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Mitigation against crude oil wax solidification using TES fin

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ABSTRACT

Crude oil stored in a cold subsea compartmented metal storage tank is constantly undergoing undesirable phase change. Thus, the prevention of the immobile wax formation for the ease of transportation in liquid phase becomes a daunting challenge. We hypothesize that a significant amount of thermal energy could be stored and discharged immediately after complete wax melting via embedded metallic fin(s) in retarding paraffin solidification process and to facilitate sustainable heating and shipment. This study employs the 2D enthalpy-based lattice Boltzmann method (LBM) that is capable of naturally capturing the innate propagation of mushy solid–liquid interface to explore the possibility of using thermal energy storage (TES) fin(s) in reducing the paraffin solidification process within a storage tank. In particular, the effects of cold wall cooling on compartment walls, selected adiabatic material, as well as TES-fin(s) positions and the corresponding aspect ratios to slow down paraffin solidification are discussed. Results show that the present optimized TES-fin configuration is capable of prolonging paraffin solidification by 94% immediately after complete melting. Interestingly, the mushy interface zone propagation rate during the paraffin wax solidification is reduced to a minimum, once the dimensionless length-to-width aspect ratio of TES-fin approaches 1.15 and most importantly, it is strongly position dependent. Overall, the present findings may serve as guidance for the long-term sustainable development in addressing the existing logistic issues on sustainable crude oil shipment from oil platforms.

1. Introduction

Ever since crude oil becomes one of the major energy resources, the precipitation of paraffin wax from crude oil has always been creating diverse production problems on the global scale (Wei, 2015), where downtimes are costly and mitigation solutions are expensive. Evidently, a major oil field may have spent more than eighteen million USD on washing out paraffin wax deposition alone (Dong et al., 2001). Such an issue is unfavorable during offshore operations due to the significant loss of heat within subsea pipelines as well as storage tanks, leading to system clogging (Hammami and Raines, 1999). Thermal properties of crude oil may vary to some extent, depending on its region of origin that determines its amount paraffin content. However, Watson characterization factors of crude oil vary less than 8% globally, based on the sample of worldwide crude oil properties (Raizi and Daubert, 1980; Whitson, 1983). In general, paraffin wax deposits demonstrate non-Newtonian characteristics and are highly adhesive to surfaces, which cause choking and most importantly reduce crude oil production over time (Hoteit et al., 2008). The upstream petroleum industry suffers a significant logistic loss such as shipment delays owing to the immobility of paraffin wax deposits, which occupy precious space in subsea storage tanks. The formation of paraffin wax is mainly caused by cold surrounding below the wax appearance temperature (WAT), which induces solidification of paraffin components in crude oil (Srivastava et al., 1993). The existing commercial solutions to mitigate such undesired paraffin wax formation include but not limited to mechanical cleaning, chemical injection and thermal insulation. Each approach possesses underlying disadvantages such as high capital cost, viability and possible environmental contamination. Even though paraffin wax is deemed undesirable, wax formation is possibly reversible and crude oil is likely to recover its Newtonian characteristics and reclaim its production value once subjected to temperatures higher than WAT (Haj-Shafiei, 2011).

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Nomenclature

c_p	Specific heat capacity, $J\,kg^{-1}\,K^{-1}$
D	Distance of solid–liquid interface, m
$f\,(x, t)$	Probability distribution function
$f^{eq}\,(x, t)$	Equilibrium distribution function
f_l	Liquid phase fraction
Fo	Fourier number
e_k	Lattice discrete velocity
H	Specific enthalpy, $J\,kg^{-1}$
l	Length, m
L	Latent heat of fusion, $J\,kg^{-1}$
k	Thermal conductivity, $W\,m^{-1}\,K^{-1}$
Ste	Stefan number
q	Heat flux, $W\,m^{-2}$
t	Thickness, m
T	Temperature, K
T_i	Initial temperature, K
T_0	Constant wall temperature, K
w	Weight factor
Z	Dimensionless parameter for transcendental equation

Greek letters

κ	$k_s/(\rho\,c_p)_{fin}$, $m^2\,s^{-1}$
ρ	Density, $kg\,m^{-3}$
α	Thermal diffusivity, $m^2\,s^{-1}$
θ	Dimensionless fin temperature
υ	$k_s/\left[D_y\,(\rho\,c_p)_{fin}\,l_{cprt,x}\right]$, s^{-1}
φ	Dimensionless time difference
Ψ	Solidified volume, %
ξ	Fin aspect ratio
λ	Solution for transcendental equation

Subscripts

ave	Average
l	Liquid phase
k	Direction index
m	Phase change
s	Solid phase
x	x-direction
y	y-direction

Superscripts

*	Dimensionless parameter
j	Iteration level

Recent studies have confirmed that heat transfer and molecular diffusion are the most dominant mechanisms responsible for the formation of paraffin wax in crude oil (Bidmus and Mehrotra, 2009). It is important to note that heat conduction plays a more pronounce role in wax deposition, i.e. solidification of paraffin within a storage tank, with respect to molecular diffusion and natural convection (Hoteit et al., 2008). Moreover, the WAT of crude oil was reported to be equivalent to the melting and solidification temperature of paraffin during various wax precipitation experiments (Bidmus and Mehrotra, 2008a, 2008b). Hence, exploration of mitigation methods against formation of crude oil wax can simply be focused on an exothermic heat conduction process in addition to solidification.

Thermal energy storage (TES) is a technology that reserves thermal energy in a storage medium to harness the stored energy later, mainly for system heating and cooling applications. To date, the technologies are leading towards long-term sustainability in order to promote efficient utilization of renewable energy. TES systems can be categorized into three major classes, namely: sensible and latent heat, as well as chemical thermal storage. Among these three classes, latent heat TES systems generally possess higher thermal energy storage capacity, allowing it to function at quasi-isothermal operation. Extensive research has been dedicated to thermal analysis and development of better phase change materials (PCMs). Recent investigations proved that PCM can be packaged into a mobilized TES unit (M-TES) to be deployed for the recovery of waste heat from the energy-emitting industrial sector to the energy-consuming residential sector, which shows promising results for replacement of conventional district heating (Guo et al., 2016; Wang et al., 2015). However, as thermal energy charge/discharge is the main feature of TES systems, PCM is hindered with low thermal conductivity (Baby and Balaji, 2014; Luo et al., 2008), despite the presence of enhancers such as porous matrix (Mancin et al., 2015; Warzoha et al., 2013; Tao et al., 2016), composites (Wang et al., 2009), and nano-materials (Hossain et al., 2015; Jourabian et al., 2013) of high thermal conductivities. One of the earlier analysis using fluid as sensible heat TES in a heat exchanger suggested that latent heat TES systems do not offer conclusive advantages in terms of system efficacy, thermophysical characteristics, and costs (Bjurstrom and Carlsson, 1985). The researchers inferred that latent heat TES systems tend to leave behind traces of unutilized and unavoidable thermal energy losses. Such feature results in long durations in either charging or discharging of thermal energy, and is predominantly affecting numerous industrial applications in thermal protection of electronics, vehicles thermal comfort, and thermal management of food (Sobolciak et al., 2016).

Prior to the emergence of the lattice Boltzmann method (LBM), mathematical modelling of solid–liquid phase change was mostly built on the basis of continuum equation, which encountered difficulties in generating numerical solutions due to the requirements of matching properties in both the solid and liquid phases (Baldoni and Rajagopal, 1997). It is crucial to note that the LBM permits an explicit approach in solving heat transfer problems involving phase change. The great advantages of employing LBM are the direct implementation of boundary conditions in complex geometries (Chen et al., 2014; Chai and Zhao, 2013), and a speedy numerical operation via simple parallelization in computation (Obrecht et al., 2011). In 2001, Jiaung et al. coupled the enthalpy formulation to the LBM to simulate two dimensional (2D) transient heat conduction with phase change, whereby mushy solid–liquid interface formation is a natural manifestation of the changes in local enthalpy states. Later, Huber et al. (2008) successfully incorporated the buoyancy effect into Jiaung et al.'s numerical algorithms, resulting in the LBM's newfound ability to simulate natural convection upon melting. Farid and Mohamed (1987) as well as Farid and Husian (1990) experimentally evaluated the melting and solidification of an encapsulated PCM in both horizontal and vertical rectangular enclosures. Note that one-dimensional (1D) heat transfer was assumed in all cases of the former study. In the latter study, a constant heat flux was imposed at one side of the vertical slab; the results obtained revealed the requirement to perform 2D heat transfer analysis. In fact, earlier computational studies reveal that the variation between 2D and 3D models has shown to be below 10%. For instance, a phase change heat transfer simulation performed on a PV/PCM (Photovoltaic/ Phase Change Material) system determined that the 2D and 3D models vary only for approximately 4.9% from each other (Huang et al., 2007). An approximated analytical approach was proposed by Lamberg to analyze solidification heat transfer in a PCM-type TES system. It was reported that solidification at macroscopic scale was mainly dominated by conductive heat transfer, and the strength of natural convection decreased drastically with time (Chabot and Gosselin, 2017; Lamberg, 2004), unlike dendritic growth at the microscopic scale (Kowalewski and Gobin, 2004).

Despite the fact that researchers have paid great attention on PCM, highly heat conductive materials, e.g. metals, as part of the thermal energy storage medium are underutilized. The discharging process of metallic fin inserts in a PCM-metal enclosure, in which PCM is now the beneficiary has not been fully understood and may be important for the development of possible TES alternatives. However, to the best of our knowledge, so far very few experimental and simulation studies