Effects of Straits on Hydro-Thermal Performance of Small Bays

Ahmet Metin GER¹

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 $\Delta r$, 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...
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](image-url)
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>
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<th>CHARACTERISTICS</th>
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<td>OUTLET</td>
<td>(b_0): half width of the outlet channel (h_0): depth of flow in the outlet channel</td>
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<td>SMALL BAY AND THE STRAIT</td>
<td>(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</td>
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<td>EFFLUENT, RECEIVING AMBIENCE, AIR, and OTHERS</td>
<td>(\Delta T_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 (\rho_\omega): ambient density (\nu_\omega): kinematic viscosity of the receiving ambience (\ell_\omega): specific heat of water (\alpha_\omega): thermal diffusivity (\Delta T_a): temperature difference between the air and the receiving ambience (K_e): Surface heat exchange coefficient (\Delta T): temperature difference between the heated effluent and the receiving ambience at the entrance of the strait (g): the gravitational acceleration</td>
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</table>

The following functional form, thus, can be formed.

\[
\Delta T = f_1(b_0, h_0, L_0, B, H, L, \Delta T_0, \Delta \rho_0, u_0, \rho_\omega, \nu_\omega, \ell_\omega, \Delta T_a, K_e, g)
\] (1)

Employing Buckingham’s \(\pi\) Theorem one obtains

\[
\frac{\Delta T}{\Delta T_0} = f_2(\text{Fr}_d, \text{Fr}, \text{Re}, \text{Pr}, \frac{K_e}{\rho_\omega c_\omega u_0}, \frac{\Delta T_a}{\Delta T_0}, \frac{L}{L_0}, \frac{h_0}{B}, \frac{H}{B}, (\frac{h_0 b_0}{B})^{1/2}, \frac{h_0 b_0}{B}, g)
\] (2)
where Fr_d is the Densimetric Froude Number at the outlet defined as Fr_d=u_0/(\rho_d g h_0/\rho_w); Fr is the Froude Number at the outlet defined as Fr=u_0/(g h_0)^{1/2}; and Re is the Reynolds Number at the outlet defined as Re=u_0(h_0 b_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 \Delta T are kept constant and L_0>>h_0 throughout the experiments, the effects of K_c/\rho_c u_0, \Delta T_0/\Delta T, h_0/b_0, H/B, and h_0/B will be insignificant and may also be disregarded. Therefore, Equation 3 reduces to

$$\frac{\Delta T}{\Delta T_0} = f_3\left(Fr_d, \frac{L_0}{h_0 b_0}^{1/2}, \frac{h_0 b_0}{HB}\right)$$  \hspace{1cm} (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

$$h_{\text{max}} \propto (h_0 b_0)^{1/2}Fr_d$$  \hspace{1cm} (4)

and

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

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

$$A_r = \frac{(h_0 b_0)^{1/2}L_0 Fr_d^{3/4}}{HB}$$  \hspace{1cm} (6)

coupling equations 3 and 6 and considering that A_r is a combination of Fr_d, (h_0 b_0)^{1/2}/L_0 and h_0 b_0/HB; equation 3 becomes

$$\frac{\Delta T}{\Delta T_0} = f_4\left(A_r, \frac{L_0}{h_0 b_0}^{1/2}, \frac{h_0 b_0}{\nu_w}\right)$$  \hspace{1cm} (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

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<th>b0 cm</th>
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<th>L0 cm</th>
<th>L cm</th>
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3. EXPERIMENTAL FINDINGS AND CONCLUSIVE REMARKS

The recorded variation of dimensionless excess temperature difference, ΔT/ΔT0, at the inlet of the strait, with the area restriction parameter, Ar, is depicted in Figure 2. In this figure, dimensionless excess temperature differences, (ΔT/ΔT0)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 \( \Delta(\Delta T/\Delta T_0) = \Delta T/\Delta T_0 - (\Delta T/\Delta T_0)_{\text{free}} \), is strongly dependent on \( A_r \), such that
\[
\Delta(\Delta T/\Delta T_0) = \Delta T/\Delta T_0 - (\Delta T/\Delta T_0)_{\text{free}} = 0.11 \ln(A_r) + 0.06
\]
as depicted in Figure 3.

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

Acknowledgement:
The author heartily acknowledges the effort of Mr. A. E. Nalbantoğlu who gathered the data used in this study. Thanks are also extended to Middle East Technical University which provided facilities for the experiments.

Symbols

\( A_r \) : Area restriction parameter  
\( B \) : Half width of the strait  
\( b_0 \) : half width of the outlet channel  
\( c_w \) : specific heat of water  
\( F_r \) : Froude Number at the outlet  
\( F_r d \) : 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  
\( R_e \) : Reynolds Number at the outlet  
\( P_r \) : Prandtl Number in the bay  
\( u_0 \) : velocity of the effluent at the outlet  
\( \alpha_w \) : thermal diffusivity  
\( \Delta T \) : 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
Δρ_0 : density difference between the heated effluent and the receiving ambience
ρ_w : ambient density
v_w : kinematic viscosity of the receiving ambience

References


