CHAPTER 84

STUDY ON BOTTOM WATER INTAKE FOR CONDENSER COOLING SYSTEM OF POWER STATION SITED ON A BAY

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ABSTRACT

This report concerns study on a method of taking the cold water from bottom layer with relation to the design of the intake structure of cooling water for the power station sited on a bay.

The quantity of cooling water used for condenser system increases year by year along with the construction of thermal power stations of large capacity. If the bottom sea water of low temperature is taken into the condenser cooling system, remarkable saving of fuel expenses can be expected due to the improvement of heat efficiency of turbine. Especially, in case that the location of intake structure of cooling water is chosen at the interior of the reclaimed land or the bay, it is absolutely necessary to take the colder water from the lower layer of the sea, in order to prevent taking hot water over the sea basin where the water temperature of the surface layer is raised by the evacuation of heat of released industrial water.

Various hydraulic problems concerning thermal density flow phenomena were examined aiming to obtain the design method of the most effective intake works of cooling water, and the authors proposed a curtain-wall type intake structure. Some results of analysis are described in this paper.

INTRODUCTION

Among the electric power generating facilities in Japan, the proportion occupied by the thermal power has rapidly increased since 1957, and the techniques in high efficient thermal power generation utilizing larger capacity boilers of higher temperature and higher pressure have made great progress in recent years. The capacity of the so-called mammoth thermal power unit is in a tendency to get larger gradually aiming at lowering of cost per kW, and it has resulted in construction of larger capacity units, for example, 265 MW per unit in 1959, and 375 MW per unit in 1963. Along with such a trend, the quantity of water used in condenser cooling system is tending to increase in total volume, and the cooling water consumption for a power station of total output of, say, 2 million kW would amount to 100 m^3/sec at maximum.

One of the important conditions for planning of thermal power station is, that the locality is capable of supplying a large quantity of cooling water constantly. However, in Japan, it is infeasible to expect to obtain plenty of cooling water from river with unstable flow, thus it is inevitable to rely upon sea water, so that large capacity thermal power stations are being constructed at seacoast one after another. Especially, there is a conspicuous tendency for these years to build thermal power stations in seaside industrial areas of reclaimed lands, and these stations take sea water for cooling system from the relatively small basin surrounded by reclaimed lands or from innermost of the bay, and in some cases, discharge warmed water into the same basin. This fact presents a serious situation in the hydraulic design of cooling water intake.

Sea water in a limited and comparatively small sea basin has its temperature raised by the natural phenomena such as atmospheric radiation and also by the exhausted heat from such plants as electric power, steel, petroleum, chemical and other works concentrated in seaside reclaimed lands The lowering of cooling efficiency is inevitable because high temperature water is taken into the cooling system. At the same time, pollution of sea water in the bay and accumulation of floating trash further aggravate the circumstance of taking of cooling water. Such situations present the following problems to be investigated for hydraulic design of intake and outlet works of cooling water at thermal power station;

(1) Possibility of obtaining low temperature cooling water by taking water from deep layer in a limited sea basin, and development of hydraulic design method of the most effective bottom water intake works for the case.

(2) Effect of temperature rise of sea water in a small basin caused by atmospheric radiation, discharge of warmed water from power station itself, heat release of industrial works and others upon the temperature of water taken into cooling system.

(3) In the case when a large quantity of high temperature cooling water is discharged into the sea basin, investigation of dynamical flow pattern and heat diffusion of the released warm water, and also method of arrangement of intake and outlet works in the same sea basin, so as to avoid recirculation of warmed water from the outlet to the intake.

In our Institute, these problems have been studied by theoretical analysis, experiments and field observations. Among them, the results of the studies concerning item (3) was reported in another paper by one of the authors, and this report treats a part of the results of studies on item (1).

MERITS AND TYPES OF BOTTOM WATER INTAKE

Several advantages obtained by installation of bottom water intake device are as follows:

(1) By taking deep layer water of low temperature, an improvement of turbine efficiency can be expected and fuel cost is much saved.

From the result of estimation of annual fuel cost saving for the case of taking low temperature water of 26 °C by installing the bottom water intake device, in comparison with the case without such a device, the annual net profit for output of one million kW amounts to about 30 million yen (that is, 83 thousand US dollars)* This is an example for Sakai-Port Thermal Power Station of Kansai Electric Power Company.

(2) Urban sewage flowing through the rivers into a bay and polluted water discharged from seaside factories are mainly of salt-free water with less density and they are considered to form a portion of upper layer water in the bay, so high quality water can be secured by taking deep layer water. At the same time, dirt and trashes floating near the sea surface are avoided from coming into the intake channel by this equipment.

(3) Larvae of marine invertebrates or planktons which deposit on the wall of intake structure and jellyfishes which cause blockade of intake screen are mostly floating in the surface layer 2 or 3 m deep. Therefore, by using deep layer water intake device, these interferences by marine invertebrates can be moderated.

(4) In general, the temperature of cooling water discharged from the outlet after passing through the condenser is about 6 °C ~ 9 °C higher than the water temperature at the intake.

By taking deep layer water of low temperature, it permits relatively lowering of the water temperature discharged from the outlet, that relieves the effects of heat diffusion of discharged warm water upon fishing ground, laver nursery and intake sites of other factories.

(5) The bottom water intake device is profitable not only in summer when water temperature is high but also in winter. Because, the water temperature of surface layer in a basin is 5 °C ~ 9 °C in winter while deep layer water shows rather high temperature of 9 °C ~ 14 °C, and the heat consumption of boiler rather increases when the temperature of cooling water falls lower than 10 °C ~ 13 °C.

The fundamental types which is considered adequate as a bottom water intake equipment are the following two:

(1) Curtain-wall type. This type has a curtain-wall lowered below the sea surface, surrounding the frontage of the intake work, and deep layer water of low temperature is taken from the opening located between the lower edge of this wall and the sea bottom. Usually, a suction pit and pumping units are provided behind the intake work, and from there water is delivered to condensers through steel conduits.

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* Basic values for estimation of annual fuel cost saving : heat consumption factor 1.917 kcal/kWh, boiler efficiency 0.877, plant utilization factor 0.70, cost of crude oil 0.65 yen/10^3 kcal, heat release from surrounding factories + 9 °C, 25 m^3/sec.

As to the type of curtain-wall, two kinds are considered, one is a rigid type using a durable material and the other a floating type using a flexible material which does not resist the wave loads. Comparing them, the latter is more advantageous from economical standpoint, but considering the ambiguous design method on wave forces acting on the flexible curtain material, the former, the rigid type, is more practical from its stability after construction.

The bottom water intake device of this curtain-wall type is generally less expensive in construction cost as compared with the underwater intake pipe mentioned below, and is especially advantageous in the case of taking a large quantity of cooling water. This type is widely applicable, since it is suitable for such a location where a certain requisite water depth is secured in the frontage of the intake work or the sea bottom has a down slope of more than 1 : 4 toward the offing, but it is disadvantageous when water depth in the frontage of the intake is shallow or the sea bottom contour is shoal to a great distance from the shore, because excavation and dredging of the sea bottom is required in such a case.

(2) Underwater intake pipe

This type consists of steel, cast iron or concrete pipes, laid on sea bottom, and the whole structure is placed under water. The upstream end of the pipeline is bent upward to which the intake opening is installed It is suitable for such a location where the sea bottom is shallow to a great distance from the shore, but it costs more than the curtain-wall type when a large quantity of water is demanded because the diameter of the intake pipe is limited in size and number of pipe-lines needs to be increased according to the quantity of cooling water. Nevertheless, this type is widely used for the cooling water intake works of the petroleum and chemical industries whether it be located in an open shore or in a bay, as it permits to make a flexible plan to suit a given contour of the sea bottom. Several examples of the intake of this type are shown in Table 1.

Table 1. Examples of cooling water intake structure of underwater pipeline type.

No.	quantity of cooling water (m^3/s)	diameter of intake pipe (m)	length of pipe line (m)	number of pipelines
1	1.67	0.80	520	2
2	0.70	0.75	400	2
3	3.82	1.20	25	2
4	10.0	2.0	40	2

The representative example of the underwater type cooling water intake pipe is that for the Tokai Atomic Power Station (Output 166 MW), which takes 16 m^3/sec of sea water from the distant offing of the Sea of Kashima (facing the Pacific Ocean) with two steel pipes of 2.5 m in diameter and 500 m long laid under sea bottom. It was designed to place the intake opening (upstream end of the pipeline) at the distant offing where no change in the sea bottom contour is caused by sand drift, rather than aiming to take bottom water of low temperature.

POSSIBILITY OF TAKING OF LOW TEMPERATURE WATER

The daily observed record of temperature of deep layer water along the coasts of Japan is very rare. Niimi deduced the temperature of deep layer water at the entrance of Sakai Port from the observed value of temperature of cooling water taken at Amagasaki No 2 Thermal Power Station, the intake opening of which is located at about 7 m below the sea surface. The result is shown in Fig. 1, in which the dotted line gives the relation between temperature of deep layer water in Sakai Port and atmospheric temperature at Osaka area.

On the other hand, it may be easily guessed that the water temperature in the basin after being surrounded with reclaimed land will become somewhat different from the previous water temperature of coastal sea surface, since the mixing of surface water with deep layer water decreases. Then, a task was performed to deduce the temperature of surface water in Sakai Port after its completion on the basis of heat budget in the basin, and its result is also shown by the solid line in Fig. 1 Figure 2 shows the monthly variation of water temperature at sea surface and in deep layer according to the results given in Fig. 1. It can been seen that the surface layer is of higher temperature for the period from April to September and the difference amounts to 4.7 ^{o}C in maximum, on the contrary, from October to March, lower layer is of high temperature.

The vertical distributions of water temperature in the relatively small basin near the sites of thermal power stations have been observed in cooperation with electric power companies, and several examples of them are shown in Fig. 3. As is clear from the figure, the sea water near the coast forms an explicit density stratification due to temperature difference during midsummer season, the depth of surface layer of warm water is approximately 4 ~ 5 m, temperature difference between upper and lower layers is 5 ^{o}C or so, and the density difference corresponding to this is of the order of 0.0017. In this manner, as the water mass near the sea surface receives much more heats by natural phenomena such as atmospheric radiation and by discharge of warm water released from factories, a so-called "water temperature interface" (horizontal boundary where the gradient of vertical temperature distribution is maximum) is formed due to the density difference corresponding to the temperature difference even though the sea water is homogeneous in quality.

Next, a question may be brought forward that, since the water temperature of sea surface in and out of a bay differs in the order of 1 ^{o}C ~ 2 ^{o}C, there would also be any difference in temperature of deep layer water in and out of the bay, and the water temperature in the bay would rise gradually by diffusion of heat released from factories into the lower layers. However, according to the observed data obtained in several harbours of equivalent size to Sakai Port, such as Yawata, Kawasaki and Mizushima, it is proved that there is the horizontal surface of discontinuity of density in the bay from the innermost to the mouth of it at the depth of about 4 ~ 5 m, which is not so much disturbed by navigation or by discharging of high temperature water, and the temperature of deep layer water in the bay is nearly equal to that outside of the bay.

Besides, according to the results of analysis of data obtained in field observations of outfall of high temperature cooling water at Mizushima Thermal Power Station, the temperature distribution of the discharged water indicates a so-called "tongue shape", the layer with comparatively high temperature being observed only in the surface layer of about 2 ~ 4 m thick occupying the area extending 50 ~ 80 m away from the outlet of the cooling system, and the released heat hardly diffuse underneath the layer of 4 m deep below the sea surface. The result of analysis shows that the heat diffusibility in the horizontal direction is of the order of about 50 ~ 80 times that in the vertical direction.

Finally, let us show the results of consecutive observations of sea water temperature for each water depth which were carried out in the basin of Sakai Port (where the intake of cooling system for Sakai-Port Thermal Power Station was to be constructed) extending over two years since August 1963. According to these data, it was confirmed that a temperature difference of about 4 °C ~ 5 °C exists between upper and lower layers in summer, and this interface lies at the depth of 4 m ~ 5 m below the sea surface. In winter, on the other hand, such stratification of water temperature was hardly observable, or, in some places, the upper layer water was rather cold, thus verifying the trend as shown in Fig 1 Figure 4 is an example of the consecutively observed data of water temperature in September at a certain place in Sakai Port, including atmospheric temperature, wind velocity and tidal level. It is also confirmed from this figure that the water temperature interface keeps stable at the depth of 4 ~ 5 m below the sea surface, in spite of tidal changes and blowing of wind with velocity amounting to 10 m/sec.

Judging from the results of various observations and investigations mentioned above, taking low temperature water from deep layer is possible and well worth practicing.

EXPERIMENTS

The fundamental experiments were performed by two-dimensional model of curtain-wall type intake structure in order to verify the possibility of taking colder water from the bottom layer of the stratified sea basin and to obtain the design method of intake works of such a type.

A schematic diagram of the experimental apparatus is shown in Fig. 5, which consists of salt-water mixing tank, stilling tank, experiment channel of 0.2 m wide, and circulating system. In the experiments, replacing thermal density flow with flow of two layers of salt and fresh water, the depression of the interface was examined at various flow quantity of taken water and different conditions of stratification. The hydraulic phenomena observed in the experiments were discussed in comparison with the theoretical calculations.

The points derived from the results of the analysis are as follows.

(1) The drawdown of interface due to taking colder water from the lower layer is controlled not only by average velocity at the intake opening, but also by velocity distribution of flow approaching the intake.

(2) It is necessary to decrease the velocity of flow toward the intake, in order not only to keep the stratified two layers from mixing, but also to prevent the slope of interface from becoming steeper even when the mixing takes place. Such phenomena appear accompanying with the effective drawing of colder water solely from the lower layer.

(3) The critical condition, under which the colder water would be drawn from the lower layer only or the lighter warm water would just begin to be drawn from the upper layer, is given by

$$\frac{\Delta h}{h_0} = \frac{\alpha F_{i0}^2}{2} \qquad (1)$$

where $$F_{i0} = u_0 / \sqrt{g \frac{\Delta \rho}{\rho} h_0}, \quad u_0 = q_c / h_0$$

q_c : critical flow rate drawn into the intake per width ($m^3/sec/m$),

Δh : distance between interface and lower edge of intake curtain-wall (m),

h_0 : height of intake opening (m)

$\Delta\rho/\rho$: relative density difference between two layers,

α : experiment coefficient.

As the result of the experiment, the value of α was determined to be equal to 5.0 for the sea bottom of an upward slope 1 : 3.5.

(4) Mixing ratios of the quantity of bottom colder water and surface warmer water were also calculated and determined experimentally for the case of drawing not only the lower but also the upper layer water, which occurs when taking the cooling water greater than the critical flow water

(5) A diagram obtained from the result of the analysis is shown in Fig. 7 This chart gives the relations between position of interface Δh , opening height of intake h_0 , temperature difference between two layers (relative density difference) $\Delta\rho/\rho$, mixing ratio of surface warmer water to total water (%) and flow rate drawn into the intake q. In this diagram, the curves for mixing ratio 0 % correspond to the critical condition taking solely the lower layer water of low temperature, that is, these curves express the following formula obtained by rewriting Eq. (1):

$$\Delta h = \frac{5}{2g(\Delta\rho/\rho) h_0^2} \quad q^2 \qquad (2)$$

(6) The temperature of drawn water was estimated by calculating potential of flow approaching the intake together with potential by thermal density distribution, and it was confirmed that the supposition of discontinuous water temperature distribution (stratification of two layers), which was a premise condition for this experiment, was adequate.

APPLICATION

The result of the fundamental experiment was applied to the hydraulic design of the intake structure of condenser cooling system for the SAKAI-Port Thermal Power Station sited on the east coast of Osaka Bay in Japan. The maximum quantity of cooling water for this power station amounts to 100 m^3/sec at the ultimate output of 2000 MW.

Before starting the construction, the field observations were carried out at the sea basin under project extending over two years, the results of which are as follows:

(1) During summer, the sea water in the bay forms a pronounced stratification of temperature. The interface, where the gradient of vertical temperature distribution is maximum, lies at the depth between 4 m $\sim$ 5 m, and the difference in water temperature between upper and lower layers is about $4^{\circ} \sim 5^{\circ}C$

(2) This interface is sufficiently stable in spite of tidal changes and blowing of wind.

(3) According to the heat budget calculus based on the observed data of meteorological factors, the ultimate water temperature in the bay after completion of land reclamation works at the Sakai Port was estimated. The water temperature of the surface layer in the bay reaches 30 $^{\circ}C$, while the bottom water temperature below the interface is 25 $^{\circ}C$.

From these points, the possibility and efficacy of taking the cold bottom water for the cooling system were made clear and it was decided to construct the intake structure of curtain-wall type for the Sakai-Port Power Station.

The designing conditions are as follows:

Maximum flow rate of cooling water: 100 m^3/sec
(As the effective width of the curtain-wall opering was chosen as 130 m, flow rate per unit width is $q = 100/130 = 0.768$ $m^3/sec/m$)

Datum elevation of sea surface: 0 P. ± 0 (L.W.L.)

Elevation of interface: O.P. - 4 m
(Based on the results of the field observations, thickness of surface layer of high temperature was assumed to be 4 m)

Difference of water temperature between upper and lower layer: 5 $^{\circ}C$

Relative density difference: $\Delta\rho/\rho = 0.0017$ (corresponding to the above temperature difference, 5 $^{\circ}C$)

Hydraulic design of curtain-wall type intake was carried out for two cases of mixing ratio, 0 % (no mixing) and 20 % as an allowable value.

According to Fig. 7, the relation between $h_0 + \Delta h$ and h_0 for the conditions $q = 0.768\ m^3/sec/m$, $\Delta\rho/\rho = 0.0017$, mixing ratio 0 and 20 % is obtained as shown in Fig. 8. The minimum point on these relation curves gives the most economical value of opening height, h_0, which minimizes the value of $h_0 + \Delta h$. Then, we obtain, for the case of mixing ratio 0 %,*

$$h_0 = 5.58\ m, \qquad h_0 + \Delta h = 8.42\ m,$$

location where the curtain-wall is installed:

depth below sea surface 4m + 8.42m = 12.42m

elevation of sea bottom O.P. - 12.42 m

elevation of lower edge of curtain-wall: O.P - 6.84 m

and for the case of mixing ratio 20 %,

$$h_0 = 4.80\ m, \qquad h_0 + \Delta h = 6.00\ m,$$

location where the curtain-wall is installed

depth below sea surface 4m + 6m = 10m

elevation of sea bottom O.P. - 10m

elevation of lower edge of curtain-wall: O P. - 5.2 m

As seen in the above results, when mixing ratio of 20 % is allowable, the curtain-wall is possible to be installed at the location 2.42 m shallower in depth as compared with the case of no mixing. Since the slope of sea bottom at the site in question is 1 : 3.5, the former case permits to install the curtain-wall closer to shoreline than the latter case (no mixing) by 2.42 × 3.5 = 8.47 m in horizontal distance.

As to the Sakai-Port Thermal Power Station, comparing the results of design calculations for various cases including above two examples, it was found that to allow to draw a small quantity of warmer surface water, say 20 %, at L.W.L. is reasonable in view of its construction cost. Therefore, based on the values obtained for the case of mixing ratio 20 %, it was decided that the curtain-wall should be installed at the location where the elevation of sea bottom is O.P. - 10 m (10 m below L.W.L) and the opening height is 4.8 m.

Shown in Fig. 9 and Fig. 10 are plan and cross-section of curtain-wall type bottom water intake structure for the Sakai-Port Thermal Power Station, and its whole view after completion (only for the first stage) is shown in Fig. 11.

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* For the case of no mixing (critical condition), h_0 which minimizes $h_0 + \Delta h$ is also given by the following equation

$$\frac{\partial(h_0+\Delta h)}{\partial h_0} = \frac{\partial}{\partial h_0}\left(h_0 + \frac{5q^2}{2g\frac{\Delta\rho}{\rho}}\ \frac{1}{h_0^2}\right) = 0, \quad \text{that is,}$$

$$h_0 = \sqrt[3]{\frac{5q^2}{g(\Delta\rho/\rho)}}$$

After completion of the first stage project (250 MW × 4 units) of this power station, the field observations were carried out in August, 1964. An example of the observed data is shown in Fig. 12 It was proved that the temperature of cooling water was 5 or 6 °C lower than that of the surface water outside of the curtain-wall and, besides, the quality of the drawn water was as remarkably clear as that of the open sea, though the surface water in the bay was extremely polluted.

EFFECT OF WIND ON STRATIFICATION

As described above, remarkable stratification of density which results from temperature difference due to heating process is usually formed in the sea basin during summer. In this situation, the wind current will first stir up the water near the sea surface and make the surface layer homogeneous by mixing process. Once this layer is established, stability at the boundary between two layers of different density becomes increasingly large, so that the eddy viscosity will be expected to decrease.

From the field observations at Mizushima Bay (cf. Fig. 13), the authors found that the eddy viscosity near the boundary was very small (about 0.05 c.g.s.) and the stratification of density was not destroyed by mixing caused by the prevailing winds of 5 ~ 10 m/sec. However, inclination of the sea surface due to wind stress generates horizontal pressure gradient which changes the distribution of density.

The water near the sea surface is transported to the interior of the bay by wind stress and piles up there. The increasing pressure due to rising of the sea surface is compensated by depression of the boundary surface, while the water in the lower layer is at rest because the frictional effect of the upper layer is interrupted at the boundary by discontinuity of density. This fact is confirmed by the field observations as seen in Fig. 13, and it is one of the important empirical facts in coastal engineering.

Supposing that an intake structure of power station is located at the innermost of a bay which has a rectangular cross-section of uniform width and the wind blows from the mouth to the innermost of the bay, the motion is considered to be two-dimensional. As shown in Fig. 14, let us take the vertical plane (x - z) along the axis of the bay and the origin at the mouth of the bay Neglecting the inertia term in the equations of motion and considering only the vertical mixing of velocity component u in the x-direction, the equations of motion under the steady state are written as follows:

$$-\frac{\partial p}{\partial x} + \mu \frac{\partial^2 u}{\partial z^2} = 0, \quad \frac{\partial p}{\partial z} + \rho g = 0 \qquad \cdots \quad (3)$$

The equations of continuity in two layers can be approximately written as

$$\int_{-h_1}^{\zeta} u_1 dz = 0, \quad \int_{-(h_{10}+h_{20})}^{-h_1} u_2 dz = 0 \qquad \cdots\cdots \quad (4)$$

where, ζ is displacement (rise) of sea surface at the distance x, h_1 displacement (drop) of interface at the distance x, measured from the intial sea surface (x-axis), h_{10}, h_{20} depth of upper and lower layer at the mouth of bay $(x=0)$ respectively, and μ eddy viscosity.

The boundary conditions are

$$\mu_1 \partial u_1/\partial z = \tau \quad \text{at} \quad z = \zeta \qquad \cdots\cdots \quad (5)$$

and

$$\mu_1 \partial u_1/\partial z = \mu_2 \partial u_2/\partial z \quad \text{at} \quad z = -h_1 \qquad \cdots\cdots \quad (6)$$

where τ is the wind stress

Assuming that the eddy viscosity μ_2 is negligible along the discontinuity of two layers, Eq. (6) becomes

$$\mu_1 \partial u_1/\partial z = 0 \quad \text{at} \quad z = -h_1 \qquad \cdots\cdots \quad (7)$$

Besides, added is another boundary condition that the rise of the sea surface and the resulting depression of the interface due to blowing of wind do not take place at the mouth of the bay, because sea water in the bay is connected with the infinite open sea at the mouth.

In integrating the fundamental equation (3), the relation between ζ and h_1 is given by the following approximation:

$$\frac{\partial \zeta}{\partial x} = \frac{\Delta \rho}{\rho_1} \frac{\partial h_1}{\partial x} \qquad \cdots\cdots \quad (8)$$

where $\Delta \rho = \rho_2 - \rho_1$

From the result of the analysis, the rise of the sea surface ζ and the depression of the interface ΔH due to the shearing stress of wind can be calculated by the following relations (cf. Fig. 14):

$$\zeta = -\frac{\Delta\rho}{\rho_2} h_{10} + \sqrt{(\frac{\Delta\rho}{\rho_2})^2 h_{10}^2 + 2\frac{\Delta\rho}{\rho_1\rho_2}\frac{\tau}{g}x} \qquad \cdots\cdots\cdots (9)$$

$$\Delta H = h_1 - h_{10} = (\rho_1/\Delta\rho)\zeta \qquad \cdots\cdots (10)$$

where ρ_1, ρ_2 : density of sea water in upper and lower layer, respectively, $\Delta\rho = \rho_2 - \rho_1$,

h_{10} : depth of upper layer at mouth of bay,

τ : shearing stress of wind,

x . longitudinal distance from mouth of bay,

g : gravitational acceleration.

The velocity of flow in the surface layer caused by the wind stress can be obtained by

$$u_1 = \frac{\rho_1 g}{2\mu}\left(\frac{\partial\zeta}{\partial x}\right)\left\{(z + h_1)^2 - \frac{h_1^2}{3}\right\} \qquad \cdots\cdots\cdots (11)$$

Based on the equations (9) and (10), the depression of the interface was calculated as an example under the following conditions:

Longitudinal length of bay L = 1.7 km, wind velocity W_{10} = 1 m/sec, 3 m/sec, 6 m/sec, depth of upper layer at mouth of bay h_{10} = 3 m, water temperature of upper layer T_1 = 30 ^oC, 32 ^oC, 35 ^oC, water temperature of lower layer T_2 = 25 ^oC, difference of water temperature between two layers ΔT = 5 ^oC, 7 ^oC, 10 ^oC.

The results of calculation are shown in Table 2.

Table 2. Depression of temperature interface due to wind stress (length of bay L = 1.7 km).

	W_{10} \ x	$\frac{L}{3}$	$\frac{2}{3}$ L	L
ΔT=5℃	1 m/sec	0.012 m	0.024 m	0.036 m
	3	0.11	0.21	0.31
	6	0.40	0.72	1.09
ΔT=7℃	1 m/sec	0.008 m	0.017 m	0.025 m
	2	0.074	0.15	0.22
	3	0.29	0.55	0.80
ΔT=10℃	1 m/sec	0.007 m	0.016 m	0.024 m
	3	0.070	0.14	0.21
	6	0.27	0.51	0.73

As the result, it is found that, if the length of a bay is 1.7 km or so, the difference of water temperature between upper and lower layer is 5 $^{\circ}C \sim 7\ ^{\circ}C$, and wind is always blowing toward the innermost of the bay with the velocity of 6 m/sec, the depression of the interface amounts to about 0.8 ~ 1.1 m at the innermost of the bay.

Thus, the drawdown of the interface due to the wind stress is about a half of or equivalent to that due to taking the cold bottom water from the lower layer and, in conclusion, the effect of wind on the stratification in a bay should be taken into consideration in designing the bottom water intake structure.

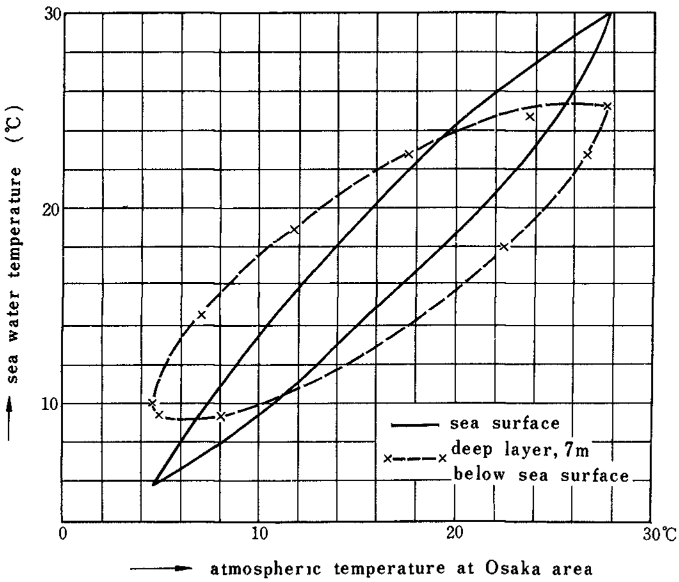

Fig. 1. Hysteresis loop of sea water temperature.

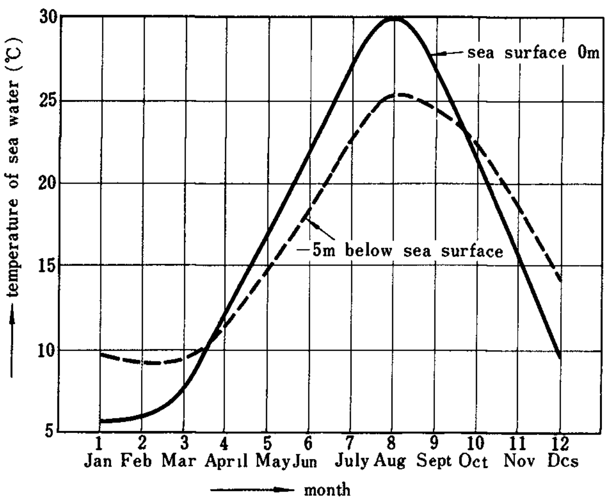

Fig. 2. Monthly variation of sea water temperaute.

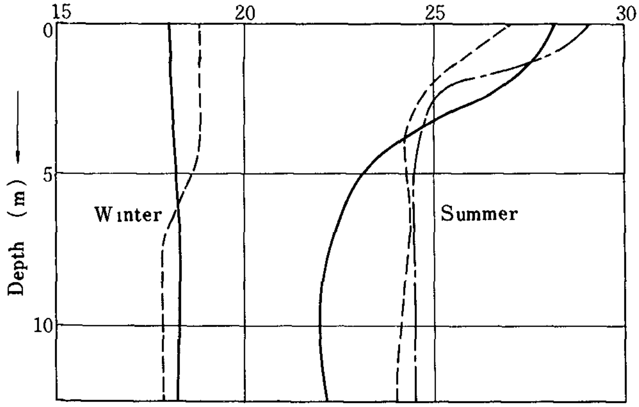

Fig. 3. Examples of vertical distribution of water temperature.

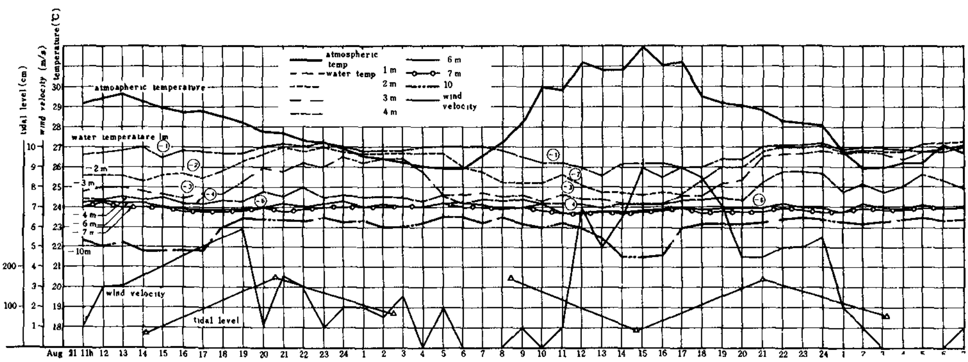

Fig. 4 An example of the results of field survey in Sakai Port.

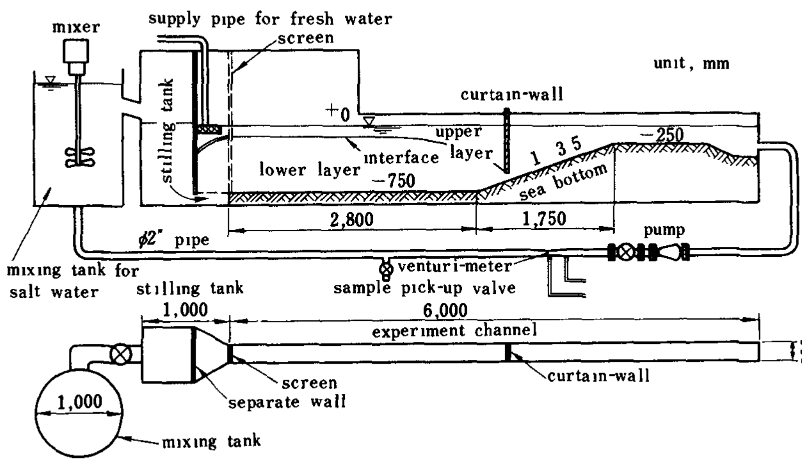

Fig. 5. Sketch of experimental apparatus.

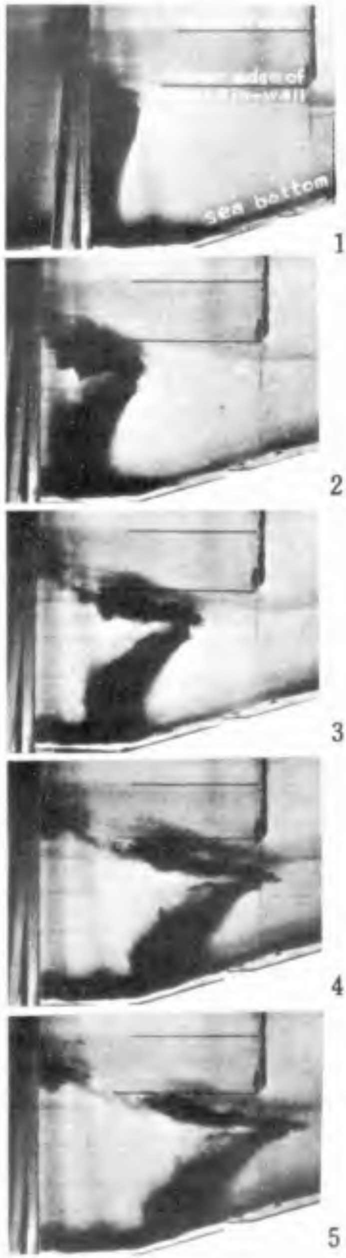

Fig. 6. Flow pattern in two-dimensional experiment.

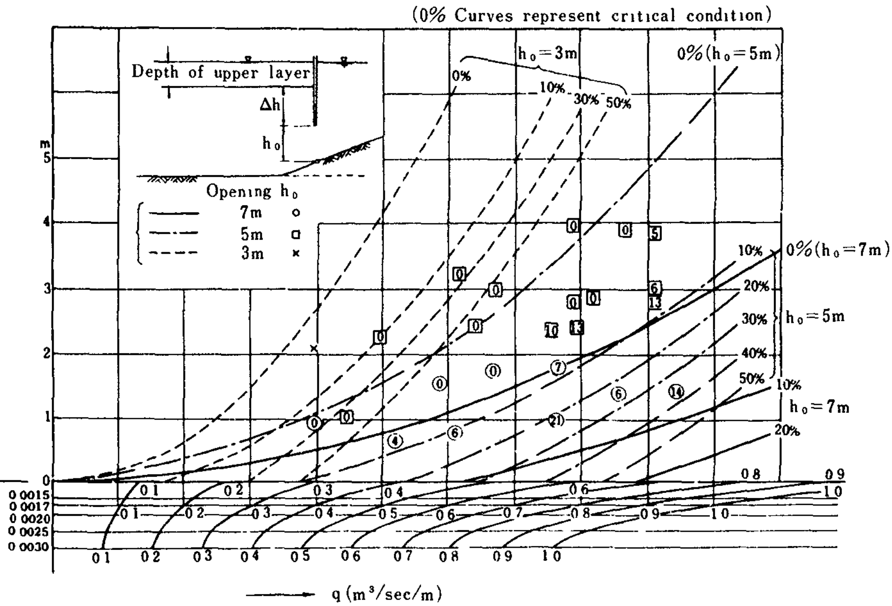

Fig. 7. Design diagram for curtain-wall type bottom water intake.

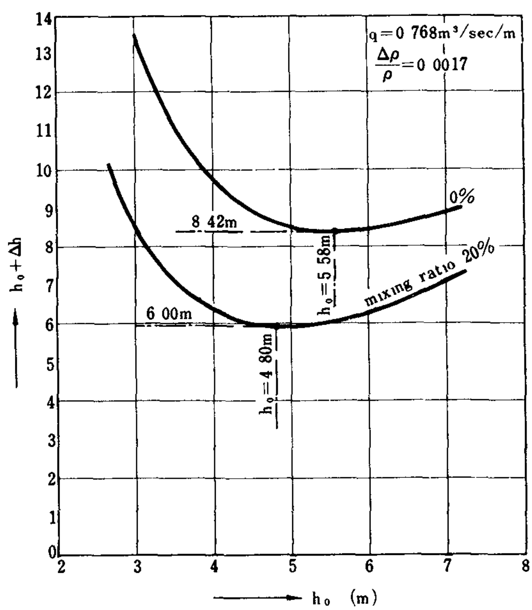

Fig. 8. Diagram obtaining the minimum value of $h_0 + \Delta h$.

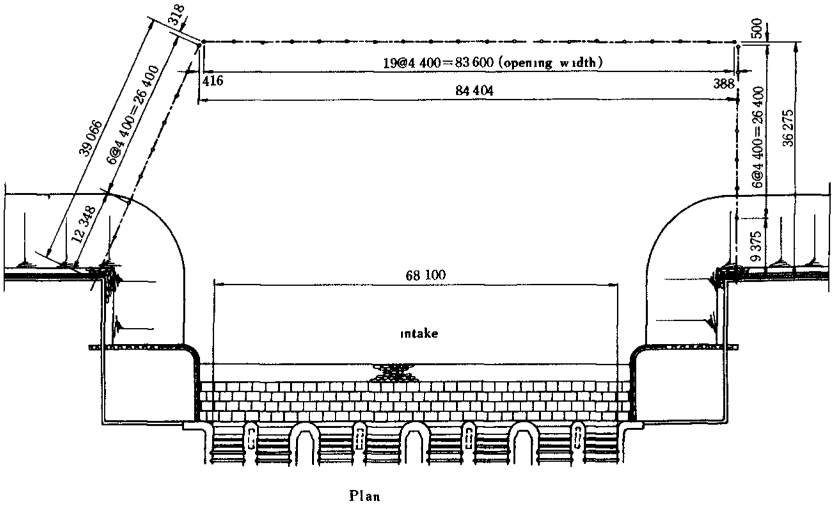

Fig. 9. Arrangement of curtain-wall for cooling water intake of SAKAI-PORT Thermal Power Station (for the first stage).

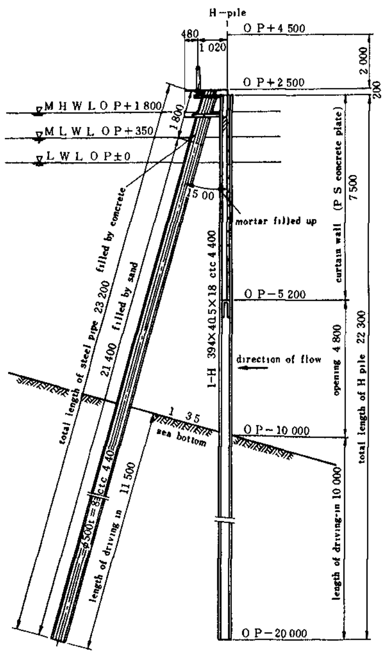

Fig. 10. Cross section of curtain-wall for SAKAI-PORT Thermal P. S.

Fig. 11. A view of curtain-wall type bottom-water intake for Sakai-Port Thermal Power Station (Kansai Electric Power Company).

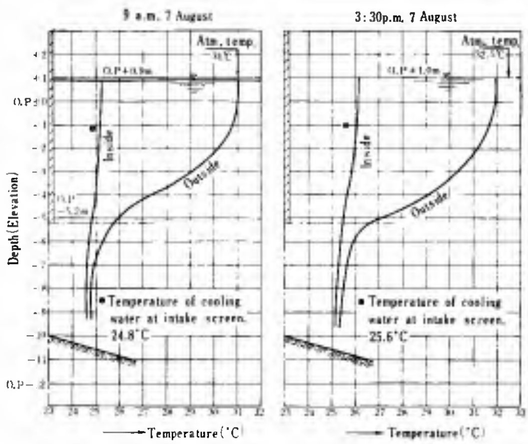

Fig. 12. An example of the results of temperature measurements for bottom water intake of Sakai-Port Power Station.

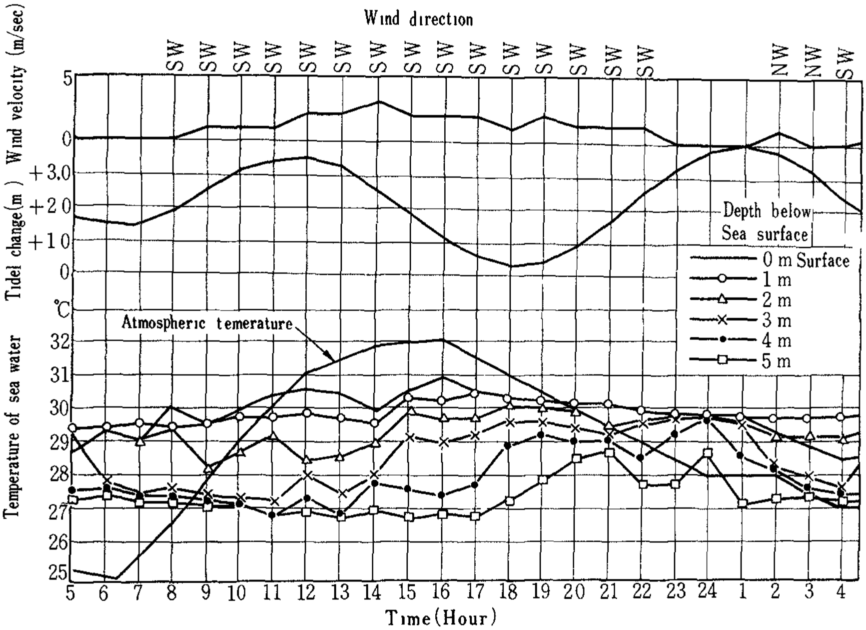

Fig. 13. An example of the results of field survey in Mizushima Bay.

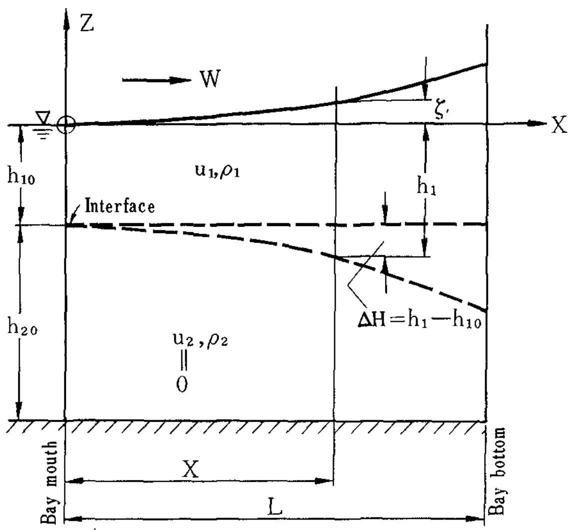

Fig. 14. Effect of wind on drawdown of interface.