Temperature Impact of the Industrial Cooling Water Discharges in a Long Boat Slip of Hamilton Harbour

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The thermal structure of industrial cooling water discharged into a long, narrow and shallow, straight open boat slip (Ottawa Street Slip, [OSS]) was investigated by field measurements during the hottest summer month in 2006. Three-dimensional hydrodynamic and thermal transport models were established and verified with measurements. The main purposes of this study were to understand the mechanism of the thermal structure in the OSS during the hot summer season under the present cooling water discharge conditions, to investigate the influence of harbour water on the thermal structure in the slip, and to establish a means for scientific predictions of the impact of cooling water discharges in a future study. Toward this end, the water temperature at multiple locations along the OSS and meteorological data near the study site were collected during the summer period of 2006. The collected data reveal: (1) during the measured summer period, the water temperature in the slip can be higher than 30°C during a period of high air temperatures; (2) water temperature variations within short periods of 15, 30, 60, and 120 minutes were no more than 4°C during the entire measurement period; (3) water temperature in the slip is controlled by both air and cooling discharge temperatures, and the cooling water temperature's increase due to industrial cooling processing seems to be relatively independent of the intake water temperature; therefore, the water temperature in the slip varied mainly with the air temperature; (4) since water temperature in the slip seemed to closely follow the intake water temperature, the intake channel may need to be optimized to maximize the possibility of getting the coolest water available from Hamilton Harbour; and (5) the cooler harbour water could not penetrate deeply into the slip. The collected water temperature data were also used for verification of three-dimensional hydrodynamic and transport models. The simulation results showed that the established model could reasonably well reproduce general thermal structures in the entire slip. This achieved the ultimate goal of the study for establishing a model to assess the impacts of further increase of cooling water discharge into the OSS.

Key words: thermal plume, numerical modelling, computational fluid dynamics, narrow slip, temperature structure

Introduction

Stream water temperature is one of the most important parameters in ecosystem studies. It is not only very important in many chemical processes present in river systems, but also influences many biological conditions and behaviours. Disruption to the thermal regime of a watercourse can significantly impact the utilization of fish habitat. Understanding natural variations in stream water temperatures is also very important in limnological studies. For instance, temperature greatly influences the rate of decomposition of organic material and the saturation concentration of dissolved oxygen (Nemerow 1985). Stream water temperature can also be one of the factors in determining the habitat potential of a stream (Bovee 1982). The most obvious effects on aquatic organisms are on their survival rate and their growth. For example, high stream water temperatures between 23 and 25°C can affect the mortality of salmonids (Bjorn and Reiser 1991). High stream water temperature can occur naturally or as a result of human impact. An example of the latter is thermal pollution and deforestation, which have been identified as having a negative impact on the thermal regime of a watercourse (Gras 1969; Brown and Krygier 1970; Hartman et al. 1987).

Knowledge and the ability to predict stream water temperature are therefore essential to solve thermal discharge problems and in conducting ecosystem environmental impact assessment studies. A better understanding of the natural thermal regime of a small stream is also very important in the management of fisheries and aquatic resources. The first step in the overall understanding of the thermal structure in streams is the ability to study and predict variation in stream water temperatures.

In general, most of the variation in stream water temperatures occurs in open-water conditions during the summer months. During winter in cold regions, the mass of water is less affected by meteorological conditions as a result of the ice cover, although small temperature changes have been monitored (Marsh 1990). Following ice breakup in the spring, heat-exchange processes between the atmosphere and the body of water take place in attempt to reach equilibrium, resulting in changes of stream water temperature (Triboulet et al. 1977).

To predict stream water temperatures, many models have been developed and used (e.g., Raphael 1962; Cluis 1972; Morin and Couillard 1990; Stefan and Preudhomme 1993). These models can be classified into
two categories (Marceau et al. 1986): (i) deterministic models (mathematical formula based), and (ii) stochastic models (statistical function based).

Deterministic models consider all relevant meteorological factors such as air temperature, solar radiation, and wind velocity (Raphael 1962; Marcotte and Duong 1973; Morin et al. 1994). These meteorological parameters are used in energy budget equations including the effects of radiation, evaporation, and convection, etc., to calculate the thermal exchange between the atmosphere and the body of water. Physical characteristics of the stream, such as water depth, inflow rates, initial water temperature, and the degree of stream ice cover, are also important parameters in this modelling approach to predict stream water temperature variations. Deterministic models have the advantage of being flexible in the modification of input parameters to study the resultant change in water temperatures. Lumped models provide model output for one point along a river system, whereas distributed models can simulate water temperatures at various locations on a given river (Morin et al. 1983). Once calibrated for given conditions, deterministic models can be applied to simulate streams under different environments. Also, these models are better adapted to thermal pollution studies, since they can consider many masses of water with different temperatures. The disadvantages of deterministic models are the amount of data required to run them and the time and expense in their development.

Alternatively, stochastic models are based on linear statistical function. The application of a stochastic model usually requires only air temperatures and a continuous time series of stream water temperature for model calibration. A statistical relationship between air and water temperatures is often determined by classical regression analysis or by using time series analysis, such as the Box-Jenkins modelling approach (Box and Jenkins 1976). The advantage of the stochastic modelling approach is in its simplicity of development and requirement for less input data. However, a stochastic model developed for a particular stream cannot easily be applied to another stream and is not as useful in ecosystem impact studies because it lacks flexibility and provides very little thermal connection of the simulated components.

The main goals of this study were to investigate the thermal structures in the Ottawa Street Slip (OSS) during the hot summer season under the present cooling water discharge conditions, and to establish a means for scientific predictions of the impact of significant future increases of cooling water discharges. To accomplish the latter goal, a commercially available computational fluid dynamics model with the capacity of simulating thermal transport was established and verified with the collected field water temperature at multiple locations along the OSS and meteorological data near the study site during the summer period of 2006.

**Background**

The OSS is a long, narrow and shallow, straight open channel connected to the south shore of Hamilton Harbour. The slip is 2,000-m long, and 10- to 30-m wide, and has an average depth of around 3 m (maximum depth is around 10 m at the location connected to the harbour). The location and shape of the OSS can be seen in Fig. 1 and 2, respectively. Two large steel mills are located on either side of the slip. There are several cooling water discharges (through discharge 2 to 7) along this slip, and a combined sewer overflow (CSO) outlet (discharge 1); their locations are displayed in Fig. 2. Temperature and flow rate of the cooling water discharges vary with time, and water temperatures measured along the slip during summer of 2006 in many locations could be higher than 30°C. Water temperature in the OSS can be influenced by many factors, such as hydraulic conditions, solar radiation, air temperature, flow exchanges between the slip and the Harbour, rain storm runoff through CSO discharge, as well as cooling water discharges. A “Declared Point of Natural Environment,” located at the same location as measurement station G (Fig. 2), was specified by Ontario Minister of Environment to regulate how high water temperature can reach at this location for the purpose of controlling the industrial cooling water discharge. In order to understand the thermal and hydraulic conditions of the OSS and to predict the impact of the thermal structure of the OSS on the surrounding area when introducing additional cooling water, a fully three-dimensional hydrodynamic model with the capacity for thermal transport modelling—based on commercial software, Star CD—was adopted and verified with measured data.

**Measurements of Water Temperature**

To investigate the present thermal structure in the slip under existing discharge conditions and to verify the numerical model, temperature data were collected with Tidbit temperature loggers along the slip from the end of June to the end of September, 2006. The accuracy of the

Fig. 1. The Ottawa Street Slip located on the South shore of the Hamilton Harbour.
Tidbit temperature logger is +/-0.2°C. Water temperatures were collected every 15 minutes and stored in data loggers. A total of 14 mooring stations were deployed along the slip. Unfortunately, two of them were lost at locations with very fast flow. Positions of all recovered stations are shown in Fig. 2, as labelled from A to L. For the purpose of investigating the possible influences of harbour water on the water temperature in the slip through bottom water exchange, stations A, B, and C in the deeper section of the slip close to the Harbour had two temperature sensors on each logger. The water temperature at 0.2 m below the surface and 0.5 m above the bottom was recorded. Also, an acoustical doppler current profiler (ADCP) was deployed inside the slip about 100 m from the Harbour during Julian day 130 to 286. The broad-band ADCP, operated at 1,200 Hz with a 1-m vertical measurement resolution, was mounted at the bottom (6 m in depth) of the slip. At the same time, the bottom temperature was also monitored at the ADCP measurement location. Both velocity vertical profiles and water temperatures were recorded in a data log every 30 minutes. The measured temperatures at different locations were plotted separately in Fig. 3 and 4; only July data (Julian day 182 to 212) used for developing and verifying model were plotted in order to make plots readable and representative, and were closely examined in most figures.

Except for the ADCP location, station A is located at the farthest downstream location of all the temperature measurement stations. It is in a deeper water region and is about 300 m away from the connecting point to Hamilton Harbour. Therefore, the Harbour’s cooler and denser water would have a larger influence on water temperature in this region than in the upstream region through bottom flow exchange. This may partially account for the difference of the measured surface and bottom water temperatures in the top panel of Fig. 3, which can be around the 5 to 7°C. To more closely examine the influence of the cooler harbour water on the water column stratification at station A (3 m in depth), the measured surface and bottom velocities along the slip at the ADCP location are plotted out in Fig. 5. It can be seen in Fig. 5 that at the mouth of the slip, flow can go in either direction (positive: outflow; negative: inflow). However, the mean flow exits the slip as indicated by larger and longer positive flows, which is expected because of the upstream net cooling water discharge and the possible CSO flow. In general, the flow velocity is small, and outflow is stronger in the surface layer (upper panel) than in the bottom layer (lower panel). However, for inflow this is opposite, i.e., there is a stronger inflow in the bottom layer. Exchange flow at this location is weak and is not expected to have a strong influence on the water temperature at station A, as indicated by the lack of correlation between the measured bottom temperatures at locations of the ADCP and station A. Therefore, stratified water temperature at station A should be mainly attributed to the strong Boyce force generated from the much warmer surface water from cooling water dischargers. Another interesting feature worth mentioning is that at station A, the top and bottom water temperatures are not well correlated compared...
with the temperatures measured at the other stations. This also indicates the lack of exchange between surface and bottom water due to the same strong Boyce force. However, at station B water temperature on the surface and bottom are about the same as shown in the middle panel of Fig. 3, which is most likely because the depth at station B is shallower (less than 2 m) than the depth at station A, and the station is further from the Harbour. The Boyce force is weaker (more vertical mixing) because of less temperature difference in the water column, and the baroclinic force generated by the temperature difference in the horizontal direction is not strong enough either to push the heavier cooler water upward or to overcome resistance of long distance travel. Therefore, measured water temperatures indicate that cooler harbour water does not penetrate into the slip beyond the location of station B.

The region from station B to the upstream end is much shallower, and the average water depth is less than 2 m, where there are six outlets discharging cooling water and a CSO effluent into the slip from various sources. The thermal structure in this region should be, as generally thought, controlled mainly by the stream coming from various discharges, and since the flow in the slip is unidirectional, the downstream flow temperature should have minimal effect on the upstream flow. Therefore, the temperature measured along the slip should not show strong correlation if the discharges are fully independent of each other, as indicated in Table 1, and upstream discharges do not hydraulically dominate the entire system. However, temperatures measured at different locations, as displayed in Fig. 3 to 4, show a strong correlation, and temperature structures followed each other very closely along the slip during the entire period even though temperature values varied from one place to another. To better illustrate correlation of water temperature from different discharges, the measured water temperatures from stations D and E were plotted in Fig. 6 for comparison. Measurements from these two stations were selected because they came from two different steel makers. Since the water temperature measurement locations were very close to the discharge outlet, the measured water temperatures should be fully independent of each other. After applying a 24 hour low pass time filter to reduce high frequency variations, it can be seen that usually the two curves follow each other reasonably well and the correlation coefficient between the two curves, which is a normalized measure of the strength of the linear relationship between two variables, is about 0.793. This strong correlation indicates that water temperature at all locations must be strongly influenced by the same factor, which should be air temperature, because all cooling water was taken from the same open water source. Figure 7 shows the temperature comparisons between air and water. In the top panel the measured air and water temperatures are presented. Even though there are many high frequency components in both measurements, the general trend of the two curves is similar. During any period when the air temperature varied consistently in one direction for a few days, the water temperature responded in the same manner for about the same period. This may be easier seen from the bottom panel after high frequencies of the measured air and water temperature were filtered out with an 8-hour time filter. For example, in July and August there are two hot episodes during which the highest water temperature (above 30°C) was recorded. When the air temperature cooled down in the fall, so did the water temperature (with slower decreasing speed) because of the water’s much larger thermal capacity.

How can water temperature be strongly influenced by air temperature in a fast-flow stream with a flow...
Thermal Structure Study and Numerical Modelling

The resident time of less than 20 minutes? The answer could come from the source of intake water. The cooling water is taken from Hamilton Harbour through a long straight intake channel, with dimensions of 520-m long by 9-m wide and variable depth ranging from 3 m at the end where a pump station is located to 7 m at the junction of the intake channel and Hamilton Harbour. The flow residence time in the intake channel is around a half hour calculated with an average flow velocity of 0.3 m/s, as estimated by the cooling water user. The 30 minute residence time is not long enough for the air temperature to have any significant influence on the water temperature. The water temperature difference between the surface and the bottom at the Hamilton Harbour end of the intake channel can vary largely during the summer within a 7-m water depth. However, because of the bottom slope, heavier cold water at the bottom has much less chance to be taken up by the cooling pump located at the other end of the intake channel. It is possible that most of the cooling water taken from Hamilton Harbour is the surface water, which is obviously greatly influenced by air temperature, and since all discharges for different cooling processes come from the same source, it is not difficult to understand why measured water temperatures in the OSS have strong correlation among them and with the air temperature. Therefore, the close relationship between Hamilton Harbour surface water temperature and air temperature is reflected in the measured water temperature data in the OSS. The industrial cooling process is not the sole major factor in determining the water temperature in the OSS under the present level of industrial cooling water discharge.

The measured temperatures showed that during the summer of 2006, water temperature in the slip could be as high as 32°C for a few days depending on weather conditions. High water temperature may cause concern due to the effect on surrounding aquatic life. However, the speed of water temperature change within a short period may be, sometimes, more sensitive for some species.

### Table 1. Water temperatures (Temp.) and flow rates of cooling water discharges provided by Dofasco at the different discharge outlets during the summer period of 2006

<table>
<thead>
<tr>
<th></th>
<th>Outlet 2</th>
<th>Outlet 4</th>
<th>Outlet 5</th>
<th>Outlet 6</th>
<th>Outlet 7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow (m³/d)</strong></td>
<td><strong>Temp. (°C)</strong></td>
<td><strong>Flow (m³/d)</strong></td>
<td><strong>Temp. (°C)</strong></td>
<td><strong>Flow (m³/d)</strong></td>
<td><strong>Temp. (°C)</strong></td>
</tr>
<tr>
<td>May</td>
<td>847</td>
<td>22.9</td>
<td>162,477</td>
<td>21</td>
<td>69,061</td>
</tr>
<tr>
<td>June</td>
<td>1,524</td>
<td>28.6</td>
<td>176,753</td>
<td>23</td>
<td>68,978</td>
</tr>
<tr>
<td>July</td>
<td>2,156</td>
<td>31.0</td>
<td>162,890</td>
<td>30</td>
<td>83,348</td>
</tr>
<tr>
<td>August</td>
<td>1,186</td>
<td>30.9</td>
<td>170,858</td>
<td>23</td>
<td>75,406</td>
</tr>
<tr>
<td>September</td>
<td>833</td>
<td>28.6</td>
<td>160,674</td>
<td>23</td>
<td>69,612</td>
</tr>
<tr>
<td>October</td>
<td>n/a</td>
<td>n/a</td>
<td>169,557</td>
<td>16</td>
<td>56,084</td>
</tr>
</tbody>
</table>

* n/a = not available.

**Fig. 6.** Comparison of the water temperatures measured at station D and E during the summer of 2006. The correlation co-efficiency of the two curves is equal to 0.7931.

**Fig. 7.** The top panel displays the measured air and water temperatures, and the bottom panel displays the same measured air and water temperature with an 8 hour filter applied.
(Sheng and Xu 2008). For this reason the maximum temperature changes during the different time spans of 15, 30, 60, and 120 minutes have been calculated from all the measured temperature data, and are listed in Table 2. The data in Table 2 indicate that for the present level of industrial cooling water discharges there are no significant short-term temperature fluctuations in any of the measured water temperatures.

### Modelling

**Modelling Considerations**

Considering that there are a number of varied cooling water discharges along the OSS, and that the heat energy can be transported by convection, diffusion, and exchange with the atmosphere through the water-air interface, in this study a full hydrodynamic model with capacity to simulate thermal transport was adopted and verified, based on all available measurements. The model would establish a means of scientific prediction of the impact of the cooling water discharges if the discharges are significantly increased by steel makers in the future. The simulation period was concentrated during the hottest month of the year. The applied fully three-dimensional hydrodynamic model used to compute the hydraulic conditions in the OSS includes the following main features:

1) Solving governing equations with the finite volume method, ensuring conservation properties of all simulated variables, which is particularly important in the simulation of heat transport;
2) Using a hybrid mesh which can represent the complex shape domain accurately;
3) Fully nonhydrostatic to better predict the vertical flow movement even though it is not very important in this study because the vertical velocity is expected to be weak;
4) Advection and diffusion calculations in three dimensions to realistically simulate the flow dynamics;
5) Various turbulent models to suit different situations;
6) Heat exchange between water and air;
7) Three-dimensional heat transport model is embedded in the hydrodynamic model to calculate heat transport in flow, and the calculated temperature is fed back to affect flow hydrodynamic conditions through the flow density changes.

Recognizing from measurements of the thermal structure in the OSS that there were no vertical temperature structures in most parts of the slip except for in the region very close to the joint of the slip and Harbour, which is not the main concern of the study because the water temperature at this location is much lower than that at the upstream area of the slip, even a two-dimensional model may be adequate in this study. The main reason to choose a fully three-dimensional model is its availability and feasibility to extend the study region into a deeper water region or into part of the Harbour if required in future.

In order to generate a good quality mesh for numerical modelling, up-to-date detailed bathymetry information of the OSS was collected. The depth-sounding data were measured by an acoustic transducer mounted on the side of a 16-foot (4.9-m) flat bottom boat. The position of the boat was determined by an onboard differential global positioning system (GPS). Both of the instruments were controlled by a laptop computer to synchronize them and to record the measured data in computer files. There are 6,253 cells in the entire mesh used for the modelling, and most simulated regions have only a single layer in the vertical direction; the three-dimensional model is operated as a two-dimensional model in this study phase. Because the OSS has a narrow, long geometrical shape, it was too crowded to see details of the cell clearly if the entire simulated mesh domain was plotted. Therefore, only the mesh in the middle section of the slip is displayed in Fig. 8.

**Table 2. Maximum temperature (Temp.) changes in a short period at all measured locations in OSS during summer 2006**

<table>
<thead>
<tr>
<th>Time Period (min)</th>
<th>15</th>
<th>30</th>
<th>60</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. Change (°C)</td>
<td>2.4</td>
<td>3.7</td>
<td>3.71</td>
<td>4.0</td>
</tr>
</tbody>
</table>

![Fig. 8. The unstructured mesh in the middle section of the Ottawa Street Slip is displayed here. It shows a very well represented geometry. The entire mesh is too crowded to be seen clearly.](image-url)
Model Input Data and Setup

To obtain realistic simulations it is always crucial to have reliable input data for driving the numerical model. In this study the following data were collected for developing and verifying the model:

1) Discharge flow rates and temperatures at most of the discharge outlets during the summer period of 2006 were provided by the cooling water user for the purpose of specifying numerical model inlet boundary conditions;

2) Temperatures at multiple locations in the slip were measured by the National Water Research Institute (NWRI) for the purpose of either verifying the model output or specifying inlet boundary conditions;

3) Meteorological data such as air temperature, solar radiation, relative humidity, wind speed, and direction at Hamilton Harbour were collected with 10-minute temporal resolution by the NWRI for calculating the heat exchange at the water free surface.

The monthly average cooling discharge data provided by the cooling water user are listed in Table 1. Discharge outlet 6 has the largest flow rate among all discharges, followed by outlets 4, 5, and 1. Discharge rates of outlet 7 from a different steel maker, located on the other side of the slip, are a very rough estimation. In general, during the hot summer the cooling water discharges are larger than during cooler months because more water may be needed in the cooling processes due to higher intake cooling water temperature. There is no discharge information given for outlet 1, however, because it comes from the discharge of a CSO facility, it only provides significant flow contribution to the slip during large storm events. The inflow rate of outlet 3 is about 10% of the flow rate of outlet 4 according to information provided by the cooling water user, which is not given in Table 1.

It is shown in Table 1 that during the summer, the discharge waters were much warmer than for other seasons, which had also been documented with temperature measured in the slip. The tendency of temperature variation with time in all provided discharge data showed a similar pattern, and cooling water in July had the highest temperature. Unfortunately, there were no temperature data given for outlet 7 by the cooling water user. The reconstructed temperatures for outlet 7 were obtained by averaging the temperature of other discharges during the same month in Table 1.

The OSS is an open stream. Even though the flow residence time is short, heat exchange between water and air through the water surface might not be totally negligible. The net heat flux accounting for the effects of solar radiation, sensible heat transfer, and latent heat transfer at the water-air interface was calculated for specifying the water surface boundary condition. Because in most parts of the slip the shore on both sides is quite high and the hydraulic flow condition is dominated by discharge flows, in this numerical study the influence of wind stress on flow movements is comparatively minimal and therefore is ignored in the numerical modelling. Since model input data are a function of time, the transit simulation was adopted for all numerical simulations, and constant eddy viscosity was assigned for the horizontal diffusion calculation. The model running time step was 90 seconds, and initially, flow velocity and temperature were set to zero and 25°C, respectively, at all points.

Discussion of Modelling Results

Since this project concerns the study of the impact of cooling water discharges on the surrounding area, and also to conserve computer running time, the numerical simulations were focussed only on the hottest month, July of 2006.

The numerical model was first tested using the discharge data listed in Table 1 as the input for the model inlet boundary condition, and net heat flux for the water-air interface boundary condition was calculated from measured meteorological data. The simulated water temperatures at measurement stations were plotted as dash curves in Fig. 9 to 11. The arrangement of plots from Fig. 9 to 11 follows the flow direction from upstream to downstream. Compared with the measured temperature represented by solid curves in all figures, the simulated water temperatures follow the mean measured water temperature reasonably well at most measurement stations except for station H (in Fig. 9) because the provided temperature for outlet 5 (see Table 1) was much higher than measured nearby. The provided discharge information is the monthly averaged data. To have the maximum influence of the data from other months for a possible better simulation result, linear interpolation was used to include temperature data of June and August. For the first half of July the numerical model inlet boundary conditions were interpolated from the June and July information, and for the second half of the month the July andAugust data were used for driving the model. This may be one of the reasons that model outputs match measurements reasonably well at the end of July. However, because the monthly average data may be just too crude to drive the model for producing detailed temperature variations, the modelled dash curves do not show any up and down variations as measured temperatures (solid curves) indicate. Unfortunately, there is no simple solution to increase the temporal resolution of the provided discharge information. Therefore, the numerical model can never be truly verified by comparison of the model output with the measurements collected every 15 minutes if provided temperature information is used as a model inlet boundary condition.

The alternative is to specify the model inlet boundary conditions with water temperature measured closest to the discharge outlet. One of the reasons to have a measurement station at each discharge outlet was to use them as a backup if good cooling water temperature
data, provided by others and serving for the model inlet boundary condition, were lacking. The temperatures modelled by the use of measured temperature as the model inlet boundary condition were also plotted in Fig. 9 to 11 with dot curves. The modelled (dot) and measured (solid) temperature curves at the measurement station near the discharge outlets match very well as shown in Fig. 9 to 11. These results should be expected because the model inlet boundary condition is specified by the measured temperature at compared locations. The purpose of showing these comparisons is to double check the specification correction of the model inlet boundary condition. The minor temperature discrepancies in the above comparisons are possible because flow temperature can slightly change within the travelling distance from the discharge outlets to the measurement station. Due to very strong discharge flow at discharge outlet 4, access to the outlet by boat was difficult; therefore, the measurement station had to be moved farther away from the outlet than for the other locations, resulting in slightly larger temperature differences between modelled and measured outputs, as indicated in Fig. 9.

The measured temperatures at stations A, B, C, and F, where they are less influenced by flows from a particular outlet, were used for verification of the model. Stations A and B are far from all cooling water discharges; therefore, they may be the most suitable for verifying the numerical model because of their independence. Comparing the solid and dot curves in middle panel with those in the bottom panel in Fig. 11, it appears that they are almost exactly the same. The correlation coefficient is about 0.985 for both measured and modelled temperatures between stations A and B, which indicates that even in an open and relatively wider region in the slip, the flow behaviour is still more like that in a narrow fast stream. The downstream flow temperature structure simply duplicates that of the upstream flow with a certain time delay. The numerical model simulated this characteristic very well. If focussing on the comparison between measurement (solid curve) and simulation (dot curve) at the same measurement station for station A or B, the two curves follow each other reasonably well, as shown in middle and bottom panel in Fig. 11. Model outputs capture this tendency and most major measurement variations. The correlation coefficients between measurements and model outputs at both stations are about the same: they are 0.6, which indicates that the numerical model performed reasonably well according to numerical modelling standards. One of the possible reasons for the numerical model not being able to predict the small changes well is numerical over-damping. This is a common problem encountered by all hydrodynamic models because numerical modelling is the calculation of average simulated variables. Another possible reason might be due to the unverified discharge rates given by the cooling water user. The monthly averaged discharge used as the model inlet boundary condition may be too crude to drive any model to produce detailed variations. Except for this tendency, the agreements between simulated and measured maximum and minimum temperature during the test period are also quite good.

Stations C and F are at locations in the middle section of the slip where they are not very close to any of the individual discharge outlets. As shown at other locations, the simulated water temperatures followed the measurements reasonably well. The major variations in the measurements were reproduced by simulation. However, the simulated temperatures were slightly lower

\[ \text{Fig. 9.} \text{ The top, middle, and bottom panels show the comparisons between the modelled and measured temperatures at measurement stations L, J, and H (refer to Fig. 2 for the location), respectively.} \]

\[ \text{Fig. 10.} \text{ The top, middle, and bottom panels show the comparison between the modelled and measured temperatures at measurement stations F, E, and D (refer to Fig. 2 for the location), respectively.} \]
than the measurements, which was not the case for other measurement locations. The reason for this may be explained by flow hydraulic conditions in the slip.

The simulated flow pattern in the middle section of the slip is displayed in Fig. 12. Since there were no flow measurements in the middle section in the slip, the flow pattern could only be analyzed according to the hydraulic principles. No confirmation was available. The flow pattern, in general, looks reasonable, as shown in Fig. 12. The permanent eddies at the corners, which is a phenomenon generally observed with fast flow emerging from a narrow channel into an open area, were regenerated by the numerical model. Because the width of the slip in the upstream and the middle section is narrow and the provided flows remain relatively constant with high flow velocity down along the straight slip, there are very few chances for flows to be laterally mixed. This results in a situation where the cross-section of the slip would be divided into the different channels controlled by the flows coming from the different outlets. Therefore, the temperature along the cross-section of the slip can be very unevenly distributed, as is shown by the varied gray scales in Fig. 12, which is a typical hydraulic flow condition in a fast straight stream. In the region around measurement station F at the displayed time, as shown in top panel of Fig. 10, the warmer water flowed through a narrow region along the right hand side shoreline. Because of measurement uncertainty (+/- 5.0 m) of the GPS used in this study, there is a possibility that the station position given by the GPS is slightly different from its actual location. If the position given by the GPS was shifted toward the left side slightly (referring to Fig. 12), it would show the modelled temperature slightly lower than the measurement. The same possible explanation is also applicable to what happens at station C.

Fig. 11. The top, middle, and bottom panels show the comparisons between the modelled and measured temperatures at measurement stations C, B, and A (refer to Fig. 2 for the location), respectively.

Fig. 12. The simulated flow pattern in the middle section of the slip. Gray scales represent the simulated absolute temperature.

**Conclusions**

The main purpose of this study was to investigate the thermal structures in the OSS during summer time under the present industrial cooling water discharge conditions, and to establish a means of scientifically predicting the impact of cooling water discharges for future study. Toward this end, a high resolution, fully three-dimensional hydrodynamic model, with the capacity of heat transfer simulation, was developed and tested with field measurements. The water temperature at multiple locations along the OSS and meteorological data near the study site were collected during the summer period of 2006 for the purpose of studying the thermal structure of the slip and establishing a forecast model, which has been achieved. The measured temperatures reveal:

1) During the summer of 2006, the water temperature in the slip was higher than 30°C during a period of hot air temperature;

2) The speed of water temperature change within 15, 30, 60, and 120 minutes was calculated, and the results are listed in Table 2; it took a minimum of 2 hours for the temperature to rise 4°C during the entire measurement period;

3) Water temperature in the slip is controlled by both air and industrial cooling discharge temperatures, and its increase due to industrial cooling processes seems to be relatively independent of the intake water temperature. Therefore, the water temperature in the slip varies mainly with air temperature;
Since water temperature in the slip closely follows the intake water temperature, the intake channel may need to be optimized to maximize the possibility of obtaining the coolest available water from Hamilton Harbour.

The numerical model was run with inlet temperatures of either user-provided or measured data. The provided monthly average temperature data are too crude to produce detailed water temperature variations for comparison with the measurements. Alternatively, the temperature data measured near discharges were used to specify water temperature of the model inlets. The simulated water temperatures at the open water region (around stations A and B), where water temperature is much less controlled by the individual outlets, agree very well with the measured data. Due to the lack of lateral mixing in the regions of narrow and high velocity flows (around stations C and F), water temperature could be very unevenly distributed along the cross-section of the slip. The measurement uncertainty of GPS data may be the reason for the slightly larger discrepancy between modelled and measured temperature, which is still well within very acceptable ranges for numerical modelling standards. The differences between numerically simulated and measured maximum temperatures during the simulated period at all compared locations are less than 1.5°C (most of them are less than 0.5°C) as listed in Table 3. Therefore, this newly developed three-dimensional hydrodynamic model verified with limited measurement data should be able to serve the study goal to produce a reasonably reliable prediction of relative maximum temperature structure changes (not the absolute temperature) under various inflow conditions. However, without reliable discharge information it is unrealistic to expect a very close agreement between the simulated and measured temperatures during the entire study period; this may not be actually needed in this application.

As mentioned before, under the present discharge level, the measured water temperature in the slip during the hottest summer day can be over 30°C, and the study results also indicate that the temperature of the intake water has a strong influence on the water temperature in the slip. Therefore, a study on the intake channel to assess the possibility of taking the coldest available water from Hamilton Harbour would be greatly beneficial for reducing the water temperature in the OSS.

4) Since water temperature in the slip closely follows the intake water temperature, the intake channel may need to be optimized to maximize the possibility of obtaining the coolest available water from Hamilton Harbour.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>H</th>
<th>J</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. meas. Temp. (°C)</td>
<td>31.3</td>
<td>31.89</td>
<td>32.03</td>
<td>32.16</td>
<td>31.77</td>
<td>32.58</td>
<td>31.99</td>
<td>30.74</td>
<td>32.83</td>
</tr>
<tr>
<td>Max. mod. Temp. (°C)</td>
<td>31.3</td>
<td>31.30</td>
<td>31.21</td>
<td>32.20</td>
<td>31.57</td>
<td>31.1</td>
<td>31.09</td>
<td>31.04</td>
<td>32.73</td>
</tr>
<tr>
<td>Difference (°C)</td>
<td>0.0</td>
<td>0.59</td>
<td>0.82</td>
<td>-0.04</td>
<td>0.2</td>
<td>1.48</td>
<td>0.9</td>
<td>-0.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

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References


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