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Stability of packed bed thermoclines

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ABSTRACT

Packed bed thermoclines have attracted considerable interest as an economical method for storing large amounts of thermal energy. They are a constituent part of a range of proposed thermo-mechanical energy storage systems, such as Adiabatic Compressed Air Energy Storage (ACAES) and Pumped Thermal Energy Storage (PTES). The low cost of the thermal storage media (crushed rock or gravel) means that even with the cost of the required compression and expansion equipment, these systems potentially have a lower Levelised Cost of Storage than batteries, especially for grid scale storage. Packed bed thermoclines rely on a stratified temperature gradient (thermal front) between heated material at the top and cooler material at the bottom. The stability of this thermal front can affect the exergetic efficiency of the store. We present a simple criterion for the stability of a thermal front and show that during discharge of a hot store, a small cold perturbation in the thermal front can develop into a cold tunnel that propagates ahead of the main thermal front. By contrast, the presence of a small hot perturbation at the thermal front prior to charging with hot gas is shown to be quickly dissipated. We also calculate a theoretical critical perturbation size required for a cold tunnel to develop ahead of the thermal front. Below this size transverse thermal diffusion is able to dissipate perturbations before they can develop. Three dimensional Computational Fluid Dynamics simulations are used to accurately visualise thermal front instabilities and also to quantify their effect on the exergetic efficiency of a cycling thermal store. Adding a small high void fraction region near the bottom of the thermal store caused a significant disruption of the thermal front on each discharge cycle and resulted in a 4.5% increase in the exergy loss rate. Low void fraction adjacent to the walls of the thermal store, which typically occurs during packing, caused a more significant 63% increase in the exergy loss rate relative to a uniformly packed thermal store.

1. Introduction

The storage of thermal energy in packed beds of rock has been the subject of numerous studies in recent years. This interest has been fuelled by new proposals to store energy [1–7] including adiabatic compressed air energy storage (ACAES) and pumped thermal energy storage (PTES), which all depend on exergetically efficient thermal stores. A stratified packed bed thermal store is charged with hot gas entering at the top, then giving up its heat to the rocks as it flows down through the bed. Discharge is affected by pumping cold gas into the bottom, which is heated by the hot rock before leaving at the top of the store. A thermal front (also known as a thermocline) moves down and up the packed bed as it is charged and discharged. The behaviour and performance of packed bed thermal stores is often simulated with one dimensional models which assume uniformity in the horizontal direction perpendicular to the main vertical flow through the thermal store [8–13]. While these may give reasonable predictions of thermal store performance, they clearly cannot predict any 3D phenomena within the packed bed.

There are experimentally validated 3D CFD simulations of packed bed thermal stores reported in the literature that do consider transverse temperature variations in thermal stores. For example, Cascetta et al. [14] show that a radial distribution in void fraction causes non-uniformities in the thermocline. Bruch et al. [15] note that stable thermocline behaviour can be degraded by non-uniformities in the inlet flow. They evaluate a thermal store where the bottom port is on one side of the store and for certain flow regimes this asymmetry causes significant disruption of the thermal front. Zavatonni et al. [16] obtained a good match between their CFD predictions and their experimental setup by using a non-uniform porosity model. These papers constitute good evidence that the stability of the thermal front is sensitive to variations in porosity. Qin et al. [17] study the stability of a molten salt thermocline packed with a quartz or sand filler. They deduced a critical flow velocity that must not be exceeded to avoid the onset of an instability in the thermocline, described as viscous fingering. The addition of quartz or sand filler materials was found to

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Nomenclature

a	Coefficient for Ergun equation
b	Coefficient for Ergun equation
β	Diameter of a pipe
α	Fluid thermal diffusivity
γ	Effective thermal diffusivity of fluid
B	Exergy
c	Thermal front velocity
Cp_f	Fluid specific heat capacity
Cp_s	Rock/solid specific heat capacity
d	Rock diameter
D	Perturbation size
e	Coefficient for temperature dependant heat capacity
ε	Packed bed void fraction
f	Coefficient for temperature dependant heat capacity
H	Enthalpy
μ	Fluid dynamic viscosity
ρ	Fluid density
ρ_s	Rock/solid density
k	Constant relating thermal front velocity to mass flow rate per unit area
k_c	Effective fluid thermal conductivity
k_f	Fluid thermal conductivity
k_t	Effective transverse thermal conductivity
K	Area porosity tensor
L	Packed bed length or pipe length
Γ	Source term for heat transfer between solid and fluid
M	Mass flow rate per unit area
$\dot{m}$	Mass flow rate
m	Mass
ν	Kinematic viscosity
ΔP	Pressure drop
P	Pressure
Pe	Peclet number
σ	Flow resistance tensor
Q	Heat flow in or out of perturbation
R	Fill ratio
S	Cross sectional area of the bulk of the packed bed
S_c	Cross sectional area of the column control volume
T	Temperature
ΔT	Temperature difference between top and bottom of thermal store
U	Velocity vector
V	Superficial velocity
x	Height of thermal front

improve stability as compared to a simple liquid thermocline. The physics of stability of a packed bed that uses liquid as the heat transfer media is quite different to one that uses gas. A liquid can generally be considered as incompressible and the pressure drop required to push the liquid through the packed bed will tend to reduce with increased temperature due to reducing viscosity. With a gas, pressure drop will increase with increasing temperature, primarily due to the relationship between density and temperature for a perfect gas. The fundamental difference between a gaseous and liquid heat transfer media is well illustrated by considering the pressure drop in a pipe using the Darcy-Weisbach equation [18]. For illustrative purposes we consider that for laminar flow the pressure drop per unit length is proportional to kinematic viscosity and can be written as follows

$$\frac{\Delta P}{L} = \frac{128\dot{m}\nu}{\pi\beta^4} \tag{1}$$

where β is the pipe diameter, $\dot{m}$ is mass flow rate and ν is the kinematic viscosity of the fluid. Simply plotting kinematic viscosity which is a fluid property as a function of temperature shows how the pressure gradient will vary with temperature for a given mass flow of each fluid (Fig. 1).

The thermocline, in a purely liquid thermal store with no packing material, is prone to a whole set of instabilities that are not present in the context of a packed bed where the scale of turbulence and large-scale fluid structures is limited by the length scale of the packing material. For example, Van-Berkel et al. [19] made a comprehensive study of the stability of liquid thermoclines showing the development of Kelvin-Helmholtz like waves in the thermal front, and Tinaikar et al. [20] studied the widening of the thermocline due to vortices generated in this region caused by the momentum of the inlet flow. Returning to packed beds with gas as the heat transfer fluid, Zavatonni et al. [21] also studied a novel method of using phase change materials in combination with a sensible heat packed bed to improve thermal store performance. They consider the result of non-uniform porosity on the thermal front, referred to here as channelling, and then show that the addition of phase change material at the top of the thermal store helps to keep a stable discharge temperature in spite of their disrupted thermal front. A common theme in the reported experimental results and CFD analysis of packed bed thermal stores is the presence of transverse variations in the thermal profile and this is often shown to be due to non-uniform void fraction or non-uniformities in the flow.

In this paper, we focus on thermal stores with a perfect gas as the heat transfer medium. We make the fundamental observation that thermoclines are stable during the charging phase but inherently unstable during discharge. While evidence of this instability can be seen in some of the results presented in the literature, we believe this observation is a point of academic interest and may be useful information for the designers of thermal stores who are striving for maximum possible efficiency. We present a theoretical model of a simplified packed bed which highlights that when cooling a packed bed, any preferentially cooled areas will result in a lower pressure drop leading to more flow and further cooling in a positive feedback loop. A small perturbation in the thermal front is seen to grow into a cold tunnel, which leads the main thermal front. When heating a packed bed, any preferentially heated area in the thermal front will have increased pressure drop, which limits flow and results in a damping effect where perturbations in the thermal front tend to be smoothed out. We also consider the effect of transverse thermal diffusion on any instabilities and calculate a theoretical critical perturbation size. Above the critical size, perturbations can develop into significant disruptions of the thermal front but below the critical size transverse diffusion is dominant and acts to dissipate the perturbation. Finally, we present results of CFD simulations of an example packed bed thermal store. We calculate the exergy loss due to the development of a thermal front following a

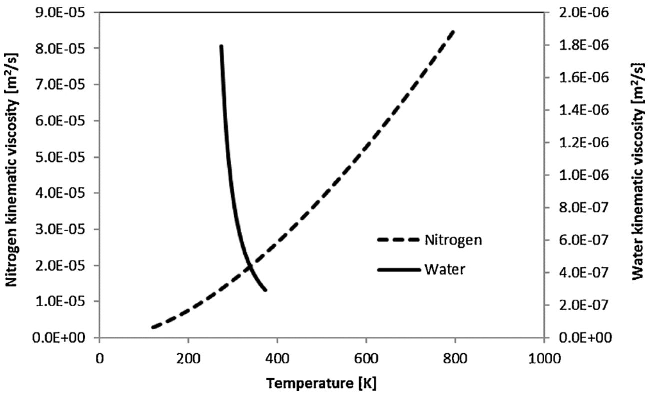

Fig. 1. Temperature dependance of kinematic viscosity for water and nitrogen.