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Thermal diffusion at Ao Phai

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Abstract

A distorted physical model of the prototype gulf area at Ao Phai, Thailand was designed and constructed in order to study the influence of release of cooling water from the proposed nuclear power plant of Thailand. The model bed was furnished with artificial roughness elements in order to fulfil the roughness condition. Steady-state currents and tide levels of three different stages of ebb tide and heated-water discharge were simulated in the model. Temperatures were measured in the model using an array of thermistor probes. Model results indicate suitable locations of intake and discharge structures and also water temperature rise distributions as function of plant load, water depth, tide level, etc.

Key words: Environmental engineering, hydraulics, hydraulic modelling, distorted model, nuclear electric power generation, waste-heat discharge, thermal pollution.

1. Introduction

With the increasing demand in electric power all over the world, waste-heat disposal has become a problem of important environmental concern. There was a proposal for constructing a nuclear power plant in Thailand having an output of 1200 megawatts needing a condenser water discharge of $70\,m^3/s$ with a temperature rise of 10°C above the intake temperature. A study was carried out at the Asian Institute of Technology, Bangkok with a distorted hydraulic model to investigate the pattern and extent of thermal diffusion resulting from the interaction of the cooling-water structure and the tidal current at the location of the proposed plant. The paper reports the results of thermal dispersion tests. The results of modelling of flow patterns for this study were reported by Ullah[1], where a description of the site, Ao Phai, of the proposed power plant was given.

The complications of modelling of heated water, identification of different stages of its dispersion and their relative importance with respect to the distance from the origin of the jet, the practice of dividing heated-water area into three regions for modelling convenience, etc., were mentioned by Ullah[1]. The works of Ackers[2], Harleman *et al*[3], Barr[4,5], Harleman[6], Harleman and Stolzenbach[7], Fischer and Holley[8] and Flugge and Schwarze[9] were reviewed in that connection.

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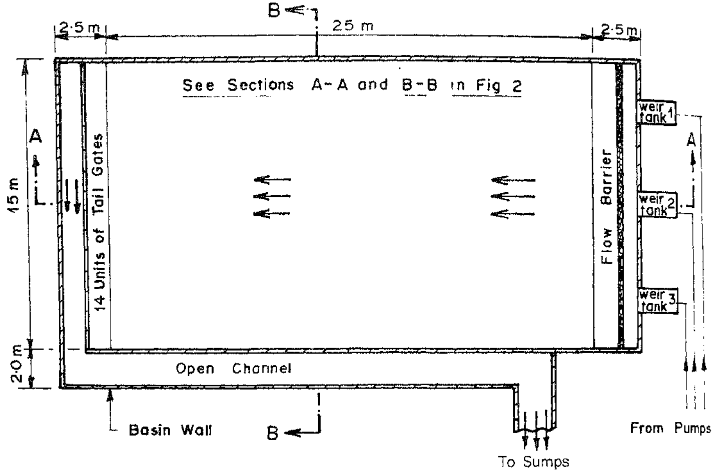


FIG. 1. Plan view of the model facility. (Reproduced with permission from the *Proc. Instn Engr (India), Civ. Engng Div. J.*, 1986, Vol 67).

2. Selection of scale ratios

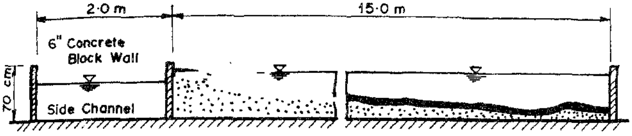
The details of the selection of scale ratios for this model were discussed by Ullah[1]. It was shown there that the scale relationship for simulating the dominant physical process of the far field, the surface heat loss, is given by

$$z_r = K_r x_r^{2/3} \cdot \tag{1}$$

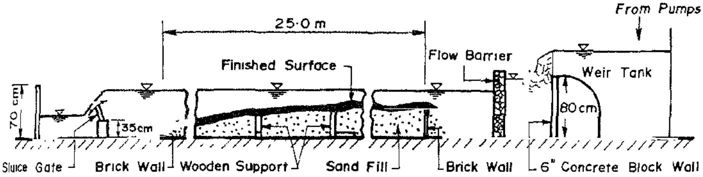
where x = horizontal length,
z = vertical length,
K = overall heat transfer co-efficient, and
subscript r = ratio between the corresponding prototype and model quantities.

The relationship is in agreement with that deduced by Flugge and Schwarze[9]. In general, the climate in the model will not be the same as in the prototype, unless a special environmentally controlled laboratory is available. Typical average values of the surface heat-transfer coefficient in the prototype and in the model are such that K_r varies between 1 and 2. However, because the exact values of K in the model and prototype were not available and as the model was exposed to open air and as well as for the sake of simplicity, $K_r = 1$ was adopted. Thus the relation between the horizontal and vertical scale ratios is,

$$z_r = x_r^{2/3}. \tag{2}$$



a) Transverse cross-section of the model (Section B–B of fig 1)



b) Longitudinal cross-section of the model (Section A–A of fig 1)

FIG 2. Cross sections of the model. (Reproduced with permission from the *Proc Instn Engr (India), Civ Engng Div. J*, 1986, Vol 67)

From the available laboratory area, a horizontal length ratio $x_r = 400$ was chosen to model a prototype area of 10 × 6 km. The vertical scale ratio thus was $z_r = 54.3$. The other scale ratios were:

$$\text{Distortion: } D_r = \frac{x_r}{z_r} = z_r^{1/2} = 7.4,$$

$$\text{Velocity: } u_r = z_r^{1/2} = 7.4 \text{ (from the Froude law)},$$

$$\text{Time: } t_r = \frac{x_r}{u_r} = z_r = 54.3,$$

$$\text{Discharge: } Q_r = A_r u_r = x_r z_r u_r = z_r^3 = 1{,}60{,}000.$$

The model was checked to have satisfied the conditions of turbulent entrainment of the jet and the ambient turbulence of the main flow.

3. Experimental programme

3.1 *Experimental set-up*

The basic experimental set-up was described by Ullah[1] while reporting the results of flow patterns of the model. The salient features of it are, however, mentioned here.

The model, constructed at the Asian Institute of Technology Research Centre, was covered overhead but was open on almost all sides. Elevations of bed contours at 1 m interval were simulated for a prototype depth range of 0–26 m. The model bed was furnished with artificial roughness elements in the form of 3 and 5 cm concrete cubes using the experimental data given by de Vries[10] as a guideline. The available facilities

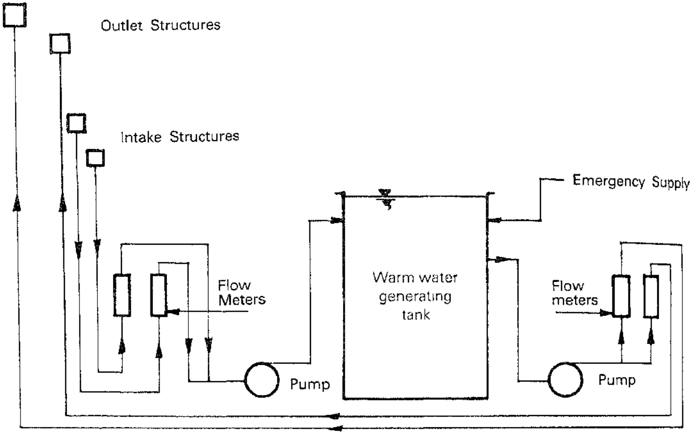
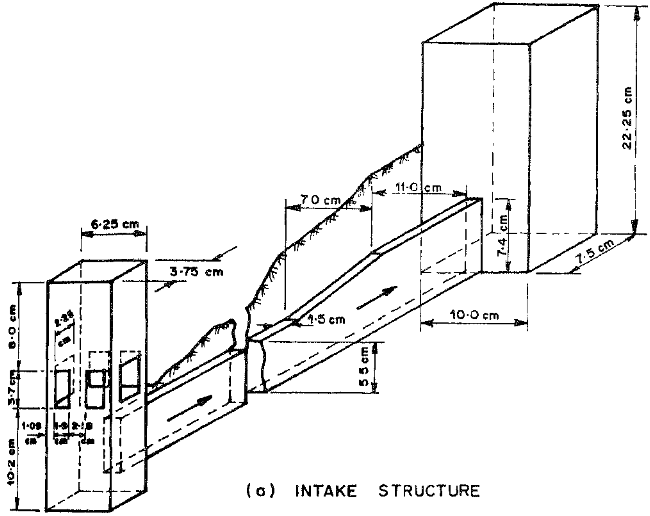


FIG. 3 Schematic diagram of the cooling-water circulation system.

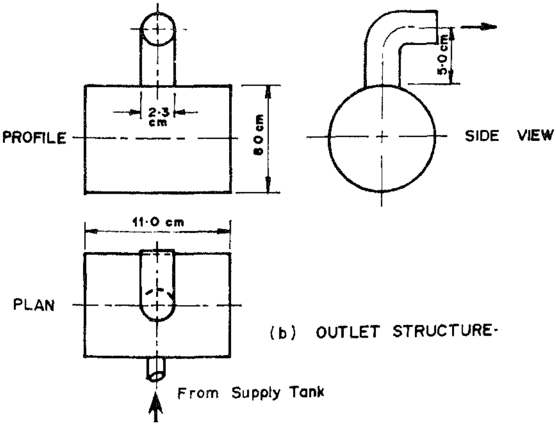
allowed generation of steady-state ebb currents only. The circulating water system had four pumps, three identical weirs and a barrier made of gravel stone as upstream control and 14 units of tailgate as downstream control. The reservoir had a total volume of 140 m^3. For ready viewing figs 1 and 2 are reproduced from Ullah[1].

The cooling-water system consisted of a cylindrical tank fitted with six immersion heaters which were regulated by a thermostat located just in front of the warm-water discharge outlet to ensure a constant temperature of the water discharged from the tank. The warm-water generating tank (fig. 3) had an emergency water intake controlled by a float which ensured constant water level.

The intake and discharge structures were designed using existing structures in Japan as guideline. A selection was made suitable for the local topographic and hydrographic conditions at Ao Phai. The prototype outlet structure selected for this purpose was a multiport diffuser having eight ports with a diameter of 1.25 m and a spacing of 5 m. The similitude rules, as derived by Koh *et al*[11] and Kato *et al*[12] for submerged multiport diffuser in distorted models, require that the local characteristics of the diffuser, such as spacing, port diameter, etc., be reduced by the vertical scale ratio, whereas the number of the ports is reduced by the distortion ratio of the model. The model diffuser, simulated accordingly, consisted of only one port with a diameter of 2.3 cm. The intake structure had skimmer wall-type openings and was connected to the shore-side reservoir structure by a closed conduit having a rectangular cross-section. The details of the intake and discharge structures are shown in fig. 4.



(a) INTAKE STRUCTURE



(b) OUTLET STRUCTURE·

FIG. 4 Details of cooling water intake and outlet structures.

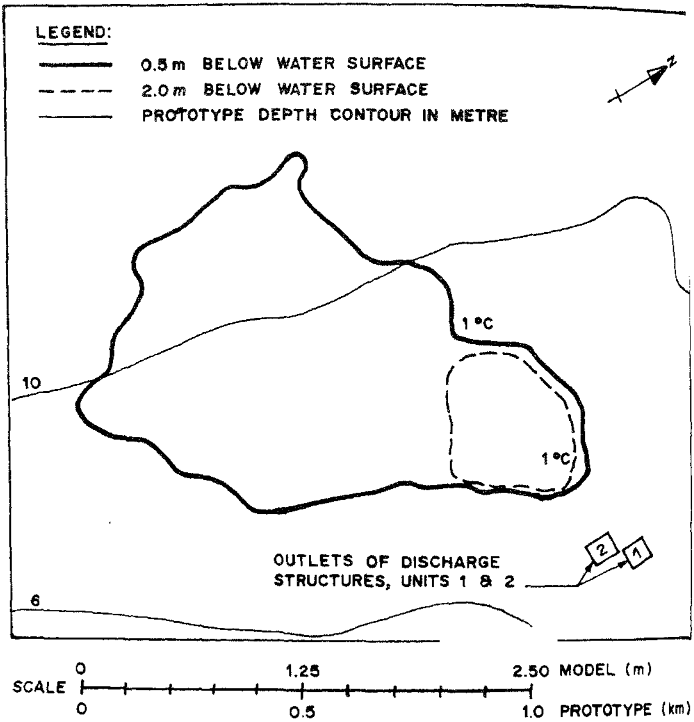


FIG. 5. Temperature rise contours at two depths for tide stage 5 with one unit in operation

Temperatures were measured in the model using an array of 30 thermistor probes mounted on a motorized-movable platform. The probes were arranged in ten rows, each containing three probes at three different levels with horizontal and vertical spacings of 20 and 3 cm respectively. The elevations of the probes could be adjusted vertically but the horizontal arrangement was fixed. The probes were connected to a printer which recorded the temperature readings against the corresponding thermistor numbers.

3.2 *Experimental procedure*

Each run was characterised by the number of condenser units in operation, ebb tide stage and tide level. Before each experiment began, the basin was filled to the desired

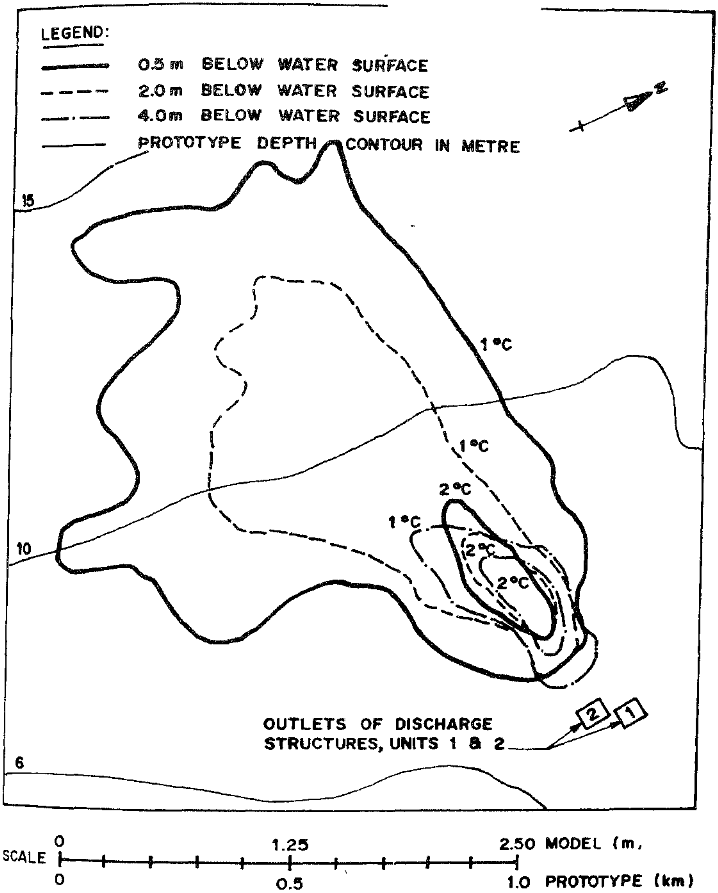


FIG. 6. Temperature rise contours at three depths for tide stage 5 with two units in operation.

tide level with corresponding discharge to represent a particular stage of the ebb tide. For the purpose of velocity calibration, field data given by EGAT[13] were used. In this reference the tidal cycle (from low water to the next low water) was divided into eight

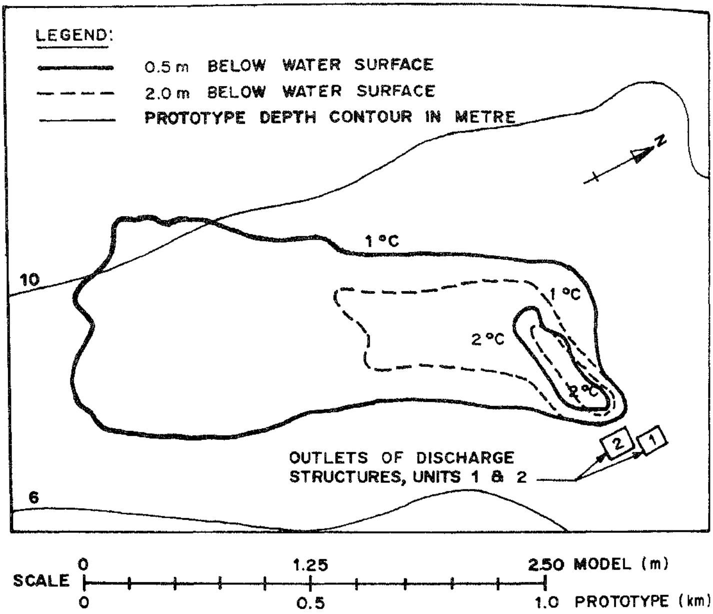


FIG 7. Temperature rise contours at two depths for tide stage 6 with one unit in operation

stages. The present study refers only to three stages, namely stages 5, 6 and 7 for which the mean water levels are, respectively, +48, +10 and −35 cm. Two pointer gauges were set up in the model on the 3- and 8-m depth contour lines at the location corresponding to the tide recording station at Ao Phai to monitor the correct water levels in the model.

The flow rate for each stage of the tide was obtained by integrating the velocity field over the prototype area represented in the model with respect to the water depth at the corresponding locations. The flow rate for a particular stage of the tide was supplied to the model through three previously calibrated weir tanks. The distribution of the total flow to these weirs was determined by observing the velocity magnitude and direction in the model. Adjustments of the downstream tail gates and upstream pumping rates were made until the best possible flow pattern was obtained.

Detailed results of the reproducibility of the flow in the model for the three stages of tide may be found in Ullah[1,14] or Vongvisessomjai *et al*[15]. It was shown there that the

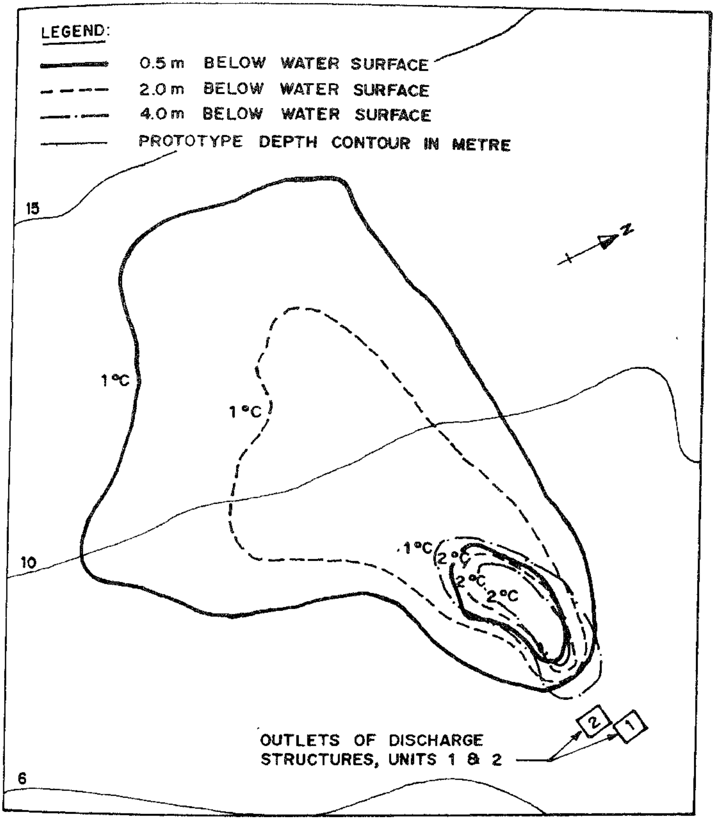


FIG 8 Temperature rise contours at two depths for tide stage 6 with two units in operation.

overall flow patterns in the model were quite satisfactory and similar to the corresponding flow patterns in the prototype. These simulated flows in the model were used for investigating the dispersion of cooling water.

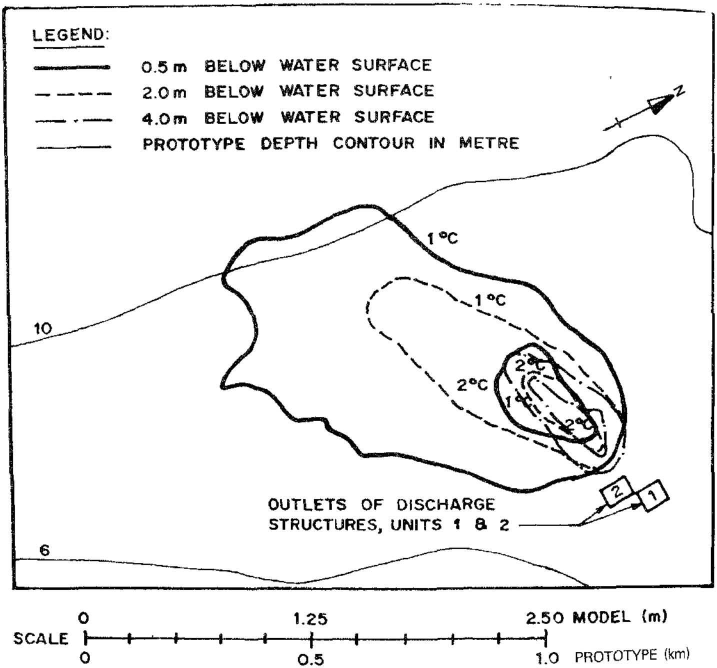


FIG. 9. Temperature rise contours at three depths for tide stage 7 with one unit in operation.

The model was allowed to run for sometime to ensure uniform temperature distribution in the basin. Before releasing any heated water into the basin, four to five scans were made to establish the ambient temperature. The intake and discharge flow system of the cooling water was adjusted to obtain the desired flow rate which is 220 cm^3/s for one unit and 440 cm^3/s for two units. The heating levels for the three indirect heaters could be adjusted to obtain the required temperature in the heating tank, which was checked from time to time with thermometers. Operation of the mixing device in the heating tank ensured proper mixing of the heated water and the cold water from the inlet pump.

The temperature measurements in the model were started when the temperature in the tank was about 10°C above the ambient temperature and constant with time. During the temperature measurements, the possibility of recirculation of condenser water from

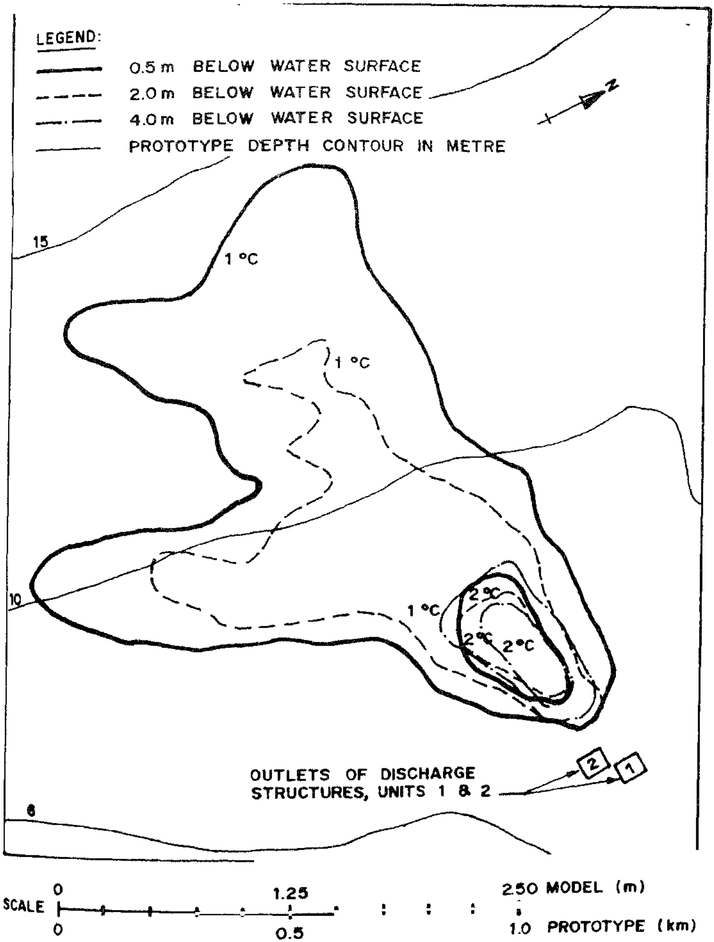


Fig. 10 Temperature rise contours at three depths for tide stage 7 with two units in operation

Table I
Experimental set-up for thermal dispersion tests

Stages of tide	Prototype elevation w.r.t. MSL (cm)	Tidal discharge in model (m^3/h)	No. of units in operation	Hot-water discharge in model (cm^3/s)	Temperature rise (°C)
5	+ 48	190	1	220	10
			2	440	
6	+ 10	223	1	220	
			2	440	
7	− 35	199	1	220	
			2	440	

the discharge structure to the intake structure was checked by observing the temperature of the intake water and the flow pattern around the intake structure. The flow pattern was observed by releasing dye and floats around the intake structure and thus estimating the area of influence and the origin of the incoming water.

4. Results and discussion

In total, six runs were performed for the investigation of thermal dispersion. A summary of different configurations is given in Table I and the results of the temperature measurements are shown in figs 5 to 10.

In the figures, contour lines of temperature rises of 1 and 2°C are presented with a distinction for three different depths — 0.5, 2.0 and 4.0 m — below the water surface. Table II shows the areas enclosed by the contours after converting to prototype areas. The highest temperature rise of 4°C was identified at some points near the outlet, but only the contours of 2°C could be drawn. The extent of thermal dispersion is properly indicated, however, by the contour of 1°C temperature rise.

It can be seen from Table II that for one unit in operation, the diffusion area of 1°C contour line for stage 5 at 0.5 m below the water surface is larger than that at stages 6 and 7, whilst the diffusion area at a greater depth for stage 5 is smaller than those for stages 6 and 7. This is due to the fact that stage 5 corresponds to a higher elevation than stages 6 and 7 (see Table II) when the warm water can be diffused more easily. The warm water during stage 5 is concentrated near the water surface with a corresponding smaller area of warm water encountered at greater depth. For stage 7 (with a lower tide elevation than stages 5 and 6) the areas of heated water, compared to the areas at the corresponding depths for stages 5 and 6, are smaller near the surface but larger at greater

Table II
Prototype-diffusion area at different depths

Tidal stage	Diffusion area/10^5 (m^2)					
	0.5 m below surface		2 m below surface		4 m below surface	
	Temperature rise (°C)					
	1	2	1	2	1	2
a) One-condenser unit in operation ($Q = 35\,m^3/s$)						
5	5.22	–	0.70	–	–	–
6	4.42	0.18	1.03	0.10	–	–
7	3.50	0.28	1.09	0.14	0.38	0.09
b) Two-condenser units in operation ($Q = 70\,m^3/s$)						
5	8.28	0.38	3.32	0.25	0.76	0.22
6	7.90	0.41	3.06	0.30	0.70	0.23
7	7.72	0.46	3.02	0.31	0.67	0.25

depths. It can be seen from Table I that the flows for tide stages 5 and 7 are about the same but it is slightly higher for stage 6. The largest dimension of the 1°C temperature rise contour was about 1 km at the water surface for these tide stages.

For the case of two-unit operation, the diffusion area for the 1°C temperature rise contour is the highest for tide stage 5 at all depths and the lowest for tide stage 7, whilst the 2°C temperature rise contours show the reverse tendency. The largest dimension of the 1°C temperature rise contour was about 1.3 km near the water surface.

The contour lines of equal temperature rise show generally that the contours for a single unit in operation are more inclined towards the shore line than those for two units in operation. This is due to the effect of the ambient current on the jet. The jet of one condenser unit is comparatively weaker and is more easily deflected by the ambient current whereas the jet of two condenser units is much stronger and is not deflected so easily.

If the condenser water from the discharge structure is drawn into the intake structure, some recirculation of the heated water would occur. No such circulation was found to occur for the tested arrangement of the intake and outlet structures. This was checked by observing the temperature of the intake water and velocity pattern in the vicinity of the intake structure by releasing a dye. Tests confirmed that the intake structure was always affected by ambient current flowing along the shore, which prevented any thermal stratification in the vicinity of the intake structure.

The steady-state model investigations of the Ao Phai power plant were carried out with the intake structure located near shore — about 250 m from the shore line — and the outlet structure offshore, about 1 km from the shore line. This system was recommended to prevent recirculation of the cooling water whilst at the same time the warm water will not be trapped in the small bays near to the power plant. As mentioned before in the various model tests no recirculation was found; so a structure, such as a breakwater located in between the intake and outlet, with the aim of preventing recirculation is not considered required.

From the construction point of view the intake structure should be located at least near to the contour of 5 m below the MSL, to provide sufficient depth for the tidal water level variation and to avoid entrainment of air in the power plant's circulation system even under extreme combinations of low tide and wave action.

In the model the outlet structure was located near the depth contour of 7 m below the MSL and this was found to be sufficiently offshore to prevent recirculation of the cooling water whilst at the same time sufficient depth was available for a submerged type of outlet structure.

The skimmer-wall intake structure as shown in fig. 4 is recommended. Slight modifications of the dimensions are allowable which will not significantly change the flow characteristics.

A submerged outlet structure was recommended because in that case the diffusion area would be considerably smaller than for a surface outlet. This can be attributed to the entrainment of the surrounding sea water when the warm water plume rises to the surface.

5. Limitations of the study

Like any other hydraulic model study, investigation of dispersion by physical modelling faces limitations which become even more complicated due to distortion. Fischer and Holley[8] discussed in detail the effects of distortion on dispersion.

For the present study, as can be verified from the velocity diagrams given by Ullah[1], transverse velocity gradients are not predominant. Although field data are not available, it is expected that the vertical velocity gradient, in the coastal area having a depth of the order of 10 m, would be quite high. It was shown in Fischer and Holley[8] that the dispersion effects will be magnified in the model having flow dominated by vertical velocity gradients.

It may be mentioned here that the present study concentrates on the far-field region to determine the extent and pattern of heated water spreading. Surface heat loss is the dominant physical process in this region. But the distortion of the dispersion phenomena due to transverse or vertical velocity gradients, as described by Fischer and Holley[8], occurs mainly in the near-field and transition region. Nevertheless, it will have some effects on the final distribution of heated water in the far-field area. For example, in this case, magnified model dispersion implies that the model results would indicate lower temperature rise and higher areal extent of low-temperature contours. So, as far as the areal extent of heated-water spread is concerned, the model results are conservative. But a higher temperature rise might be expected in the central part of the heated-water spread than that predicted in the model.

It was mentioned before that in the absence of exact information of heat-transfer characteristics in the model and prototype, it was assumed K_r to be 1. Since the model was exposed to open air, the K values in the model and prototype might be expected to be close. But, because of the overhead cover of the model and different meteorological aspects of the coastal and inland areas, the values of K in the model and prototype would not be exactly the same. Thus the assumption $K_r = 1$ brings along some limitations. Choosing a K_r value less than it should be means that the model was distorted more than it should have been. Thus the ultimate effect of this limitation is again magnified dispersion effects in the model.

The roughness elements, in the form of 3- and 5-cm concrete cubes, would introduce additional turbulence near the bed of the model. It may be noted that this arrangement is unlike the case of metal strips covering the whole depth. If this turbulence, originating from the near-bed area, can penetrate up to the mid-depth and near-surface water, its effect, like the previous two items, would be to magnify the dispersion effects. It may be mentioned that to avoid this additional turbulence near the heated-water outlet, the surrounding area was kept free of any artificial roughness blocks.

Another limitation of the model results is the unsteadiness of the prototype flow which was not possible to simulate in the model. This absence of unsteadiness will diminish the dispersion effects in the model compared to that in the prototype. So, this will balance some of the magnifying dispersive effects caused by the previous three items.

One more limitation of the model is the use of single port in place of the multiport prototype diffuser, which has been necessitated by the distortion ratio of the model.

So, it is clear that the limitations of the experimentations had distorted the results, probably to a small extent. The amount of distortion of the results can not, however, be quantified. Thus the quantitative figures reported here regarding the extent and pattern of heated-water spread can not be expected to be exact. However, the decisions reached following the qualitative guidelines of the results should be acceptable.

6. Conclusions

The experimental set-up in the model, with the intake and outlet structures located about 250 m and 1 km, respectively, from the shore line, was found to prevent recirculation of cooling water. The water depth at the location of the intake structure was sufficient for tidal level variation without any entrainment of air in the power plant's circulation system. The water depth at the location of the outlet structure was sufficient for a submerged type of outlet structure.

With this submerged discharge structure, diffusion was found to be limited to a small area just in front of the outlet. For the case of one unit in operation, the diffusion area corresponding to 1°C temperature rise is about 1.7 km^2, and though varying with time, it is contained in a rectangle of dimensions 3×1.3 km nearly parallel to the shore line of which the centre is situated about 700 m from the outlet. Moreover, outside this rectangle the temperature rise can be practically considered as negligible.

While the results reported here should generally be acceptable, because of the unavoidable limitations of the study, qualitative evaluation rather than quantitative utilization of the results is stressed.

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