SURFACE DISCHARGES OF WARM WATER FROM THERMAL POWER STATIONS INTO RIVERS

Kassem Salah El-Alfy

Irrigation & Hydraulics Dept., Faculty of Eng., Mansoura University, Egypt

ABSTRACT

The existing of thermal power stations on rivers results in many environmental problems. The discharging of the cooling system of the thermal power stations into rivers may be surface discharge, submerged point discharge and submerged multi-port diffusers. In this research paper, the study was focused on the most common surface discharge method. In this research paper, isotherm map, centre line of temperature decay, and isotherm areas were studied. A field investigation was carried out on both Talkha and El-Kurimat thermal power plants. A comparative study was carried out between the aforementioned parameters of Talkha and El-Kurimat power plants and the corresponding calculated ones from formulas developed by the other researchers. Also, the field data of heated discharges is analyzed to show the influence of ambient velocity, jet densimetric Froude number, aspect ratio on plume trajectory and centre line of temperature decay. Isotherm area data from field studies are used to investigate the relationship between excess temperature and isotherm areas of the plumes. It is found that the relationship between the excess temperature and the isotherm area of the studied Egyptian thermal power plants falls within the Frigo et al. [1] data envelope, which is still remain a good guide for expecting the isotherm areas. Also, the study concluded that the formulas presented in this paper could be help in predicting the main thermal lineament downstream the surface discharge outlets of the thermal power stations cooling system into rivers.

Keywords: Thermal pollution- Surface discharge- Isotherm area- Plume.

INTRODUCTION

The cooling water of the thermal power plant is considered one of the most pollution sources of rivers, especially for the liquid natural gas stations, which require large amount of refrigeration water. Thermal pollution affects both the physical and chemical characteristics of the flowing water. Also, thermal pollution affects on morphology of the rivers due to the growth of the water plants depending on the water temperature increase and sedimentation process. As stated by D.S. Miller and B. A. Brighouse [2], the chemical reactions is approximately doubled for each 10 °C temperature rise, which increase the sedimentation due to changes of water properties, changes in flocculation, and ion exchange.

The cooling systems of thermal power stations may be one of the following:

1- surface discharge system,
2- submerged point discharge system, and
3- submerged multi-ports diffusers system.

The most common surface discharge system is the main aim of this research paper. The flow of plumes may be in shallow water or in deep water. The water is considered shallow if the plume reaches the bottom of the river at a definite distance, S, [6] and it can be classified according to the following:
- Shallow water: $h_{max}/H > 0.75$
- Deep water : $h_{max}/H < 0.75$

in which

h_{max} the maximum depth at which plume will reach if it is not restricted by the bed = $0.42\ F_0\ A^{0.25}\ (h_o b_o)^{0.5}$;
H water depth at the distance from the outlet $S = 5.5\ F_0 A^{1/4} \sqrt{h_o b_o}$;
S distance along plume centre line;
F_0 densimetric Froude number;
A aspect ratio = h_o / b_o;
h_0 outlet flow depth; and
b_0 half width of the outlet.

The densimetric Froude number is calculated as follows:

$$F = \frac{U}{\sqrt{\frac{\Delta\rho}{\rho} gd}}$$

in which

U local velocity of warm jet;
$\Delta\rho$ density difference between the ambient and discharged water;
ρ ambient density;
d outfall depth; and
$\Delta\rho/\rho$ density difference ratio depends on ambient temperature and excess temperature discharge [2].

In 1969, Tamai and Wiegel [11] studied the surface and subsurface temperatures and temperature fluctuations for discharges having densimetric Froude number between 2.4 and 11.3. In 1971 Stolzenbach and Harleman [10] developed a three-dimensional theory for prediction of temperature with the region dominated by turbulence from a heated discharge. In 1971, Klliot and Harkness [6] carried out their study on plume measurements to predict the size, shape, and orientation of the plume. In 1974, Shirazi [9] analyzed statistically some published laboratory and field data of the surface discharges. In 1974, Kyser and Paddock [8] used the data from some sites to study the centre line of temperature decay and isotherm areas for different plumes. Koester, [7] studied the effect of submergence ratio of heated water jet and a shallow bottom on jet characteristics. He compared his results with those resulted by using Stolzenbach model [10].

The plume regions may be divided into near field, which extends to contour line of 2 °C temperature difference [2], far field, in which the plume dominates by buoyancy and ambient effects, and in between there is an intermediate field. In this research paper the study includes both the near and far field.

Centre line of temperature decay

Miller and Brighouse [2] developed the following equation for the centre line of temperature decay from field and laboratory analysis as follows:

$$\frac{\Delta T}{\Delta T_0} = 3.774\left[\frac{S}{\sqrt{h_0 b_0}}\right]^{-0.405} F_0^{-0.373} A^{-0.131} \alpha^{-0.084} \tag{1}$$

in which

$\Delta T/\Delta T_o$	excess temperature ratio;
S	distance from the outlet on the centre line of the plume;
F_0	densimetric Froude number (the ratio of inertia to buoyancy forces acting on the discharge);
α	angle between the centre line of the outlet and the river measured in the downstream direction of the flow (in radian);
ΔT	difference between local temperature at any point and normal ambient temperature;
ΔT_0	difference between discharged water temperature at the outlet and normal ambient temperature;
h_o	outlet flow depth;
T_o	discharged water temperature;
b_o	half width of the outlet; and
A	aspect ratio $=h_o/b_o$.

Plume trajectory

According to Miller et al. [2], the plume trajectory in shallow water could be given by the following relationship:

$$\frac{y}{\sqrt{h_0 b_0}} = 2.55\left[\frac{x}{\sqrt{h_0 b_0}}\right]^{0.378} R^{-0.849} F_0^{-0.601} A^{-0.166} \alpha^{0.084} \tag{2}$$

in which

x, y	the coordinates of the plume trajectory;
R	current velocity/ warm jet velocity;
F_0	densimetric Froude number;
α	angle of the outlet (in radian);
h_o	jet flow height; and
b_o	half width of the outlet.

THE FIELD DATA

The surface discharge cooling system is considered the simplest way for discharging the cooling water into rivers, but the prediction of the plume through river is very difficult. Since the relative cost of the surface discharge of the cooling system of the thermal power plant is very low compared with the other two types, the most cooling systems of the thermal power plants in Egypt is surface discharge type. In this research paper, Talkha and El-Kurimat power stations, in Egypt were used as cases study. General layout of intakes and outlets of Talkha power station, which sits on Damietta Nile branch in Dakahelia Directorate is shown in Fig. 1-a. The surface discharge cooling system of Talkha power plant consists of two outlets with 30 m apart. The first outlet for discharging the cooling water of 2x50 M.W units, while the second one for cooling 2x210 M.W units. The discharge used for the cooling system is 2.11 million cubic meters per day, which is considered 46.88% of the minimum flow (4.5 M m^3/day) and 60% of discharge at winter maintenance period [4]. The width of the outlet channel of 2x50 M.W units is 9.5 m, while 2x210 M.W units is 12.1 m width, and outfall depth was found to be 1.95 and 2.46 m, respectively. The temperature of the river was measured and it was found to be 15.7 C^0 (in January 2003), while the temperature at the outlet was found to be 23.2 C^0. Also, general layout of the intake and outlet of El-Kurimat thermal power plant 1200 M.W, which sits on Nile River km 839.150 D.S. Aswan high dam in south of Geza Directorate is shown in Fig. 1-b. The surface discharge cooling system of El-Kurimat power plant is 3.46 million cubic meters per day, which is considered 10% of the minimum flow discharge of the Nile River at that site [5]. The width of the outlet channel is approximately 55 m, and outfall depth was found to be 4 m. The temperature of the river was measured and it was found to be 16.7 C^0 (in January 2003), while the temperature at the outlet was found to be 23.0 C^0.

The field measurements of the warm water of the outlet at Talkha and El-Kurimat power plant were carried out by the writer in co-operation with the Hydraulic Research Institute (HRI) by using a boat to survey the area around and downstream the outlets of the power station. The temperature sensing probes, global positioning system (GPS), and thermostat were used in recording the temperature and the coordinates at different points as illustrated in Fig. 1-c. The water temperature at different points at the outlet and in the downstream area of the river was measured until the temperature arrives to the normal temperature of the stream. The measurements were carried out at 0.75 m under the water surface. Surfer program was used in drawing the isotherm map of the temperature at the power station outlet as illustrated in Figs. 2-a and 2-b. Also, both the cross-section characteristics and the flow properties are measured upstream Talkha power plant intake (sec I), between the intake and the outlet (sec II), and downstream the outlet (sec III) as illustrates in Table 1:

Table 1 Cross-sections properties at Talkha thermal power station site

Sec.	Q M m^3/day	A m^2	V m/s	d_{max} m
I	7.48	376.8	0.23	7.5
II	5.34	311.7	0.198	4.31
III	7.48	247.62	0.35	4.31

Type of flow:

-For 2x50 M W. units

Local velocity of warm jet (U) was found to be 0.36 m/sec.

According to Miller et al. [2], when ΔT_0=23.2-15.7=7.5°C and the ambient temperature equals to 15.7°C , the value of $\Delta\rho/\rho$ = 0.0015

$h_{max} = 0.42\ F_0\ A^{0.25}\ (h_o b_o)^{0.5}$

$$F_0 = \frac{U}{\sqrt{\frac{\Delta\rho}{\rho} gd}} = \frac{0.36}{\sqrt{0.0015x9.81x1.95}} = 2.125$$

h_o=1.95 m b_o = 9.5/2 = 4.75

aspect ratio =h_o/b_o = 1.95/4.75 = 0.41

h_{max} = 0.42 x 2.125 $(0.41)^{0.25}$ $(1.95x4.75)^{0.5}$ = 2.173

S_{max}= 5.5 F $A^{0.25}$ $(h_o b_o)^{0.5}$

S_{max}= 5.5 2.125x $0.41^{0.25}$ $(1.95x4.75)^{0.5}$ = 28.46 m

at the distance 28.46 on the plume centre line H=1.95

h_{max}/H = 2.173/1.95 = 1.114 >0.75 ---------- shallow water

-For 2x210 M W. units

Local velocity of warm jet (U) was found to be 0.753 m/sec.

$$F_0 = \frac{U}{\sqrt{\frac{\Delta\rho}{\rho} gd}} = \frac{0.753}{\sqrt{0.0015x9.81x2.46}} = 3.96$$

According to Miller et al [2], when ΔT_0=23.2-15.7=7.5^0 C and the ambient temperature equals to 15.7°C, the value of $\Delta\rho/\rho$ = 0.0015

$h_{max} = 0.42\ F_0\ A^{0.25}\ (h_o b_o)^{0.5}$

F_0 =3.96

h_o=2.46 m b_o = 12.1/2 = 6.05 m

aspect ratio =h_o/b_o = 2.46/6.05= 0.41

h_{max} = 0.42 x 3.96 $(0.41)^{0.25}$ $(2.46x6.05)^{0.5}$ = 5.13

S_{max}= 5.5 F $A^{0.25}$ $(h_o b_o)^{0.5}$

S_{max}= 5.5 x 3.96x $0.41^{0.25}$ $(2.46x6.05)^{0.5}$ = 67.2 m

at distance 67.7 on the plume centre line it was found that the flow depth was 2.7 m.

h_{max}/H = 5.13/2.7 = 1.9 >0.75 ---------- shallow water

Centreline of temperature decay

$$\frac{\Delta T}{\Delta T_0} = 3.774\left[\frac{S}{\sqrt{h_0 b_0}}\right]^{-0.405} F_0^{-0.373} A^{-0.131} \alpha^{-0.084}$$

Applying the different parameters of Talkha and El-Kurimat power plants on the foregoing relationship of shallow water leads the results shown in Fig. 3.

Plume trajectory

$$\frac{y}{\sqrt{h_0 b_0}} = 2.55 \left[\frac{x}{\sqrt{h_0 b_0}} \right]^{0.378} R^{-0.849} \; F^{0.601} \quad A^{-0.166} \, \alpha^{0.084}$$

Substituting the different parameters of Talkha and El-Kurimat power plants through the aforementioned equation of the plume trajectory leads to the results shown in Figs. 4-a, and 4-b, respectively.

ANALYSIS AND DISCUSSION OF THE RESULTS

Isotherm maps of warm water resulting from the cooling systems at the outlets of both Talkha and El-Kurimat thermal power plants are illustrated in Figs. 2-a and 2-b. The isotherm map illustrated in Fig. 2-a shows that the two plumes in Talkha power plant interact at distance of approximately 185 m, which is considered a small distance. This could be explained due to the fact that the discharged warm water from the upstream outlet of 2x210 M.W. units is very big compared with the discharge of the downstream outlet of 2x50 M.W. units, and the two plumes are in the same direction of the current. Also, the obstructing effect of the jet to the ambient current causes the current to slow down and converting the kinetic energy of the flowing water to a static energy affecting on the boundary of the plume. The entrainment forces on the plume boundary cause the jet to be bent in a cross-flow, in which the degree of bending depends on the velocity of the ambient current. Fig. 2-b illustrated that most of the excess temperatures are diluted in a small distance downstream the outlet This is referred to the high velocity of the exist water from the cooling system channel in the entrainment region, in which the rapid dilution occurs due to mixing caused by the high velocity of the outlet. The figure also shows that the advection region in El-Kurimat power station outlet is long compared by that region in Talkha power station outlet. This could be explained due to the fact that in El-Kurimat outlet the direction of the warm water is approximately parallel to the River flow, which results in no significant lateral buoyancy spreading and small secondary flows.

Fig. 3 shows the relationship between the relative excess temperature against the term $(S/\sqrt{h_o b_o})$, which represents the centreline of temperature decay in both Talkha and El-Kurimat thermal power plants. The figure shows that the dilution rate of the temperature is high near the outlet. This could be explained due to the high value of the densimetric Froude number in the entrainment region in which the inertia force is more than the buoyancy forces, which means a rapid mixing as a result of the high velocity of the jet. So the mixing and spreading of high temperature water occurs vertically, which causes a rapid dilution. Also, it is observed that away the outlet, the rate of temperature decay is slow and the temperature is transported in the downstream direction in the advection region. This could be attributed due to the fact that the densimetric Froude number falls below one (the buoyancy forces dominate), which means that the velocity is low compared with that in the entrainment region and mixing is mainly due to lateral turbulent diffusion and secondary flow. Also, the rapid mixing in entrainment region causes the densimetric Froude number to be decreased, hence the rate of the vertically entertainment decreases. Figs. 4-a and 4-b illustrate a comparison between the theoretical trajectory of the plume and that investigated from field study at Talkha and El-Kurimat power plants. The figures show that there is a consistent to a good extent between the plumes trajectory of Talkha and El-Kurimat power plants and that calculated by Eq. 1. The small difference in the values of the two centre lines in Talkha Power plant. could be referred to the interaction between the two plumes of the two outlets.

The relationship between the excess temperature and plume area/flow rate is shown in Fig. 5. Fig. 5 shows that the field data of both Talkha and El-Kurimat power plants lie through the envelope of Asbury-Frigo, which is still remain a good guide for expecting the isotherm areas [1,3]. The figure shows that most of field data is near to the upper boundary of the envelope, which represents the calm ambient conditions, which exists in the Nile River at the outlet of the cooling systems. A comparative study was carried out between the relationships of the excess temperature against the term ($S/\sqrt{h_o b_o}$) resulted from both the measured data at Talkha and El-Kurimat power plants and that calculated from Eq. 1 as shown in Figs. 6-a and 6-b, respectively. It is found that the measured field data is approximately near to that computed by using Eq. 1. The small difference in the results could be refereed some to the measuring process, and the other to the effect of cross-flow ratio, in which the effect of cross-flow ratio R (current velocity/discharge velocity) does not appear in Eq. 1.

Figs. 7 and 8 show the relationships between the relative excess temperatures against the relative widths at different cross-sections downstream the outlet of Talkha power plant shown in Fig.1. Fig. 7 shows that the relative width of the plume of the first outlet (2x210 MW, Q=17.78 m^3/s) is very small (b/B=0.096). Also, the big slope of the line represents cross-section (1) means that there is a high dilution of the excess temperature. The aforementioned phenomenona could be attributed due to the fact that cross-section 1 lies at the core region of the jet of the first outlet, in which the plume width is very small due to the high velocity of the jet compared with the ambient velocity. Also, Fig. 7 shows that the relative widths of the plume increase from cross-section 1 to cross-section 4 and slightly to cross-section 5, respectively, in which a second jet of the second outlet (2x50 MW, Q=6.67 m^3/s) is interacted with the first big plume at cross-section 4. This could be explained as the plume from cross-section 2 is in the entrainment region, in which the warm water is spreading in both the vertical and horizontal directions due to mixing resulted from the large velocity gradient. The small increase in relative width of the plume from cross-section 4 to cross-section 5 (0.034) is referred to the interaction of the second outlet in the main plume. Fig. 8 shows that the relative widths in the downstream of the second outlet decreases from cross-section 6 to cross-section 8. This could be explained due to the fact that the plume is in advection region, in which the temperature decay in this region is slowly and the warm water is transported bodily in downstream. The dilution is due to lateral turbulent diffusion and secondary flows, which slowly erode the offshore edge of the plume. Also, it is found that the transverse decay rate of temperature beside the left bank is small compared with the other side of the plume due to the later turbulent diffusion and secondary flows at the other side of the flow, which decay the plume temperature.

CONCLUSIONS

From this research paper the following points could be concluded:-

1- The plume surface areas for excess temperature ratios ($\Delta T/\Delta T_o$) is greater than 0.3 for the two studied power plants, which is agreed with Asbury and Frigo [1,3].
2- The obstructing effect of the jet to the ambient current causes the current to slow down and converting the kinetic energy of the flowing water to static energy affecting on the boundary of the plume.
3- The small velocity of the ambient causes the plume to be extended to a long distance downstream the outlet of the power plant, in which the degree of the warm jet bending depends on the velocity of the ambient current.
4- The most of the field data is near to the upper bound of the Frigo envelope, which represent the calm ambient conditions, which is existed in the Nile River at the outlet of the two cooling systems.
5- The dilution of the temperature is high near the outlet in the entrainment region, while it is observed that away the outlet the temperature decay is slow and the temperature is transported in the downstream direction.
6- Eq.1 could be used in predicting of the excess temperature ratios ($\Delta T/\Delta T_o$) due to surface warm water discharging through rivers for the Egyptian boundaries in the Nile River. Also, Eq 2 could be used in calculating the plume trajectory with a considerable accuracy to save a considerable amount of time and expense.

NOMENCLATURE

The following symbols were used in this research paper:

A	aspect ratio h_o / b_o;
b_0	half width of the outlet;
d	outfall flow depth;
F_0	densimetric Froude number (the ratio of inertia to buoyancy forces acting on the discharge);
h_0	outlet depth;
h_{max}	the maximum depth at which plume will reach if it is not restricted by the bed;
H	water depth at the distance $S=5.5\ F_0 A^{1/4}\sqrt{h_o b_o}$;
R	current velocity/ warm jet velocity;
S	distance from the outlet on the centreline of the plume;
T_o	discharged water temperature;
U	local velocity of warm jet;
x, y	the coordinates of the plume trajectory;
α	angle between the centre line of the outlet and the river (in radian);
ρ	ambient density;
$\Delta\rho$	density difference between the ambient and discharged water;

$\Delta\rho/\rho$ density difference ratio depends on ambient temperature and excess temperature ratio;

ΔT difference between local temperature at any point and normal ambient temperature;

ΔT_0 difference between discharged water temperature at the outlet and normal ambient temperature; and

$\Delta T/\Delta T_o$ excess temperature ratio.

ACKNOWLEDGEMENTS

The measured data in this paper were carried out in co-operation with Hydraulic Research Institute (HRI), the National Water Research Centre, Ministry of Water Resources and Irrigation. The different instruments, the apparatuses, and the financial support of this investigation which were provided from the Hydraulic Research Institute (HRI) are gratefully acknowledged.

REFERENCES

1- Asbury, J.G. and Frigo, A.A., “A phenomenological relationship for predicting the surface areas of thermal plumes in lakes” Argonne National Laboratory, Report ANL/ES-5, April 1971.

2- D.S. Miller and B.A. Brighouse, “Thermal discharges” Published by British Hydromechanics Research Association.

3- Frigo, A.A., “Prediction of surface plume areas associated with heated discharges into large lakes – a phenomenological model” Proc. 15th Conf., University of Wisconsin, Int1. Assoc. for Great Lakes Research, pp 583-587, 1972.

4- Hydraulic Research Institute (HRI), “Hydraulic model design of Talkha power plant”, Technical report, Delta barrages, Egypt, 2003.

5- Hydraulic Research Institute (HRI), “Hydraulic model design of El-Kurimat power plant”, Technical report, Delta barrages, Egypt, 2003.

6- Klliot, R.V. and Harkness, D.G., “A phenomonological model for the prediction of thermal plumes in large lakes”, Proc. 15th Conf., Great Lakes Res., 1971.

7- Koester, G.E, “Experimental study of submerged single-port thermal dischargs” S.M. Thesis, Dept. of Civil Engineering, M.I.T., 1974.

8- Kyser, J.M., Paddock, R.A., “Analysis of three years complete field temperature data from different sites of heated surface discharge into lake Michigan” Symposium of physical and biological effects on environment of coling systems, and thermal discharges at nuclear power stations, Oslo, Paper LAEA-SM-187/42, August 1974.

9- Shirazi, M.A., “Some results from experimental data on surface jet discharge of heated water”, Pac. N.W. Env. Lab., E.P.A. Nat. Env. Res. Center, 1974.

10- Stolzenbach, K.D., and Harleman, D.R.F., “An analytical and experimental investigations of surface discharges of heated water” R.M. Parsons Laboratory, Dept. Civil Engineering, M.I.T., Report No. 135, 1971.

11- Tamai, N., Wiegel, R.L., « Horizontal surface discharge of warm water jets” Proc. of ASCE Journal of power division, Vol. 95, no po2, pp 253-276, October 1969.

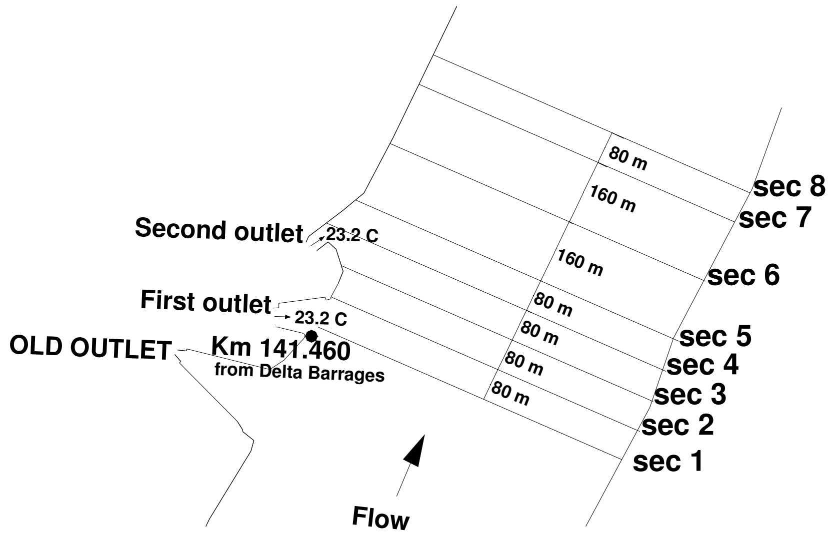

Fig. 1-a General layout of Talkha power plant.

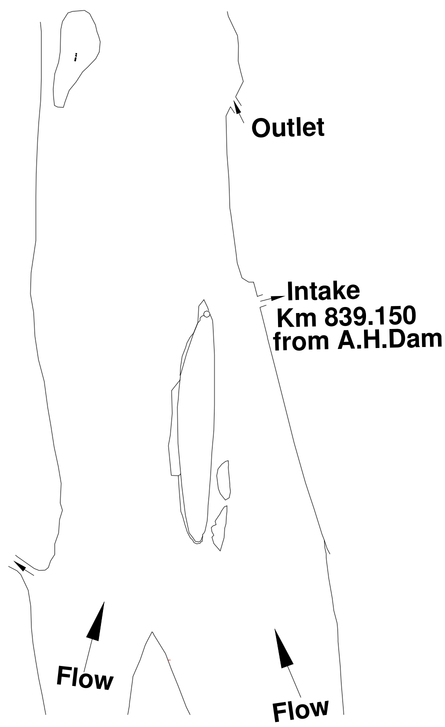

Fig. 1-b The general layout of El-Kurimat Power plant.

Fig.1-c Recorded temperature at Talkha Power plant outlets.

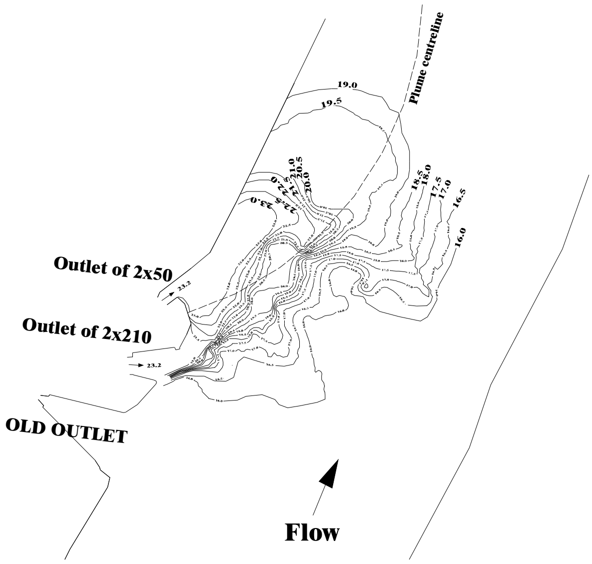

Fig. 2-a Isotherm mapat Talkha power plant.

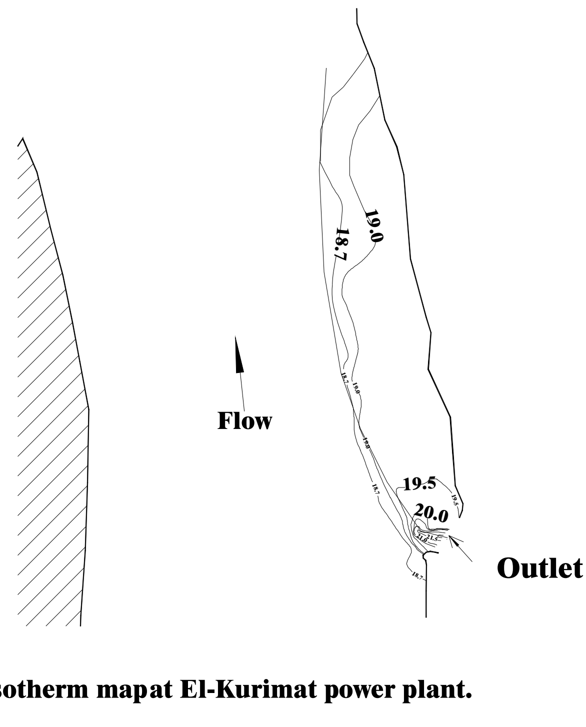

Fig. 2-b Isotherm mapat El-Kurimat power plant.

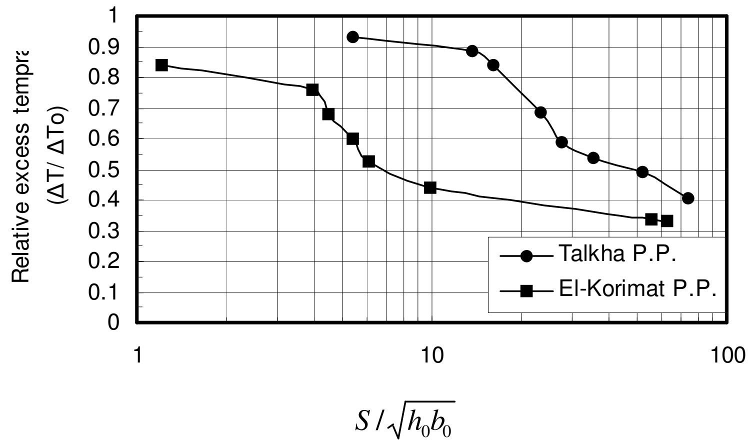

Fig. 3 Centreline of temprature decay.
(after D.S. Miller and B.A. Brighouse 1984).

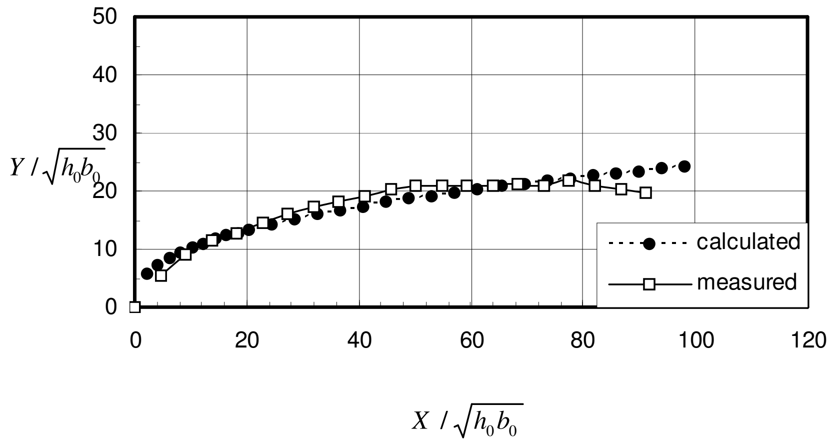

Fig. 4-a Trajectory of plume centreline at Talkha cooling system outlet.

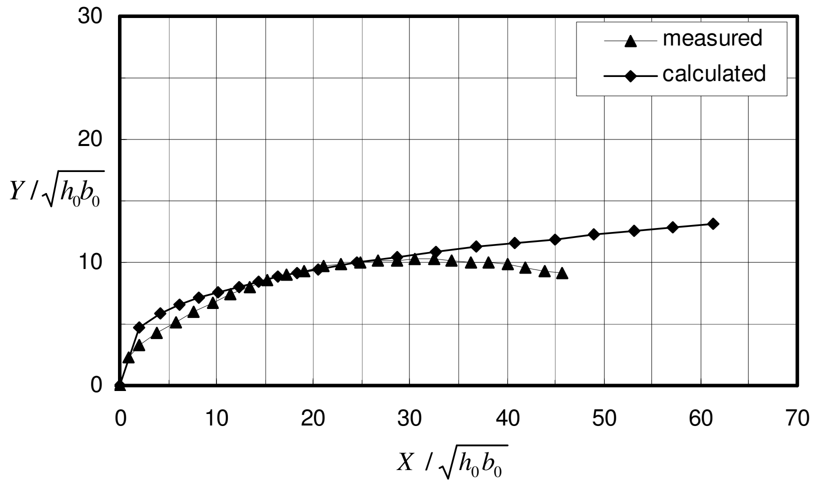

Fig. 4-b Trajectory of plume centreline at EL-Kurimat cooling system outlet.

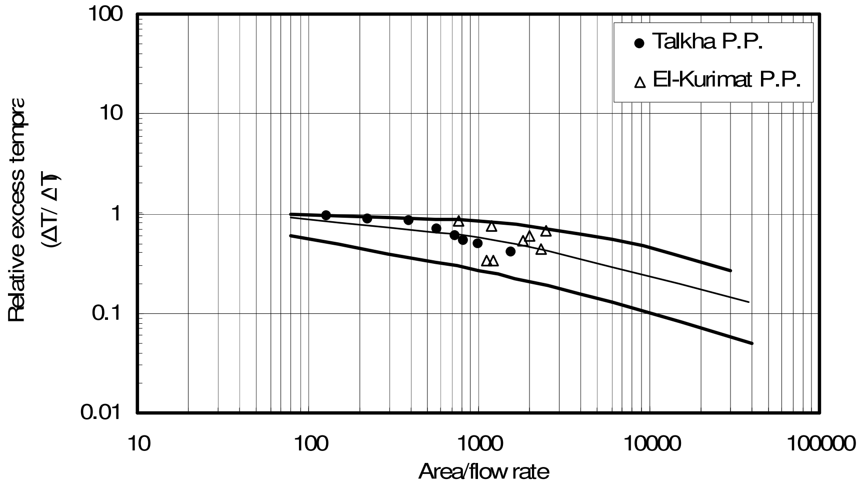

Fig. 5 Isotherm areas of two power plants.
(after D.S. Mller and B.A. Brighouse 1984).

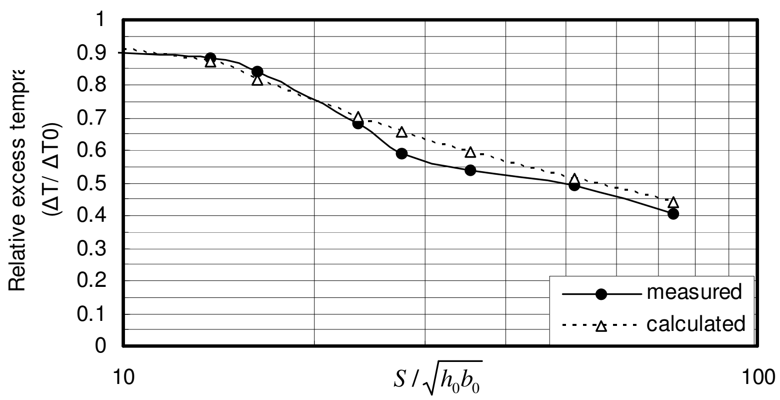

Fig. 6-a Comparison between measured and calculated values of excess temprature on the centreline temprature decay at Talkha Power plant.

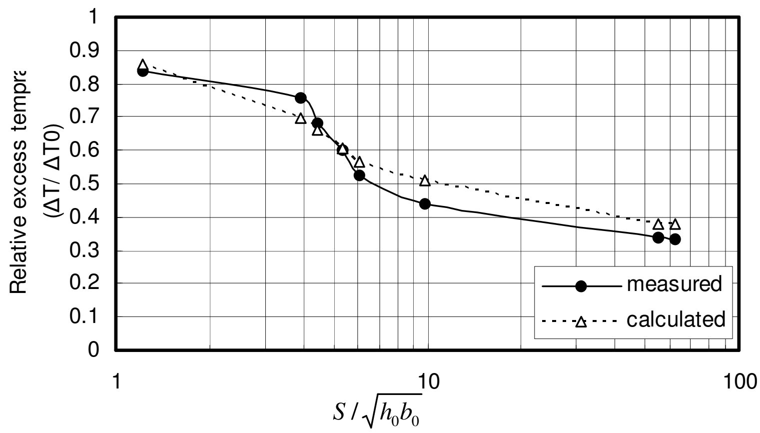

Fig. 6-b Comparison between measured and calculated values of excess temprature on the centre line temprature decay at El-Kurimat power plant.

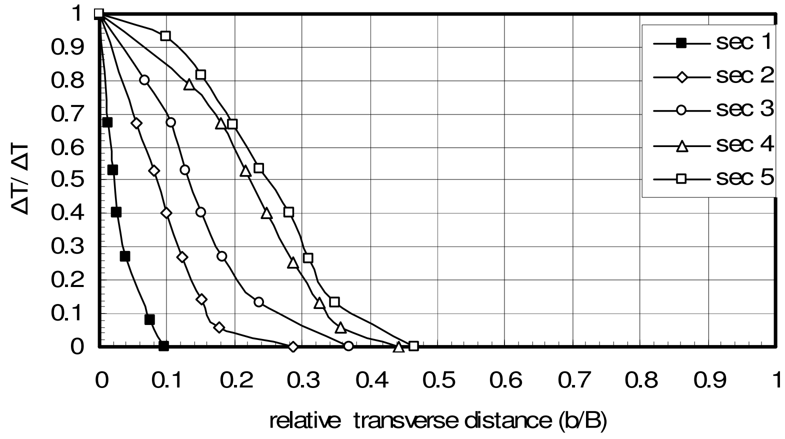

Fig. 7 The transverse dilution of excess temperature at the first outlet of Talkha power plant.

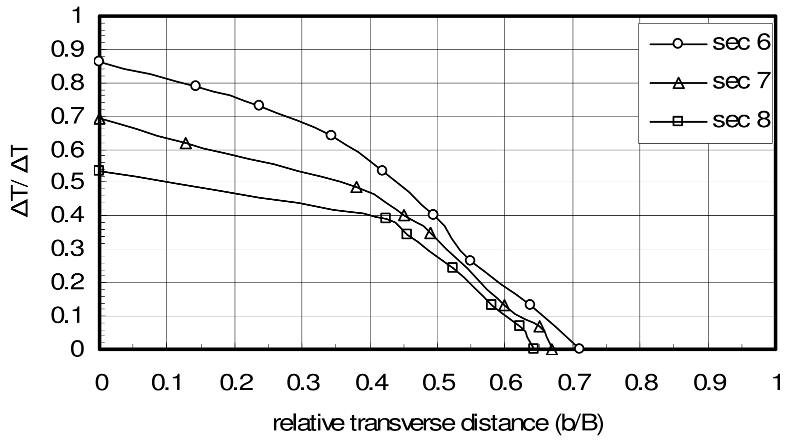

Fig. 8 The transverse dilution of excess temperature downstream second outlet of Talkha power plant.