EXPERIMENTAL INVESTIGATION OF THE EFFECT OF TEMPERATURE ON FLOW PATTERN OF A SEDIMENT RETENTION POND

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ABSTRACT

Existing studies of sediment retention ponds (SRPs) have examined the effect of pond layout, inlet and outlet geometry and installation of baffles on the performance of the SRPs. However, the effect of a temperature difference between the pond and the inflow is a neglected phenomenon, with the buoyancy forces arising from differences in temperature potentially changing the flow in the pond. This study evaluates the effect of these temperature differences on the flow pattern and residence time in a retention pond. In this research an innovative experimental setup was used to create the temperature differentials. The results reveal that cold inflow sinks to the bottom of the pond while hot inflow remains at the surface, and in both cases the inflow moves more rapidly towards the outlet than in the isothermal case. A counter current occurred at the bottom or the surface of the pond for colder or hot influent, respectively. These thermally induced flows significantly reduced the hydraulic performance of the pond and caused severe short-circuiting. The results also show that the temperature differences in the pond decrease with time, yet small temperature differences persist with the pond remaining stratified.

Keywords

Sediment retention ponds; Hydraulic performance; Temperature differential; Residence Time; Buoyancy driven flow

PRESENTER PROFILE

Originally from Iran, Ehsan holds a Bachelor's degree in Civil Engineering from Karaj Azad University, Iran. Ehsan did his Master's in Hydraulic Structures at the Babol University of Technology in 2013. He is currently at the last year of his PhD at the University of Auckland.

1 INTRODUCTION

Sediment retention ponds (SRPs) have been used for many years, to minimise the adverse impacts of urbanization (ARC, 2003; S. Khan et al., 2013; Vymazal, 2014). The treatment efficiency of the pond is directly linked to its hydraulic efficiency. The amount of mixing in SRPs is a major factor that can affect the hydraulic performance of the ponds. The no-mixing condition, which is known as plug flow, is the most efficient hydraulic condition and deviation from plug flow reduces hydraulic efficiency (von Sperling, 2002). The design of stormwater ponds is currently based primarily on the assumption that plug flow conditions prevail in the pond and that 100% of the pond volume is used. This is not the case for most ponds, as the flow structure is normally composed of zones of recirculation and eddies (Kadlec, 1994).

Several factors affect the hydrodynamics of a pond which can be divided into physical and environmental parameters. Physical parameters are characteristics of the ponds such as positioning and orientation of pond inlets and outlets, pond geometry, and the location and orientation of baffles. Environmental parameters of the ponds are external driving forces such as wind and temperature (Shilton, 2005). Most of the open literature on the hydraulic performance of SRPs has been focused on the physical parameters. Previous research concerning the effect of physical parameters on pond hydraulic efficiency has investigated pond layout (Persson, 2000; Su et al., 2009), inlet and outlet design (Bodin et al., 2012; Pearson et al., 1995; Persson, 2000), floating treatment wetlands (S. Khan et al., 2013) and baffles (De Oliveira et al., 2011; Farjood et al., 2015). The inflow characteristics and local meteorological conditions are the most important parameters in creating stratification. The most probable causes of creating stratification are differences in temperature and salinity (Adamsson et al., 2006). Regarding temperature difference, the results of tracer studies indicate that temperature variation causes short-circuiting in ponds (Macdonald et al., 1986; Pedahzur et al., 1993). Goula et al. (2008, p. 2) numerically investigated the effect of influent temperature variations in a sedimentation tank for potable water treatment and found that "only 1 °C between influent and tank content is enough to induce a density current." Few studies have been found that experimentally investigate the temperature influence on stormwater ponds. One example is Watters (1972) who investigated the effect of influent temperature variations in a waste stabilization pond. In his research, the temperature differences were experimentally investigated by changing the density of the influent using salt water. Therefore, systematic studies on temperature difference effects are still needed for better understanding of the hydrodynamics of SRPs.

The primary aims of this study are to investigate how buoyant, neutrally buoyant or negatively buoyant inflows affect the residence time and flow pattern in a modeled retention pond.

2 MATERIALS AND METHODS

2.1 TRACER STUDIES

Hydraulic residence time (HRT) is a key factor in investigating the treatment efficiency of ponds and wetlands. The HRT delineates the time a parcel of water spends within a system, and it depends on the streamline of each particle (Nix, 1985; Thackston et al., 1987). Since each particle of water pursues a particular path, there is a specific HRT for each of the water parcels. These variations in HRT can be explained by generating the residence time distribution (RTD) curves which represent the temporal probability distribution of non-reacting tracer particles within the system (Van de Vusse, 1959).

Tracers such as cation lithium (Kadlec, 1994), anion bromide (Grismer et al., 2001), or fluorescent dyes (Sher Khan, 2012) can be added at the system inlet as an impulse or step change (Werner et al., 1996) to create RTD curves. In this study Rhodamine WT (RWT) was selected as the tracer dye due to the numerous advantages over the other tracers such as being readily soluble in water, highly detectable by fluorometers, mostly unaffected by background fluorescence, minimally degradable in short times, harmless in low concentrations (Wilson et al., 1968) and cost effective.

2.2 HYDRAULIC PERFORMANCE

Hydraulic performance of ponds can be evaluated by analysing the residence time distribution (RTD) curve. In this study, the hydraulic performance of the pond was assessed using the hydraulic indices recommended by Farjood et al (2014) which are t_5 for short-circuiting (SC), the moment index (MI) for the hydraulic efficiency, and the Morril index (Mo) for mixing. t_5 is the normalised time for passage of 5% of added tracer to exit through the outlet. The Morril index, Mo, is defined as t_{90}/t_{10}, where t_{10} and t_{90} are the times for 10% and 90% of the added tracer to exit the system, respectively. Mo values close to 1 show a more plug flow like regime, and increase with increase in the degree of mixing. The moment index proposed by Wahl et al. (2010) is defined as:

$$MI = 1 - \int_0^1 1 - t'C'(t')dt' \tag{1}$$

Where $C' = C / C_0$, C is the concentration of tracer, C_0 is the amount of tracer added to the pond divided by the pond volume, $t' = t / t_n$ is normalised time which is the measured time divided by the nominal residence time, and *MI* is bounded from zero to one. To reflect the effective volume of the pond and the distribution of hydraulic residence time, it is beneficial to measure (λ) as the second hydraulic efficiency measure, given by:

$$\lambda = \frac{t_p}{t_n} \tag{2}$$

Where t_p is the peak time, and t_n is nominal residence time.

2.3 EXPERIMENTAL SETUP

The physical model is a trapezoidal pond made from transparent acrylic sheets fitted on a steel frame with top dimensions of 4.1 m × 1.6 m, 0.3 m deep, and bank slope of 2:1. The pond is preceded by a rectangular tank of dimensions 0.3 × 1.6 × 0.2 m serving as the sediment forebay (Figure 1) (Farjood et al., 2015; S. Khan et al., 2011). The facility was designed so that the temperature differential could be created using two separate systems and monitored with a thermometer. Before starting the experiments, the water in the tank is pumped to the forebay and over a level spreader into the retention pond. The effluent at this stage is carried by a 40 mm pipe to the waste. After ensuring steady flow conditions in the pond, the effluent of the pond and the water in the tank are recirculated in two different systems. Each system consists of two heater/chiller units to change the temperature of the water. After changing the temperature of the water, the water in the tank is pumped to the pond and the tracer experiments are conducted by adding Rhodamine WT uniformly across the spread inlet width. For the outlet, three perforated T-bars are fixed to an outlet riser to model a floating decant dewatering system. The perforated T-bars are constructed from PVC pipe with a diameter of 48 mm.

Five rows of 6 mm diameter holes on each of the T-bars allow the water to leave the pond. The T-bars are fixed to a 250 mm long, vertical PVC pipe with 200 mm internal diameter, which serves as the outlet riser (Farjood et al., 2015). The T-bars are fixed to the outlet riser at 220 mm from the bottom and are about 80% submerged in the 245 mm water depth during the tests for 1 l/s and fully submerged in the 265 mm water depth for 2 l/s. The tracer concentration in the outflow is continuously measured using a Cyclops-7TM fluorometer manufactured by Turner Designs.

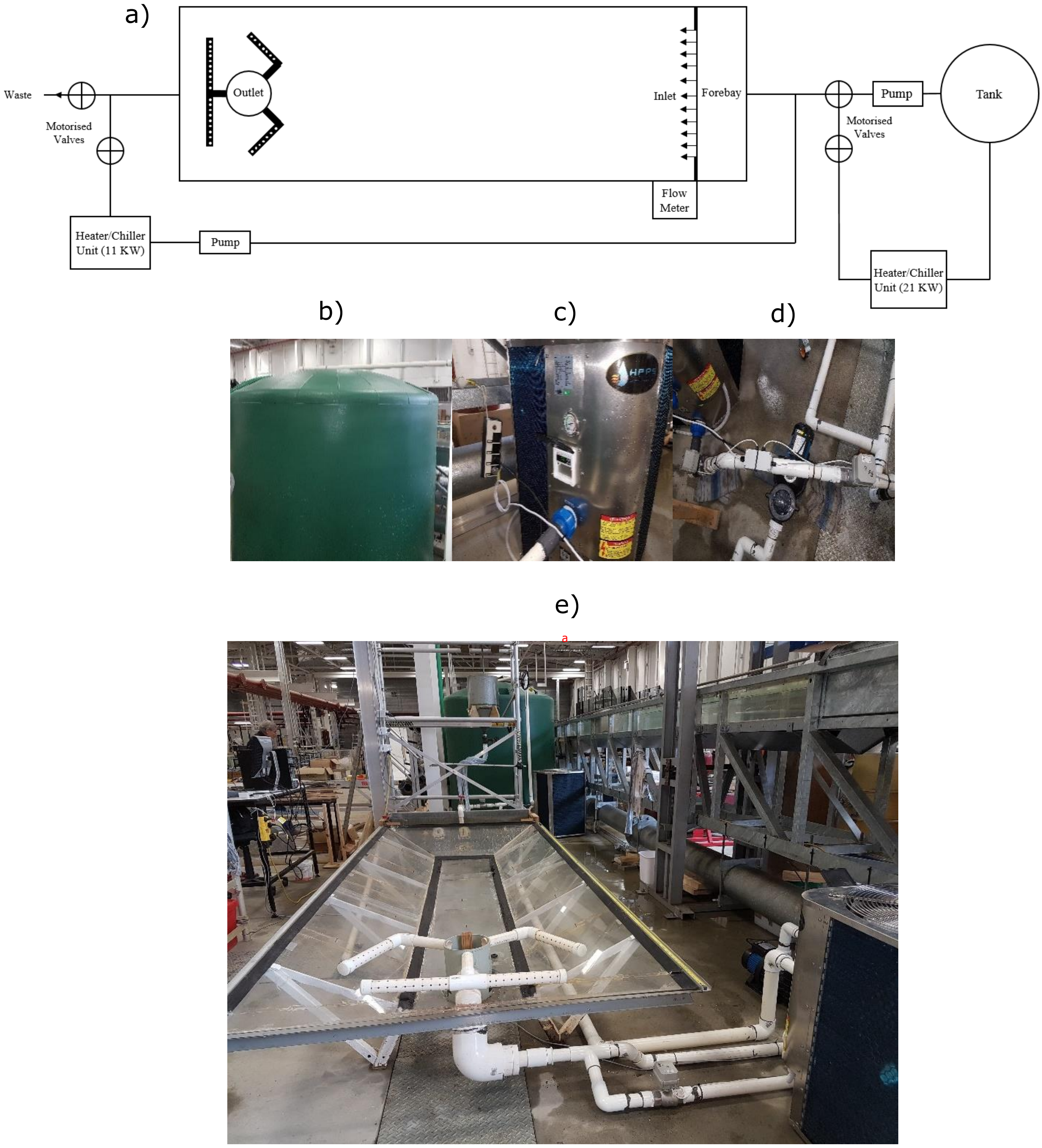

Figure 1 a) Schematic diagram of the experimental setup, b) Pump and motorized valves, c) Heater/ Chiller unit, d) Tank, e) The physical model viewed from the outlet

3 RESULTS AND DISCUSSION

3.1. EFFECT OF TEMPERATURE VARIATIONS ON RTDS

To test the effect of temperature variations on the performance of the pond, two cases were selected. In the first case, the temperature of water in the pond was hotter that the influent (positive values of ΔT where ΔT= Initial temperature of water in the pond – Inflow temperature). In the second case, the temperature of water in the pond was colder than the influent (negative values of ΔT). Tables 1 and 2 give a list of the density stratified flow experiments with the experimental results that were performed at different temperatures. The temperature of the inflow for cases 2-6 was lower than the temperature of the pond fluid while the reverse was true for the experiments of cases 7-11. Figures 2-3 illustrate some typical RTD curves for the two cases above. Also shown in Figures 2-3 are the uniform temperature experiment (ΔT=0). It can be seen from these figures that temperature differences between the pond water and inlet can cause significant changes in RTD curves and consequently can change the hydraulic efficiency of the retention pond. For both + ΔT and -ΔT temperature differences, as the temperature differences increase, the RTD curves have a sharper peak and the maximum normalised concentration is also increased. There is also a clear trend of decreasing time to reach the peak which shows the poor efficiency and short-circuiting.

The reasons for these differences are given as follows. When ΔT>0 the inflow tracer flows along the bottom of the pond due to its higher density. The movement through the pond is faster due to the higher velocities that occur near the pond bottom due to the influence of the confinement of the inflow. The inflow, in this case, rises up at the end of the pond and exits through the outlet. This causes the tracer to take a shorter time to reach the outlet. The same is true when ΔT<0. The tracer is concentrated in the top of the pond, and it thus reaches the outlet in a shorter time interval.

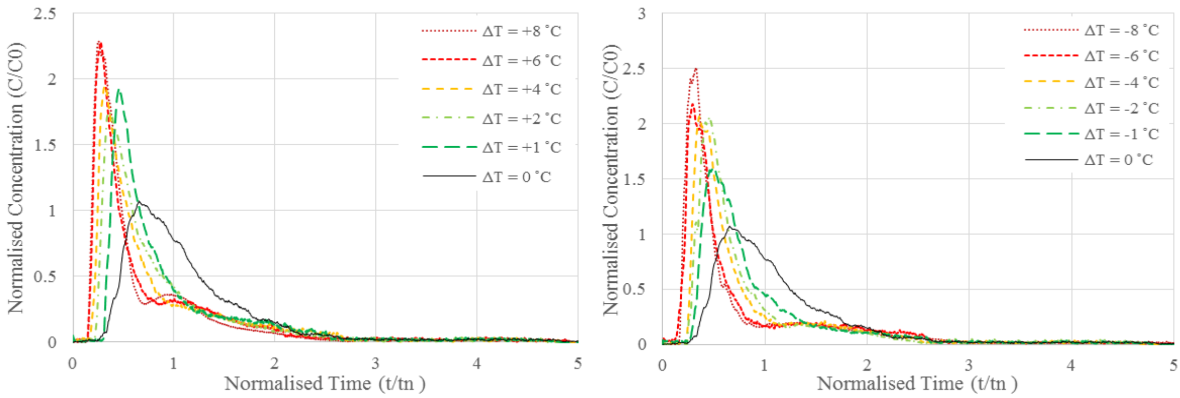

Figure 2 RTD curves with constant inlet temperature and different colder and hotter initial pond temperatures (1 l/s)

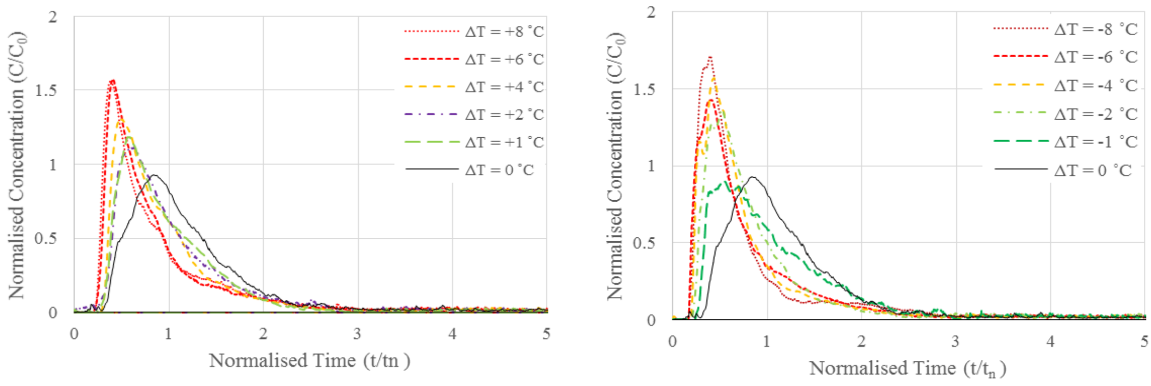

Figure 3 RTD curves with constant inlet temperature and different colder and hotter initial pond temperatures (2 l/s)

The relationships between the RTD curves and temperature differences are shown graphically in Figures 4-5. As shown in these figures, there is a clear trend of all index values decreasing with increase of the temperature difference emphasising the importance of temperature effects on the hydraulic behaviour of retention ponds. It is apparent from these figures that even a one-degree temperature difference can significantly reduce the hydraulic efficiency and can cause severe short-circuiting. This finding is consistent with that of Goula et al. (2008) study, who concluded that "only 1 °C between influent and tank content is enough to induce a density current". The temperature difference also decreases the Morril index, which is indicative of decreased mixing levels in the pond for both hot and cold influent. It is also clear that the slope of these trends decreases with increasing temperature difference for both 1 l/s and 2 l/s. For the flowrate of 1 l/s, the hydraulic indices rapidly decrease for 1 °C - 2 °C temperature difference between the influent and the pond, while the decreasing trend is lower for 2 °C - 8 °C. For the flowrate of 2 l/s, the same trend was observed in the hot influent case while the initial rapid decreasing trend for the hydraulic indices was detected only up to 1 °C temperature difference between the influent and the pond for cold influent.

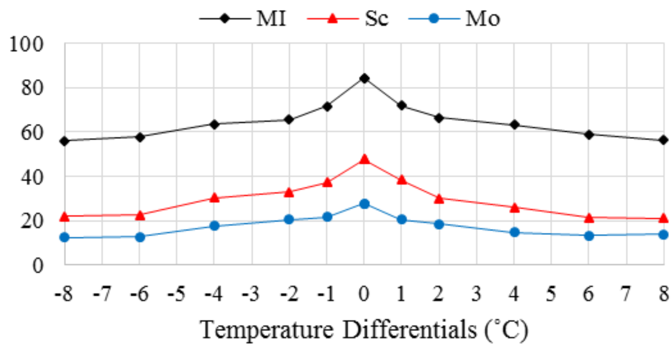

Figure 4 Relationships between the hydraulic index values and temperature differences (1 l/s)

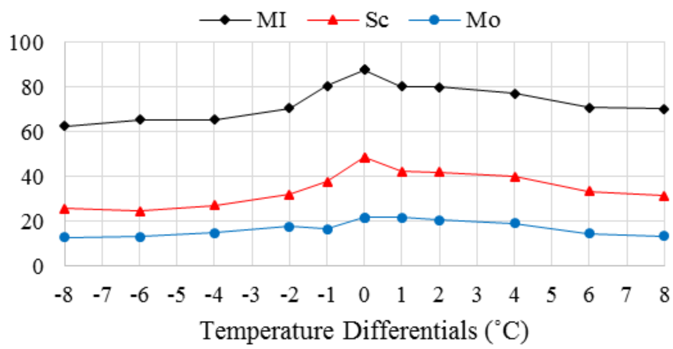

Figure 5 Relationships between the hydraulic index values and temperature differences (2 l/s)

Table 1 Hydraulic index values for different temperatures (1 l/s)

Model Case	ΔT (°C)	SC (%)	MI (%)	Mo (%)
1	0	47.63	84.29	27.57
2	+1	38.24	71.68	20.50
3	+2	30.09	66.35	18.43
4	+4	25.95	63.09	14.58
5	+6	21.46	58.77	13.17
6	+8	21.02	56.34	13.96
7	-1	37.32	71.62	21.54
8	-2	32.94	65.60	20.40
9	-4	30.34	63.52	17.57
10	-6	22.43	57.78	12.65
11	-8	22.04	55.85	12.40

Table 2 Hydraulic index values for different temperatures (2 l/s)

Model Case	ΔT (°C)	SC (%)	MI (%)	Mo (%)
1	0	48.60	87.56	21.82
2	+1	42.26	80.27	21.62
3	+2	42.02	80.03	20.49
4	+4	40.06	76.99	19.21
5	+6	33.35	70.79	14.68
6	+8	31.38	70.31	13.42
7	-1	37.72	80.51	16.69
8	-2	31.98	70.66	17.69
9	-4	27.05	65.43	14.77
10	-6	24.52	65.40	13.17
11	-8	25.70	62.54	12.73

3.2. EFFECT OF TEMPERATURE ON FLOW PATTERN

The effect of buoyancy was found to be very significant and the velocity and temperature fields were strongly affected by thermal stratification. The results presented here concern the two flow configurations (hot influent and cold influent) of Figures 6-7 and the time-dependent velocity contours, obtained experimentally, are shown. As the temperature difference increases, the buoyancy effect increases and pushes the streamlines upwards or downwards for hot and cold influent, as expected. This results in a narrower flow region near the surface or bottom and consequently larger flow velocities. This, in turn, causes a circulation flow or counter-current in the lower region for hot influent and upper region for cold influent, the strength of the circulation increasing as temperature difference increases, and gives rise to larger shear in the upper region for hot influent and lower region for cold influent.

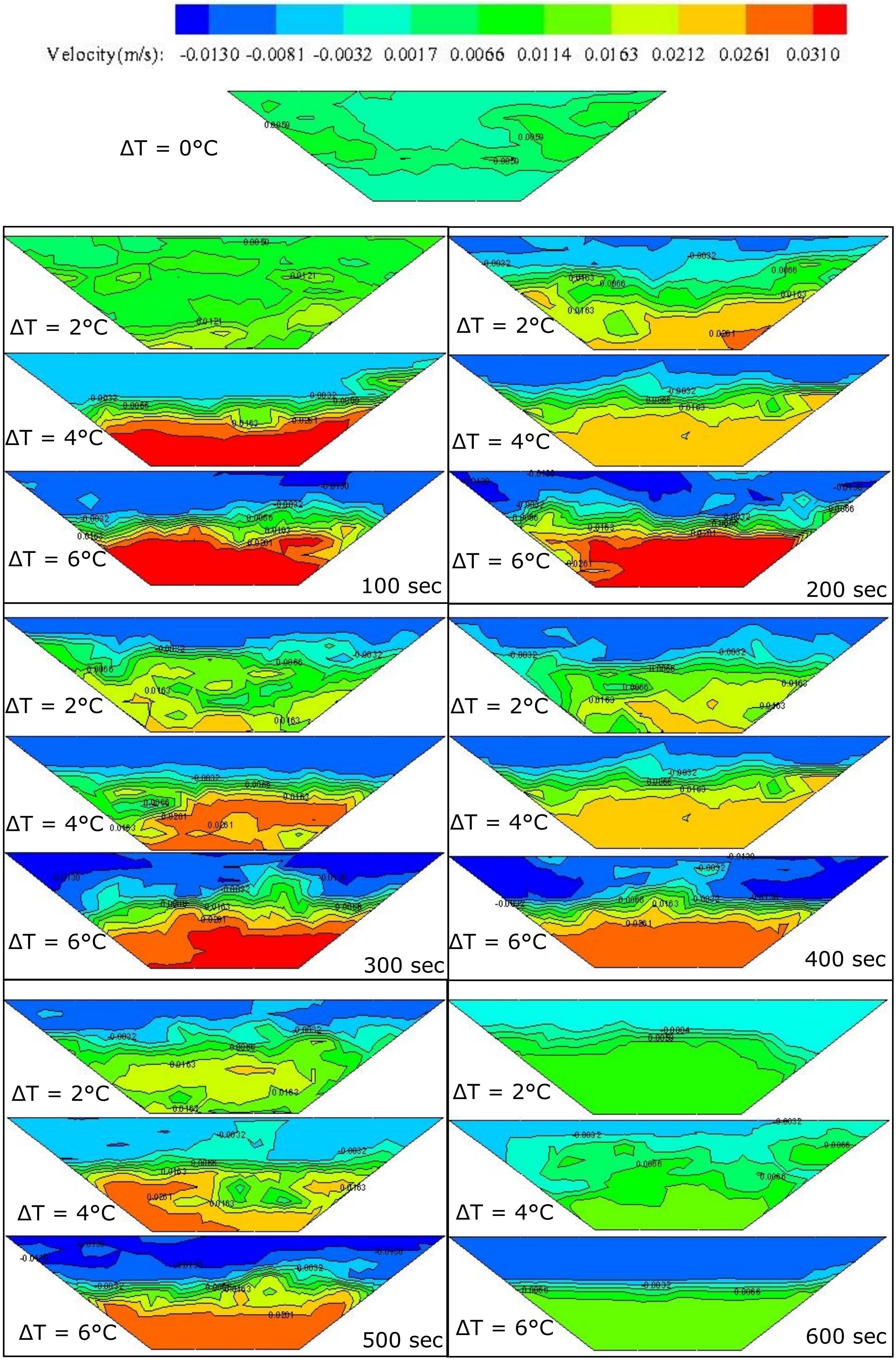

Figure 6 The velocity contours on the centreline cross section of the pond

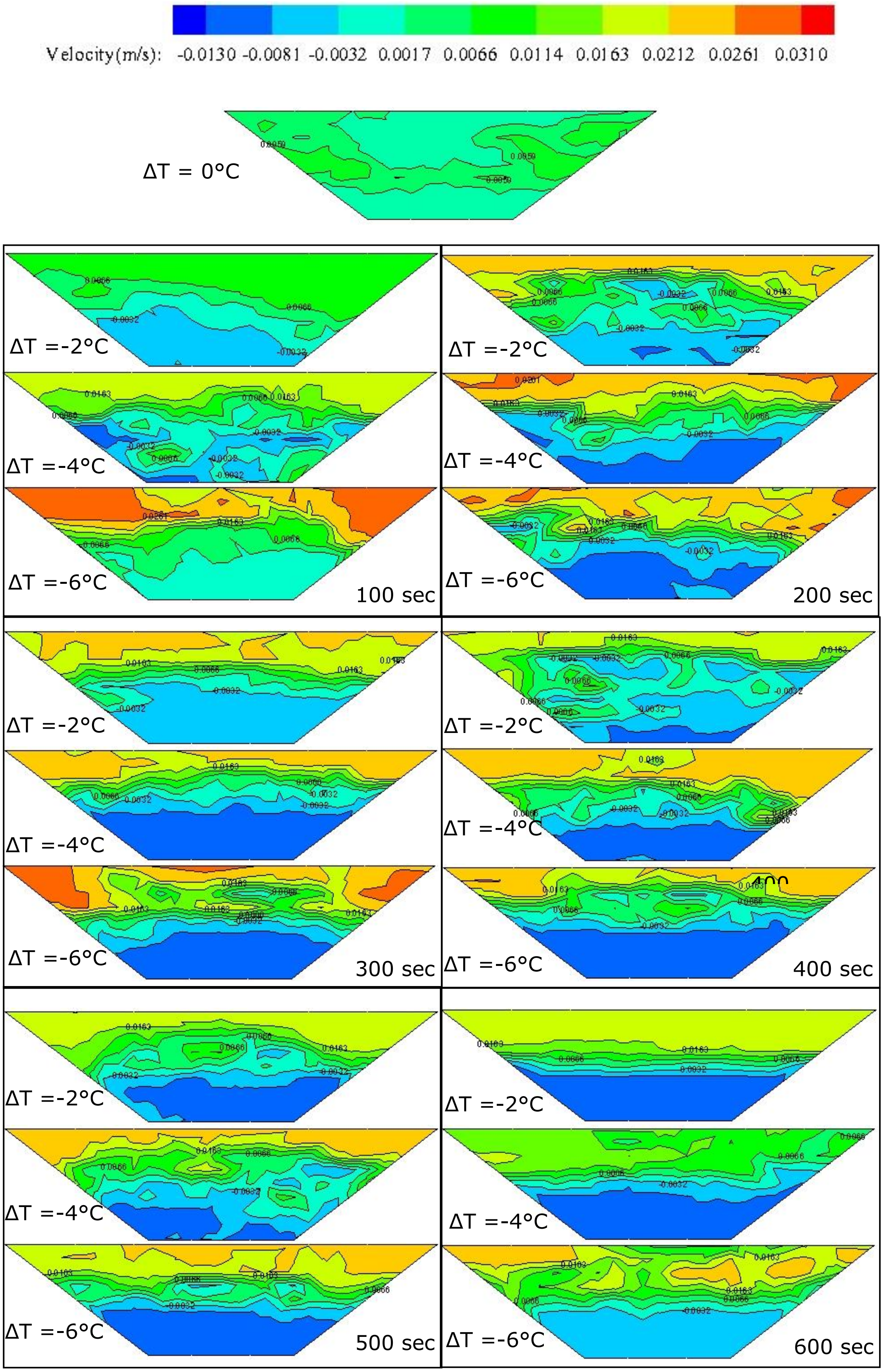

Figure 7 The velocity contours on the centreline cross section of the pond

It is apparent from Figures 6-7 that time has a key role, in that the negative effect of temperature variations becomes weaker after about 600 seconds from the beginning of the simulation. For continuous inflow, as elapsed time increases the temperature difference decreases, the velocity decreases and the bottom or top preferential flow becomes weaker and the flow tends to return to its isothermal form. It is also important to note that even after 600 seconds from the beginning of the simulation the flow velocity is still greater at the bottom or top of the pond for both cold and hot influent cases; this observation is relevant to longer term effects of temperature variations.

4 CONCLUSIONS

The following conclusions are drawn from this study:

1. Temperature variations in a pond can significantly change the hydraulic performance of the pond. Even with 0.5°C degree of Celsius temperature difference between the pond water and inlet, the hydraulic efficiency, short-circuiting, and mixing indices are reduced.

2. The decrease of hydraulic efficiency in the pond can be attributed to the temperature induced flow pattern, which has a significant role in creating short-circuiting. For colder influent, the inflow sinks to the bottom of the pond and moves rapidly towards the outlet, while in the case of hotter influent the inflow tends to move to the top of the pond.

3. Inflow particles moved very fast in the first 100 seconds from the beginning of the simulations and this high velocity was more severe for high temperature differences. A circulation flow or counter-current was also observed in the lower region for hot influent and upper region for cold influent, with the strength of this circulation increasing as temperature difference increases.

4. For experiment durations up to 600 seconds, the preferential flow pattern evident in density difference experiments becomes considerably weaker as the experiment continues. However, the flow velocity is still greater at the bottom or top of the pond for both cold and hot influent cases.

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