



Full Length Article

Transient mass transfer ahead of a hot solvent chamber in a heavy oil gravity drainage process

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ABSTRACT

As one of the hybrid steam–solvent processes, hot solvent injection is a promising heavy oil recovery technique. It takes advantage of both thermal recovery processes (quick thermal conduction and viscosity reduction) and solvent-based processes (lower energy consumption and less green-house gas emission). In comparison with conventional cold solvent processes, hot solvent processes can greatly improve oil production. This paper develops a transient mass transfer model to analyze the heavy oil–hot solvent mixing process during a hot solvent injection process. Modeling results show that a moderate elevation in temperature leads to a slight improvement in solvent dissolution but a large enhancement in oil drainage. It is found that the gravity drainage rate of solvent-diluted heavy oil depends strongly on the heated oil viscosity. Furthermore, it shows that temperature falloff slows down oil drainage, which suggests that temperature should be maintained stable during a hot solvent injection process.

1. Introduction

There are about eight trillion barrels of non-conventional heavy oil in place all around the world, which are mainly located in Canada, Venezuela, and Russia. Recovery of such viscous crude oils has practical importance due to the depleting reserves of conventional oils and the increasing demand for fossil fuels [6,7]. Producing such heavy crudes from underground is a rather challenging task because of their high viscosity and low mobility under reservoir conditions. Viscosity reduction is normally the first and key step in an in-situ recovery process. Generally speaking, there are three categories of methods to make heavy oil from almost motionless to readily mobile.

The first method uses heat to reduce heavy oil viscosity. As shown in Fig. 1a, heavy oil becomes less viscous and flowable. Another method to bring down heavy oil viscosity is through solvent dilution, which is realized by continuous or periodic injection of a liquid solvent (benzene, kerosene, toluene, etc.) or a vaporized solvent (light alkanes, nitrogen, carbon dioxide, etc.) [3–5,10,35,18]. With an increase in solvent content, heavy oil viscosity can also be brought down from hundreds of thousands of centipoises to a fairly low level (Fig. 1b). However, due to the constraint in an oil produc-

tion rate, this type of techniques such as vapor extraction (VAPEX) [11,3] and cyclic solvent injection (CSI) [23] are still in the stage of laboratory research and development at present. Even so, these processes have some prominent advantages over thermal recovery methods, including fewer surface facilities, less energy consumption, and in-situ upgrading [39].

The last method combines heating and dilution together to take advantage of both processes, so as to recover bitumen in a more cost-efficient and environment-friendly manner. A variety of hybrid processes have been proposed in the past two decades. One hybrid process is the simultaneous or alternately injection of steam and solvent, which is represented by expanding-solvent SAGD [27,28,2,30,18], a solvent aided process [13–15], and other forms. Another hybrid process is the injection of a heated solvent, represented by hot solvent injection [29,16]. For example, a patented solvent injection process, Nsolv, injects a pure and moderately heated solvent to extract heavy oil. It is being tested in an Athabasca pilot plant and its performance was reported to be promising in terms of oil production, greenhouse gas emission reduction, in-situ upgrading, and energy consumption [29].

The idea of using a hot vaporized solvent to recover heavy oil from an underground reservoir has been studied for almost four decades [1]. Previous studies on such processes were tested mainly through physical ex-

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Nomenclature

Notations

A_o, B_o	constant coefficients in Eq. (12)
A_s, B_s	constant coefficients in Eq. (13)
c	concentration, dimensionless
c^*	saturation concentration, dimensionless
D	diffusivity, m^2/s
f_s, f_o	weight volume factors for a heavy oil and a hot solvent, dimensionless
g	gravity acceleration, m/s^2
k	absolute permeability, m^2
$k_{ro,rw}$	oil-phase relative permeability at min water saturation, dimensionless
L	length, m
m	Corey coefficients, dimensionless
q	oil flow rate, m^3/s

S_o, S_{io}, S_{or}	oil, initial oil, and residual oil saturation, dimensionless
S_{wc}	connate water saturation, dimensionless
t	time, s
T	temperature, $^{\circ}C$
u	gravity drainage velocity, m/s
U	boundary moving velocity, m/s
x	distance, m

Greek symbols

α, β	constant coefficient in Eq. (17)
γ_o, γ_s	specific gravities of oil and solvent, dimensionless
θ	slip angle, degree
μ_o, μ_s, μ	oil, solvent, and mixture viscosity, Pa·s
ξ	distance in a moving frame, m
ρ, ρ_g	densities of mixture and solvent vapor, kg/m^3
τ	time in moving frame, s
ϕ	porosity, dimensionless

perimentation and numerical simulation [23,16,45]. Both approaches have their respective inherent limitations to understand the fundamental recovery mechanisms. For example, sandpack tests have difficulty in exhibiting the dynamic fluid properties in a transition zone, whereas simulation results can be misleading due to the relatively larger numerical

dispersion and smaller physical diffusivity [32,37,38,36,12], and a grid-block size for field-scale simulation is usually too big (about 1 m) to accurately characterize the transition zone (thickness is around 0.20 m in a field-scale solvent vapor extraction process) [41]. Therefore, accurate modeling studies are desirable to better comprehend these processes.

This paper develops a mathematical model for the transient mass transfer of hot solvent in heavy oil. Fluid properties across a transition zone such as solvent concentration, viscosity, diffusivity, and a drainage velocity are accurately calculated. Sensitivities of solvent injection temperature, heavy oil viscosity, and a temperature variation to the solvent dissolution and oil drainage rate are analyzed, respectively, and the corresponding conclusions are made.

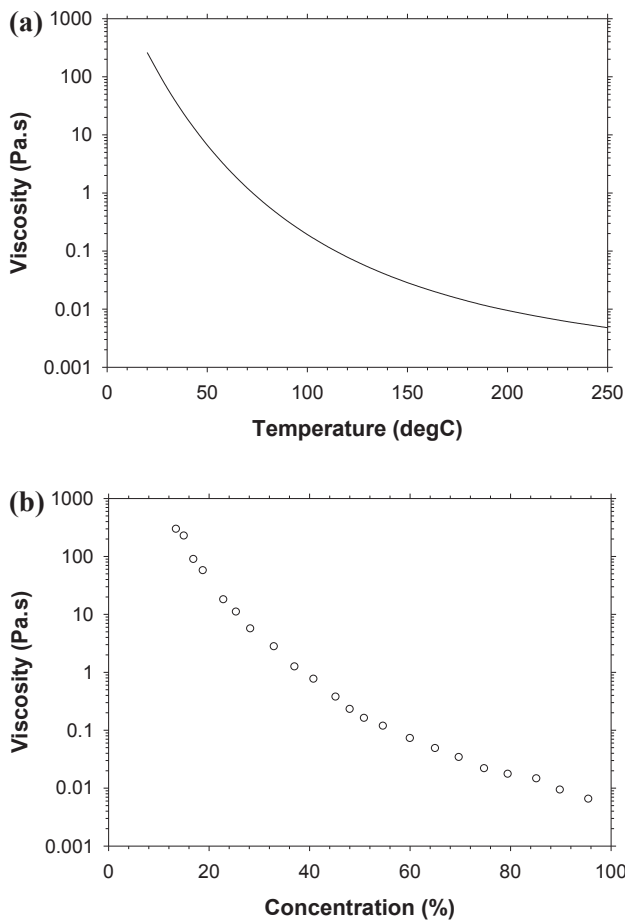


Fig. 1. Respective effects of (a) temperature and (b) solvent concentration on the viscosity of Athabasca bitumen [26,3].

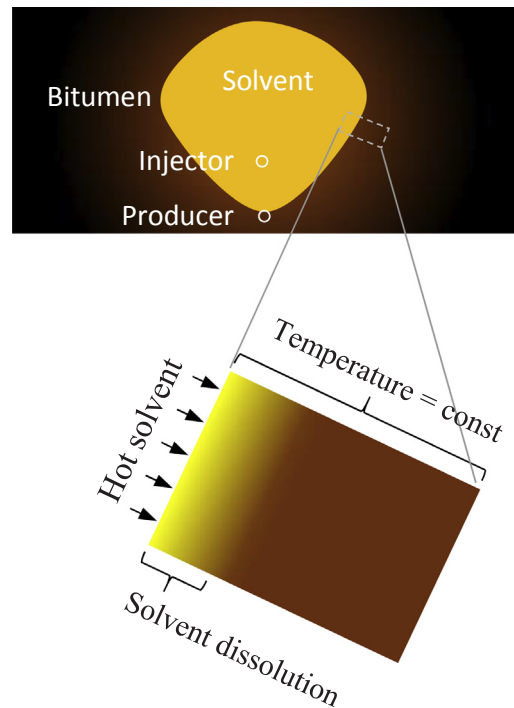


Fig. 2. Schematics of a hot solvent process.

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