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Research Paper

Spatio-temporal disruption of thermocline by successive laminar vortex pairs in a single tank thermal energy storage

Aashay Tinaikar, S. Advaith, Utpal Kumar Chetia, K.V. Manu, Saptarshi Basu *

Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

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ABSTRACT

The stratification efficiency of single tank thermal energy storage is affected by the internal mixing processes, especially in the thermocline region due to disturbances of different kinds. To study the mixing dynamics at the interface, we have conducted detailed numerical and supporting experimental studies for different Atwood numbers (stratification levels). Numerical experiments were conducted with two successive vortex pairs with three different time-lags (short, medium and long). For the short time-lag case, the preliminary vortex pair merges with the ensuing vortex pair. The merged single vortex pair peels back the thermocline layer causing mixing of the hot and cold fluids. The thermocline thickness increases as a result of the entrainment of the cold fluid into the hot fluid. The peeling process continues until buoyant forces leads to plume like structures that penetrate into the lighter fluid. For the medium and large time-lag cases, such merging of vortices was not observed. The vortex pair interacts separately with the thermocline region. The plume structure created by the first vortex pair interacts with the ensuing vortex pair. The altered interface (thermocline) thickness strongly depends on the nature of the vortex–thermocline interaction mechanisms. The thermocline effectiveness decreases consequent to such interactions and have been quantified in details in the current work.

1. Introduction

In concentrated solar power (CSP) plants, parabolic troughs in conjunction with thermal energy storage (TES) produce the power required to operate the generator. TES, an important subsystem of the CSP provides the required stability in power by regulating the discrepancy between the supply and demand. Out of the many identified storage technologies, a single tank TES offers the most economical storage option for CSP applications.

In a single tank TES, the hot and cold heat transfer fluids (HTF) are stored in an inherently stable stratified configuration. The hot and cold fluids are separated by a region of large density gradient called "thermocline" of thickness δ (Fig. 1a). The stability of the thermocline is one of the crucial factors that govern the efficiency of a single tank TES [1,2]. A stable TES can significantly enhance the efficiency of the CSP plant. Instabilities inevitably cause undesirable mixing inside the tank. Mixing broadens thermocline thickness and reduces thermal storage performance.

Viscous fingering is a commonly observed phenomenon in dual media (porous filled) tanks and Kelvin–Helmholtz instability (shear instability) can generate vortices inside the TES. These vortices evolve and disrupt the thermocline region [3,4]. The resultant undesirable mixing of fluids disturb the thermal stratification inside the tank [5]. These types of interface-collapses are observed during the charging cycle when the temperature of the incoming fluid is lower than that of the stored hot-fluid temperature [3,4]. Slight variations in density can also cause Rayleigh–Taylor instability, leading to formation of vortices. Hence, it is highly desirable to predict the structure and path of vortices as well as the physics behind the interaction dynamics.

The interaction of vortices with the thermocline region is a very complex problem with enormous technological interest. Depending on the boundary and operating conditions, the vortex pairs can either penetrate or bounce from the thermocline region [6]. This collision is baroclinically enhanced and can generate strong vortical mixing inside the tank. Depending on the flow conditions, rich and diverse flow structures like 'plume', 'billow' and 'internal gravity waves' were observed in the vicinity of the thermocline. Similar vortex–thermocline interactions can be observed in many natural phenomena and have myriad applications across numerous fields of science and technology. The interaction of wake-vortices created by ships/submarines with thermocline in the ocean, the propagation of trailing-vortices generated by airplanes in the

* Corresponding author.
E-mail address: sbasu@mecheng.iisc.ernet.in (S. Basu).

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Nomenclature

a	distance between vortex centres, m
A	Atwood number
d	diameter of the tank, m
g	acceleration due to gravity, m/s^2
h	height of the tank, m
Re_v	vortex Reynolds number
L_p	penetration length, m
T	absolute temperature, K
u	radial velocity, m/s
v	axial velocity, m/s
x	radial direction, m
y	axial direction, m
δ	thermocline thickness, m
Γ	circulation, m^2/s
μ	viscosity, N s/m^2
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ	flow time, s
ω	vorticity, 1/s
N	Brunt–Väisälä frequency, Hz
p	time period, s
k	thermal conductivity, W/mK
c_p	specific heat, kJ/kg K
Ri	Richardson number
T_h	hot fluid temperature, K
T_c	cold fluid temperature, K
ω_c	characteristics frequency of the vortex, 1/s
δ_s	disruption Index
f_1, f_2	primary and secondary peak frequency for all simulation cases, Hz
t^*	non dimensionalized time
u^*	non dimensionalized velocity
ω_{max}	core vorticity, 1/s
τ_1	time lag, s
T^*	non dimesionalized temperature profile along the axial length of TES

atmosphere and the discharge of buoyant jets from power plants are few examples.

Linden had analyzed the collision and the subsequent mixing induced by a turbulent vortex on a sharp-density interface [7]. Owing to the impact of this collision, both the interface and the vortices were distorted. The buoyancy forces cause the interface to recoil and splash the dense fluid into the lighter counterpart. Linden had put forward the concept of connecting the penetration length of vortices and entrainment rate with Froude number (*Fr*). In a similar study [6], had shown that in the Boussinesq limit, the interaction dynamics of laminar vortices (of size a and strength Γ) with a thin interface was essentially governed by the parameter AR, where A was the Atwood number across the interface and $R = a^3 g/\Gamma^2$. This parameter AR physically represents the ratio of buoyancy force and inertia force (Richardson number). For low Richardson number cases, the vortices penetrated the interface. During this process, the vortices shrunk and some of the dense fluid was ejected back into the lighter fluid. At large Richardson number cases (high AR), the vortex–density interface interaction bores resemblance to vortex–wall interaction. The effects of Froude number, Atwood number and Reynolds number on a weak stratified interface had been studied by Marcus and Bell [8]. At high Reynolds numbers, they had observed the formation of secondary and tertiary vortices.

Formation of internal gravity waves were seen during the propagation of vortices through density stratified interface. Orlandi et al. had conducted experimental and numerical simulations of the impact of a vortex pair on a linearly stratified interface [9]. The objective of their study was to find out the criteria for gravity wave generation by a descending vortex. Orlandi et al. had posited that gravity waves can be created only when $\omega/N < 1$, where ω is the characteristic frequency of the vortex and N is the Brunt–Väisälä frequency respectively. They had observed a linear dependence of maximum penetration length with Froude number

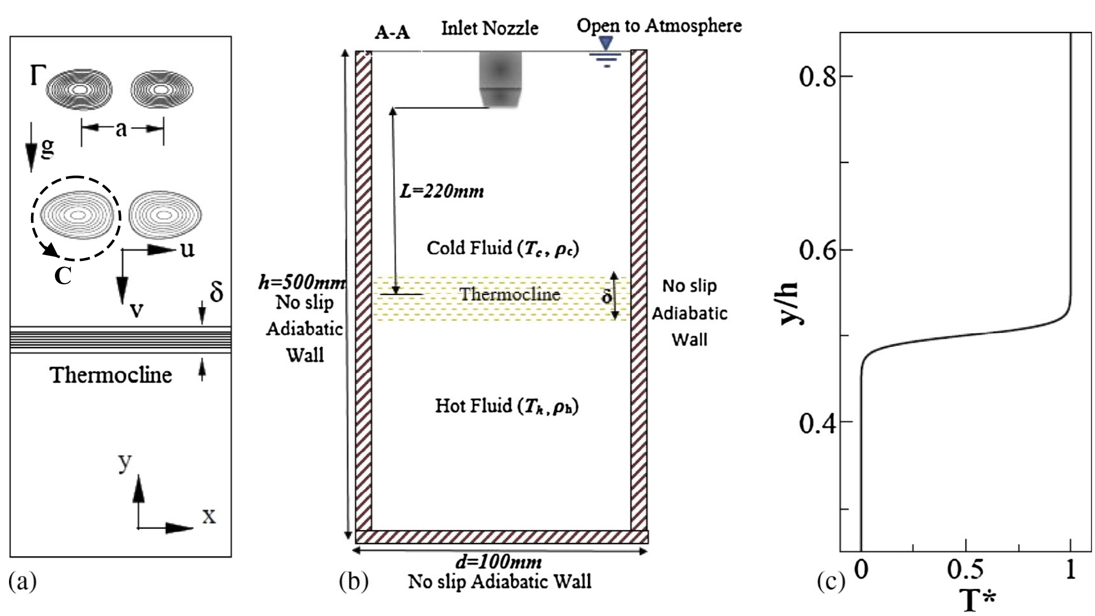

Fig. 1. Schematic of (a) the computational domain, (b) boundary conditions, and (c) non dimensionalized temperature profile.