STUDY OF NEAR FIELD PERFORMANCE OF MULTI-PORTS DIFFUSER IN RELATIVELY DEEP RIVERS

دراسة الأداء المجالى القريب لمصب متعدد الفتحات في الأنهار العميقة نسبيا

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الخلاصة:

هذا البحث يقدم دراسة معملية لمشكلة محطات القوى الحرارية و التي تصرف الماء الساخن في الأنهار العميقة بشكل نسبي. و يعتبر النهر عميق عندما يكون النفث المتدفق حر الانتشار داخل عمق المياه فى النهر بدون الاصطدام بالقاع أو الصعود الى أعلى سطح الماء مما يساعد على سرعة تخفيف درجة حرارة المياه المنصرفة إلى النهر. و قد تم تثبيت عمق الماء (H) خلال التجارب. و يعتبر الهدف الرئيسي من هذه الدراسة هو استنباط معادلة عامة يمكن استخدامها فى تصميم مخارج محطات القوى الكهربائية الحرارية و التي تصرف مياهها الساخنة فى الأنهار العميقة لتحقيق الخفض السّريع للتركيز الحراري وتقليل طول منطقة الخلط لتقليل التأثيرات البيئية الناتجة عن التلوث الحراري. و قد تم دراسة تأثير المتغيرات المختلفة المتعلقة بكل من خصائص النهر وخصائص مخرج تصريف الماء الساخن للمحطة على التخفيف السّريع لتركيز الماء الساخن فى منطقة الخلط. و هذه المتغيرات هى سرعة التدفق لمياه المخرج (V)، سرعة التدفق لمياه النهر (U)، عدد فتحات المشتت (n) و المسافة بينها (s)، وقطر فتحات المشتت (D)، الزاوية الرأسية لفتحات المشتت (θ) و ارتفاع فتحات المشتت عن قاع النهر (h)، عمق التدفق فى النهر (H) و كذلك الزاوية الأفقية بين فتحات المشتت و اتجاه السريان فى النهر (β). و بتحليل النتائج المعملية وجد أن التركيز الحراري النسبي (C_m/C_o) فى منطقة الخلط تتناسب تناسبا طرديا مع كل من $V/U, n, \theta h/H, \beta$ في حين تتناسب تناسب عكسيا مع (s/D). كما وجد أن أقصى تركيز حرارى قد حدث عندما تم تخطيط المشتت بحيث كان موازيا لاتجاه السريان فى النهر. و قد تم استنباط معادلة لحساب التركيز الحراري في منطقة الخلط معتمدة على العوامل السابقة. و قد تم مقارنة النتائج المعملية الناتجة بواسطة Mouad (٧) بتلك الناتجة من تطبيق المعادلة المستنبطة و قد أعطت تقاربا بدرجة عالية و بقيم عالية لمعامل التقارب.

ABSTRACT

In this paper an experimental study is presented for the problem of the thermal power stations, which is discharging the hot water into relatively deep rivers. The receiving water of the river is said to be deep when the jet is free to mix due to entrainment and buoyancy and is not constrained by neither the river bed nor the water surface [6], which increases the temperature dilution. The water depth (H) is constant during the experiments. The main objective of this paper is to develop a new general equation, which can be used in designing the multi-ports diffuser of the thermal power plant discharging hot water into relatively deep rivers. Also, the rapid dilution and minimizing of the mixing zone length of the hot water to reduce the environmental effects are considered. In this paper, the effects of the different parameters related to both the out-fall structure and the river characteristics on the rapid dilution of the hot water concentration (C_m/C_o) are considered. These parameters are, the effluent/ambient velocity ratio (V/U), the number of ports (n), the spacing between the ports with respect to its diameter (s/D), the vertical angle of ports in combination with the ratio of its height to the flow depth (θh/H), and the horizontal angle between the diffuser line and the flow direction (β). The analysis of the experimental results shows that the relative thermal concentration (C_m/C_o) is directly proportional to V/U, n, θh/H, and β, while it is inversely proportional to s/D. Also, it is found that the maximum value of C_m/C_o occurs when the diffuser is aligned parallel to the direction of flow. A general equation between the relative

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thermal concentration (C_m/C_o) and the aforementioned parameters is developed. The comparative study between the experimental results, which is carried out by Mowed [7], and the corresponding results by applying the developed equation, illustrates that there is a good compatibility between the two results.

LITRATURE SURVEY

In Egypt, there are many thermal power plants, which discharge the hot water into the Nile River. As stated by Miller and Bridhouse [6], the receiving water body is said to be deep when the jet is free to mix due entrainment and buoyancy and is not constrained by the river bed or the water surface. The aforementioned condition was established in this research. Hodgson et al. [4], found that the heat was de-stabilized with the river temperature up to 3.0 km downstream the out-fall structure, which could be reflected on the physical and chemical properties of the flowing water. The Egyptian law (No 48) issued by the Ministry of Water Resources and Irrigation in 1982, which is concerned with the protection of Nile River from pollution, specified that the maximum allowable temperature rise above ambient flow is 5° C, and the temperature of the discharging water to the Nile River should not be more than 35° C. So, the rapid dilution and minimizing of the mixing zone of the thermal water should be considered as a very important subject.

In 1992, Hodgson and Rajaratnam [4] studied the thermal concentration, which is produced by a circular jet discharged from the bed vertically into relatively deep open channel. They stated that the relative thermal concentration (C_m/C_o) is a function in both the relative velocity of the nozzle flow (V/U) and the dimensionless distance from the nozzles (x/D) as follows:

$$\frac{C_m}{C_o} = 1.09\left(\frac{Vx}{UD}\right)^{0.56} \qquad (1)$$

where

C_m	maximum thermal concentration at any section in the ambient river;
C_o	thermal concentration at the diffuser outlets;
D	nozzle diameter;
U	ambient river velocity;
V	effluent velocity; and
x	perpendicular distant to the diffuser line in the downstream direction.

The foregoing equation was developed and could be valid only for one nozzle discharging vertically from the bed of the channel.

In 1988, Mowad et al. [7] studied the effect of the relative velocity of the nozzle flow (V/U) on the relative thermal concentration (C_m/C_o). They [7] concluded that, the increasing of the value of the relative velocity (V/U) led to a considerable decreasing in relative thermal concentration (C_m/C_o). This fact conflicted with Eqn. (1), as it gives higher values of C_m/C_o with the increase of V/U for constant values of x/D. So, the dimensionless term Vx/UD should be divided into two terms, V/U and x/D, and the effect of each term on C_m/C_o has to be studied individually. Also, Mowad et al. [7] studied the effect of the spacing between nozzles with respect to its diameter s/D on the relative thermal concentration C_m/C_o. They [7] found that the increase of s/D led to a considerable decrease in the value of C_m/C_o, but his study was built on a few laboratory data, so he did not develop a general formula indicating this effect.

In 1992, Adams et al. [1] deduced the following formula for the near-field dilution of co-flowing diffuser (the nozzles of the diffuser are pointing into the same direction as the ambient cross-flow).

$$\frac{C_m}{C_o} = 0.5\left[\frac{UH}{VB_o} + \sqrt{\left[\frac{UH}{VB_o}\right]^2 + \frac{2h\cos\theta\sin\gamma}{B_o}}\right] \tag{2}$$

in which

B_o the equivalent slot width = $\pi D^2 / 4L_D$;
h elevation of the nozzle outlet above the river bed;
H ambient water depth;
L_D the diffuser length;
θ vertical angle between diffuser nozzles and the horizontal; and
γ nozzle angle relative to diffuser axis.

The effect of the spacing of the nozzles with respect to its diameter (s/D) is neglected in Adams'equation, as he replaced the individual ports of the diffuser by an equivalent single diffuser having the same flow discharge. This could be valid only for the case of closely spaced ports and consequently, the influence of the individual ports could not be felt. So, the study of the effect of s/D on C_m/C_o in a wide range of measurements is required. Also, in Eqn. (2) the horizontal angle of the diffuser line with the flow direction (β) is neglected. This means that, the use of Adams'equation for predicting the thermal concentration is so limited in practical applications.

THEORETICAL STUDY

The relative thermal concentration (C_m/C_o) could be defined as follow [8]:

$$C_m / C_o = (T_m - T_a) / (T_e - T_a)$$

where

T_m ambient temperature at any section with thermal effluent;
T_a local ambient temperature without thermal effluent; and
T_e the maximum effluent temperature from the diffuser.

The relative thermal concentration (C_m/C_o) could be considered as a function in both the diffuser characteristics and the ambient river properties. Thus, as illustrated in Figure (1), the principal independent variables are the ambient velocity (U), the effluent velocity (V), the depth of the ambient flow (H), the distance downstream the diffuser (x), the diffuser nozzle diameter (D), the number of nozzles (n), the spacing between nozzles (s), the horizontal angle between the axis of the diffuser and the ambient flow direction (β), the vertical angle of the diffuser nozzles on the horizontal (θ), and the height of the nozzle outlet from the river bed (h). So, the formula between the relative thermal concentration (C_m/C_o) and the independent parameters can be expressed as:

$$C_m / C_o = f\,(x, U, H, W, V, D, s, n, h, \theta, \beta, \Delta\rho) \tag{3}$$

Eqn. (3) can be described in the following general dimensionless form [8]

$$\frac{C_m}{C_o} = f\left[\frac{x}{D}, \frac{V}{U}, n, \frac{s}{D}, \frac{\theta h}{H}, \beta\right] \tag{4}$$

where

x perpendicular distant to the diffuser line in the downstream direction;
n number of diffuser ports; and
s spacing between diffuser nozzles.

From the literature review, it is found that the use of the formulae, which were mentioned in [1], [7], and [4] are so limited in practical application, because in each formula one parameter or two are neglected, which may have a great effect on the value of C_m/C_o. Also, their formulae are based on a few data and for special cases of diffuser installation. So, the need for developing a general accurate formula for multi-ports diffuser including the foregoing parameters that might affect the value of the relative thermal concentration (C_m/C_o) is needed.

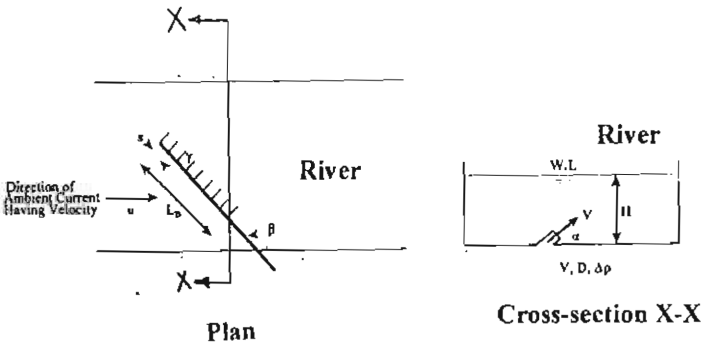


Figure (1) River and diffuser parameters affecting the relative thermal concentration (C_m/C_o)

EXPERIMENTAL SETUP

A fixed bed flume is constructed in the Hydraulics Research Institute (HRI) to study the performance of the series of unidirectional multi-ports diffuser discharging hot water across a part of the channel width [9]. The flume is constructed, from cement and sand mortar over a sand layer of thickness of 0.5 m, to minimize the transferred heat from the discharging hot water to the flume bed. The dimensions of the flume are 15.0 m length, 2.0 m width, and 0.50 m depth. The flume is provided with an earthen basin, which is fed directly from the Nile River by a pipeline of 40.0 cm diameter. Water is pumped from the basin to the flume inlet by a centrifugal pump of total capacity 100 L/s through a pipeline of 25 cm diameter. The water is released from the end of the flume directly to the Nile River again through an underground pipeline of 40 cm diameter. Since, the flume is fed and drained from and to the Nile River, the recirculating of hot water into the model is prevented.

A series of undirectional multi-ports diffuser with nozzles diameters of 3.2, 6.4, 9.6, 12.7, and 15.8 mm are manufactured and used through the experimental work. The distance between any two adjacent nozzles centerline is kept constant (twice the port diameter), so that the spacing between the nozzles with respect to its diameter (s/D) could be changed by closing or opening the even numbers of the nozzles. The length of the diffuser (L_D), is defined as the distance between the centers of the outermost nozzles. A calibrating program is carried out on all the instruments and data acquisition system (thermostats, boiler, electromagnetic currentmeter and electromagnetic flowmeter). Errors are obtained and are considered for all tests. The general arrangement of the laboratory flume is shown in Figure (2).

The heated discharge is delivered from a controlled temperature boiler. A constant temperature with an accuracy of ± 0.3 C° could be obtained from the boiler. The hot water flow rate, which is measured by electromagnetic flowmeter is controlled by a valve installed on the outlet pipe of the boiler. A double manifold system is manufactured to ensure an equal discharge distribution on the different nozzles, which are positioned at the appropriate location of 1 cm above flume floor.

The temperature measurement system consisted of thirty-two temperature sensing probes and thirty-two channel scanner capable of scanning the probes every two minutes. One probe is used in the manifold system to monitor the discharge temperature, and the remaining probes are used in recording the receiving water temperature. The thirty-one probes are mounted on a woody bridge with equal distanees, which covers the whole width of the flume. The bridge is manufactured so that it could be moved easily in both the vertical and the horizontal directions above the flume walls.

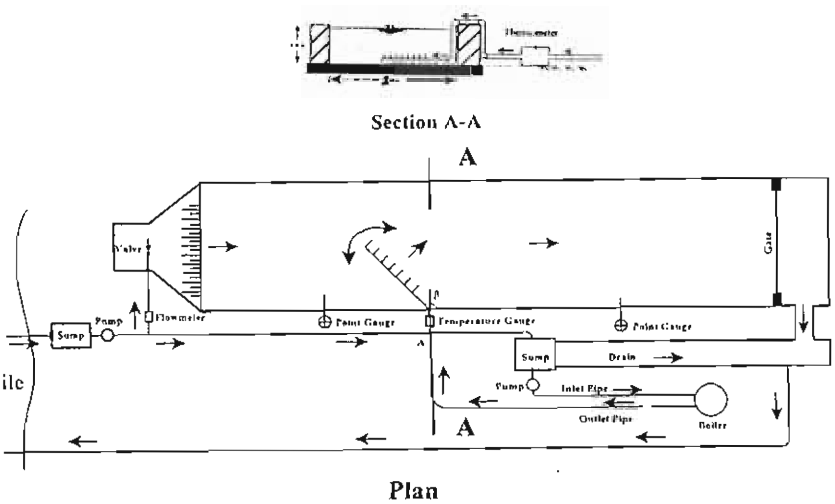


Figure (2) The general arrangement of the laboratory flume

EXPERIMENTAL PROGRAM

The flow velocity is adjusted to be uniform along the width of the flume by using number of wood bars with equal distances that are installed at the entrance of the model. The Reynolds number of the jets for all the experiments is kept to be greater than 4000. The water depths in the flume range from 18 cm to 39 cm, which found to be sufficient for the jet to be mixed freely without any astriction from neither the flume bed nor the free water surface. The experimental program is divided to five main groups according to the direction of the diffuser line with the flow direction (angle β) as illustrated in Figure (1). The angle β is measured from the side wall of the flume in the downstream direction to the diffuser line. The considered values of the angle β are 90°, 112.5°, 135°, 157.5° and 180°. In each group, 125 experiments are performed under the practical ranges of x/D =10 to 100, V/U = 4 to 10, n = 8 to 24, s/D = 4 to 12, θ = 1.57 (90°) to 3.14 (180°); and h/H = 0.1 to 0.3.

For each test, the temperature readings of the probes are recorded after a certain time, at which the discharge plume reaches to the far flume end, and the steady state condition in the vicinity of the diffuser is well established. The temperature readings are carried out at six distances downstream the diffuser. These distances are determined so that the range of x/D= 10 to 100 is covered. At each position, three sections are selected at 0.2, 0.5, and 0.8 H. At each section, thirty-one probes are scanned three times, and the highest of the three is taken as the maximum temperature concentration (C_m).

ANALYSIS AND DISCUSSION OF THE RESULTS

As stated in the theoretical study, it is found that the relative thermal concentration (C_m/C_o) is affected by certain parameters such as x, D, V, U, n, θ, H, s, and β. In this experimental work, the ranges of these parameters are as follows:

1- V/U = 4 to 10	2- n = 8 to 24
3- s/D = 4 to 12	4- θ = 1.57 (90°) to 3.14 (180°)
5- h/H = 0.1 to 0.3	6- β = 1.57 (90°) to 3.14 (180°).

The relative thermal concentration (C_m/C_o) is measured in the flume downstream the diffuser site in the range of x/D = 10-100. Figure (3) shows the effect of dimensionless distance downstream the diffuser site (x/D) on the relative thermal concentration (C_m/C_o). The figure illustrates that C_m/C_o is inversely proportional to x/D. This is referred to the initial momentum, which carries the jets into the receiving water for a considerable distance and the turbulence causing entrainment is generated at the interface between the jets and the receiving water. Although the turbulence presented in the ambient flow has less intensity than that generated by the jets, the rate of entrainment of the deflected jets might be increased and consequently another dilution can be created or in other words a low concentration of the temperature is formed.

Four tests are chosen as samples to explain the flow field of the multiple-ports diffuser in the receiving water body. In every test (125 run) two runs are selected to represent both the high and low boundary conditions of the experiments. The first sample is chosen to indicate the effect of the velocity ratio (V/U) on the flow field of the multiple-ports diffuser. In this case, it is found that at a large distance downstream the diffuser line, the concentration profile has two peaks. This is in fact due to the circulation caused by the component of the cross flow velocity perpendicular to the deflected jet, which is compatible with the study carried out by Wright (1997), [10]. Figure (4) illustrates the relationship between C_m/C_o versus x/D for different values of (V/U). Form the figure, it can be concluded that the relative thermal concentration (C_m/C_o) is directly proportional to the velocity ratio (V/U). Also, from the results it is clear that the decreasing in the relative thermal concentration C_m/C_o is clearly affected by the change of V/U in the mixing zone (low values of x/D), which indicates the importance of the dimensionless parameter V/U, especially, in the mixing zone.

The second sample of the tests has the same dimensionless parameters of the first test except that the value of relative spacing (s/D =12 to 4) and the number of ports (n =8 to 24). In this case, the jets are merged at a distance less than that in the case of the first test and the influence of individual ports is not felt. Generally, it is found that the jets tend to be merged further in downstream with the increase of V/U and s/D. Figure (5) shows the effect of both the numbers of ports in the diffuser (n) and the relative spacing between these ports (s/D) on the relative thermal concentration (C_m/C_o). The results indicate that the value of C_m/C_o is inversely proportional to the value of s/D, while it is directly proportional to the value of (n). This can be explained that when the distance between the ports is relatively small, the jets tend to entrain each other's at a closer distance to the diffuser. So the ambient diluting water is less entrained into the core of the merged jets and hence more thermal concentration is occurred. When the space between ports (s) is increased, the merging of the jets that allow the individual jets to be distinct is delayed, which results in less thermal concentration.

The third sample is considered to indicate the effect of the parameters V/U, and θh/H on the flow field of multiple-ports diffuser in the vertical direction, which are increased from 4 to 10 and from 0.157 to 0.942, respectively. Figure (6) shows the variation of the relative thermal concentration (C_m/C_o) versus the relative downstream distance (x/D) for different values of $\theta h/H$, which range between 0.157 and 0.942. The figure shows that the value of C_m/C_o is directly proportional to the value of $\theta h/H$. This can be attributed due to the fact that the increase of $\theta h/H$ leads to a weakly deflected plume regime with surface interaction and upstream spreading, while the decrease of $\theta h/H$ leads to an intermediate regime with significant blocking and stagnant wedge formation. With more decreasing of $\theta h/H$ value, a strongly deflected regime in which the plume gradually rises to the free surface is formed, which results in less thermal concentration.

The fourth sample shows the variation of the relative concentration (C_m/C_o) versus x/D for different values of the horizontal angle between the diffuser line and the flow direction (β), which varies between β = 1.57 (90°) to β = 3.14 (180°) as shown in Figure (7). The figure indicates that the relative thermal concentration (C_m/C_o) is directly proportional to the angle of the diffuser line with the flow direction (β). When the angle β was small as much as possible, the volume of receiving water available for mixing with effluent is the largest volume. With the increase of β, the volume of water is decreased, which affected the mixing process and consequently, a high thermal concentration occurs.

Development of the Empirical Formula for Computing the Relative Thermal Concentration (C_m/C_o)

Based on the regression analysis of the experimental results (data-fitting program), the relationship between relative thermal concentration (C_m/C_o) and the aforementioned dimensionless terms is developed as follows:

$$C_m/C_o = 0.20\,(x/D)^{-0.52}\,(V/U)^{0.6}\,(n)^{0.43}\,(s/D)^{-0.48}\,(\theta h/H)^{0.25}\,(\beta)^{0.8} \qquad (5)$$

Both the measured data and the predicted values of C_m/C_o by using the aforementioned formula are plotted against each other's as shown in Figure (8). It is found that the correlation factor between both the measured and the predicted results is 0.95, (R^2 = 0.91).

A Comparative Study With Moawad Et Al. [7]

The validity of the developed formula is tested against the laboratory data performed in 1998 by Moawad [7]. This experiments were carried out to study the mixing of the circular multiple jets discharged into relatively deep river cross floes. Experiments carried out by Moawad [7] were performed for the effluent/ambient velocity ratio V/U varying from 3.5 to 10. Three ports were used and the spacing between the ports was varied from 8 D to 16 D, where D is the diameter of the nozzle. The variation of the experimental results of C_o/C_m versus the dimensionless distance (x/D) is compared to the corresponding values of C_o/C_m obtained by the developed formula under the same condition for eight experimental cases as shown in Figure (9). From the figure, it is clear that the best fit for each experiment followed the same shape and the same trend as that obtained by the developed formula. All the values of the correlation factors between the measured and the predicted values of C_o/C_m for the eight experiments are found to be more than 0.95, (R^2 >0.9). These results indicate the validity of the developed formula and its importance in predicting the relative thermal concentration resulted from a submerged multi-ports diffuser discharging hot water in a relatively deep river.

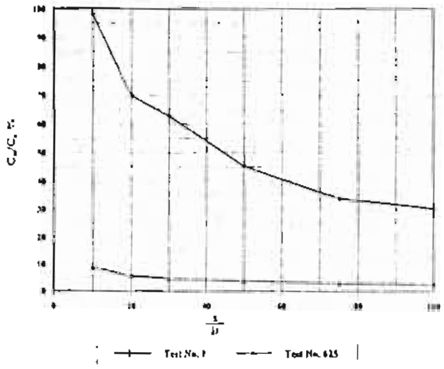
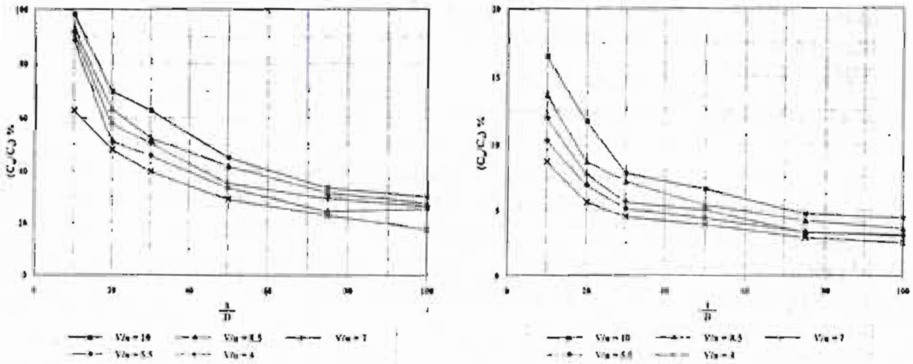
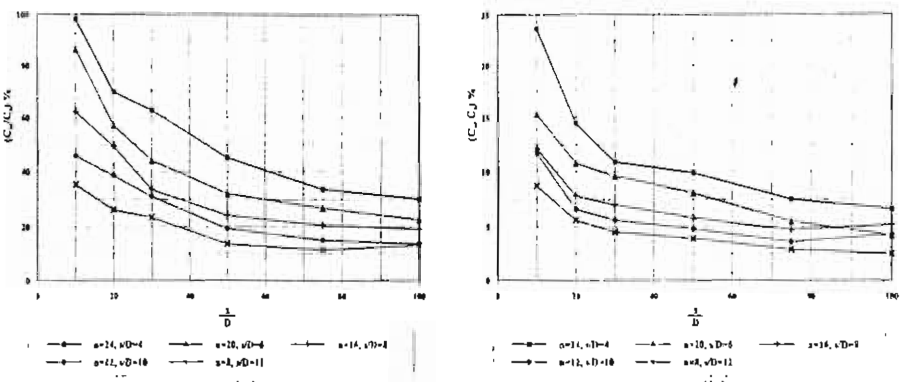


Figure (3) Variation of C_m/C_o versus x/D
Cases of experiments represent high and low boundaries of the data envelope



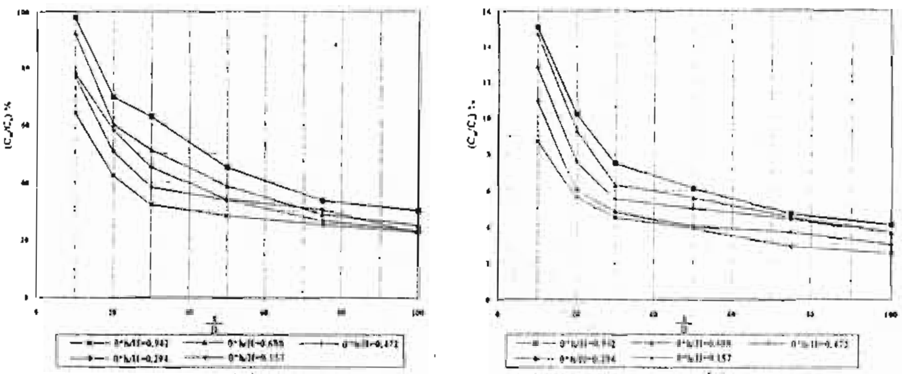
(a) (b)

Figure (4) Variation of C_m/C_o with x/D Under Different Values of V/U
(a) cases of experiments represent the high boundary of data envelope
(b) cases of experiments represent the low boundary of data envelope



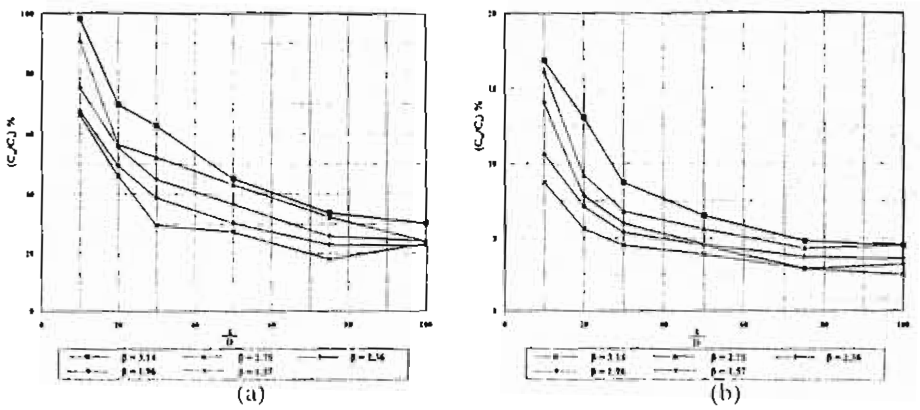
(a) (b)

Figure (5) Variation of C_m/C_o with x/D Under Different Values of s/D and n
(a) cases of experiments represent the high boundary of data envelope
(b) cases of experiments represent the low boundary of data envelope



(a) (b)

Figure (6) Variation of C_m/C_o with x/D Under Different Values of θ h/H
(a) cases of experiments represent the high boundary of data envelope
(b) cases of experiments represent the low boundary of data envelope



(a) (b)

Figure (7) Variation of C_m/C_o with x/D Under Different Values of β
(a) cases of experiments represent the high boundary of data envelope
(b) cases of experiments represent the low boundary of data envelope

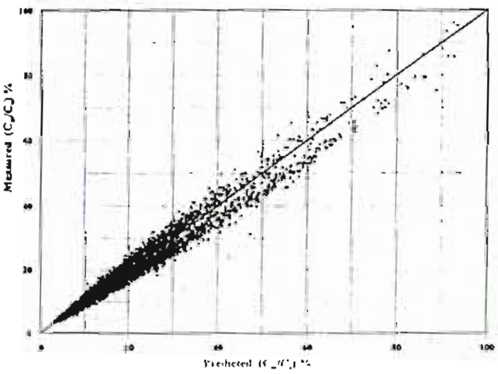
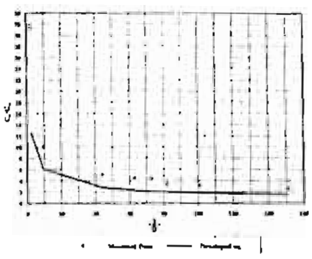
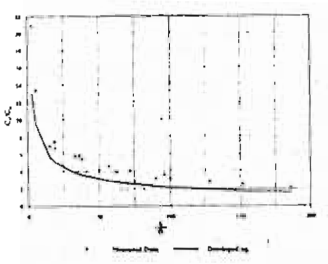


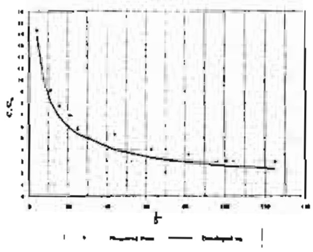
Figure (8) Comparison Between Measured and predicted C_m/C_o



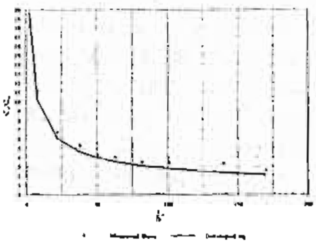
a) V/U=3.5, n=3, s/D=8



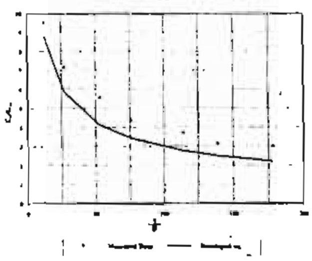
b) V/U= 5, n=3, s/D=8



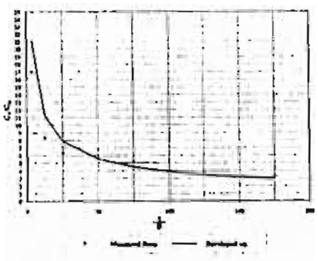
c) V/U=8, n=3, s/D=8



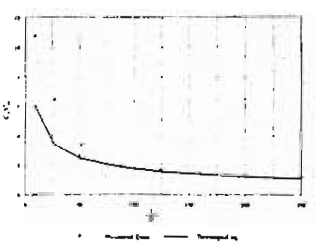
d) V/U= 10, n=3, s/D=8



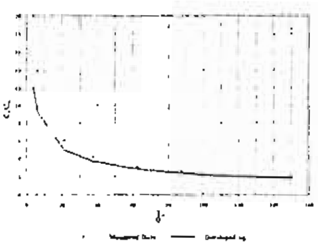
e) V/U=5, n=3, s/D=8



f) V/U= 8, n=3, s/D=8



g) V/U=5, n=3, s/D=16



h) V/U= 8, n=3, s/D=16

Figure (9) Comparison of Measured and Predicted C_o/C_m for Multi-port Diffuser in Deep Water

CONCLUSIONS

From the analysis of the experimental results it can be concluded that:

1-The relative thermal concentration (C_m/C_o) is directly proportional to V/U, n, θ h/H.

2-The relative thermal concentration (C_m/C_o) is inversely proportional to x/D and s/D.

3-Within the data range of the tested diffusers, the maximum values of C_m/C_o are obtained when the diffuser is aligned parallel to the flow direction for the maximum values of V/U, n, and θh/H.

4-The minimum values of C_m/C_o are obtained when the diffuser is aligned perpendicular to the flow direction and for the minimum values of V/U, n, and θh/H.

5-Based on the analytical regression of the experimental results, the relationship between the relative thermal concentration (C_m/C_o) versus the above dimensionless parameters is developed with a correlation factor of 0.95.

6-The validity of the developed formula is tested against two sets of both field and laboratory measurements. It is found that, the best fit of the tested data followed the same shape and the same trend that is obtained by the developed formula.

7-The analysis of the results indicate the validity of the developed formula and its importance in predicting the relative thermal concentration from a submerged multi-ports diffuser discharging hot water in relatively deep rivers.

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NOTATION

The following symbols are used in this paper

B_o equivalent slot width.
C_o thermal eoncentration at the diffuser outlets = $T_e - T_a$.
C_m maximum thermal concentration at any section downstream the diffuser = $T_m - T_a$.
C_m/C_o relative thermal concentration at any section downstream the diffuser = $T_m - T_a / T_e - T_a$.
C_o/C_m dilution of thermal concentration at any section downstream the diffuser = $T_e - T_a / T_m - T_a$.
D nozzle diameter.
H ambient water depth.
h elevation of nozzle outlet above the bed river.
L_D length of diffuser.
n number of diffuser ports.
Q_a ambient river discharge.
Q_e effluent discharge.
s spacing between diffuser nozzles.
T_a local ambient temperature without thermal effluent.
T_e effluent temperature.
T_m ambient temperature at any section with thermal effluent.
U ambient river velocity.
V effluent velocity.
x perpendicular distance to the diffuser line in the downstream direction.
γ nozzle angle relative to diffuser axis.
$\Delta\rho$ density difference.
β horizontal angle between the diffuser line and the flow direction.
θ vertical angle between diffuser nozzles and the horizontal.