Proceedings of ICFDP 8:
8th *International Congress of* Fluid Dynamics & Propulsion
December 14-17, 2006, Sharm El-Shiekh, Sinai, Egypt

ICFDP8-EG-164

THERMAL POLLUTION PLUME FROM A SUBMERGED CO-FLOWING MULTI-PORT DIFFUSER OF POWER PLANTS

Mariam Gabr Salim Ali

Researcher Assistant, Environment and Climate Change Research Institute, National Water Research Center, Ministry of Water Resources and Irrigations, EL-kanater El-Khairia, Egypt

Email: mariam_gabr_salim@hotmail.com

Mahmoud Fouad
Professor, Faculty of Engineering, Cairo University, Egypt

ABSTRACT

The thermal power plants cause thermal pollution of water. The high temperature negatively affects the *physical, biological, and chemical parameters* inside water. Thermal discharges from industrial processes and power generation can cause temperature increases in the receiving water. The rate of chemical reaction is doubled for each 10^{o}C temperature rise that affects the overall productivity of water species. In this study, an experimental set up was employed to test a submerged co-flowing multi-port diffuser that affects the thermal area of pollution of the electrical power plant cooling system. Formula and curves were developed of the thermal pollution induced by the submerged co-flowing multi-port diffusers discharging hot water. The predicted formula could help as a design equation to predict the minimum dilution of the thermal plume according to discharging rates in Egypt. This predicted formula also could help in updating the Environment and Water legislations in Egypt

INTRODUCTION

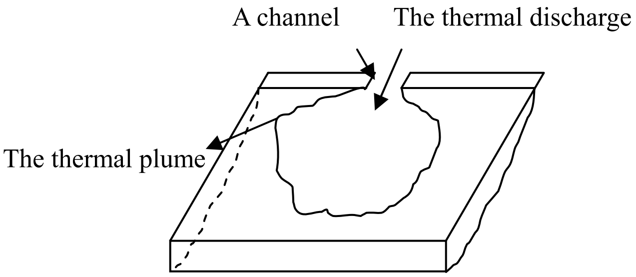
Egypt has the highest growth rates of population in the Arab World of about 70 million. Egypt had an installed electric generating capacity of 18.119 gigawatts in 2003/2004 with plans to raise capacity to over 23.0 gigawatts by 2010. The high growth rate of population increases the total electricity generation from 89.19 gigawatts in 2002/2003 to 95.183 gigawatts in 2003/2004, with an annual growth rate of 6.72%. The Thermal power plants are the main source of thermal pollution. The thermal discharges from the cooling systems of these plants negatively affect the aquatic species adjacent to it. Thermal power plants produce electricity by converting the chemical stored energy in the fossil fuel or uranium into electrical energy. This process is unnatural organized process, so according to the second low of thermodynamics excess heat will be created. This excess heat heats the surroundings of the ***thermal power plants causing thermal pollution***. The common types of fossil fuels are natural gas, coal, and oil, as they contain high stored chemical energy. The stored energy produces heat that drives turbines to create electric energy through a process called Rankine Cycle. There are two ways to discharge heated water as shown in figure (1).

Surface discharge

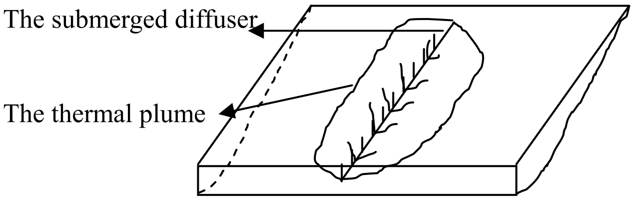
Heated water is discharged from a surface channel to the ambient flow. The flow has a low discharge velocity. This means that the buoyancy force dominates the momentum force.

Submerged discharge

Heated water is discharged from a submerged diffuser. The flow has a high discharge velocity. This means that the momentum force dominates the buoyancy force.



(a) Surface discharge



(b) Submerged discharge

Figure (1) Ways of thermal discharges, Miller and Brighouse

Thermal electricity generation in Egypt

About 73% of Egypt's electric generating capacity is thermal and 15% hydroelectric, mostly from the Aswan High Dam. “Electricity generated by thermal power stations decreased from 68.442 gigawatts hour in 2002/2003 to 68.218 gigawatts hour in 2003/2004, with a decreasing rate of 0.33 percent. In the late1970s, only 4% of the thermal power stations were being generated using natural gas as fuel. By 2003/2004, increased to about 92% as a result of the state policy to promote the use of natural gas to replace petroleum products, thereby maximizing the economic and environmental benefits of using natural gas, figure (2).

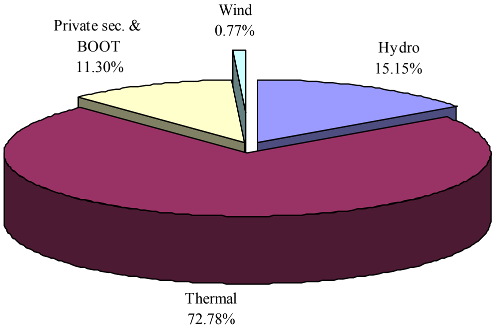


Figure (2) Installed capacity in Egypt, 2003-2004

Thermal pollution effects

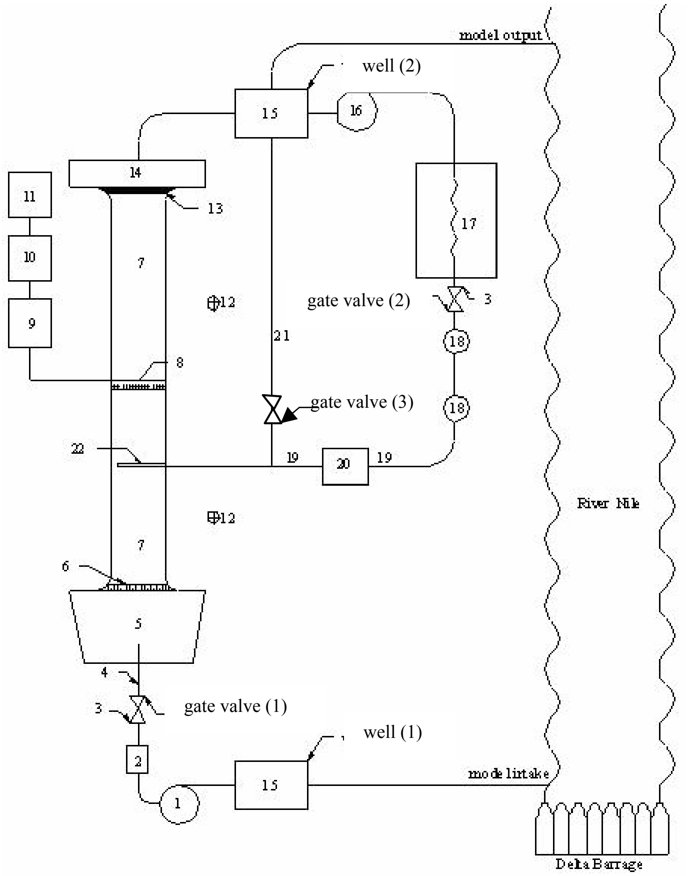
The excess temperature decreases the dissolved oxygen inside water and increases the respiration and the heart rate of fish that decrease the metabolism process. The excess temperature increase the BOD and decrease the photosynthesis process resulting in more drops in dissolved oxygen that cause the death of aquatic life. The excess temperature slow the metabolic reaction as it acts like an inhibitor.

NOMENCLATURE

The objective of the present work is to study the minimum dilution of thermal pollution of multiple jets of a co-flowing submerged multi-port diffuser of different ratios of x/d and U_o/U_a.

EXPERIMENTAL SETUP

The experimental tests were carried out in a rectangular flume inside the northern experimental hall of the Hydraulic Research Institute (HRI). The flume has dimensions of 0.4m deep, 2m wide, and 15m long. Figure (3) shows a schematic diagram of the feeding (circulating) system process. The centrifugal pump (1) discharged the ambient cold water from the well***1*** (15) filled from the River Nile through underground pipes and channels. The ultra-sonic flow meter (2) and the gate valve***1*** (3) were used to control the ambient discharges trough the inlet ambient cold water pipe (4) to the model entrance (5). The wooden screen (flow straighter) (6) at the beginning of the model (7) was consisting of equally size wooden bars at equal distances to uniformly distribute the flow and to dissipate energy to minimize the turbulent flow. The temperature measurement system consisted of 23 temperature probes. The probes were used to monitor the receiving water temperature. A standard thermistor was used to monitor the ambient cold water discharges. The thermistors were mounted on a movable measuring thermistors carriage (8) over the flow field. Temperatures at desired horizontal and vertical locations in the thermal discharge were obtained by moving the probes, allowing measurements of the thermal plume in the x, y, and z directions. The thermistors were connected to the scaling units (9), the data logger (10) and the computer (11) that they together formed the complete temperature measuring system. Two point gauges (12) were used to measure the water level across the model. A revolving tail gate (13) was used to adjust the water level across the model at the beginning of the model exit (14). The ambient cold water was discharged from well***2*** (15) by the centrifugal pump (16) to the electric water heater (boiler) (17) to fill it up and to discharge the hot water to the model. The discharged hot water from the boiler was adjusted by the gate valve***2*** (3). Two electro magnetic flow meters (18) were used to measure the hot water discharge through the diffuser feed line (19). First, the hot water was discharged through the diffuser bypass line (21) until the model temperature was homogeneous, and then the hot water was discharged through the submerged diffuser (22) into the model. The hot water box (20) was used to measure the inlet hot water temperature. The outflow from the model was discharged to well***2*** (15) to the River Nile again.



1	133lit/s centrifugal pump	12	Two point gauges
2	Ultra-sonic flow meter	13	Revolving tail gate
3	Three gate valves	14	Model exit
4	Inlet ambient cold water pipe (20cm diameter)	15	Two wells
5	Model entrance	16	34lit/s centrifugal pump
6	Wooden screen(flow straighter)	17	Electric water heater
7	Model	18	Two electro magnetic flow meters
8	Measuring thermistors carriage	19	Diffuser feed line(5cm diameter)
9	Scaling units	20	Hot water box to measure the inlet hot water temperature
10	Data logger	21	Diffuser bypass line(5cm diameter)
11	Computer	22	Co-flowing submerged multi-port diffuser

Experimental procedure

The model basin water level was adjusted to 0.3m depth. The electric water heater (boiler) was adjusted to the desired temperature, and then allowed to flow through the diffuser bypass line. An initial temperature scan was taken to ensure that the basin temperature was homogeneous. The diffuser bypass line was closed, the diffuser feed line opened, and the flow rate adjusted to the desired value. Probes were scanned after ten minutes, until the discharge plume had reached the far basin, and steady state conditions had been established. During each test, hot water flow and temperature and ambient cold water flow and temperature were continually monitored, and adjusted as necessary. Temperatures were measured upstream and downstream from the discharge section of the basin in order to determine the excess temperature distribution through the basin. The diffuser pipe was 5cm diameter that was equipped with twenty ports of 1cm equivalent diameter. All the ports were directed in the downstream direction at a 20^{o} angle with horizontal, as suggested by both **Parr and Melville and Miller and Brighouse.** The temperature difference was constant at 12 ^{o}c that was recommended the most effective temperature difference by **Kotob and Shawky.**

Experimental program

Most of the experimental work, according to the available literature, showed that the most effective parameter on the thermal plume was the velocity ratio (U_o/U_a), so this study aims to study the mixing zone area of the thermal plume at different velocity ratio in the 3-dimensions x, y, and z in open channels. Before the experimental work was carried out, calibrations were made for all the instruments (thermistors and flow meters). The probes were calibrated in an isothermal insulated container where water temperatures inside the container were varied and the reading of the probes were taken three times for each run and also compared with a standard thermometer. The two electromagnetic flow meters were calibrated in a 1m length, 1m width, 1m depth basin. The water level readings of the basin were obtained by the basin indicator. The discharge of the flow meter and the water level inside the basin were measured after equally time steps. The ultra-sonic flow meter was calibrated by its manufacturing company. Errors were taken into consideration for each measurement. The ambient water discharges were 4lit/s, 8lit/s, 12lit/s, 16lit/s, 20lit/s, and the hot water discharge was 2.5lit/s. the measuring thermistors carriage had an easy motion to measure the temperature in x, y, and z direction at 5796 (46y*9x*14z) nodes. 5 experiments of 630 runs were done

EXPERIMENTAL RESULTS AND DISCUSSION

The mixing process of the hot water discharge from the ports (jets) of the submerged diffuser into the ambient receiving water is due to **four forces**. **The first** force is the initial jet **momentum force** that carries the jets from the ports into the ambient receiving water for a considerable distance. **The**

second force is the **buoyancy force** of the hotter jet water that tends to deflect the jet upward. **The third** force is the **turbulence force** generated between the jets and the receiving water cause the entrainment. So the jets diameters increase, while their velocities decrease. **The fourth** force is the **drag force** from the ambient flow, which with the entrainment resulted from the turbulence force direct the jets downstream in the ambient flow direction.

The tests were done with the following assumptions:

- The jet turbulence was a function of the ports discharge and diameter.
- The ambient flow turbulence was a function of the ambient flow velocity and flow depth, so the relative depth H/d was maintained at 30 to ensure that the jets did not surface in the mixing region.
- The density difference due to temperature difference between the discharged hot water and the cold ambient water, i.e. buoyancy force, was maintained constant all over the test runs.

From the above, it could be concluded that the most useful dimensionless variable is U_o/U_a, the momentum ratio of hot to ambient water velocity, and the **independent variables** are:

- H, the free stream depth (water depth), m
- L_D, length of the diffuser, m
- Q_o, the port initial discharge (jet discharge), m^3/s
- U_a, the ambient velocity, m/s

The **dependent variable** is:

- S_{min}, the minimum dilution equal to C_o/C_m

The mixing zone of the tested diffuser

Five tests were done to explain the mixing zone of the jets into the receiving ambient water. The temperature field was measured and plotted upstream and downstream the submerged diffuser in the transverse direction y, the vertical direction z, the longitudinal direction x. The maximum concentration (T_m-T_a) was examined in the 3 directions to show the thermal plume concentration through the test runs. ***The values of the discharge ratios (NQ_o/Q_a) were 0.625, 0.313, 0.208, 0.156, and 0.125. The corresponding velocity ratios (U_o/U_a) were 238.64, 119.32, 79.55, 59.66, 47.73; these ranges were higher than in previous studies that ranged from 0.001 to 0.1 for the discharge ratios and ranged from 2 to 150 for the velocity ratios. The higher values of the discharge ratios (NQ_o/Q_a) were selected in this study to cover the practical situation in Egypt, where most of the thermal power plants discharge hot water in the River Nile and mostly in its branched small canals that have low ambient velocities with respect to the thermal power plant discharge velocities. Also this range covers the Winter Closure period in Egypt when the ambient velocity nearly equal zero and the thermal power plants could not stop discharging the hot water.***

1. The maximum longitudinal temperature difference between the mixing zone temperature and the ambient cold water temperature to indicate the thermal plume upstream and downstream, figure (4).

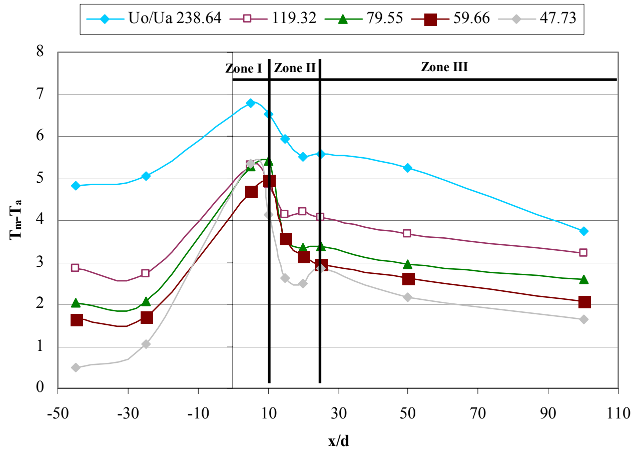


Figure (4) The maximum longitudinal maximum concentration of the tested diffuser

The figure shows that the maximum (T_m-T_a) for all the velocity ratios U_o/U_a is ranging, with a value of 1.9 ^{o}c, from 6.77 ^{o}c at x/d=5, U_o/U_a=238.64 to 4.9 ^{o}c at x/d=15, U_o/U_a=59.66. The minimum (T_m-T_a) for all the velocity ratios U_o/U_a, with a value of 3.2 ^{o}c, is ranging from 3.7 ^{o}c at x/d=100, U_o/U_a=238.64 to 0.47 ^{o}c at x/d=-45, U_o/U_a=47.73. The maximum longitudinal concentration increase as the dimensionless velocity parameter U_o/U_a increase, and there are 3 zones downward of the flow field from the multiple jets, zones I, II, and III. **Zone I**, occurred to a distance where x/d =5 for $U_o/U_a \leq$ 119.32 and x/d =10 for $U_o/U_a >$ 119.32 as the jets move perpendicular to the ambient flow without any interference (merging) with each others. The vertical motion of the jets is due to their momentum and buoyancy force is the dominant force. The jets z-velocity tends to decrease, while their diameters increase with respect to the dimensionless length parameter x/d due to the entrainment caused by the turbulence force generated between the jets and the ambient flow in addition to the drag force from the ambient flow also. It is also founded that zone I length decreased as the dimensionless velocity parameter U_o/U_a increase.

Zone III, occurred nearly to a distance where x/d ≥25, where the jets were completely merged and were bent horizontally with the ambient flow. The jets movement in z-direction and the jets diameters increase tend to continue as in zone I, but at slower rate.

Zone II, is a transition zone. These observations were mentioned in previous studied by **Moawad and Rajaratnam,** and **Shawky**. The thermal plume was founded to be extended behind the diffuser, where the maximum longitudinal concentration decreases upward direction.

2. The maximum transverse temperature difference between the mixing zone temperature and the ambient cold water temperature to indicate the thermal plume along the diffuser width, figure (5).

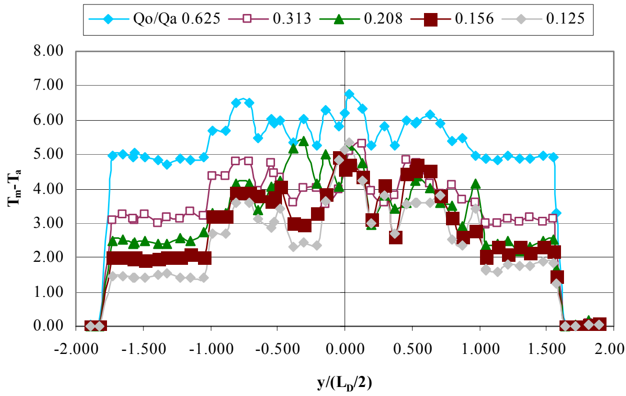


Figure (5) The maximum transverse concentration of the tested diffuser

The figure shows that the maximum (T_m-T_a) for all the velocity ratios U_o/U_a is ranging, with a value of 1.9 ^{o}c, from 6.77 ^{o}c at $y/(L_D/2)$ =0.034, U_o/U_a=238.64 to 4.9 ^{o}c at $y/(L_D/2)$ =-0.042, U_o/U_a=59.66. The minimum (T_m-T_a) for all the velocity ratios U_o/U_a with a value of 0.005 ^{o}c, is ranging from 0.008 ^{o}c at $y/(L_D/2)$ =1.642, U_o/U_a=238.64 to 0.003 ^{o}c at $y/(L_D/2)$ =1.718, U_o/U_a=47.73.. It could be concluded that the maximum transverse concentration increase as the dimensionless velocity parameter U_o/U_a increase. The maximum temperature difference has its higher values near the diffuser center in the range **$-1 \leq y/(L_D/2) \leq +1$**, while it starts to decrease rapidly outside that range until it diminished at **$y/(L_D/2) > \pm 1.5$**.

3. The maximum vertical temperature difference between the mixing zone temperature and the ambient cold water temperature to indicate the thermal plume along the model depth, figure (6).

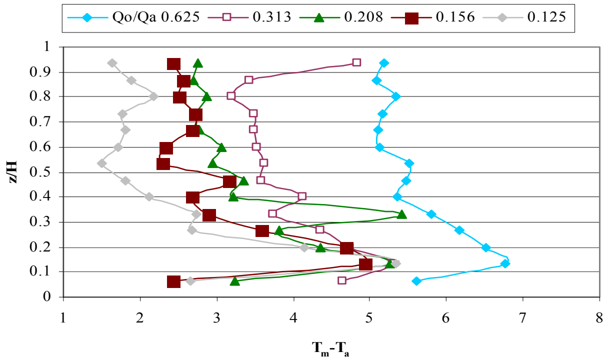


Figure (6) The maximum vertical concentration of the tested diffuser

The figure shows that the maximum (T_m-T_a) for all the velocity ratios U_o/U_a is ranging, with a value of 1.9 ^{o}c, from 6.8 ^{o}c at z/H=0.133, U_o/U_a=238.64 to 4.9 ^{o}c at z/H=0.133, U_o/U_a=59.66. The minimum (T_m-T_a) for all the velocity ratios U_o/U_a, with a value of 3.6 ^{o}c, is ranging from 5.1 ^{o}c at z/H=0.867, U_o/U_a=238.64 to 1.5 ^{o}c at z/H=0.533, U_o/U_a=47.73. It could be concluded that the maximum vertical concentration increase as the dimensionless velocity parameter U_o/U_a increase. The maximum temperature difference has its higher values deeply in front of the jets at z/H= 0.133 while it starts to decrease upward vertically to the surface.

The developed formula of the minimum dilution of the tested diffuser

The measured data was analyzed to calculate the minimum dilution (C_o/C_m) to have the dimensionless empirical formula has the following dimensionless form:

$$\frac{C_o}{C_m} = 11.47874\left(\frac{x}{d}\right)^{0.275258}\left(\frac{U_o}{U_a}\right)^{-0.47275}$$

The difference between the measured and predicted data was plotted in figure (7). This slightly high value of error was due to the high values and high range of the velocity ratios (U_o/U_a) that ranges from 47.7 to 238.6.

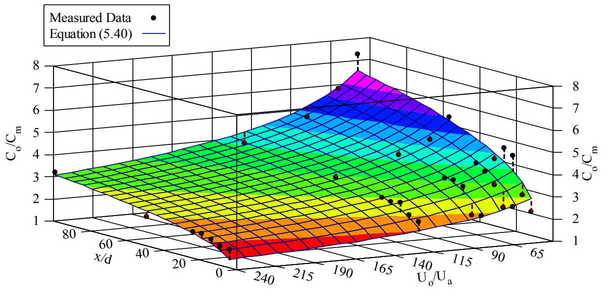


Figure (7) Comparison of the measured and predicted C_o/C_m for the tested multi-port diffuser

The Verification of the developed formula of the minimum dilution of the tested diffuser

The validity of the developed formula of the minimum dilution of the tested diffuser was tested against the **laboratory and prototype Quad cities data of Parr and Melville, Hinwood and Wallis, Moawad and Rajaratnam, and Shawky.** Figure (8) shows a comparison of the measured and predicted C_o/C_m for the Quad cities multi-port diffuser and the previous equation. Figure (9) shows a comparison of the measured and predicted C_o/C_m for the Hinwood & Wallis field data in an estuarine channel near the mouth of Port Phillip Bay in Australia and the previous equation. Figure (10) shows a comparison of the measured and predicted C_o/C_m for the Moawad & Rajaratnam field data and the previous equation.

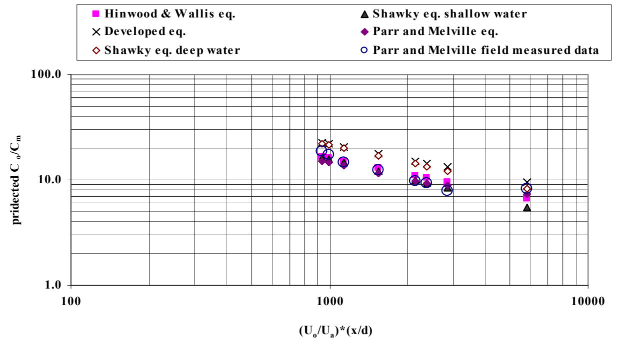


Figure (8) Comparison of the measured and predicted C_o/C_m for the Quad cities multi-port diffuser and the previous equations

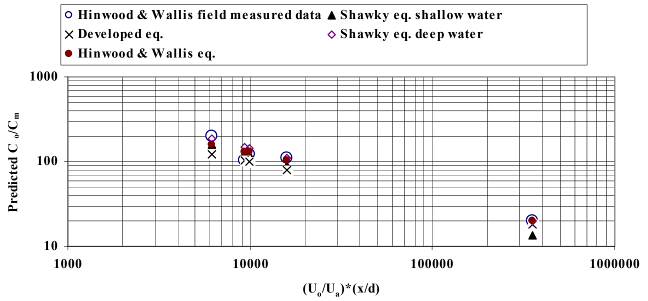


Figure (9) Comparison of the measured and predicted C_o/C_m for the Hinwood & Wallis field data and the previous equations

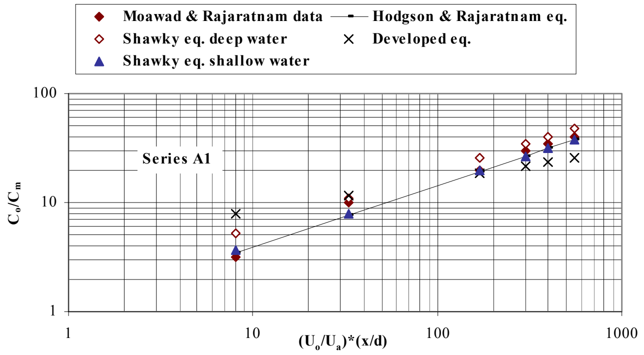


Figure (10) - (a) series A1 (ℓ/d=8, U_o/U_a=3.5, H/d=34)

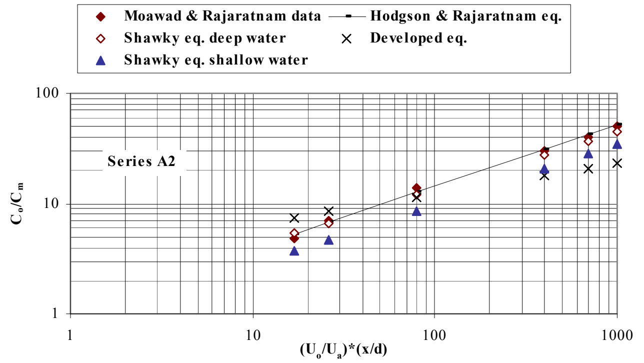


Figure (10) - (b) series A2 (ℓ/d=8, U_o/U_a=5, H/d=34)

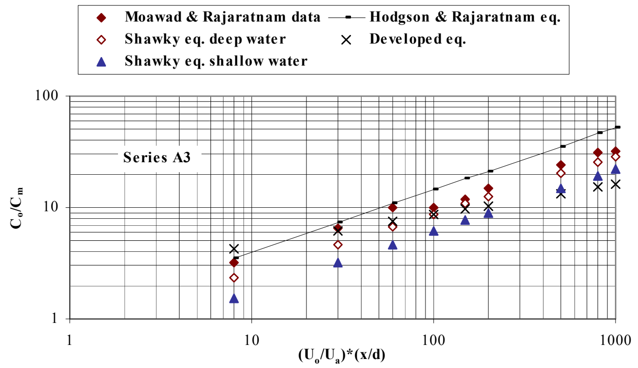


Figure (10) - (c) series A3 (ℓ/d=8, U_o/U_a=8, H/d=44)

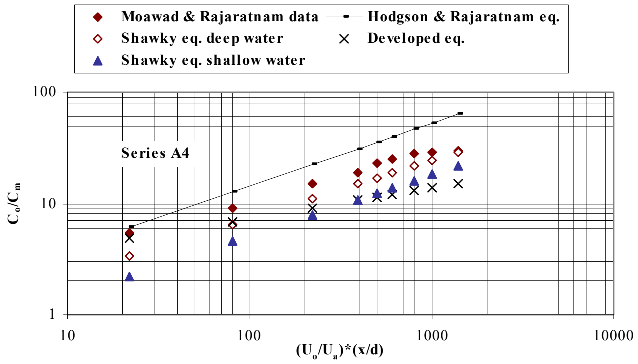


Figure (10) - (d) series A4 (ℓ/d=8, U_o/U_a=10, H/d=57)

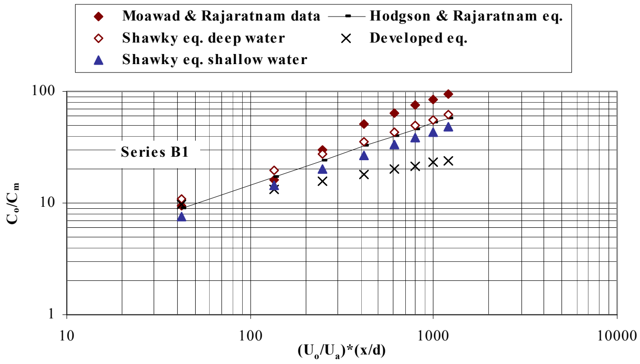


Figure (10) - (e) series B1 (ℓ/d=16, U_o/U_a=5, H/d=45.5)

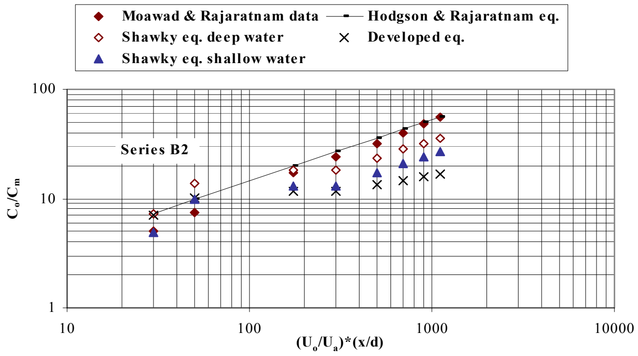


Figure (10) - (f) series B2 (ℓ/d=16, U_o/U_a=8, H/d=45.5)

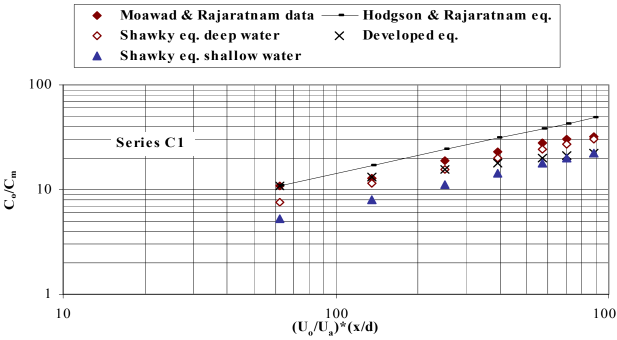


Figure (10) - (g) series C1 (ℓ/d=8, U_o/U_a=5, H/d=45.5)

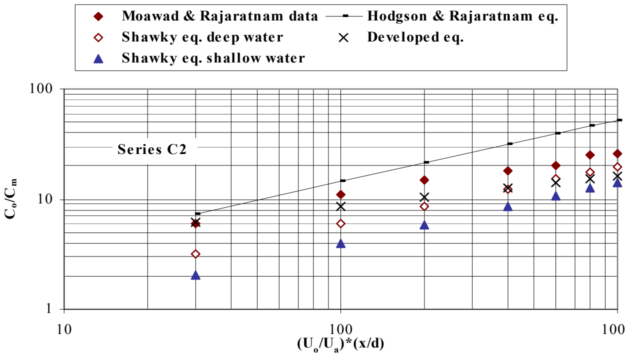


Figure (5.10) - (h) series C2 (ℓ/d=8, U_o/U_a=8, H/d=45.5)

Figure (10) Comparison of the measured and predicted C_o/C_m for the Moawad & Rajaratnam field data and the previous equations

CONCLUSIONS

In general it is concluded that the effluent/ambient velocity ratio U_o/U_a is the most important parameter that affects the thermal pollution. If the velocity ratio U_o/U_a is high this means that the jet momentum force is high so carries the jets into the ambient receiving water for a considerable distance. On the other side if this velocity ratio U_o/U_a is low the turbulence force generated between the jets and the receiving water would deflect the jets downstream direction decrease the spread of the jets into ambient water. It is clear that the predicted formula has the same shape and trend of the other previous equations. There is a good agreement between the predicted minimum dilution formula and the previous empirical equations. This agreement indicates the validity of the measured data of this study. The predicted formula could help as a design equation to predict the minimum dilution of the thermal plume according to discharging rates in Egypt. This predicted formula also could help in updating the Environment and Water legislations in Egypt.

ACKNOWLEDGMENTS

The experimental work of this study was performed in the Hydraulic Research Institute (HRI), National Water Research Center (NWRC), Ministry of Water Resources and Irrigation (MWRI).

REFERENCES

1. **Cormix** the United States Environmental Protection Agency -supported mixing zone model and decision support system for environmental impact assessment of regulatory mixing zones resulting from continuous point source discharges, **website**, http://www.cormix.info/index.php.
2. **Country Analysis Briefs**, energy information administration United States government, website, http://www. Egypt country analysis brief. htm, and http://www. eia.doe.gov., (2004).
3. **Energy in Egypt 2003-2004**, Ministry of Planning, Organization for Energy Planning, Egypt, (2005).
4. **Environmental Protection Agency (EPA),** United States website, http://www.epa.gov., (2005).
5. **Hinwood, J. B., and Wallis, J. G.,** "Initial dilution for outfall parallel to current" ASCE, journal of hydraulic engineering, Vol. 111, No. 5, May (1985).
6. **Kotob, O. A.** "An experimental and analytical investigation of waste heat dissipation in Rivers" MSc. Faculty of Engineering, Cairo University, (2002).
7. **Miller D. S. and Brighouse B. A.,** " Thermal discharges " A guide to power plant and process plant cooling water discharges into rivers, lakes and seas" Publication ISBN 0 906085 93 4 British Hydrodynamics Research Association 1984.
8. **Moawad, A. K., and Rajaratnam, N.**, "Dilution of multiple circular jets in cross flows" ASCE, journal of environment engineering Vol. 124, No. 1, (1998).
9. **Parr, A.D., and Melville, J.G.,** " Near field performance of river diffusers " ASCE, journal of environmental engineering, Vol. 107, No. EE5, (1981).
10. **Shawky, Y. M.,** "Near field performance of river multi-port diffuser" Ph.D. Faculty of Engineering, Minufiya University, (2001).
11. **Van Wylen G. J., and Sonntag R. E.** " Fundamentals of classical thermodynamics" third edition, published by John Wiley. Inc., (1985).

ANNEX A

ABREVIATIONS

C_m : maximum concentration at any section in the mixing region (= T_m- T_a), ^{o}c

C_o: initial concentration at port (= T_o- T_a), ^{o}c

d: port diameter (jet diameter), m

H: the free stream depth (water depth), m

ℓ: spacing between ports=L_D/N-1, m

L_D: length of the diffuser, m

N: number of ports
Q_a: the ambient discharge, m^3/s

Q_o: the port initial discharge (jet discharge), m^3/s

S_{min}: the minimum dilution equal to C_o/C_m

T_a: ambient temperature, ^{o}c

T_m: maximum temperature in the mixing zone, ^{o}c

T_o: the port initial temperature, ^{o}c

U_a: the ambient velocity, m/s
U_o : the port initial velocity (jet velocity), m/s
x: longitudinal distance downstream from port, m

y: the distance along the initial direction of the jet, m

z: vertical distance measured from the bed, m