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Effects of Straits on Hydro-Thermal Performance of Small Bays

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ABSTRACT

The heated surface jet discharged into a bay which is connected to a larger body of water through a strait may experience bifurcation in the bay and stratification in the strait. The combined effects of bifurcation and stratification may lead to a substantially greater rise in temperature than the rise expected in case of unrestricted receiving body of water. In this study, the behavior of heated effluents discharged into bays with a restricted access to a large body of water is scrutinized experimentally by the help of a scaled physical model. Dimensional analysis leads to a new dimensionless parameter A_r, area restriction parameter, on which the difference between the excess temperatures at the inlet of the strait for restricted and free receiving mediums, $\Delta(\Delta T/\Delta T_0)$ is shown to be strongly dependent.

Keywords: Heated effluents, surface jets, excess heat.

1. INTRODUCTION

Thermal Power Plants are still in use to provide energy to satisfy the ever-increasing energy demand. Being the most convenient and cheapest method, cooling water from the condensers in the form of heated effluent is discharged to the nearest body of water. The excess heat thus introduced may cause irreversible changes in the immediate vicinity of the discharge. If the receiving medium is a bay with a geometrically restricted access to a larger body of water in the form of a strait, the heat to be build up in the small bay may be prohibitively high. This will not only reduce the performance of the power plant but also damage the aquatic environment permanently.

A heated effluent discharged at the surface into a body of water is called a surface buoyant jet. The temperature difference between the effluent and the receiving ambient results in a density disparity, which causes the buoyant forces to affect the behavior significantly.

Several attempts have been made to describe and predict the behavior of heated surface effluents. Some studies focused on the cooling ponds for which the receiving volume is

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limited in size and used also as the source of cooling water (1,2,3,4,5). The majority of the work, however, focused on the behavior of heated surface effluents into an infinitely large body of water. Policastro and Tokar (6) summarized and compared the models available. Among the available mathematical simulations, the model of Stolzenbach and Harleman (7) is selected as the benchmark for this study.

The three-dimensional model developed by Stolzenbach and Harleman (7) simulates the heated surface effluent from a rectangular channel into an infinitely large, non-stratified body of water. The model can be used to predict the behavior of the heated effluent to the extent that not only the centerline temperature variations but also the spatial extent of the heat contamination can be assessed.

When the heated effluent is discharged into a small bay with a restricted access to a larger body of water, the behavior of the jet is greatly influenced by the geometrical characteristics of the bay and the strait. The strait being the only connection between the bay and the large body of water may cause the heated surface jet to be divided into two parts; one leaving the bay through the strait and the other circulating in the bay. Furthermore, the buoyancy effects may cause a layered flow in the strait.

Thus, combined effects of bifurcation and stratification may lead to a substantially greater rise in temperature than the rise expected in case of infinitely large receiving medium as demonstrated by Nalbantoğlu (8) and Ger (9). The data used in this work is the data originally collected by Nalbantoğlu (8) in a similar attempt made to study the behavior of heated effluents discharged in a bay with a restricted outlet to a larger body of water.

2. THE EXPERIMENTAL SETUP AND THE EXPERIMENTS

The idealized model of the experimental set up is as depicted in Figure 1. In this figure, all geometric variables of interest in the process are also identified.

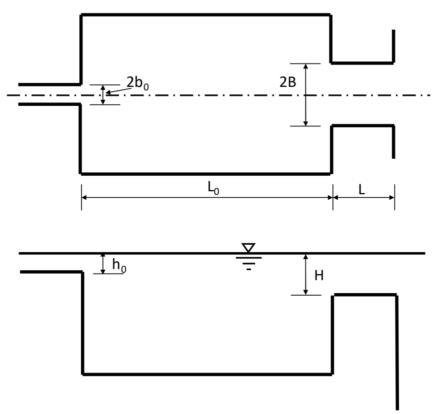

Figure 1 - Schematic representation of the idealized model

ΔT, temperature difference between the heated effluent and the receiving ambience, at the entrance to the strait was chosen as the independent variable representing the effect of the strait on the behavior of the heated effluent issued into the restricted bay. The variables that may contribute to the behavior of the effluent are listed in Table 1.

Table 1 - The list of contributing variables

CONTRIBUTOR	CHARACTERISTICS
OUTLET	b_0: half width of the outlet channel h_0: depth of flow in the outlet channel
SMALL BAY AND THE STRAIT	L_0: length of the small bay B: half width of the strait H: depth of flow in the strait L: length of the strait
EFFLUENT, RECEIVING AMBIENCE, AIR, and OTHERS	ΔT_0: temperature difference between the heated effluent and the receiving ambience $\Delta\rho_0$: density difference between the heated effluent and the receiving ambience u_0: velocity of the effluent at the outlet ρ_w: ambient density ν_w: kinematic viscosity of the receiving ambience c_w: specific heat of water α_w: thermal diffusivity ΔT_a: temperature difference between the air and the receiving ambience K_e: Surface heat exchange coefficient ΔT: temperature difference between the heated effluent and the receiving ambience at the entrance of the strait g: the gravitational acceleration

The following functional form, thus, can be formed.

$$\Delta T = f_1(b_0, h_0, L_0, B, H, L, \Delta T_0, \Delta\rho_0, u_0, \rho_w, \nu_w, \alpha_w, c_w, \Delta T_a, K_e, g) \quad (1)$$

Employing Buckingham's π Theorem one obtains

$$\frac{\Delta T}{\Delta T_0} = f_2\left(Fr_d, Fr, Re, Pr, \frac{K_e}{\rho_0 c_w u_0}, \frac{\Delta T_a}{\Delta T_0}, \frac{L}{L_0}, \frac{h_0}{b_0}, \frac{H}{B}, \frac{(h_0 b_0)^{1/2}}{L_0}, \frac{h_0 b_0}{HB}, \frac{h_0}{B}\right) \quad (2)$$

where Fr_d is the Densimetric Froude Number at the outlet defined as $Fr_d=u_0/(\Delta\rho_0 gh_0/\rho_w)$; Fr is the Froude Number at the outlet defined as $Fr=u_0/(gh_0)^{1/2}$; and Re is the Reynolds Number at the outlet defined as $Re=u_0(h_0b_0)^{1/2}/\nu_w$; Pr is the Prandtl Number in the bay defined as $Pr=\nu_w/\alpha_w$.

The effects of Fr, Re, and Pr may be neglected (29). Furthermore, since u_0 and ΔT_a are kept constant and $L_0>>h_0$ throughout the experiments, the effects of $K_e/\rho_0 c_w u_0$, $\Delta T_a/\Delta T_0$, h_0/b_0, H/B, and h_0/B will be insignificant and may also be disregarded. Therefore, Equation 3 reduces to

$$\frac{\Delta T}{\Delta T_0} = f_3\left(Fr_d, \frac{L}{L_0}, \frac{(h_0b_0)^{1/2}}{L_0}, \frac{h_0b_0}{HB}\right) \quad (3)$$

At this step, in order to emphasize the presence of the strait a new parameter is introduced; the ratio of the nominal cross-sectional area of the effluent at the location of the inlet in the absence of the strait to the cross-sectional area of the strait. The representative depth h_{max} and half width y_c are reported to be

$$h_{max} \propto (h_0b_0)^{1/2}Fr_d \quad (4)$$

and

$$y_c \propto L_0\, Fr_d^{-1/4} \quad (5)$$

as given by Harleman (10) and Jen et. Al. (11). Thus, the new parameter, area restriction parameter A_r is defined as

$$A_r = \frac{(h_0b_0)^{1/2}L_0Fr_d^{3/4}}{HB} \quad (6)$$

coupling equations 3 and 6 and considering that A_r is a combination of Fr_d, $(h_0b_0)^{1/2}/L_0$ and h_0b_0/HB; equation 3 becomes

$$\frac{\Delta T}{\Delta T_0} = f_4\left(A_r, \frac{L}{L_0}, \frac{L_0}{(h_0b_0)^{1/2}}\right) \quad (7)$$

Once the functional relationship, of Equation 7, that can be used in investigating the effect of restriction imposed by a strait on the behavior of a heated effluent was established, an experimental setup was designed to facilitate the observation of the aforementioned effects of the strait on the behavior of the heated effluent.

The experiments were carried out using several different combinations of geometric variables. The characteristics of the experiments run are listed in Table 2. In this Table, T_0, T_w, and T are temperatures measured at the outlet, at the small bay, and at the inlet of the strait, so that $\Delta T_0=T_0-T_w$ and $\Delta T=T-T_w$. In Table 2, the respective values of the variables appearing in Eqn. 7 are also included.

Table 2 - Observed and reduced values of the variables involved

Code no	H cm	B cm	T_O ^0C	T_w ^0C	h_0 cm	b_0 cm	u_o m/s	L_0 cm	L cm	T ^0C	Ar	$L_0/(h_0b_0)^{1/2}$	L/L_0	$\Delta T/\Delta T_0$
101	1.9	24.7	36.5	15.3	2.0	0.5	0.2	40.0	10.0	25.5	3.327	40.000	0.250	0.481
102	6.9	2.2	36.8	15.0	2.0	0.5	0.2	40.0	10.0	28.3	10.178	40.000	0.250	0.610
103	6.9	7.2	36.6	15.0	2.0	0.5	0.2	40.0	10.0	23.0	3.125	40.000	0.250	0.370
104	14.4	2.2	37.0	15.0	2.0	0.5	0.2	40.0	10.0	26.8	4.853	40.000	0.250	0.536
105	14.4	7.2	37.1	15.0	2.0	0.5	0.2	40.0	10.0	22.1	1.479	40.000	0.250	0.321
106	24.4	7.2	34.0	15.0	2.0	0.5	0.2	40.0	10.0	21.4	0.946	40.000	0.250	0.337
201	1.9	7.2	30.7	10.5	2.0	0.5	0.2	30.0	20.0	24.6	9.526	30.000	0.667	0.698
202	1.9	24.7	28.5	10.5	2.0	0.5	0.2	30.0	20.0	20.3	2.963	30.000	0.667	0.544
203	6.9	2.2	29.6	10.4	2.0	0.5	0.2	30.0	20.0	22.0	8.852	30.000	0.667	0.604
204	6.9	7.2	29.1	10.5	2.0	0.5	0.2	30.0	20.0	19.5	2.748	30.000	0.667	0.484
205	14.4	2.2	29.3	9.7	2.0	0.5	0.2	30.0	20.0	19.7	4.250	30.000	0.667	0.510
206	14.4	7.2	30.8	9.0	2.0	0.5	0.2	30.0	20.0	18.6	1.238	30.000	0.667	0.440
207	24.4	2.2	29.5	10.5	2.0	0.5	0.2	30.0	20.0	18.8	2.513	30.000	0.667	0.437
208	24.4	7.2	29.1	10.5	2.0	0.5	0.2	30.0	20.0	18.0	0.777	30.000	0.667	0.403
301	1.9	7.2	29.5	11.0	2.0	1.0	0.2	40.0	10.0	24.8	18.691	28.284	0.250	0.746
302	1.9	24.7	29.3	11.5	2.0	1.0	0.2	40.0	10.0	22.0	5.512	28.284	0.250	0.590
303	6.9	2.2	31.2	11.5	2.0	1.0	0.2	40.0	10.0	25.9	16.116	28.284	0.250	0.731
304	6.9	7.2	30.8	11.5	2.0	1.0	0.2	40.0	10.0	22.0	4.981	28.284	0.250	0.544
305	6.9	24.7	31.3	10.5	2.0	1.0	0.2	40.0	10.0	19.2	1.418	28.284	0.250	0.418
306	14.4	2.2	30.0	11.2	2.0	1.0	0.2	40.0	10.0	23.2	7.969	28.284	0.250	0.638
307	14.4	7.2	30.8	10.0	2.0	1.0	0.2	40.0	10.0	19.7	2.353	28.284	0.250	0.466
308	14.4	24.7	30.3	10.6	2.0	1.0	0.2	40.0	10.0	18.9	0.699	28.284	0.250	0.421
309	24.4	2.2	29.7	10.7	2.0	1.0	0.2	40.0	10.0	22.9	4.720	28.284	0.250	0.642
310	24.4	7.2	30.0	10.3	2.0	1.0	0.2	40.0	10.0	19.6	1.424	28.284	0.250	0.472
311	24.4	24.7	30.6	9.6	2.0	1.0	0.2	40.0	10.0	17.3	0.406	28.284	0.250	0.367
401	1.9	7.2	30.5	10.0	2.0	1.0	0.2	30.0	20.0	26.4	13.487	21.213	0.667	0.800
402	1.9	24.7	29.2	11.2	2.0	1.0	0.2	30.0	20.0	23.1	4.133	21.213	0.667	0.661
403	6.9	2.2	31.7	10.4	2.0	1.0	0.2	30.0	20.0	26.9	11.802	21.213	0.667	0.775
404	6.9	7.2	29.7	10.5	2.0	1.0	0.2	30.0	20.0	23.0	3.818	21.213	0.667	0.651
405	6.9	24.7	31.3	11.0	2.0	1.0	0.2	30.0	20.0	20.6	1.068	21.213	0.667	0.473
406	14.4	2.2	30.0	10.0	2.0	1.0	0.2	30.0	20.0	23.7	5.907	21.213	0.667	0.685
407	14.4	7.2	30.8	10.8	2.0	1.0	0.2	30.0	20.0	21.4	1.778	21.213	0.667	0.530
408	14.4	24.7	30.3	11.4	2.0	1.0	0.2	30.0	20.0	20.8	0.529	21.213	0.667	0.497
409	24.4	2.2	29.7	10.7	2.0	1.0	0.2	30.0	20.0	22.1	3.540	21.213	0.667	0.600
410	24.4	7.2	30.0	10.3	2.0	1.0	0.2	30.0	20.0	20.0	1.068	21.213	0.667	0.492

3. EXPERIMENTAL FINDINGS AND CONCLUSIVE REMARKS

The recorded variation of dimensionless excess temperature difference, $\Delta T/\Delta T_0$, at the inlet of the strait, with the area restriction parameter, A_r, is depicted in Figure 2. In this figure, dimensionless excess temperature differences, $(\Delta T/\Delta T_0)_{free}$, in the case of unrestricted receiving body of water at the respective locations as predicted by Stolzenbach-Harleman (S-H) are also included for the facilitation of comparison.

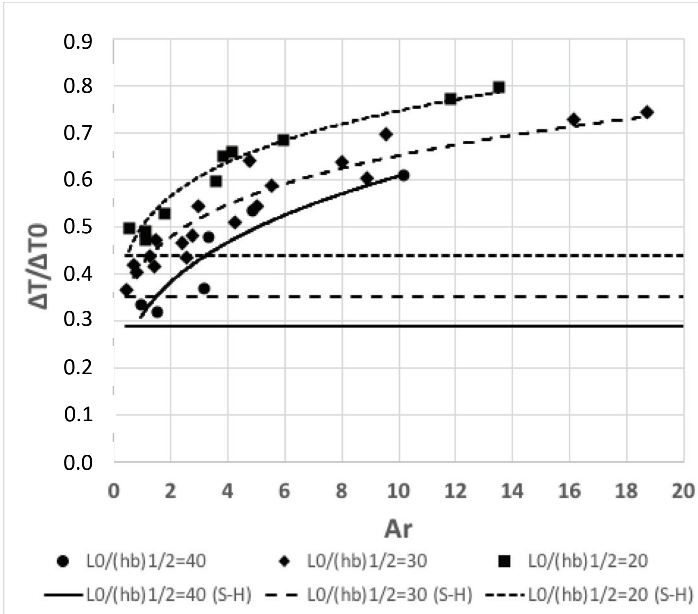

Figure 2 - Variation of heat built up at the inlet of the strait

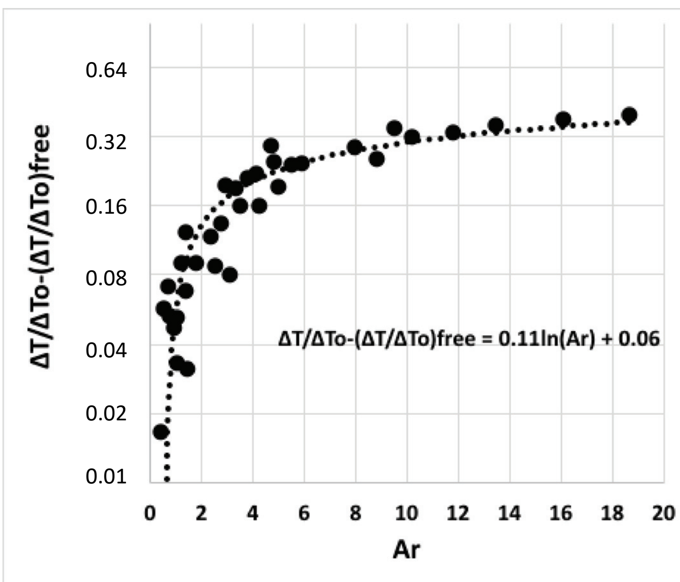

Figure 3 - Variation of difference between the excess temperatures at respective locations for restricted and free receiving mediums

Investigation of the data reveals that the difference between the excess temperatures at the inlet of the strait for restricted and free receiving mediums, $\Delta(\Delta T/\Delta T_0)$, defined as $\Delta(\Delta T/\Delta T_0) = \Delta T/\Delta T_{o.}-(\Delta T/\Delta T_o)_{free}$, is strongly dependent on A_r, such that

$$\Delta(\Delta T/\Delta T_0) = \Delta T/\Delta T_{o.}-(\Delta T/\Delta T_o)_{free} = 0{,}11\ \ln(A_r) + 0.06 \qquad (8)$$

as depicted in Figure 3.

The experimental findings strongly suggest that the excess temperature rise, $\Delta(\Delta T/\Delta T_0)$, at the entrence of the restricting strait can be predicted once the A_r, the restriction parameter, is known.

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Symbols

A_r : Area restriction parameter

B : Half width of the strait

b_0 : half with of the outlet channel

c_w : specific heat of water

Fr : Froude Number at the outlet

Fr_d : Densimetric Froude Number

G : the gravitational acceleration

H : depth of flow in the strait

h_0 : depth of flow in the outlet channel

L : length of the strait

L_0 : length of the small bay

K_e : Surface heat exchange coefficient

Re : Reynolds Number at the outlet

Pr : Prandtl Number in the bay

u_0 : velocity of the effluent at the outlet

α_w : thermal diffusivity

ΔT : temperature difference between the heated effluent and the receiving ambience at the entrance of the strait

ΔT_a : temperature difference between the air and the receiving ambience

ΔT_0 : temperature difference between the heated effluent and the receiving ambience

$\Delta \rho_0$: density difference between the heated effluent and the receiving ambience

ρ_w : ambient density

ν_w : kinematic viscosity of the receiving ambience

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