



# Effect of vapour–liquid phase behaviour of steam–light hydrocarbon systems on steam assisted gravity drainage process for bitumen recovery

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## ABSTRACT

The vapour–liquid phase behaviour of steam–solvent (light hydrocarbon) systems used in an oil sands recovery process called steam assisted gravity drainage (SAGD) is examined. Analysis shows that condensation occurs over a temperature range and that a concentration gradient exists between the liquid and vapour phases. In a large range of solvent concentrations, water condenses first from the vapour phase. Solvent only condenses first from the vapour phase at extremely high solvent volume fractions. Due to water condensing first at most concentrations, the ability of the solvent to directly contact the bitumen in the reservoir depends on the orientation of the vapour–liquid interface and the relative position in the vapour chamber. Addition of solvent into a mature SAGD operation can also cause a temporary suppression of the steam–oil ratio (SOR) due to the change in the temperature at the vapour–liquid interface. This effect must be taken into account in interpreting experimental or simulation results. The addition of solvent not only changes the temperature but also decreases the heat of condensation of the mixture. As the concentration of solvent changes, the SOR is also expected to change.

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## 1. Introduction

Steam assisted gravity drainage (SAGD) is a thermal process currently being developed for widespread commercialization of bitumen recovery in Western Canada [1]. When it is applied to suitable reservoirs, SAGD is capable of high production rates and recovery factors exceeding 65% [2]. A major drawback of the process is its high energy intensity and associated CO<sub>2</sub> emissions.

A process called expanding solvent SAGD (ES-SAGD) or solvent co-injection with SAGD is currently under intensive research to help address the high energy costs of SAGD. In general, the new technique continuously injects vaporized hydrocarbons, such as propane, butane, up to C<sub>12</sub>, or in various mixtures, along with the steam [3–5]. The injected solvent is intended to assist bitumen recovery through dissolution into the oil phase to reduce bitumen viscosity in conjunction with the viscosity reduction through heating. Many studies and trials project that the addition of solvent will increase recovery rates and simultaneously reduce the steam usage or steam oil ratio (SOR) [6–8].

One aspect of solvent co-injection with steam that has not been studied is the vapour–liquid phase behaviour involved in solvent–steam co-injection process. It is not well understood how the co-injection can impact the gravity drainage process. In a constant pressure process like SAGD where only one component (water) is used, the dew point and bubble point temperatures are the same.

When hydrocarbon solvents are mixed with water, partial pressures come into play such that the dew point and bubble point of the system separate. In the steam chamber, the concentrations of water and solvent in the liquid and vapour phases are transient between the dew point and bubble point. The appearance of a temperature range for condensation and a concentration gradient between liquid and vapour phases introduces additional considerations when applying solvent co-injection. In this paper, both the phase behaviour and the potential impact on SAGD are examined.

## 2. Water–hydrocarbon vapour–liquid phase behaviour

To illustrate the vapour–liquid phase behaviour of water–hydrocarbon systems, a phase diagram of water–hexane (C<sub>6</sub>) mixture is generated for a system in a typical pressure–volume–temperature (PVT) test cell. Similar to a SAGD vapour chamber, the pressure in PVT cell is maintained constant. In this case, the phase change is achieved by the change in cell temperature through heat transfer between the mixture inside the cell and the heating system on the exterior of the cylinder. When the temperature changes, to keep the pressure constant, the cell volume is allowed to change to compensate for the changing densities and phases.

The PVT cell begins with a mixture of 0.03 mole fraction C<sub>6</sub> and 0.97 mole fraction H<sub>2</sub>O (corresponding to 18% liquid volume fraction of C<sub>6</sub> at 25 °C) both in vapour form at 2.0 MPa. Steam–solvent hybrid studies often suggest applicability to low pressure reservoirs and typically use pressures ranging from 1.5 to 2.2 MPa for both

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simulation and laboratory studies [3–9]. Thus 2.0 MPa was chosen so as to conform to the wide range of previous studies. The cell temperature is reduced at constant pressure until the vapour first begins to condense (in PVT cell case the cell volume is decreased at constant composition condition). Liquid for either component first appears when the temperature equals the saturation temperature of the component at its partial pressure as seen in the following equation:

$$T \leq T_{\text{sat},i}(x_i P_{\text{cell}}) \quad (1)$$

where  $T$  is the cell temperature,  $T_{\text{sat},i}$  is the saturation temperature of  $i$ th component, and  $P_{\text{cell}}$  is the cell pressure.

The water–hydrocarbon vapour–liquid phase behaviour is calculated using tabular thermophysical properties of pure substances obtained from the National Institute of Standards and Technology (NIST) Chemistry WebBook (<http://webbook.nist.gov/chemistry/>). The following steps were applied to create a plot of temperature and mole fraction for a solvent mixed with water at a constant total pressure:

- (1) Plot temperature–composition line for water condensation using

$$T = T_{\text{sat,H}_2\text{O}}[(1 - x_{\text{Solv}})P_{\text{cell}}] \quad (2)$$

- (2) Plot temperature–compositions line for solvent condensation using

$$T = T_{\text{sat,Solv}}[(x_{\text{Solv}})P_{\text{cell}}] \quad (3)$$

- (3) Draw horizontal line at intersection point between water and solvent condensation lines.

For water–C6 system, the first condensate occurs at 483.9 K for water. However, as water condenses out of the vapour phase, its mole fraction in vapour phase decreases. Reduction of mole fraction and partial pressure reduces the temperature at which water will condense. This means that the condensation of water proceeds at constantly decreasing temperatures. At the same time, the mole fraction and partial pressure of C6 gradually increases which in turn raises the saturation temperature of C6. Water continues to be the only component condensing until the mole fractions of the two components remaining in the vapour phase reach such a ratio that both of them have partial pressures corresponding to the current cell temperature and condense simultaneously. For the system used in this example at 2.0 MPa, the co-condensation occurs at 446.1 K with a C6 mole fraction of 0.575. At this point, both water and C6 will condense at constant temperature until all the vapour in the PVT cell becomes liquid.

If these calculations are performed for the entire range of mole fractions, Figs. 1 and 2 can be generated. Fig. 1 shows the concentration of

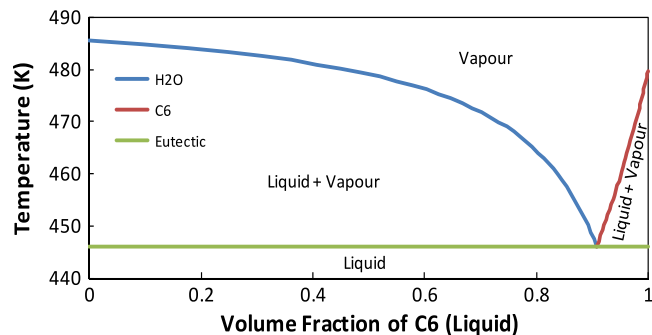


Fig. 2. Condensation temperature of water and hexane mixture at 2 MPa as a function of liquid volume fraction of hexane (calculated at 25 °C).

C6 in mole fraction and Fig. 2 shows the concentration of C6 in liquid volume fraction both at 25 °C. The upper curved lines show the temperature and concentration where the first component begins condensing. The curve on the left side indicates fractions where water condenses first while the curve on the right side indicates the fractions where C6 condenses first. The lower horizontal line shows the temperature at which both components have fully condensed to the liquid phase. Furthermore, application of the lever rule to Fig. 1 can calculate mole fractions remaining in the liquid or vapour phase.

Figs. 1 and 2 show that regardless of starting concentration, the temperature and concentration at which both components will condense simultaneously remains constant (with constant pressure). It is also apparent from the graphs that the two vapour–temperature curves also express the lowest temperature at which that specific composition can exist in the vapour phase. Thus the two curves can also be viewed as showing the concentration of the vapour phase with temperature.

Figs. 1 and 2 ignore the small amount liquid solubility of solvent in water and vice versa. Since the solubility is very low, the results are not significantly impacted. To demonstrate this, Fig. 3 shows a reproduction of Fig. 1 generated using CMG WinProp [10]. Differences appear when comparing the calculated boiling points of pure substances while the overall shape of the diagram remains unchanged. Another difference is the liquid solubility of water in C6 which produces a single phase liquid region on the far right side of the diagram.

Similar calculations with differing solvents or at varying pressures can be performed to obtain charts with similar overall shapes and behaviour as shown in Figs. 1 and 2. Looking at the entire range of solvents and potential pressures for a steam–solvent process, it becomes clear through Figs. 4–7 that the majority of the

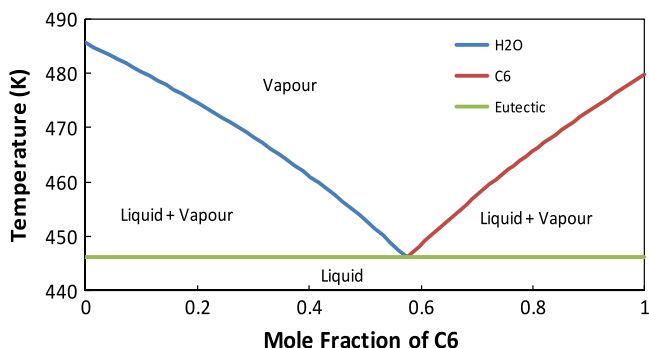


Fig. 1. Condensation temperature of water and hexane mixture at 2 MPa as a function of mole fraction of hexane.

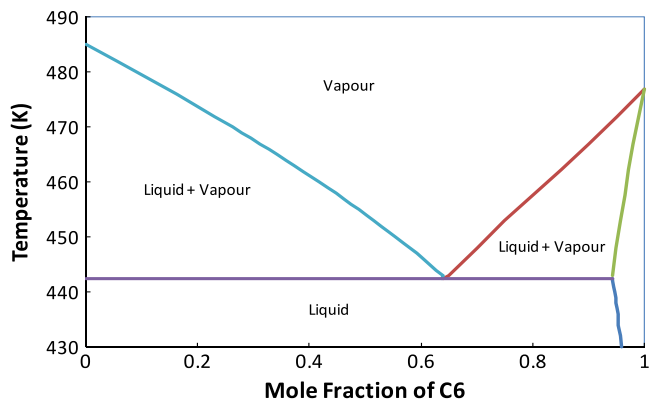


Fig. 3. WinProp reproduction of Fig. 1.

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