملوث الابتدائية إلى سرعة المجرى المائي (R)، زاوية دخول التدفق المائي الملوث إلى المجرى المائي (θ) و كذلك 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 0,60 متر وعمق 0,25 متر حيث تم عمل مصب جانبي أفقي من المياة الملوثة عند سطح المياه بالقناة المكشوفة. تم توصيل المصبات المختلفه على حده. تم تغير زاوية ميل المصب على الاتجاه الطولي للسريان بالقناة المكشوفة لتأخذ°90و°30. كذلك تم تغير التركيز الابتدائي للملوث خمس مرات وأيضا تم تغير نسبة السرعة الابتدائية للتدفق الملوث إلى سرعة المياه بالمجرى المكشوف خمسة مرات. وقد تم استخدام كلوريد الصوديوم كمادة ملوثه. استخدمت نظرية الأبعاد في إيجاد بعض العوامل الغير بعدية والتي بني على أساسها تحليل ومناقشة النتائج المعملية. كان من أهم النتائج المستخلصة من هذا البحث الاتى:

1. خصائص التدفق المائى السطحى الملوث كيميائيا فى مجرى مكشوف من أبعاد هندسية وهبوط فى السرعات وخفض فى التركيز الكيميائى للملوث يعتمد على العوامل المدروسة (شكل المصب – السرعة الابتدائية للتدفق – زاوية ميل مصدر التدفق – التركيز الابتدائى للملوث)
2. تم استنتاج معادلات تجريبية يمكن بواسطتها التعرف على الخصائص الهندسية والبيئيه لهذا التدفق المائى الملوث كيميائيا فى مجرى مائى مكشوف .