Chapter 4 Design of Thermal Outfalls

4.1 Thermal Outfall

4.2 Design of Structures for Thermal Discharges

4.3 An Example Design: The San Onofre Units 2 and 3 Thermal Discharge System

Objectives:

- Understand differences between thermal outfall and waste outfall
- Deal with requirements of hydraulic modeling of thermal discharge systems
- Follow step-by-step design of example system

4.1 Thermal Outfall

4.1.1 Thermal and Wastewater Discharges

• Thermal outfall

- heated water(thermal effluent) from coastal power plant

→ siting and initial dilution

- momentum is dominant than buoyancy ($\Delta\rho / \rho \sim 0.0025$) → momentum jet

- sited in shallow water → unstable flow condition

- heated discharge affects water environment → thermal pollution, thermal effect

Difference between typical thermal and wastewater diffusers (Jirka, 1982)

	Thermal Discharges	Wastewater Discharges
discharge (m^3/s)	80	8
buoyancy, $\Delta\rho / \rho$	0.0025	0.025
momentum flux (m^4/s^2)	400	40
depth of discharge	~10 m	20~30 m (~60 m)
required dilution	10^1	10^2
intake structures	yes	no

4.1.2 Thermal Outfalls in Korea

4.2 Design of Structures for Thermal Discharges

• Design goal - minimize detrimental effects of the discharge on the environment

• Discharge of waste heat (warmed effluent) from power plant

a. surface discharge through canal across the beach

b. submerged single point outlet at some distance from the shore

c. submerged multiport diffuser

• Regulations - Federal Water Pollution Control Act Amendments (1972)

4.2.1 Thermal and Wastewater Discharges

(1) Analysis of thermal discharges

- Combination of large flow, shallow discharge, and large momentum causes that thermal discharges tend to be dynamically active modifying the density distribution of the ambient flow field.
- Analysis using the existing theories on buoyant jets are deficient.
- Physical model is used to determine expected thermal plume behavior.

(2) Complications in thermal discharge:

a. recirculation between the discharge and intake

b. re-entrainment of old diluted effluent into the discharge plume

4.2.2 Hydraulic Modeling of Buoyant Discharge Systems

• Hydraulic modeling requires geometric, kinematic, and dynamic similitudes.

• Dynamic similitude

- Most important phenomenon is interplay between momentum and inertia of the flow and internal gravity forces due to buoyancy.

• Important mechanisms

  - geometric configuration
  - source mass flux
  - source momentum flux
  - source buoyancy flux
  - ocean density stratification
  - ocean temperature stratification
  - bottom and internal friction
  - energy dissipation
  - surface heat exchange
  - ocean turbulence
  - ocean currents

• Dimensionless groups important to the thermal discharge problems

  - Froude number

$$F_s = \frac{u}{\sqrt{gd}}$$

  - Internal (densimetric) Froude number

$$F_s = \frac{u}{\sqrt{g\left(\frac{\Delta\rho}{\rho}\right)d}}$$

- Reynolds number

$$R = \frac{ud}{v}$$

- Friction factor f

- Surface heat exchange coefficient number

$$k = \frac{K}{\rho c_p u}$$

in which $u =$ characteristic velocity; $d =$ characteristic length;

$n =$ kinematic viscosity; $g =$ gravitational acceleration;

$\rho =$ density; $\Delta\rho =$ density difference between discharge and ambient;

$K =$ surface heat exchange coefficient; $c_p =$ specific heat.

• Reynolds similarity:

- To achieve dynamic similitude, the values of dimensionless numbers in the model and the prototype must be the same.
- However, it is impossible to satisfy the condition that both Froude and Reynolds numbers in the model and the prototype are the same.
- In thermal discharge, Reynolds similarity is usually relaxed (ignored) if the flow in the model is turbulent.

→ jet Reynolds No., $R_j = u_j D / v$, $R_j > 1000 \sim 2000$, $D =$ port diameter

→ ambient Reynolds No., $R_a = u_a H / \nu$, $R_a > 2000$, H = water depth

• Friction factor similarity:

- Friction factor ratio, fr is more of importance than Reynolds number.
- It is impossible to decrease the friction factor in the model because Reynolds number in the model is much smaller than that of prototype.
- Interfacial friction is of more importance than bottom friction.
- Distortion of model can satisfy the friction factor similarity.

• Surface heat exchange similarity:

- Phenomenon of surface heat exchange is usually not of importance near the discharge so that unless the model covers a very large area, it may be ignored.

• Distortion of model :

- Near the jet, jet diameter, port spacing, and depth should all be scaled according to the vertical scale.
- Far from the discharge, due to the individual jets being quickly intermixed, the characteristics of the diffusion structure would be governed by the mass, momentum, and buoyancy fluxes per unit length of the diffuser.

→ Total length of the diffuser should be modeled by the horizontal length scale.

4.3 An Example Design: The San Onofre Units 2 and 3 Thermal Discharge System

4.3.1 Description

- Design of outfalls and intakes of the San Onofre Nuclear Generating Station, Units 2 and 3 near San Clemente, California (Koh, et al., 1974)
- Requirements for San Onofre Nuclear Generating Station, Units 2 and 3

  - flowrate each 52.5 m^3 each

  - power generation 1140 Mw per unit

  - temperature rise $\Delta T < 20^{\circ} F (11.1^{\circ} C)$ for effluent

  $\Delta T < 4^{\circ} F (2.22^{\circ} C)$ at the shoreline, bottom, and beyond 1000 ft (305 m) from the discharge

- Comparison between San Onofre thermal discharge and Sand Island wastewater discharge

	San Onofre thermal discharge	Sand Island wastewater discharge
Flowrate Unit 1:	22 m^3/s	1~9 m^3/s
Unit 2, 3:	52.5 m^3/s each	
$\Delta\rho$	0.003 gm/cc	0.025 gm/cc
	(ΔT_0 = °F)	
Dilution	5~10	100~1000
depth of discharge	12 m	72 m

4.3.2 Design

(1) Approximate design

- Bathymetry at the site reveals that ocean bottom is sandy with a slope of 1/200.

→ To reach a depth of 15 m requires a distance of 2450 m offshore.

- Initial dilution should be five to meet regulations $(\Delta T_0 / \Delta T = 20/4 = 5)$.

- Total volume of fluid involve after a dilution of five is $525 \text{ m}^3\text{/s}$

$(= 5 \times 105 \text{ m}^3\text{/s})$

- Volume flux ocean water would be $0.6L \rightarrow 0.6L = 525 \rightarrow L = 875 \text{ m}$ length of diffuser ~ 1000 m

(2) Hydraulic modeling

- Hydraulic modeling is concerned with near and intermediate fields.

i) Near field

- Dominant dynamic features are jet discharge and entrainment of ambient fluid producing the initial dilution.
- Extent of near field is a few multiples of the depth.
- Port spacing is close enough so that there is interference between adjacent jets, as desired for approximating a line source.
- Reynolds number is not modeled, but it should be kept high enough to ensure turbulent flow from the model nozzle.

•Jet dilution at the surface

$$S_0 = f\left(\frac{y_0}{d}, \frac{u_j}{\sqrt{g'd}}, \frac{b}{y_0}, \frac{a}{d}, \Phi, \theta, a, \frac{u_j}{u_c}\right)$$

in which $S_0 =$ initial dilution at the surface (center of jet):

$y_0 =$ depth over center of nozzle; $d =$ jet diameter $= (C_c)^{1/2} D$;

$D =$ port diameter; $C_c =$ contraction coefficient; $u_j = q / (\pi d^2 / 4)$;

$q =$ port discharge; $g' = g\Delta\rho / \rho$;

$\Delta\rho / \rho =$ relative density difference (ambient density - jet density);

$b =$ port spacing, $a =$ height above bottom to center of nozzle;

$f =$ jet inclination to horizontal;

$q =$ angle of current direction to diffuser direction;

$\alpha =$ angle of current direction to jet direction; $u_c =$ current velocity.

•Froude law is used in near field.

$$F_r = \frac{u_r}{\sqrt{g_r' y_r}} = 1$$

$$u_r = \sqrt{g_r' y_r}$$

in which $y_r =$ vertical length ratio ; $y_p / y_m = d_p / d_m$; $g_r' =$ effective gravity ratio.

- If free surface effects are unimportant, ordinary Froude number may be neglected.

•Reynolds number in a Froude model:

$$R_r = \frac{u_r d_r}{v_r}$$

$$R_r = \frac{\sqrt{g_r' y_r^2}}{v_r}$$

- For San Onofre discharge,

$R_p = 2.2 \times 10^6$; $R_m > 1000$ (to obtain fully turbulent jet)

$R_r = 2200$ and $g = 0.0028 / 0.0041 = 0.68 \rightarrow y_r < 226 \rightarrow$ choose $y_r = 200$

ii) Intermediate field

- Flow becomes horizontal in two layers-upper warm water layer overriding the ambient cold seawater.
- Currents are induced in the ambient seawater by the entrainment of the jets.
- Induced flow pattern is driven by the momentum and buoyancy in the jet.
- Resistance to flow arises from bottom friction and interfacial friction between warm and cool layers.

• Froude law

- Froude law is used to reproduce the correct buoyancy effect.
- Richardson number ratio is to be 1.

→ Internal stratified flow phenomena such as generation and breaking of interfacial waves are correctly modeled dynamically.

$$Ri = \frac{g}{\rho}\frac{\frac{d\rho}{dy}}{\left(\frac{du}{dy}\right)^2}$$

$$Ri = \frac{g'_r y_r}{u_r^2} = F_r^{-2} = 1$$

• Friction effects

- Friction effects should be properly modeled in this zone.
- Bottom friction of the current depends on the friction factor f .

$$f = f(R_c, 4y_1 / k)$$

in which $y_1 =$ total local depth; $k =$ bottom roughness,

$R_c =$ Reynolds number for the current, given as

$$R_c = \frac{4u_c y_1}{v}$$

- For San Onofre

$u_c = 5$ cm/s

$u_c = 5$ cm/s

$y_1 = 12$ m

$n = 12\times10^7$ m^2/s (sea water at 15℃)

$k = 15$ mm

$4y_1 / k = 4(12) / 0.015 = 3200$

$R_c = 4(0.015)(12) / 12\times10^7 = 2\times10^6$

By Moody friction factor diagram, $f_p = 0.015$

- For hydraulic model with scales of $y_r = 200$ and $g_r' = 0.68$,

$u_r = (200\times0.68)^{1/2} = 11.7 \ \rightarrow \ u_{cm} = 5 / 11.7 = 0.43$ cm/s

$y_m = 12 / 200 = 0.06$ m

$v_m = 10.2\times10^{-7}$ m$^2 / s$

$R_{cm} = (0.0043)(0.06) / 10.2\times10^{-7} = 1\times10^3$ →laminar flow

By Moody friction factor diagram, $f_m = 0.06$

- ratio of friction factors

$$f_r = f_p / f_m = 0.015 / 0.06 = 0.25$$

→ need to shorten horizontal dimensions by distortion to counteract excessive friction in the model

$f_r =$ friction slope = vertical distance / horizontal distance

→ $f_r = y_r / L_r = 0.25$

→ DF (distortion factor) $= L_r / y_r = 4$

- Interfacial friction between warm and cold layers

  - Model interfacial friction is too large, so is counteracted by reducing horizontal dimensions.
  - Interfacial friction factors depend on both Richardson and Reynolds numbers.

[Re] Distorted model

- Length of diffuser must be scaled by the horizontal length.
- Port spacing must be scaled by the vertical length to preserve correct ratio of b / y_0

→ $L_r = n_r b_r = n_r y_r$ → $n_r = L_r / y_r = DF = 4$

in which $n =$ number of ports.

→ Ports per unit length of diffuser and momentum, volume, and buoyancy fluxes per unit length are locally undistorted.

- Length of initial mixing zone must be scaled by the vertical length.
- Time-scale ratio in unsteady flow must be

$$t_r = L_r / u_r = L_r / (g_r' y_r)^{1/2} = 800 / (0.68 \times 200)^{1/2} = 68.6$$

iii) Far field

- Far field is dominated by heat loss and long-term advection.

• Summary of San Onofre Unit 2 and 3 Diffusers

Length	768 m per unit
number of nozzles	63 per unit
port spacing	12.2 m
jet diameter at vena contracta	0.52 m
jet velocity at vena contracta	4 m/s
nozzle angle up from horizontal	20°
nozzle angle with axis of diffuser	25° (alternating)
elevation of center of nozzle above the sea floor	1.74 m
orientation	perpendicular to shore
distance from shore for most inshore nozzle	1065 m for Unit 3 1830 m for Unit 2