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Rayleigh–Taylor instability in a thermocline based thermal storage tank

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ABSTRACT

Numerical simulations are performed to study the stability characteristics of a molten salt thermocline storage unit. Perturbations are introduced into a stable flow field in such a way as to make the top-fluid heavier than the fluid at the bottom, thereby causing a possible instability in the system. The evolution pattern of the various disturbances are examined in detail. Disturbances applied for short duration get decayed before they could reach the thermocline, whereas medium and long duration disturbances evolve into a "falling spike" or "stalactite-like" structure and destabilize the thermocline. Rayleigh–Taylor instability is observed inside the storage tank. The effect of the duration, velocity and temperature of the disturbance on thermocline thickness and penetration length are studied. A quadratic time dependence of penetration length was observed. New perspectives on thermocline breakdown phenomena are obtained from the numerical flow field.

1. Introduction

Rapid development in various engineering fields has drastically brought down the cost of generating solar power, making it an increasingly viable source of energy. However, among the shortcomings of a solar power unit are the intermittent nature of production of power and dependence on large and heavy storage batteries. In order to avoid intermittency of power generation due to the diurnal variation of sunshine some form of efficient cost effective energy storage is essential. It has been found that storage of energy via heat (Thermal energy storage: *TES*) – especially in modern Concentrated Solar Power (*CSP*) plants – is economical and viable than storage in batteries [1]. Currently, TES is designed by using molten salts (typically nitrates of potassium and sodium) as storage medium, which are maintained above their melting point [2]. Heat exchangers are used to discharge the sensible heat of the storage media to the working fluid of the power cycle.

Various types of *TES* technologies, such as the two-tank direct and in-direct system and the single-tank thermocline system have been tested and implemented in solar power plants [3,4]. In a two tank direct storage system, the heat-transfer fluid (*HTF*) from a low-temperature tank flows through a solar receiver, where it gets heated to a high temperature. The heated *HTF* subsequently flows to another tank for storage. In case of two tank indirect system, two different fluids are used for heat-transfer and storage purposes.

In a single tank thermocline storage system, the hot, lighter fluid is kept on top and the dense, cold fluid at the bottom, separated by buoyancy forces. In this system a narrow separation region with large temperature gradient (called "thermocline") forms at the interface of the two isothermal regions as shown in Fig. 1. During charging process, hot fluid enters into the tank from the top causing the thermocline to move down-wards, forcing out the existing cold fluid from the bottom of the tank. While discharging, hot fluid is discharged from the top of the tank causing the thermocline to move upwards. Thickness of thermocline (region of large significant thermal gradient) depends on many parameters like the properties of the fluid, the charging/discharging flow rates, heat load and the temperature difference between the cold and hot fluids. However, various instabilities and heat loss inside the *TES* can broaden the thickness of the thermocline, thereby causing an undesirable mixing of the hot and cold fluid [5]. Thus a comprehensive understanding of stability of the thermocline is necessary in a single tank storage system.

Recent numerical simulations have revealed [6–9] many design aspects of a single tank storage system. Flueckiger & Garimella [6] have investigated the behavior of molten salt tank under cyclic

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Nomenclature

A_t	Atwood number	T_d	temperature of disturbance fluid, K
α	growth rate	T_h	temperature of hot fluid. K
d	diameter of the tank, m	T_{in}	temperature of fluid at inlet, K
h	height of the tank, m	τ	flow time, s
k	thermal conductivity, m	τ_d	duration of disturbance, s
L_p	penetration length, m	τ_h	duration of hot fluid, s
λ	wavelength, m	τ_c	Critical flow time ($\sqrt{h/A_t g}$), s
μ	viscosity, Ns/m^2	τ^*	non dimensionalized flow time ($\tau V/h$)
ν	kinematic viscosity, m^2/s	τ_p	non dimensionalized flow time (($\tau-\tau_{sd})/\tau_c$)
Re	Reynolds number	τ_{sd}	staring time of disturbance fluid, s
Re_p	perturbation Reynolds number	u	radial velocity, m/s
ρ	density, kg/m^3	v	axial velocity, m/s
T_c	temperature of cold fluid, K	g	acceleration due to gravity, m/s^2
		x	radial direction, m
		y	axial direction, m

operations. They have examined the possibility of tank shell failure via thermal ratcheting by measuring the hoop stresses. Xu et al. [9] simulated the effect of properties of filler material on thermocline behavior. They have found that the thermocline thickness can be decreased by decreasing the conductivity of filler materials. Yang & Garimella [8] have studied the effect of Reynolds number on discharge efficiency for adiabatic and non-adiabatic thermoclines. Flueckiger et al. [7] have reported the role of granule diameters on different efficiencies of a dual-media tank. A comprehensive review regarding efficiencies of a single tank storage unit can be found in Haller et al. [10]. However, these works addressed the design concerns as well as properties of filler material and heat losses rather than analyzing the thermal and hydrodynamic stabilities of the thermocline.

Recently, Qin et al. [5] have proposed four stability criteria for a filler material based single tank thermal storage. By using Darcy's flow analysis, they posited that the interstitial velocity must be under a critical value for the hot fluid to displace the underlying cold fluid. For cold fluid to displace the above hot fluid the interstitial velocity must be greater than the critical value. The proposed critical velocity is a function of gravity, velocity, density, viscosity, porosity and permeability.

None of these studies reported in the literature look at the effect of transient operating conditions on a thermocline based stable system. One such transient effect is the variation of temperature and thermo-physical properties of incoming fluid during charging operation. Such variations are quite common due to the fluctuations in solar heating. In such cases, the temporal disruption of

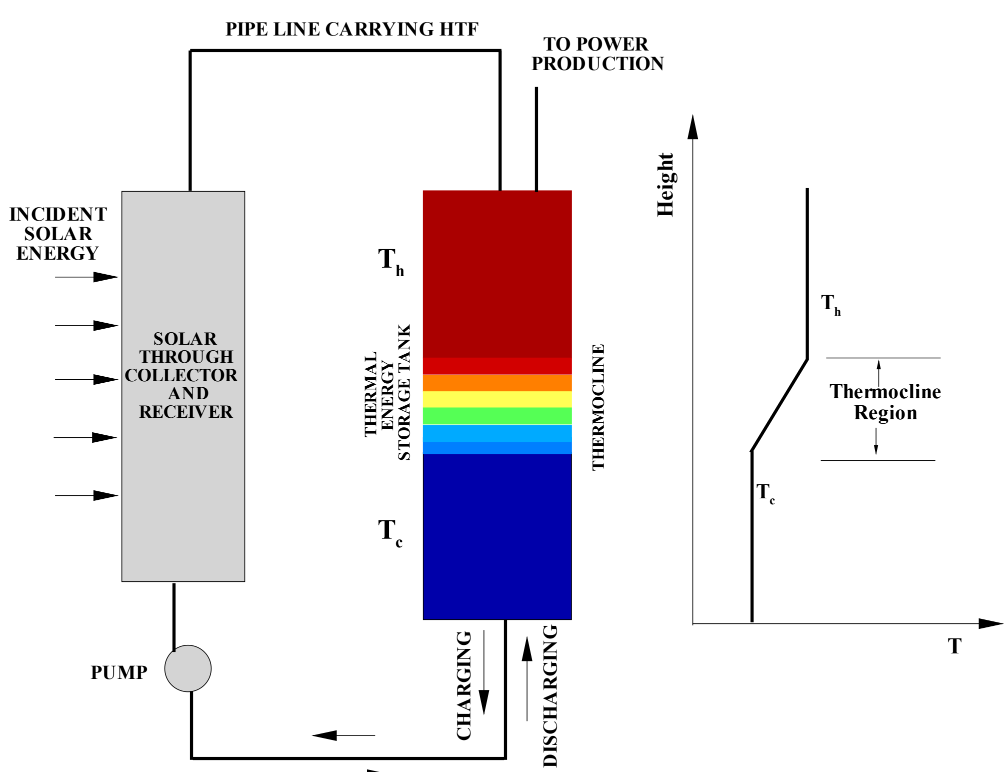

Fig. 1. Thermocline storage concept.