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Water Column Destratification Using a Pulsed Jet System

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Abstract

The efficiency at which drinking water reservoirs can be artificially destratified by mechanical or pneumatic pumping systems depends upon numerous factors, including the rate at which water is pumped from one vertical level to another. To date, no studies have been cited that examine whether it is possible to enhance destratification efficiency by using a pulsed flow instead of a continuous one in order to determine whether a pulsed flow could enhance mixing rates, a set of detailed laboratory experiments was undertaken using a vertical positively-buoyant jet mixing system to destratify a two-layer stably-stratified water column. The pulsing flow considered had a continual –on-off- cycle with the on- and off- times kept constant within any one experiment, but varied between different experiments. The results showed that when the on-flow time was short and the off-flow time relatively long the leading vortex that formed at the initiation of the on-flow significantly reduced the mixing rates, and hence the efficiency.

Introduction

Artificial destratification systems form an integral part of many drinking water reservoir management schemes. Essentially, these devices are used to break down the thermal stratification that develops in these water bodies during the warmer months of the year. If left unabated, the stratification can build to such a level that it strongly inhibits the vertical exchange of bottom water with the wind-stirred surface layers. Subsequently, oxygen-consuming biological and chemical processes in the bottom layers can use up all available oxygen, resulting in the development of anoxic conditions [1]. The water is then rendered unusable for consumption.

Destratification devices vary dramatically in size and nature, with examples including bubble plumes, impellers, deep-draw aerators and jet pumps [1,2,3]. One common element of previous studies on destratification systems was that they all operated in a continual flow manner. That is, once activated, the pumping process continued with a constant flow rate either until the water column became destratified to an extent deemed appropriate by the operators (if at all achievable) so that the system could be turned off, or the device broke down.

This paper presents the results obtained from an experimental study aimed at determining what influence the pulsing of a positively buoyant jet destratification system (as depicted in Figure 1) would have on the systems operating efficiency. The following sections will detail the methodology used in this study, then present and discuss the results, and finally show the conclusions. It will be shown that pulsing can have a detrimental influence on mixing rates.

Methodology

A series of laboratory experiments was conducted within a 1.7x1.7x0.9 m glass-sided experimental tank that was initially set up with a two-layer water column structure. The upper layer was tap water while the bottom layer was made denser by the addition of dissolved sea salt. Both layers had an initial thickness of 350 mm. The destratification system consisted of a small electric pump and pipe system. Salty water was drawn horizontally from the bottom layer at an elevation of 50mm from the tank base and released through a 11.7mm nozzle vertically downward into the fresh top layer at a depth of 65mm (a schematic of the experimental arrangement is given in Figure 1).

A solenoid valve (Burkert, Type 6013) and programmable electronic controller timer (Burkert, Type 1078-1) controlled the on/off flow rate of the jet. This system allowed the jetting fluid to be pulsed in a square wave pattern with the flow rate being either in an *on*-flow state (full flow) or an *off*-flow state (no flow). This system allowed flow rates to be cycled in a continual *on-off* pattern with the *on*-flow time (t_{on}) and the *off*-flow time (t_{off}) being constant for each experiment, but, if required, varied from one experiment to another. The *on*-flow rate for each experiment in this study was kept constant at 2.29×10^{-5} m^3s^{-1}.

The structure of the water column density profile within the tank was derived from data collected using a microscale temperature and conductivity probe (PME Model 125) connected to a 16 bit A/D card (IOTech Daqboard 200) and a personal computer. The probe was calibrated against a standard Orion temperature and conductivity meter. The probe was vertically traversed through the tank (between the depths of 5 mm and 680 mm) at a rate of 0.029 ms^{-1} using a computer controlled traversing mechanism (Velmex Pty Ltd). Data were collected at a rate of 10 Hz, with profiles being taken every 10 min during an experiment. To compensate for any probe drift, the calculated values of density were corrected by using mass conservation [5]. That is, the mean density of each profile was made equivalent (if required) to that of the first profile.

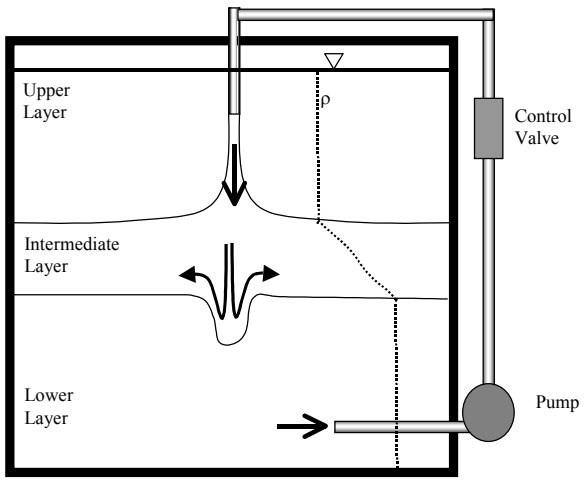

Figure 1. Schematic of the experimental arrangement used in this study. Thick arrows indicate direction of main flow.

Water Column Mixing

As depicted in Figure 1, when the jetting process commenced the positive buoyancy of the jetted water allowed it to readily penetrate downwards through the upper layer, where the jetting fluid entrained the surrounding ambient water, thus increasing its volumetric flow rate and decreasing its density. The positive buoyancy of the jetting/entraining water acted to enhance the downward motion of the flow. The jet then readily penetrated through the interface and into the bottom layer. In this region the jetting/entraining fluid experienced negative buoyancy with respect to the ambient (lower layer). This resulted in the jetting/entraining fluid penetrating only to a finite depth before stopping and rising to a level of neutral buoyancy, whereupon it spread laterally, forming an intermediate layer of mixed fluid.

When the water was pumped using the pulsing process the jetting/entraining flow behaved in a similar manner to a continuous flow except that it was of finite length. This meant that the injected fluid was entering a disturbed ambient (from the previous pulse of fluid) on initiation of the jetting process and not moving directly into previously injected fluid (as is the case for a continuous flow).

Figure 2 presents an example of the change in water column density structure that occurred during a pulsed flow experiment. The intermediate layer is seen to expand up into the surface layer at a rate faster than it expanded down into the bottom layer. The growth rate of the intermediate layer decreased with time, which was the case for all experiments conducted in this study. As the intermediate thickness grew the jetting/entraining fluid spent more time in the intermediate layer. Consequently, the amount of bottom and surface layer fluid that could be entrained by the jet would decrease with time. In effect, the intermediate layer was recirculating itself.

As indicated in Figure 2, the lower interface of the intermediate layer remained sharp throughout all experiments, while the upper interface decreased in gradient with time. This (along with the density field changes) indicated that the upper layer contributed more to the growth of the intermediate layer than did the lower layer.

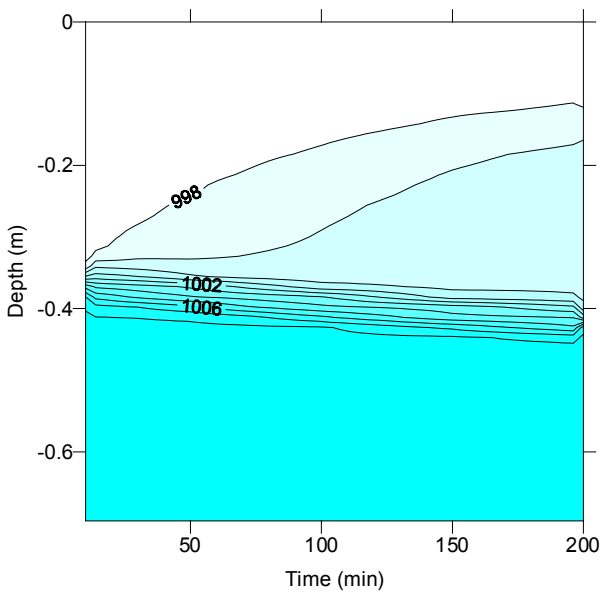

Figure 2. Water column density structure as a function of time for one pulse jet experiment. Here t_{on} = t_{off} = 1 sec, Fr_o = 18.3 and St = 50. Contour intervals are 1 kgm^{-3}.

Mixing Efficiencies

Various studies of destratification devices in the laboratory (or via numerical simulations) have found that the efficiency at which these devices operate depends upon the level of water column stratification, the amount of kinetic energy the device imparts on the water and the depth of operation. The efficiency at which destratification systems vertically mix the water column is regularly expressed as:

$$\eta = \frac{\Delta PE}{\Delta KE} \tag{1}$$

where ΔPE is the increase in water column potential energy resulting from an input of kinetic energy over a given time period (ΔKE) by the destratification system.

For a pumped constant-velocity positively buoyant jet mixing system, where heavy fluid is pumped upwards to a level of lower density before being released, laboratory studies [4] found η was a function of the Froude number, Fr_o, and an ambient stratification number, St, (both based upon the source conditions), which were respectively defined as:

$$Fr_o = \frac{V}{\sqrt{gD_o \frac{\Delta\rho_o}{\rho_o}}} \tag{2}$$

and

$$St = \frac{\Delta\rho_o}{D_o} \Big/ \frac{d\rho_a}{dz} \tag{3}$$

where V is the velocity of the fluid exiting the jet, D_o is the diameter of the nozzle, g is the acceleration due to gravity, $\Delta\rho_o$ is the density difference between the exiting jet fluid and the ambient, ρ_o is the jet density, ρ_a is the ambient density and z is the vertical coordinate. Stefan and Gu [4] observed a systematic decrease in mean η from 35 to 18 % as the destratification parameter, Fr_o^2/St, increased from 0.5 to 2.5.

For this paper a total of 15 experiments were conducted with 8.3< Fr_o <18.3. As the flow rate and viscosity were kept almost constant (slight temperature effects would have caused slight changes), the *on*-flow Reynolds number for all experiments was ≈2000. In this study it was not necessary to vary St as [4] had already shown that the ratio of $Fr_o^{\ 2}$/St was the controlling parameter.

The energy input for a continuous flow rate, Q, over a time, Δt, was determined from (in keeping with [4]):

$$\Delta KE = \frac{1}{2} Q\left(\rho_o V^2 + \Delta\rho_o L g\right) \tag{4}$$

where Q is the jet volumetric flow rate and L is the distance between the water intake and the outlet levels. The two terms within the brackets of Eq. [4] represent the kinetic energy input and the pressure difference caused by the density stratification (see [4]). The potential energy of one profile was determined from

$$PE = \int g\rho(z) z dz \,. \tag{5}$$

Estimates of ΔPE were obtained from the change in PE over time. For the pulsed jet experiments, the time period Δt was replaced by $\Delta t * t_{on}/(t_{on}+t_{off})$, so that only the *on*-flow portion of an experimental is considered. The values of η were then derived from Eq. [1].

In this experimental study it was found that η was constant over time (see Figure 3). That is, η did not change as the intermediate layer thickness increased, which indicates the destratification process is momentum-dominated with buoyancy having little effect on the mixing. This is different from the case of negatively-buoyant destratification systems [6,7], whose efficiencies were a function of the layer thickness. However, the data presented in Figure 3 is consistent with [4], who used a similar destratification process.

Figure 4 presents results of the mixing efficiencies derived from this experimental study where the flow rate was either constant (t_{off}=0), or pulsed with t_{on}=t_{off} (from 1 to 5 sec). For comparative purposes some average η values from the continuous flow experiments of [4] are also presented. The scatter in the data is in keeping with that of [4], indicating an error estimate of < +/- 5% is expected. The data reveals that the pulsing of the jet in this uniform cyclic pattern seemed to have little influence on η, with the dependence upon $Fr_o^{\ 2}$/St remaining. Therefore, the actual rate at which the water column would be destratified would be less for pulsed than for non-pulsed systems at a rate proportional to the time scale ratio $t_{on}/(t_{on}+t_{off})$.

When the duration of t_{off} was varied (from 1 to 5 sec) while keeping t_{on} constant (at 1 sec), there were once again no discernible differences between the continual flow experiments and the pulsed flow experiments (see Figure 5). This information (along with that observed in Figure 4) indicates that for $t_{off} \leq t_{on}$, the mixing efficiencies remains a function of the ratio Fr_o^2/St only and is independent of the pulsing nature. Therefore, it should seem inappropriate to pulse a destratification system, since more time would be required to mix the water column and that pulsing a flow is mechanically more difficult.

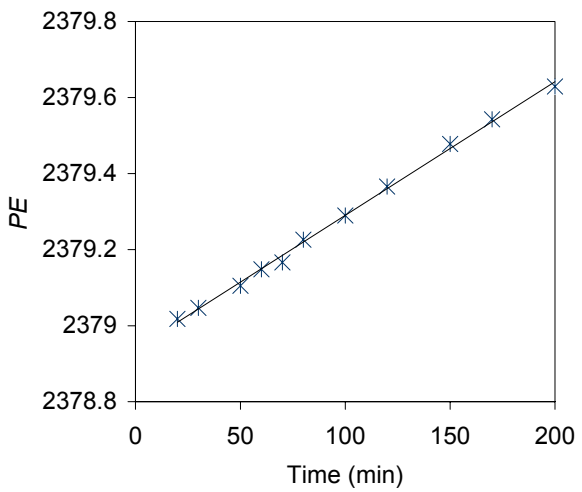

Figure 3. Plot of PE as a function of time from the beginning of the destratification process. The data was derived from the same data set used to derive Figure 2,

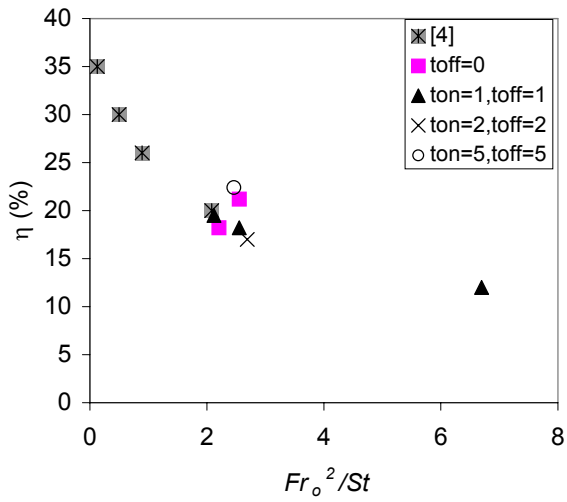

Figure 4. Plot of mixing efficiency against the dimensionless destratification parameter. Data presented are for continual flow (t_{off} =0), the average results derived from Stefan and Gu [4]) and t_{off} = t_{on} experiments.

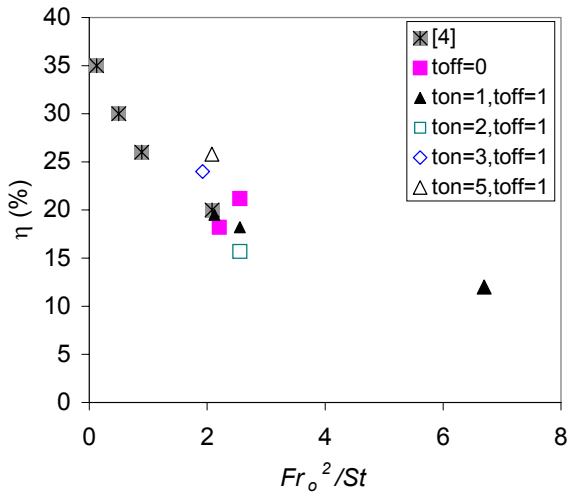

Figure 5. Plot of mixing efficiency against the dimensionless destratification parameter. Data presented are for continual flow (t_{off}=0), the average results derived from Stefan and Gu [4]), and t_{on} = variable and t_{off}=1 sec experiments.

Figure 6 presents data derived from the experiments where t_{off} was constant and short (1 sec), while t_{on} was varied (from 1 to 5 sec). Again, for comparative purposes, the constant flow rate experiments are also shown. The data reveals that while the case as t_{off} = t_{on} = 1 sec behaves like a continuous flow longer t_{off} times have a dramatic influence on η. Indeed, for t_{on} = 5 sec very little mixing was evident, even after some hours had elapsed. A comparison between Figure 4, 5 and 6 indicates that the ratio t_{on}/t_{off} is an indicator of the likely mixing rates. Pulsed flows of the nature $t_{on}/t_{off} \geq 1$ have similar η for the same Fr_o^2/St. However, for the case $t_{on}/t_{off} < 1$ η are dramatically reduced. The lower the ratio t_{on}/t_{off} the smaller the η. Further studies will be required to quantify this relationship.

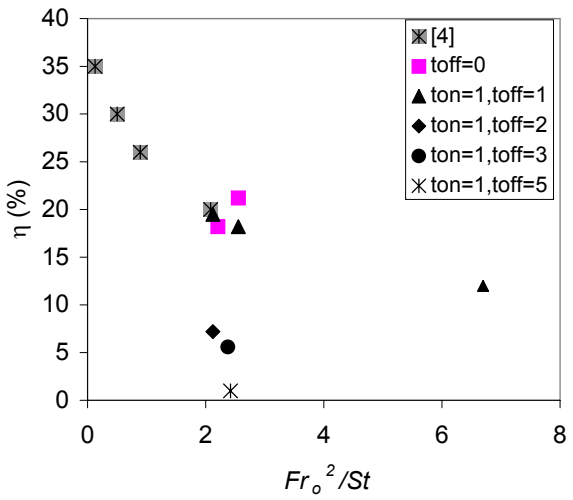

Figure 6. Plot of mixing efficiency against the dimensionless destratification parameter. Data presented are for continual flow (t_{off} = 0), the average results derived from Stefan and Gu [4]) and t_{on} = *1 sec* and t_{off} = variable experiments.

To help explain the reduction in η with short t_{on} and long t_{off}, it is important to consider the nature of a pulsing jet. Upon initiation of a jet flow a leading edge vortex will develop. This vortex contains mostly bottom fluid and has an inefficient entrainment mechanism. Since the vortex has a density of the bottom layer and it does not entrain much surrounding fluid as it progresses through the upper layers; it will readily penetrate through to the base of the intermediate layer and back into the bottom layer. It will therefore induce little mixing, thus being an inefficient destratification mechanism. If there is a short time between pulses the leading edge vortex will have to penetrate into turbulent motions resulting from the previous pulse which will help break it down, and hence enhance mixing. Thus, the longer the t_{off} and the shorter the t_{on} the lower the η. Therefore, to reduce the loss in η, it is important that the influence of the leading edge vortex be minimised.

The t_{on} times were chosen for this preliminary study so that the leading edge vortex was fully developed, while t_{off} was chosen arbitrarily as it was the intent to gain an initial insight into pulsed positively-buoyant jet mixing systems. Further work is required to determine the mixing behaviour under conditions where the t_{on} is sufficiently short so that the leading edge vortex does not fully develop. Further, if the unsteady nature was going to have a significant enhancement effect on the destratification process then it would need to work in tandem with some other system timescale, such as the internal seiching period and/or the time it would take for the jet to become a plume.

Conclusions

This experimental study examined the mixing efficiency of a positively buoyant pulsed-jet destratification system applied to a stably stratified two-layer water column. An intermediate layer was observed to form between the upper and lower layers upon initiation of the mixing process. The growth rate of this layer decreased with time.

The mixing efficiency of the destratification process was found to be a function of the dimensionless destratification parameter Fr_o^2/St, the lower the number the smaller the mixing efficiency. This is in keeping with previously published work for positively buoyant jet mixing systems. It was also found that the pulsing on/off ratio, t_{on}/t_{off} strongly influenced the mixing efficiency with small values (> 1) having a detrimental influence on the mixing process as a result of a leading edge vortex that formed during the initiation of the *on*-flow.

The findings of this study imply that the mixing efficiency of the destratification process may be reduced when a positively buoyant jet mixing system is pulsed. Therefore, as no overall gain in efficiency or mixing rates was observed it is recommended that pulsing be avoided.

Acknowledgments

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References

[1] Cox, J. D., Padley, M. B. and Hannon, J. (1998) Use of computational fluid dynamics to model reservoir mixing and destratification, *Wat. Sci. Tech.*, **37** (2), 227-234.

[2] Imteaz, M. A. and Asaeda, T. (2000) Artificial mixing of lake water by bubble plume and effects of bubbling operations on algal bloom, *Wat. Res.*, **34** (6), 119-129

[3] McAuliffe, T. F. (1990) The triumphs and tribulations of artificial mixing in Australian water bodies, *Water*, **17** (4) 22-23.

[4] Stefan, G. H. and Gu, R. (1991) Efficiency of jet-mixing of temperature stratified water, *J. Environ. Engn*, **118** (3), 363-379.

[5] Park, Y., Whitehead, J. A. and Gnanadeskian, A. (1994) Turbulent mixing in stratified fluids: layer formation and energetics, *J. Fluid Mech.*, **279**, 279-311

[6] Larson, M. and Jonsson, L. (1994) Mixing in a two-layer stably stratified fluid by a turbulent jet, *J. Hydraulic. Res.,* **32** (1), 271-289

[7] Larson, M. and Jonsson, L. (1996) Efficiency of mixing by a turbulent jet in a stably stratified fluid, *J. Dynamics Atmos. Oceans,* **26**, 63-74