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Original Citation

Ali, Jafar, Fieldhouse, John D., Talbot, Chris J. and Mishra, Rakesh (2009) Thermal discharge of warm water into cooler stagnant water. In: What Where When: Multi-dimensional Advances for Industrial Process Monitoring. Proceedings. University of Leeds, Leeds, pp. 227-238.

Thermal discharge of warm water into cooler stagnant water

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Abstract

This paper is concerned with development of a predictive tool to determine the heat diffusion profile for heated water discharge into a body of stagnant receiving water. The process makes use of a thermal imaging camera to measure the discharge plume from a range of sites in order to observe the actual discharge and then to provide a mathematical model that will allow British Waterways to satisfy the Environmental Agency regulations. In addition the sites are replicated in a laboratory environment with a scale model tank that allows the mixing zones to be measured under variable conditions. In this case the heated water is dyed to provide a visual plume in addition to the thermal image. The plume and mixing zone are then predicted using appropriate software such as Matlab, the model being optimised to reflect the real measured discharges.

1. Introduction

The disposal of heated water from power plants and cooling systems into natural water environment is one of the major environmental problems. Water is normally withdrawn from natural or artificial sources to the cooling system heat exchanger, the cooling water increases in temperature within the system then it's discharged back into the lakes, rivers or canals resulting in a rise in the bulk temperature of the surrounding water. The main effect of the increased in ambient water temperature is the reduction of the dissolved oxygen which might put fish life and other aquatic life-form at risk. The increase in temperature also affects on the balance of the natural and biological process in the water. There are large number of studies of this type regarding water mixing, heated water discharge into a cooler water, the majority of them are based on assumptions, some use experimental model tanks but do not validate with real field trials whereas others only make use of mathematical models and again do not validate with field trials. In this paper a study of heated water discharge into stagnant water is described using a new technique. A thermal camera is used to measure the heat diffusion profile on the surface of the receiving water using a number of British Waterways canal sites. The sites are then replicated in a laboratory environment using a scale model tank. The combined results are then used to develop a two dimensional mathematical model for subsequent discharge evaluation. In addition Matlab software is used to develop the model towards a three dimensional representation showing the distribution of heat through out the canal. This is carried out using variable values of heat diffusion coefficients. This work is currently limited to the study of heated water discharge into the body of stagnant (stationary) receiving water. The majority of work in this paper concentrates on the initial process – that of determining the heat diffusion profile and plume shape on the surface of the receiving water. At the moment the University of Huddersfield have 3 sites licensed to extract water for cooling purposes. All these sites have comprehensive records and all show that the process is safe for aquatic life. British Waterways' one dimensional mathematical model suggests they will not be safe and if the model is over-conservative in its prediction then British Waterways may be rejecting licensing applications that are in reality safe. It is this situation that demands a more realistic prediction tool be developed; a tool that is readily understood, adequate for the level of the applications and easily manipulated to represent the varied situations that are likely to be experienced.

2. Field Trial

The Central Services Building at University of Huddersfield was selected as the primary site for initial investigations as thermal plume of the flow occurs below a bridge and so is clearly defined. This is shown in Figure 1. The University has a licence from British Waterways to use the CSB site as part of the building cooling system. As such the University is allowed to extract cold water from the canal and discharge warm water into it.

By law the maximum temperature of canal ambient should not exceed 28˚C, the reason being that the water begins to de-oxygenate and so the health of aquatic life is put at risk. As a result of such regulations the University of Huddersfield have to maintain a complete record of extraction volumes, inlet temperatures, discharge temperatures and surrounding environmental parameters.

a) Bridge over discharge pipe

b) Discharge pipe with beam showing grid graduations.

Figure 1: View of Central Services Site

To monitor the whole site it was necessary to establish a reference grid over which the results of water flow and temperature would be measured across, along and below the surface of the canal. The centreline of the outlet pipe and the end position of the pipe served as the zero position. A graduated pole was laid along the banking to give the linear reference points and a second pole was fixed at 90° to the banking to give the transverse reference positions. A third vertical pole was secured to the main pole to which the thermocouple probe and flow meter could be attached. This third pole was also graduated to indicate depth. The arrangement is generally as shown in Figure 1(b). Ambient canal water temperatures were recorded 15m upstream and downstream of the outlet discharge point. Both the ambient canal water and air temperatures were recorded with the use of 'k' type thermocouples with digital meter at the start and end of the trial. The canal water temperature was then measured and recorded at the grid points at depths: the surface, at mid depth and 50mm above the bed.

3. Laboratory Experiment

The laboratory experiments were conducted using a tank, 2m long by 1m wide and 0.3m deep. It was constructed of acrylic so as to allow visual observation of the thermal plume including photographs and videos of experiments. The tank is a 1/10th scale model to represent most anticipated situations that may exist in practice.

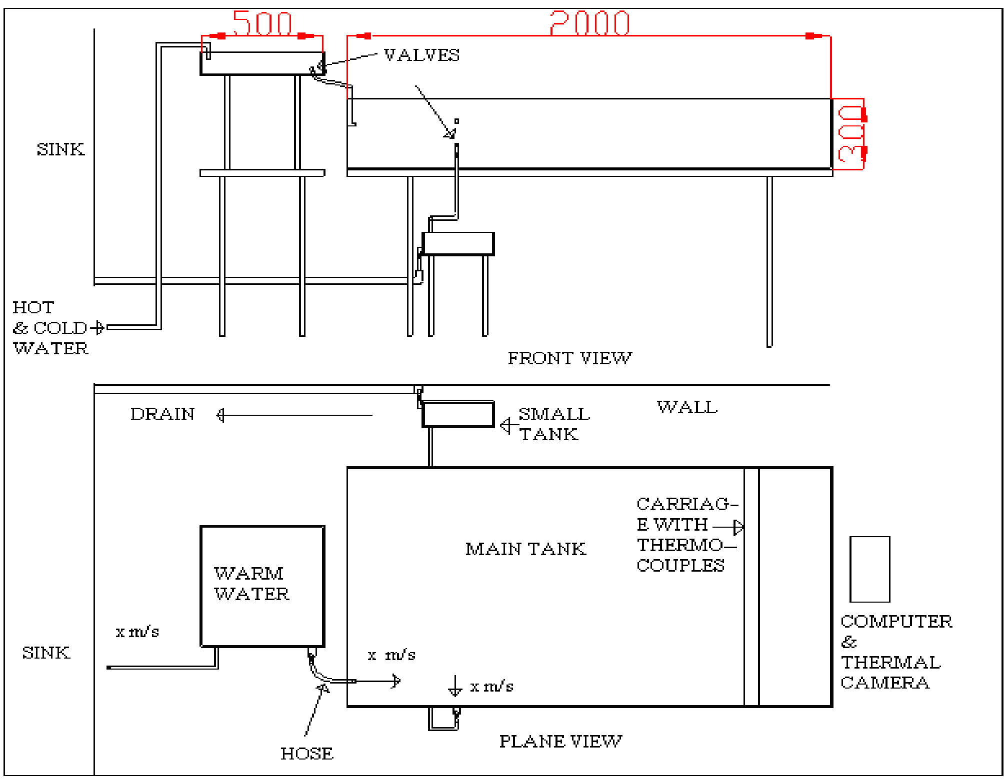
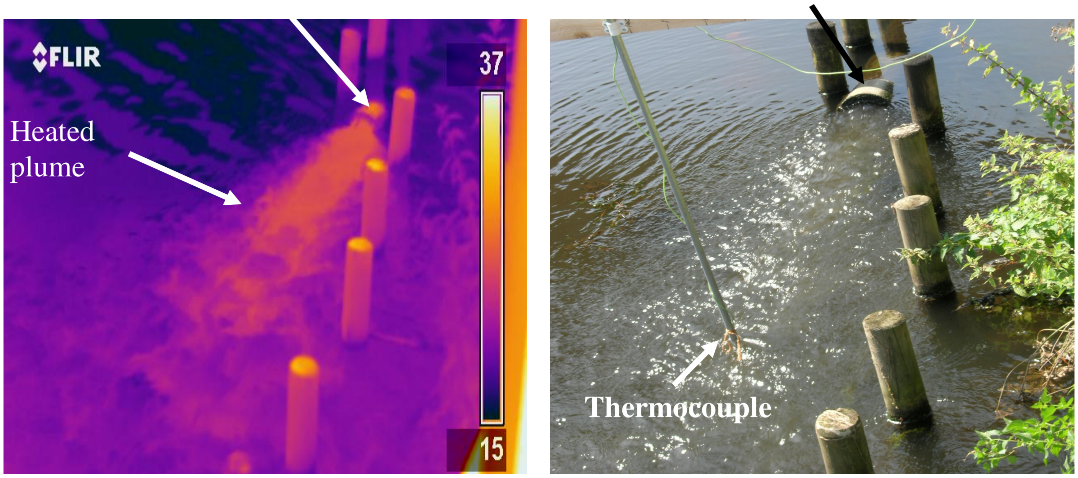


Figure 2: Schematic diagram of experimental setup

The depth is 300mm, length 2000mm and width 1000mm. A schematic of the experimental setup is shown in Figure 2. The moveable plastic discharge nozzle is 15mm diameter. The outlet of the jet discharge can be located at any side of the tank and at any desired depth; intake pipes are located at the end and side of the tank at variable depth and are provided with flow control valves. The position of discharge and intake will be based on their location on the simulated site. The discharge is supplied from a constant head cistern connected to main hot and cold water pipes with flow control valves to maintain the required temperature, discharge speed is controlled by a valve, a by-pass line was installed to allow preliminary adjustment of temperature and flow before water was discharged into the tank. Intake water returns to a small tank where the temperature and flow are measured then extracted to drainage.

4. Thermal Camera:

The method employed in this study to observe the heat distribution on surface of the canal is to use a Thermal Camera. The thermal camera shows the heat diffusion on the surface of a hot body by transforming an infrared image coming of a hot body into radiometric so translating the data into a coloured image which is representative of the thermal gradients across the body. The image may be observed on a LCD monitor and stored for future analysis and interrogation. A typical thermal image and normal colour image is shown in Figure 3. It is necessary to set the camera to a right emissivity (the capacity of a surface to emit heat, at a given temperature) which for water is 0.96. To avoid unnecessary and unwanted reflections it is necessary to ensure the thermal camera is placed in a position that is directed to the test body without the

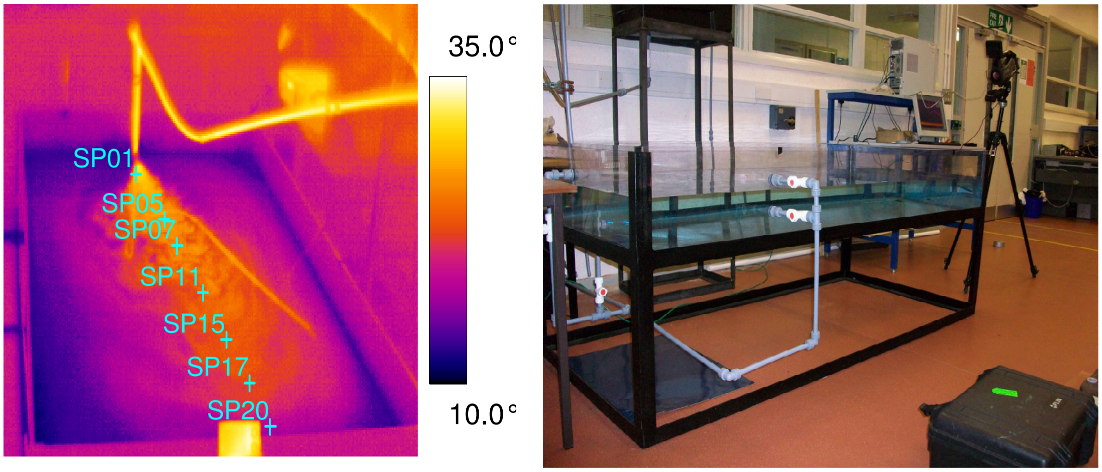


a. Thermal image b. Digital image

Figure 3: Thermal and digital image of plume from downstream CSB site

effects of reflection - which is the most problematic issue facing the thermographer - especially with thermal water studies

Figure 3 shows the thermal and digital image for discharge water from the Central Service Building at the University of Huddersfield into Huddersfield Broad Canal. Figure 4 shows images of the laboratory tank and a typical discharge plume into the tank. Note how the camera records the hot pipe leading to the nozzle



a. Heat diffusion on surface of tank

b. Model tank

Figure 4: Thermal and digital image of model tank

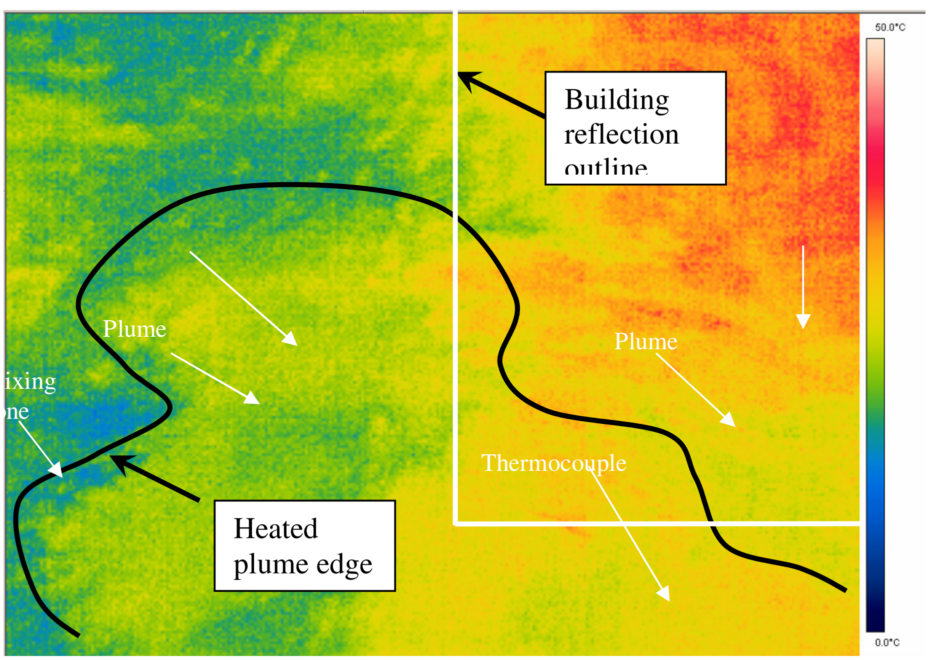


Figure 5: Heat diffusion (submerged discharge) on surface of Birmingham canal BBC Mailbox site

It is difficult to use the thermal camera for submerged discharge studies because of reflection issues.

Figures 5 and 6 show such a recording from a submerged discharge but the plume effect is not observed until the warm water rises to the surface. To complete the study it is necessary to determine the heat diffusion profile below the surface to the bed of the canal using a temperature probe. It is for that reason that a mathematical model has to be developed.

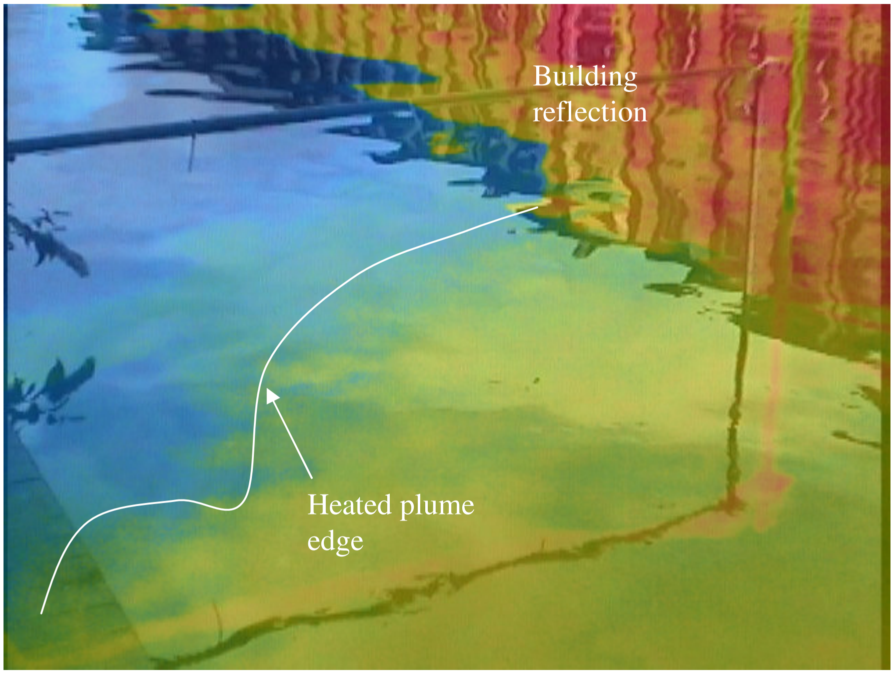


Figure 6: Merged digital and thermal image shows reflection effects

5. Mathematical Model:

The domain in Figure 7 shows the flow directions, the axes and the diffusion coefficient directions, which are involved in the mathematical model. The main equation used is the advection diffusion equation as shown in Equation 1. The left hand side of the equation represents flow and the right hand side diffusion. To produce the model it considered that the coefficient of heat diffusion is applied accordingly to suit the characteristics in the lateral and vertical directions – that is across the flow and depth-wise. The flow in the third direction, along the x axis, which is considered longitudinal downstream of the discharge, is velocity dependant. Steady state condition is considered to be when the temperature does not change with time and is further downstream beyond the plume.

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} + V\frac{\partial T}{\partial y} + W\frac{\partial T}{\partial z} = Dx\frac{\partial^2 T}{\partial x^2} + Dy\frac{\partial^2 T}{\partial y^2} + Dz\frac{\partial^2 T}{\partial z^2} \qquad (Equation\ 1)$$

Where T is temperature, t is time, U, V, W velocity in x, y and z direction respectively, Dx, Dy, Dz are diffusion coefficients in x, y and z direction respectively.

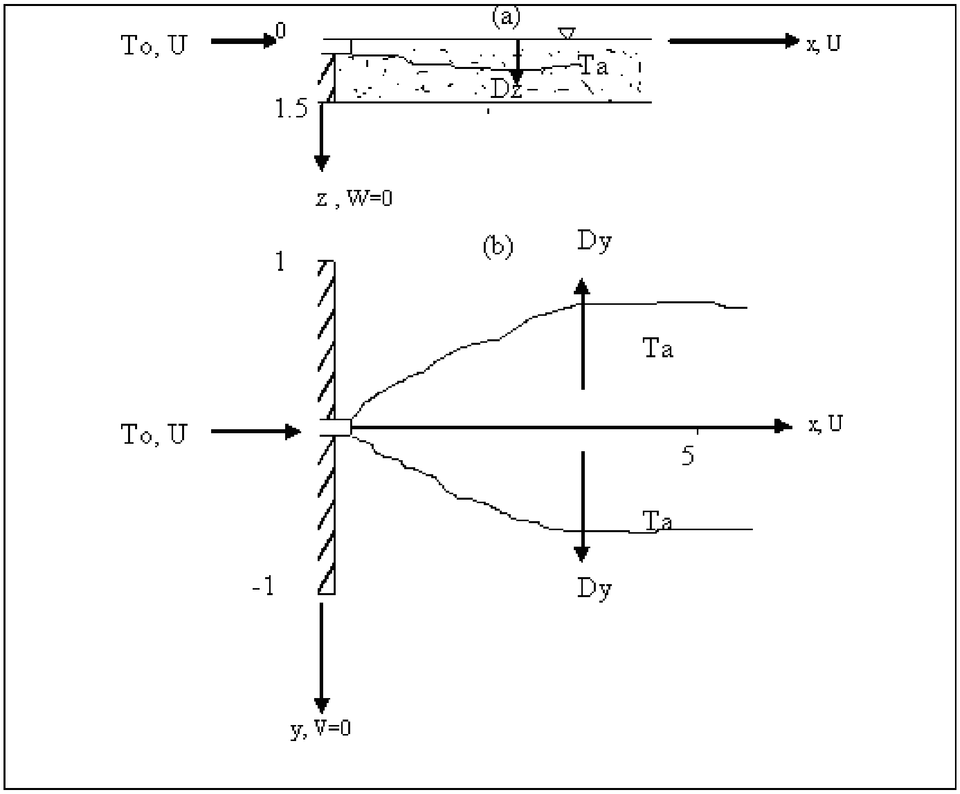


Figure 7: Flow configuration, a. (sectional view), b. (plan view)

$$\frac{\partial T}{\partial t} = 0$$

$$U\frac{\partial T}{\partial x} = Dy\frac{\partial^2 T}{\partial y^2} + Dz\frac{\partial^2 T}{\partial z^2} \qquad (Equation\ 2)$$

$$U\frac{\partial T}{\partial x} = Dy\frac{\partial^2 T}{\partial y^2} \qquad (Equation\ 2a)$$

Solution of the partial differential equation 2a (Crank, 1970) gives:

$$T = \frac{A}{\sqrt{\frac{x}{U}}} e^{-\frac{y^2}{4Dx/U}} \qquad (Equation\ 3)$$

$velocity\ U = \frac{x}{t} \quad sub\ to\ (3), yields:$

$$T = \frac{A}{\sqrt{t}} e^{-\frac{y^2}{4Dt}} \qquad (Equation \quad 4)$$

At the discharge point of the jet the boundary conditions will be:

T=To at x=0 -b < y < b

T= Ta at x=0 -b > y > b

To, Ta are discharge and ambient temperature respectively.

If M is the total heat diffusion in canal with infinite length:

$$M = \int_{-\infty}^{\infty} Tdy \qquad (Equation\ 5)$$

Sub A into Equation 4: is giving the spreading of an amount M of heat discharge at x=0

$$T = \frac{M}{2\sqrt{\pi.D.t}} e^{-\frac{y^2}{4Dt}} \qquad (Equation\ 6)$$

$$T(x,y) = (\frac{To - Ta}{2})(erf\,\frac{b-y}{2\sqrt{p.x}} + erf\,\frac{b+y}{2\sqrt{p.x}}) + Ta \qquad (Equation\ 7)$$

Equation 7 gives the heat diffusion on the surface of canal. For the diffusion towards the bed equation7 becomes:

$$T(x,y) = (\frac{To - Ta}{2})(erf\,\frac{b-z}{2\sqrt{p1.x}} + erf\,\frac{b+z}{2\sqrt{p1.x}}) + Ta \qquad (Equation\ 8)$$

6. Diffusion Coefficient

When warm water discharges into stagnant receiving water, the warm water will spread out in all three directions x, y and z. This occurs because of the random motion of molecules for the heated water – the process being called diffusion. The diffusion coefficient is variable from one location to another even along the same canal. It varies in all directions as its value is influenced by many parameters such as flow, cross section of canal, shape of bed, concentration of discharge and ambient temperature. In fact its value is hard to predict and for that reason researchers undertaking thermal discharge studies tend to avoid the use of this value. The diffusion coefficients used in these studies are $0.002m^2/s$, $0.00005m^2/s$ in y and z direction respectively and so the parameters p, p1 become 0.018m and 0.005m respectively. By applying the developed equations in Matlab the heat diffusion profile on the surface will be as shown in Figures 8a and sectional profile as in Figures 9a whereas Figures 8b and 9b show the heat diffusion profile for smaller values of p, p1 (diffusion coefficients).

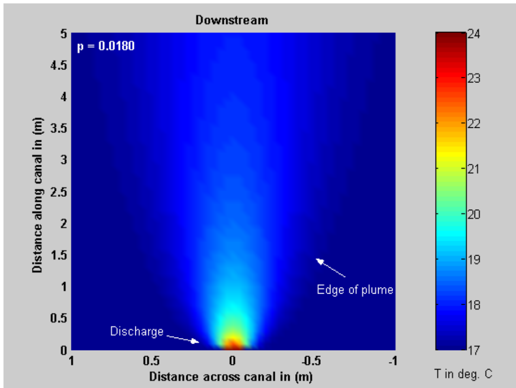


Figure 8.a: Heat diffusion on surface of canal CSB site (plan view)

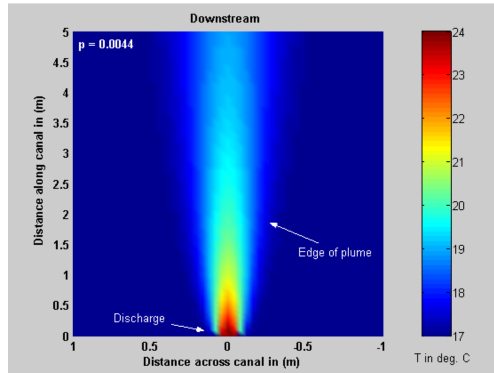


Figure 8.b: Heat diffusion for a smaller value of p. (plan view)

Figure 8 Heat Diffusion on surface for variable "p".

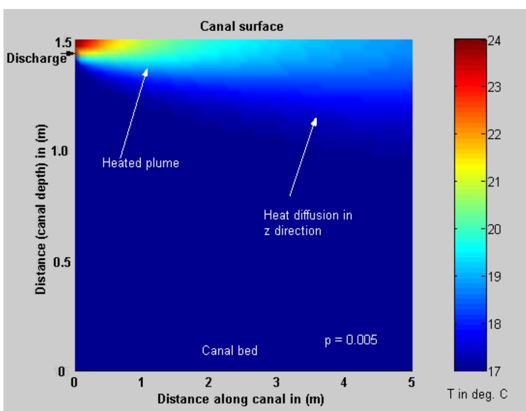


Figure 9.a: Heat diffusion through the depth of canal CSB site (sectional view)

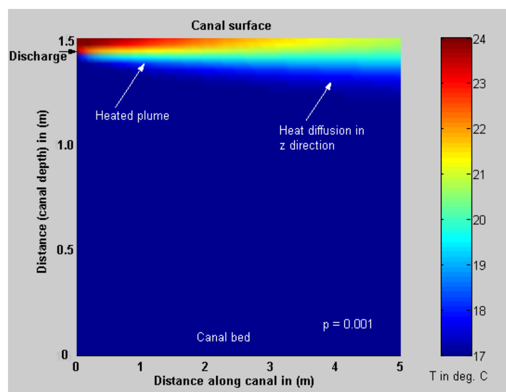


Figure 9.b: Heat diffusion for smaller value of p1. (sectional view)

Figure 9 Heat Diffusion with depth for variable "p"

7. Results and Discussion

Figure 3 shows the comparison of the discharge plume at the Central Services Building (CSB) taken with a digital camera and the thermal imaging camera. The outlet pipe is semi-submerged and the mixing plume can be clearly seen on the canal surface. The images clearly show the extent of the plume downstream and to the sides but what is not evident from the thermal images is the three dimensional effect of the plume and how the temperature dissipates through the depth of the canal. The centreline temperature measurements by thermocouples on the site trial, along with the experimental data, are compared to the centreline temperature measured by the thermal camera and the data obtained by the mathematical model. The results are shown in Figures 10a&b where it is seen that the general form of the graphs are similar.

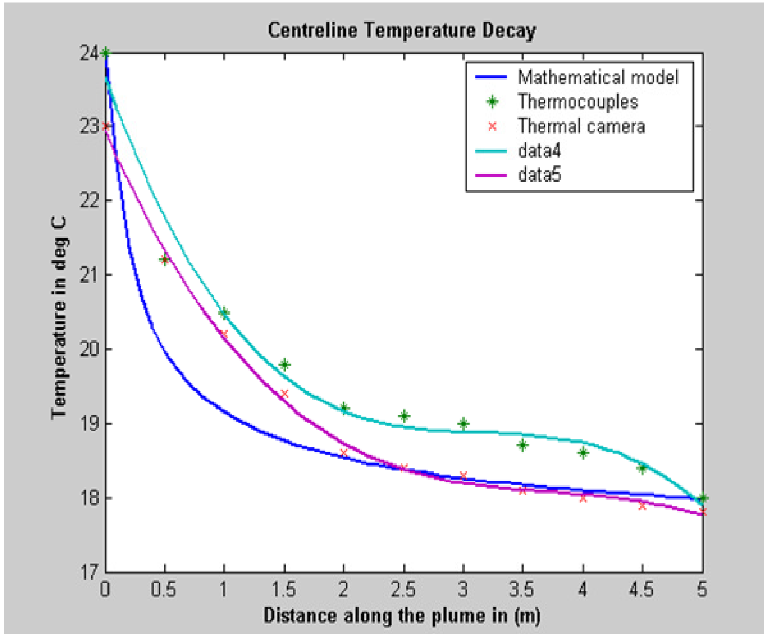


Figure 10.a: Centreline temperature decay

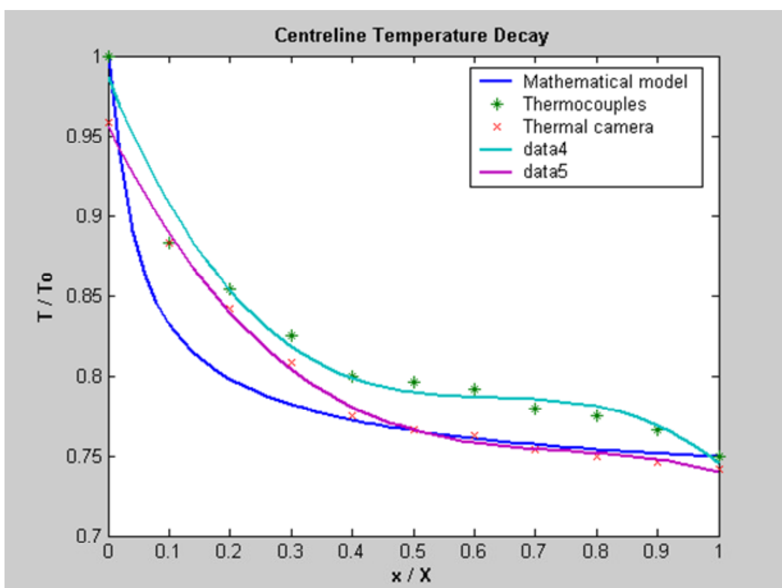


Figure 10.b: Centreline temperature decay

The temperature distribution on the surface and through canal depth which was obtained by the mathematical model (and then applied in Matlab) is illustrated in Figures 8 and 9. What can be seen also from the Matlab results (figures 8.b and 9.b) are the effects of parameter p (diffusion coefficient/ discharge velocity) on the shape of plume, with higher value of p resulting in wider plume and mixing zone and vice versa.

8. Conclusion

This paper presented a new technique in the studies of thermal discharge and heat diffusion profile prediction. The technique makes use of a Thermal Camera to observe the heat distribution on the surface of receiving water and the extent of the mixing zone and as such the heated areas can be clearly identified by the thermal images. Mathematical models have been developed and compared to the temperature measurements on a selected canal site as well as the results obtained from the laboratory experiments using the 1/10th canal simulation model. The initial Matlab results compare favourably with the site and laboratory results and also identified the effects of heat diffusion coefficient on the width of plume – that is a larger plume is observed for high diffusion coefficient discharge.

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11. Acknowledgement

The University of Huddersfield would like to thank British Waterways for their support and assistance with this project.