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SALT-FINGERING OF POLLUTANT VERTICAL MIXING IN STATIC THERMAL-STRATIFIED WATER*

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Abstract: Pollutant vertical mixing in stratified waters is a key factor that affects the vertical pollutant distribution in deep thermal-stratified reservoirs. This article presents an experimental study of the vertical mixing in thermal-stratified waters and an analysis of the retarded tracer jet diffusion in the thermocline layer. In the experiment, Reynolds number rapidly decreases from 10^4 to 10^1. The stronger the stratification, the more seriously retarded the mixing will be. Some small tracer blobs may penetrate the thermocline layer into the hypolimnion layer even the main tracer cloud is retarded. According to its appearance, it can remain with salt-fingering, where the blobs are isolated away from the main cloud and mixed with the surround cold water in the hypolimnion layer. Therefore, the vertical distribution of the tracer under the thermocline layer would take larger values than expected. According to measurements, the isolated blob contents are accounted for about 5%-20% of the main tracer cloud, and are decreased with the increase of the stratification intensity. Results also show that the stronger the stratification, the smaller finger width would be. The averaged width of the incipient fingers is proportional to –0.3272 power of the temperature gradient, $\Delta T/\Delta z$, or -0.2823 power of the thermal Rayleigh number, Ra_T, in the turbulent jet fluid.

Key words: thermal-stratified water, vertical mixing, retard, double diffusion, salt-finger

1. Introduction

A number of huge and deep reservoirs were built and are being built in the southwest of China. Thermal-stratification was usually observed in these reservoirs[1]. To deal with pollutant diffusion, or unexpected pollution incidents in these reservoirs and to provide support for decision-making, one should have a good understanding of the vertical mixing mechanism in stratified reservoirs.

In the stratified geophysical systems (lakes, fjords and oceans) and the interior of a stratified ocean, the diapycnal mixing was often considered[2]. Two- and three-dimensional numerical simulations of mixing in a stably stratified shear layer also revealed diapycnal mixing[3]. Fan et al.[4] investigated the vortex formation for a round transverse jet in shallow water. Qiu[5] found that the vertical turbulent intensity is affected by stratification, and vertical fluctuations decay more rapidly with the presence of stratification.

Double-diffusive fingering convection is important in many engineering applications and natural processes. Fingering instability occurs in a double-diffusive fluid layer in which the faster-diffusing component (heat) is stabilizing and

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the slower-diffusing component (solute) is destabilizing[6]. In a heat-salt double diffusion, the potential energy locked in the unstable component is released through the more rapid molecular diffusion of heat than salt[7]. The strong layering in the ocean was observed near fronts, where large horizontal gradients of temperature and salinity were present. Turner measured the vertical fluxes of heat and salt across an interface containing fingerings[8]. He related the magnitudes of the fluxes of heat and salt to the temperature and salinity of the layers on either side of the interface, and demonstrated that the vertical transport of salt was considerably increased by the presence of the fingering. Green and Diez found that fingering convection increased the transport of plankton[9]. The finger structure was also observed in the sediment movement by Chen[10], when the finger was in the formation stage, vortex rings were seen forming at the tip of individual fingers, as observed by Green[11].

Turner proposed the density stability ratio[6], $R_\rho = \alpha\Delta T / \beta\Delta S$, to indicate the relative strength of double diffusion, where $\alpha = -\rho^{-1}\partial\rho / \partial T$ is the thermal expansion coefficient of the order of 10^{-5}, $\beta = \rho^{-1}\partial\rho / \partial S$ is the haline contraction coefficient of the order of 10^{-4}, ρ is the density, and ΔT, ΔS are the vertical temperature and salinity gradients, respectively[12]. The rates of transport of salt and heat depend on the characteristics of the convection cell, such as the fluid velocity and the width of the fingers, and the intensity of turbulence in the mixed layers across the fingering region[13]. Sreenivas et al.[14] studied double-diffusive fingering convection with two-dimensional numerical simulations, results of these simulations indicated that finger width was inversely proportional to the thermal Rayleigh number, $Ra_T = g\alpha\Delta T d^3 / \nu k_T$, where g is the gravity acceleration, ν is the kinematic viscosity of the fluid, k_T is the thermal diffusivity, and d is the vertical characteristic length, ΔT is the temperature difference across the vertical characteristic length. The interaction between salt fingers and turbulence was well reviewed by Taylor[15]. He found that the fingers tend to be disrupted by the turbulent motions, and that fingers reform quickly after turbulent disruption.

Studies of vertical mixing in stratification water are usually focused on diapycnal mixing, while studies of double diffusion emphasize the diffusion of two components of different molecules, which was rarely considered in jet diffusion in stratification waters, and was generally investigated in a static system.

The turbulence kinetic energy of a huge and deep reservoir is very low, its vertical mixing is mainly affected by the vertical temperature gradient structure. In this article, in order to understand the pollutant diffusion mechanism, the tracer diffusion in static state thermal-stratified waters was investigated in the laboratory, measurements of the detailed structure of laboratory heat-solute fingers were made, and the impact of turbulence on the double-diffusion was closely observed.

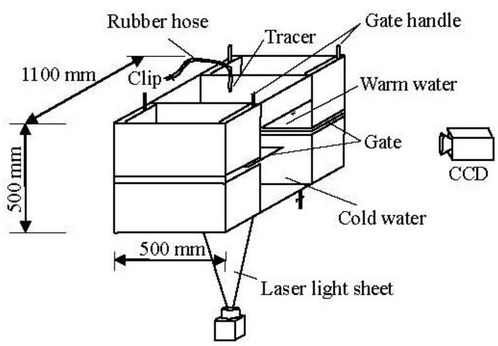

Fig.1 A diagram of the apparatus

2. Experimental setup

A two-layer thermal-stratification environment is created in a rectangular tank (Fig.1), in which a gate is placed in the middle to separate the initial layers. The experiments were carried out in a Perspex tank of 500 mm×500 mm in cross-section and 500 mm deep. In the tank, the cold water was deposited in the lower part, and then the warm water was introduced into the upper part. When the gate was removed slowly, a stratified water body was obtained. The different water temperatures of the layers lead to different stratification intensities. A rubber hose was used to release the tracer (Fig.1). The tracer was stored in one end and held by clipping the other end of the hose before the experimental run, and then it was released right at the center near the water surface by opening the clip. According to the measurements, the water body thermal-stratification structures were almost in a steady state during the experimental runs. Figure 2 shows the selected stratification curves at different time, where Z is the depth.

5 different densities of tracers were investigated in the experiments, including aqueous solutions of NaCl with Rhodamine B or Sodium Fluorescein (Table 1). The density of the tracer was measured by Anton Paar Density Meter DMA 35n. Figure 3 summarizes the tracers' temperature-density profiles.