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Numerical simulation investigations of the applicability of THAI in situ combustion process in heavy oil reservoirs underlain by bottom water

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Abstract

The presence of a bottom water (BW) layer in heavy oil reservoirs can present substantial problems for efficient oil recovery for all recovery techniques. Hence, it is necessary to know how particular production processes are affected by different BW layer thicknesses, and how standard production procedures can be adapted to handle such reservoirs. Toe-to-heel air injection (THAI) is a thermally efficient process, generating in situ energy in the reservoir by burning a fraction of the oil-in-place as coke and has the potential to economically and environmentally friendly work in reservoirs with BW layer. However, to ascertain that, studies are needed first. These are conducted via numerical simulations using commercial reservoir thermal simulator, CMG STARS. This work has shown that the shape of the combustion zone in THAI remains forward-leaning even in the presence of a BW layer, indicating that the process is stable, and that there is no oxygen bypassing of the combustion front. However, the oil recovery rate is highly negatively affected by how large the thickness of the BW zone is, and the severity of such effect is determined to be proportional to the thickness of the BW layer. This study also shows that there is a period of low oil production rate which corresponds to mobilised oil displacement into the BW zone which in turn causes a surge in water production rate. The practical implication of this is that prolonged period of low oil production rates will expose companies and/or investors to higher risk due to the oil market volatility. In this study, it is also revealed that the height of the mobilised oil that is displaced into the BW zone equates to that of the displaced and replaced water thereby implying that when the BW layer thickness is 50% that of the oil layer (OL), less than 50% of the mobilised oil will be recovered when the entire reservoir is swept by the combustion front. Therefore, conclusively, applying the THAI process in its conventional form in reservoirs containing bottom water is not recommended, and as a result, a new strategy is needed to enhance process economics by improving the oil production and hence recovery rates.

Keywords

In situ combustion (ISC); Enhanced oil recovery (EOR); Tar sand/heavy oil/bitumen; Reservoir simulation; Toe-to-heel air injection (THAI)

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1. Introduction

Toe-to-heel air injection (THAI) is a variant of conventional in situ combustion (ISC) that uses a horizontal production well to recover mobilised partially upgraded heavy oil or bitumen. The Whitesands THAI field pilot at Conklin, Alberta, Canada, operated for five years by Petrobank, upgraded the bitumen by up to 4.5 API points (Petrobank, 2007, 2008, 2009). In addition, the THAI pilot run by Petrobank at Kerrobert, Saskatchewan, Canada, initially produced oil upgraded by up to nearly 6–8 API points. Its follow-on semi-commercial expansion achieved in situ upgrading in the range of 4–6 API points (Turta, 2018). This represents significant 'added value' to producers of lower value heavy oil and bitumen. The THAI process has a number of advantages, such as high energy efficiency, requirement of minimal surface upgraders, providing environmentally friendly operation since CO_2 can be sequestered, providing heavy-to-light oil upgrading within the reservoir, etc. (Ado, 2021a, 2022; Rabiu Ado, 2017; Rabiu Ado et al., 2018; 2017; Turta et al., 2020; Wei et al., 2020a, Wei et al., 2020b), over the currently used steam-based heavy oil commercial recovery techniques which are water-, wastewater-, energy-, and carbon-intensive, etc. (Gates, 2010; Gates and Larter, 2014; Shi et al., 2017; Wang et al., 2019; Zhao et al., 2013, 2014). However, it is necessary to understand how the THAI process can be run effectively in less than ideal reservoirs, such as those with bottom water.

It is common to find bitumen and heavy oil deposits underlain by a bottom water layer (BWL). The Whitesands Pilot had an oil zone thickness of 30 m and a bottom water thickness of ~1–2 m (Petrobank, 2009). Water production is an inevitable outcome for reservoirs with a BWL (Zhao et al., 2006). For example, attempts to produce heavy oil reservoirs in Saskatchewan by conventional steam-based means rapidly result in excessive water production (Saskoil and Butler, 1990). However, it seems likely that careful design of production process and well placement can significantly alter outcomes, and, thence, the efficiency of oil production.

For the SAGD process, Saskoil and Butler (1990) have shown that the higher the thickness of the BWL compared to that of the oil layer (OL), the lower the cumulative oil recovery. However, they found that water production from the BWL was greatly reduced by operating the production wells at pressures close to that of the BWL, and that the well configuration adopted had a significant effect on cumulative oil recovery. Liu et al. (2014) conducted numerical simulation studies of feasibility of application of SAGD process in offshore heavy oil reservoirs that are underlain by bottom water (BW) layer. They found that the process performance is highly negatively affected to the extent that the ultimate oil recovery is decreased by up to 10% OOIP.

A field trial of in situ combustion (ISC) in a reservoir with BWL at North Tisdale, Wyoming, had a low oxygen utilisation and it is thought this was because the injected air flowed through the BWL (Turta et al., 2009). However, a number of other field trials of ISC in reservoirs with BWLs have shown no clear evidence of air bypassing the combustion zone through the bottom water. Given these mixed findings from the field, more detailed investigation of the problem is required.

The impact of BW on ISC has also been studied experimentally using a physical model of a heavy oil reservoir, where the underlying BWL was either one-third or two-thirds the thickness of the oil zone (Turta et al., 2009). In this laboratory-scale study of ISC, it was found that the combustion front remained in the upper part of the sand-pack and only a limited amount of oil drained into the BWL, mainly near the injector and producer wells. It was also concluded that the combustion-front propagation was unstable, with a propensity to die-away, perhaps when the flow went predominantly through the BWL (Turta et al., 2009). The laboratory-based model facilitated inspection of the sand-pack following the end of the experiment which revealed a carbonized layer formation at the uppermost boundary of the BWL, and which may have limited air flow through the BWL (Turta et al., 2009). Overall, the laboratory tests showed that, at the start, the combustion front developed mainly at the oil-water interface, even when the injection well was perforated at its upper part. Thereafter, following the building of some hydraulic resistance due to the formation of an oil bank in the relatively cold oil region, the combustion front advanced mainly in the oil zone for a while, before finally returning to the water zone. Eventually the combustion front stalled completely. It was also suggested that air short-circuiting through the BWL led to low temperature oxidation of the oil (Turta et al., 2009). However, due to the observation of the erratic movement of the combustion front in the experiments, there is some doubt to how well experimental runs would scale-up to field scale.

Until now there has been only a single inconclusive investigation of how operation of the THAI process would be affected by the presence of a BWL available in the literature (Ado, 2020a). Turta et al. (2009) have suggested that the THAI process may be successful when the BW thickness is less than 10% of that of the oil layer. They also offered a preliminary screening criterion, which suggested applying conventional in-situ combustion in reservoirs with BWLs when the BW thickness is 25% that of the oil layer, or less. Therefore, in this paper, the models used for the simulation of THAI in reservoirs with BWLs will first be described. This work then will consider the effect of BWL thickness on the operation of the THAI process, and look at various potential strategies to reduce the potential for water production from the BWL.

2. Reservoir models development

Prior to going into details about the below-constructed reservoir models, it is worth to outline the workflow for this study. The models in this study are initially derived from the THAI physical experiment conducted by Xia and Greaves (2002) against which a laboratory-scale numerical model was developed and validated by Rabiu Ado et al. (2017). The validated model was then systematically upscaled based on sound theoretical background to full field-scale as can be found in Ado (2020b, 2020c). The field-scale model is then used in this study after aquifer (i.e. bottom water) with its properties is incorporated to it as shown below (Fig. 1) and as can be found in the other 2nd part of this study (Ado, 2020a).

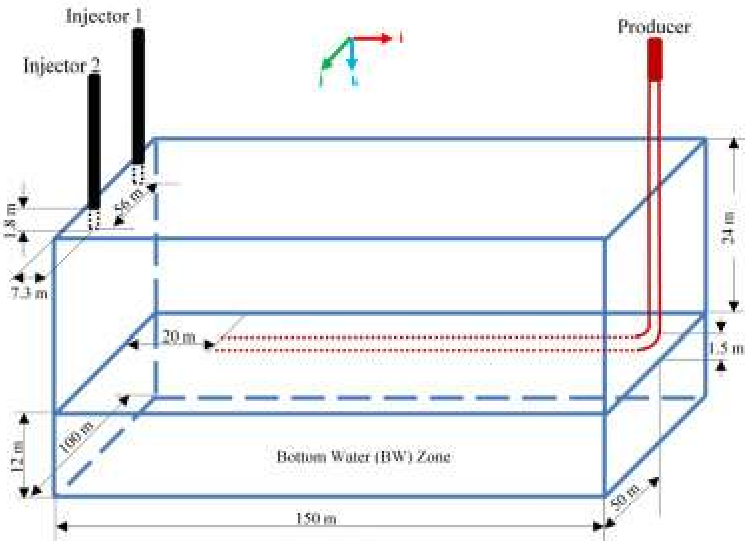

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Fig. 1. Schematic diagram of dimensions and wells layout for model of reservoir with BWL. This is for model BW2 which has BWL thickness to OL thickness ratio of 1:2.

2.1. Reservoir dimensions and wells configuration

In this study, the effect of the thickness of the BWL, compared to constant oil layer (OL) thickness, has been investigated at field scale. For this, two models, namely BW1, and BW2, were developed. The oil in the model reservoirs was Athabasca bitumen, and the oil properties were the same as those given in Rabiu Ado et al. (2018, 2017), Ado et al. (2019), and Ado (2020b, 2020c, 2020d, 2020e, 2021b, 2021c, 2021d). In BW1, the BWL to OL thickness ratio was 1:4, while it was 1:2 in BW2. For both models, the BWL was attached to the reservoir section, as shown exemplified in Fig. 1. The length of the reservoir was chosen to be 150 m because the process reaches steady state after the combustion front has swept a few metres along the axial length of the reservoir. It is also found to be enough to provide a representative result while reducing the computational time substantially. Thus, the oil layer has dimensions of 150 m by 100 m by 24 m whilst that of the bottom water zone in model BW2 is 150 m by 100 m by 12 m, thereby making the whole reservoir to have dimensions of 150 m by 100 m by 36 m (Fig. 1). For model BW1, the whole reservoir has dimensions of 150 m by 100 m by 30 m. In either of the two models, two vertical injectors (VI) wells with a horizontal producer (HP) well were configured in a staggered line drive pattern. Furthermore, in either of the two models, the HP well was located on the bottom horizontal layer of the oil layer (OL) zone which is approximately just 1.5 m above the oil-water interface (Fig. 1). This position was chosen because Lau (2000) observed an increase in oil production rate when he modelled basal combustion with the well located at the oil-water contact. It should be noted that no water source or sink wells were included in the bottom horizontal layer of the BWL zone, implying that the BW is static rather than active.

2.2. Model key input parameters

The model key input parameters which are for the actual typical Athabasca bitumen reservoir and which include the reservoir initial conditions, its petrophysical parameters, and the boundary conditions are shown in Table 1. Apart from via the VI and HP wells, a no-flow boundary condition was assigned to the whole reservoir, and as a result, only heat transfer via conduction takes place from the overburden and underburden sides of the reservoir. Prior to air injection and initiation of combustion, steam was injected via the two VI wells at a rate of 495 bbl day^{-1} for a period of 104 days which are similar to the field values reported by Petrobank (2008). The other input parameters such as the relative permeability curves, the pressure, volume, and temperature properties of each oil pseudo-component, the oil pseudo-components viscosities as function of temperature, the oil pseudo-components K-values as function of temperature and pressure, etc. can found in Rabiu Ado et al. (2017).

Table 1. Reservoir properties and injection and production conditions.

Reservoir initial temperature and pressure	**20 °C and 2800 kPa**
Initial oil (S_{oi}), gas (S_{gi}), and water (S_{wi}) saturations	S_{oi} = 80%, S_{gi} = 0%, and S_{wi} = 20%
Porosity	34%
Horizontal and vertical absolute permeabilities	6400 mD and 3450 mD
VI and HP wells internal diameter	178 mm
Producer back pressure	2800 kPa
Steam injection pressure	5500 kPa

Reservoir initial temperature and pressure	20 °C and 2800 kPa
Steam injection rate (Cold Water Equivalent)	495 bbl day^{-1} (CWE)
Air injection rate per VI well	10000 Sm^3 day^{-1}
Total air injection rate via the two VI wells	20000 Sm^3 day^{-1}

2.3. Kinetics scheme and its parameters

Ado (2020c) has identified that there are two kinds of thermal cracking or pyrolysis kinetics schemes that are used to simulate in-situ-combustion-type processes, like the THAI process. These are (i) the direct conversion thermal cracking kinetics scheme which has the forms of *[Math Processing Error]*, *[Math Processing Error]*, *[Math Processing Error]*, *[Math Processing Error]*, *[Math Processing Error]*, *[Math Processing Error]*, etc., such that each of the stoichiometric coefficients, *[Math Processing Error]* has a single value and therefore, is uniquely identified, and (ii) the split conversion thermal cracking kinetics scheme which has the form of *[Math Processing Error]* such that there are infinite number of possible combinations of the stoichiometric coefficients *[Math Processing Error]* and *[Math Processing Error]*. Therefore, the former type, which has similar forms to those developed and reported by Phillips et al. (1985), Belgrave et al. (1993), and Kapadia et al. (2013), has lower number of input parameters than the latter type, which is the same as that developed and reported by Perkins (2018). This latter type is highly indeterminable since apart from having the frequency factor and the activation energy as constant input parameters, the stoichiometric coefficients must be considered as variables rather than constant input parameters. In the same paper, Ado (2020c) went on to show that at field scale, the first type of the kinetics scheme (i.e. the direct conversion kinetics scheme) has a far better predictive ability. Another study conducted by Ado (2020e) in which comparison of simulation results of three numerical models having different kinetics schemes and their respective parameters against experimental results of the THAI process revealed that the Phillips et al. (1985) kinetics scheme which is of the form of direct conversion thermal cracking kinetics schemes has a better predictive ability than the Belgrave et al. (1993) and the split conversion thermal cracking kinetics scheme (Ado, 2020e). Therefore, the Phillips et al. (1985) kinetics scheme and parameters which were slightly adjusted and validated against 3-dimensional combustion cell experimental results of the THAI process as can be seen in Rabiu Ado et al. (2017) and Ado (2020e), which are then subsequently systematically transformed to field scale application as can be seen detailed in Ado (2020b) are used in this study. Furthermore, the kinetics scheme and its parameters have been well-tested in various studies (Ado, 2021c; 2021d). Therefore, in all the THAI numerical simulation models reported in this work, the kinetics scheme and its field scale parameters, which are listed in Table 2, are used. With regards to the combustion reactions, Ado (2020e) has shown that in the THAI process, only the high-temperature oxidation reactions are dominant and that the effect of low-temperature oxidation reactions, which are taken from the Belgrave et al. (1993) and which are in parallel to those reported by

Perkins (2018), is negligible. Furthermore, even though that the combustion reactions of the oil pseudo-components have been included, their effects in the THAI process have been found to be negligible since only a small minor fraction of oxygen is present ahead of the high-temperature-oxidation front (i.e. in the cold oil zone where, also, temperatures are very low that reaction rates are negligible).

Table 2. Field scale kinetics scheme used in this work (Ado, 2020b, 2020e). IC, Immobile pseudo-component; MC, mobile pseudo-component; LC, light pseudo-component.

Reactions	**Activation Energy (kJ mol^{-1})**	**Frequency Factor**
IC → 2.0471 MC	239.01	8.186×10^{16} (min^{-1})
MC → 0.4885 IC	215.82	7.209×10^{14} (min^{-1})
MC → 2.3567 LC	184.88	2.425×10^{11} (min^{-1})
LC → 0.4243 MC	180.45	3.264×10^{11} (min^{-1})
IC →77.4563 COKE	180.88	4.969×10^{11} (min^{-1})
IC + 98.869 O_2 → 77.456 $CO_{1.947}$ + 46.904 H_2O	138.00	2.772×10^{3} (min^{-1} kPa^{-1})
MC + 49.069 O_2 → 37.075 $CO_{1.947}$ + 25.953 H_2O	138.00	2.772×10^{4} (min^{-1} kPa^{-1})
LC + 32.025 O_2 →14.600 $CO_{1.947}$ + 35.623 H_2O	138.00	2.772×10^{5} (min^{-1} kPa^{-1})
COKE + 1.22 O_2 → $CO_{1.875}$ + 0.565 H_2O	123.00	1.530×10^{5} (min^{-1} kPa^{-1})

2.4. Simulator and discretisation

The simulations of the THAI process reported in this work were conducted with a commercial computer modelling group (CMG) reservoir thermal simulator known as STARS. However, the reservoir system chosen to be studied (Fig. 1) has to first be discretised into a number of gridblocks so that the highly non-linear partial differential equations are transformed into Algebraic equations before being coupled with the discretised horizontal wellbore equations for simultaneous solution. The STARS solves the fully implicit finite difference discretised equations using Newton methods. In the case of models BW1 and BW2, the reservoir is, in each model, discretised into 90 grid points in the ***i***-th direction × 57 grid points in the ***j***-th direction × 11 grid points in the ***k***-th direction, thereby giving a total of 56430 gridblocks which are fine enough to capture the full physicochemical processes and fluid flows. The simulations were run on a computer which has two 8-parallel processors (i.e. a total of 16 cores and 32 threads). The STARS simulator has a parallel processing solver which is called PARASOL and which is capable of using up to a maximum of 8 threads. Since the computer used has 32 threads, it implies that only 25% of the CPU of the computer was used and that was why the models did not take expensive time to be run despite the complexity of the processes governing the operation of the THAI process.

For additional details about the procedure to construct the numerical models in this study, the reader could consult the thesis of Rabiu Ado (2021b) where it explained right from development of laboratory-scale numerical models of Athabasca tar sand that is validated against experimental results (Ado et al., 2019; Rabiu Rabiu Ado et al., 2018; 2017), to developing field scale numerical models based on theoretically systematic upscaling procedure that leads to physicochemically meaningful predictions (Ado, 2020b; 2020c), to using the field scale models to carry out multiple studies of the THAI process such as exhaustive research about how to handle heavy oils and bitumen reservoirs containing bottom water in this study and its 2nd part (Ado, 2020a), extensive study of the effect of reservoir pay thickness on the performance of the THAI process (Ado, 2020d), unpublished study on best wells configuration and feasibility of incorporation of electrical heating coils around the HP well to accelerate oil production rates or for the purpose of heating an annular layer of catalyst such as exists in the THAI-CAPRI process, etc.

3. Results and discussions

As mentioned above, model BW1 had a BWL thickness of 6 m, which is 25% that of the oil layer (OL). In the case of model BW2, the thickness of BW is 12 m, making it 50% that of the OL (see Fig. 1). However, as a benchmark, to assess the performance of these two models, their oil production rates and cumulative oil recoveries were compared with those of the base-case model (BW0) which has no bottom water. To reiterate, in all the two models (BW1 and BW2), the horizontal section of the HP well was placed in the bottom horizontal layer of the oil layer zone just 1.5 m above oil-water interface, while in the base-case model (BW0), the HP well is placed in the bottom horizontal layer of the oil layer zone, just 1.5 m above the underburden. The pre-ignition heating cycle (PIHC) was conducted by injecting steam at the rate of ≈495 bbl (CWE) day^{-1} via the two VI wells and for a period of 104 days. The combustion was run for two years (i.e. 730 days) by continuously injecting 20000 Sm^3 day^{-1} of air via the two VI wells. This makes the total process time to be 834 days.

3.1. Oil production rates

In the first case study (BW0), which contained no bottom water, oil production began 60 days after the start of the pre-ignition heating cycle (PIHC). Fig. 2 shows that the presence of BWL delayed the oil production by 4 days in model BW1. In the case of BW2, the oil production began after 190 days from the initiation of air injection (Fig. 2). Throughout the PIHC, the oil production rate for model BW0 was greater than those for models BW1 and BW2. However, on commencement of air injection, model BW1 exhibited a similar characteristic behaviour to BW0 in terms of a brief surge in the oil production rate. This was caused by the displacement of already mobilised oil by the injected air. From around 210 days, the oil production rate in BW0 steadied out at a value of ≈35 m^3 day^{-1} up to the end of the combustion period (Fig. 2). For BW1, the oil production rate, over 130–210 days, was maintained at 20 m^3 day^{-1}. The production rate then increased steadily to reach a peak of 47 m^3 day^{-1} at 300 days, before it declined and remained at a constant value of 32 m^3 day^{-1} between 470 and 530 days. At point A′, at 530 days, as indicated by the blue arrow in Fig. 2, the oil rate dropped to almost zero for a period of 4 days before it thereafter picked up and increased nearly steadily, reaching 30 m^3 day^{-1} at 834 days (Fig. 2). Between 250 and 340 days, there was a steady increase in the oil production rate in BW2, from 3 to 30 m^3 day^{-1}. From 340 to 470 days, the oil production rate in model BW2 slightly increased from 30 to 32 m^3 day^{-1}. Similar to in model BW1, BW2 also had a sudden decline in oil production which occurred at point B' (i.e. 470 days), and which is indicated by the green arrow in Fig. 2. However, the abrupt drop in oil production rate in model BW2 occurred 60 days earlier than in BW1. Beyond point B′, the oil rate increased slowly, reaching a value of around 21 m^3 day^{-1} at 834 days. Overall, Fig. 2 shows that, as with SAGD, for example, the oil production rate in the THAI process is significantly affected by the presence of bottom water and that it is also dependent on the thickness of the BWL.

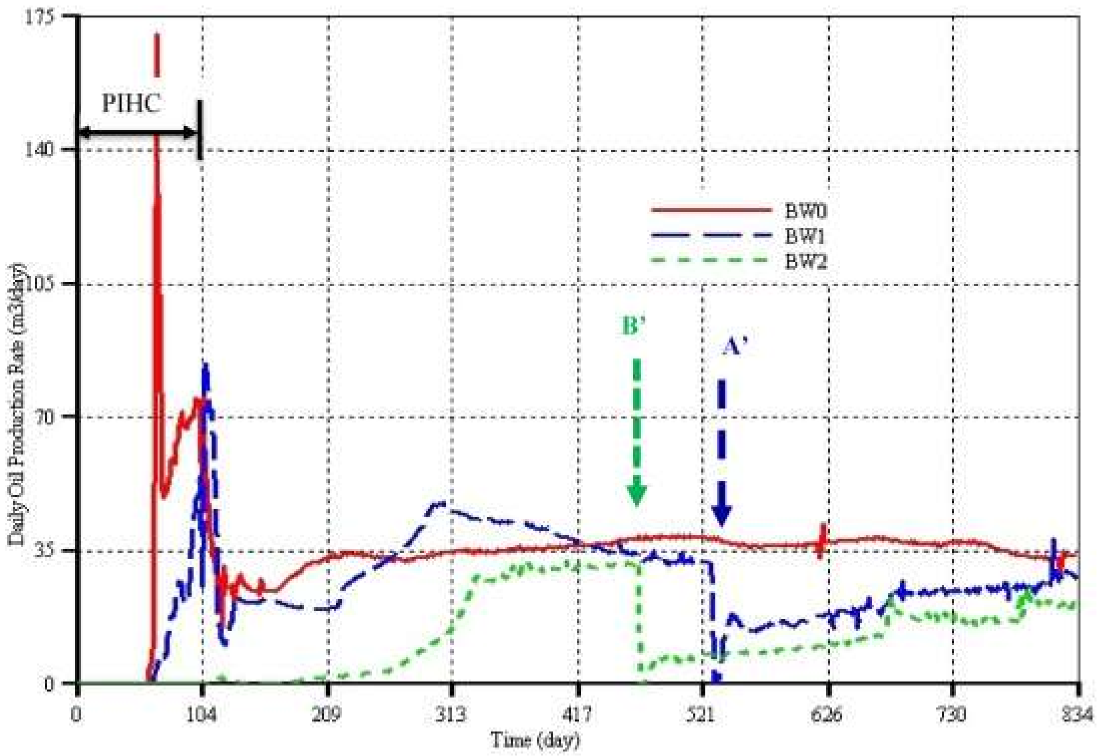

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Fig. 2. Effect of BWL thickness on THAI oil production rate.

3.2. Water production rate

Fig. 3 shows that the water production rate predicted by model BW0 was lower than that for models BW1 and BW2 throughout the duration of the process except at between 500 and 530 days where that in model BW1 is lower. This was because only the reservoir water and that generated by combustion were being produced in model BW0. During the PIHC, models BW1 and BW2 had essentially the same water production rates, which indicates that nearly the same quantity of oil was mobilised by the steam and displaced into the BWL zone. The large mobility contrast between oil and water meant that the latter was forced to flow to the producer well due to displacement by the former. Since the water production rate for BW2 was larger than that for BW1 throughout the combustion period, it follows that the thicker the BWL, the higher the water production rate. This is also supported by the earlier observation showing that BW2 has lower oil production rate (Fig. 3). As will be shown later, the thicker the BWL, the larger the quantity of the mobilised oil that can be trapped into the thief zone (i.e. the BWL). It is noted in Fig. 3 that there was a period of sudden surge in water production rates seen for both BW1 and BW2 models. In particular, it can be seen in Fig. 3 that, the periods of these surges, marked as points A and B for BW1 and BW2, respectively correspond to the periods of sharp drop in oil production rates found in Fig. 2. The sudden rise and fall in water and oil rates respectively, and their respective gradual decrease and increase are caused by the drainage of the mobilised oil into the BWL zone. This occurs when the mobile oil zone (MOZ) approaches the 'end of the drained oil zone'.

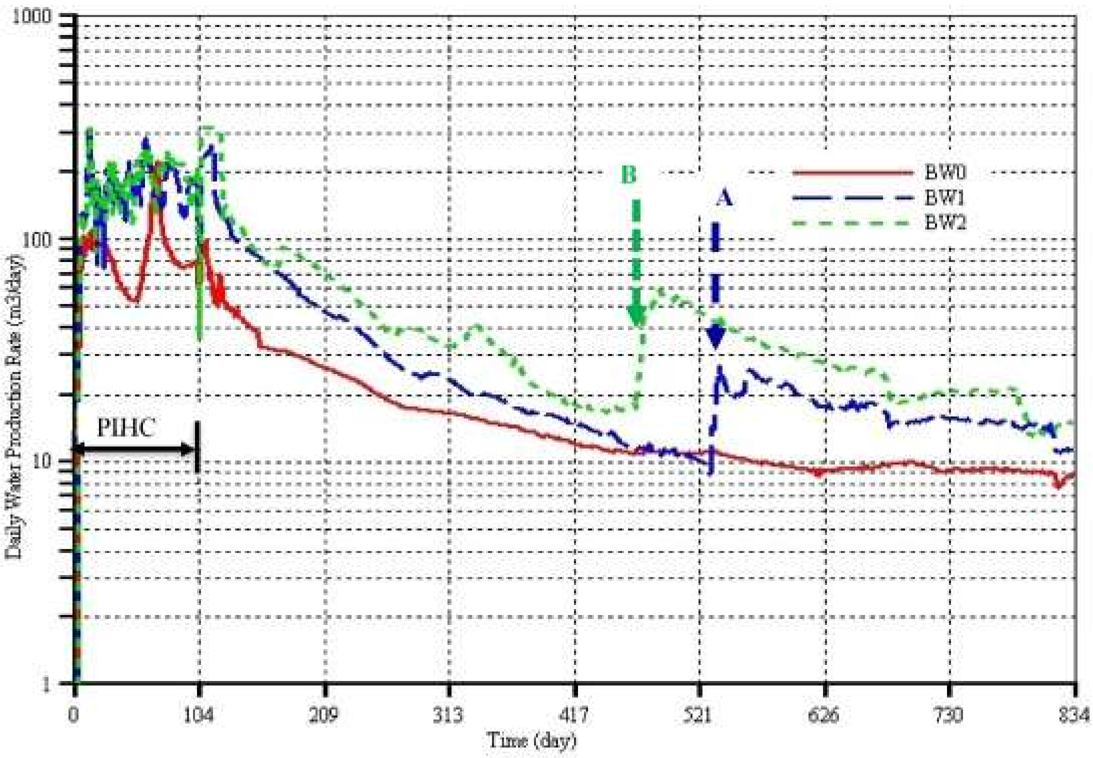

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Fig. 3. Daily water production rate for reservoir models with differing BW thickness. The double-headed arrow indicates the PIHC.

3.3. Cumulative oil production

Fig. 4 shows that using the same air injection rate (and hence the same cumulative volume of air), the cumulative oil produced depends upon the thickness of the BWL. When the BWL thickness was a quarter of the OL thickness (i.e. in model BW1), the cumulative oil recovered decreased from 28420 m^3 in BW0 to 21660 m^3, which was a 24% decrease. Further, an increase in the BWL thickness to half that of the OL thickness (i.e. in model BW2) resulted in a decrease in the cumulative oil production by 65% of that recovered in model BW0. This shows that increasing the BWL thickness by a factor of two caused a reduction in the cumulative oil production by a factor of around 3, implying that the thicker the BWL relative to the oil layer, the worst the performance of the THAI process in reservoir with BW. In addition, the periods of sharp decline in oil production rates could be observed in the cumulative oil production curves of models BW1 at 530 days and BW2 at 470 days, where they are marked by the sudden decrease in the slope of the two curves (Fig. 4) respectively.

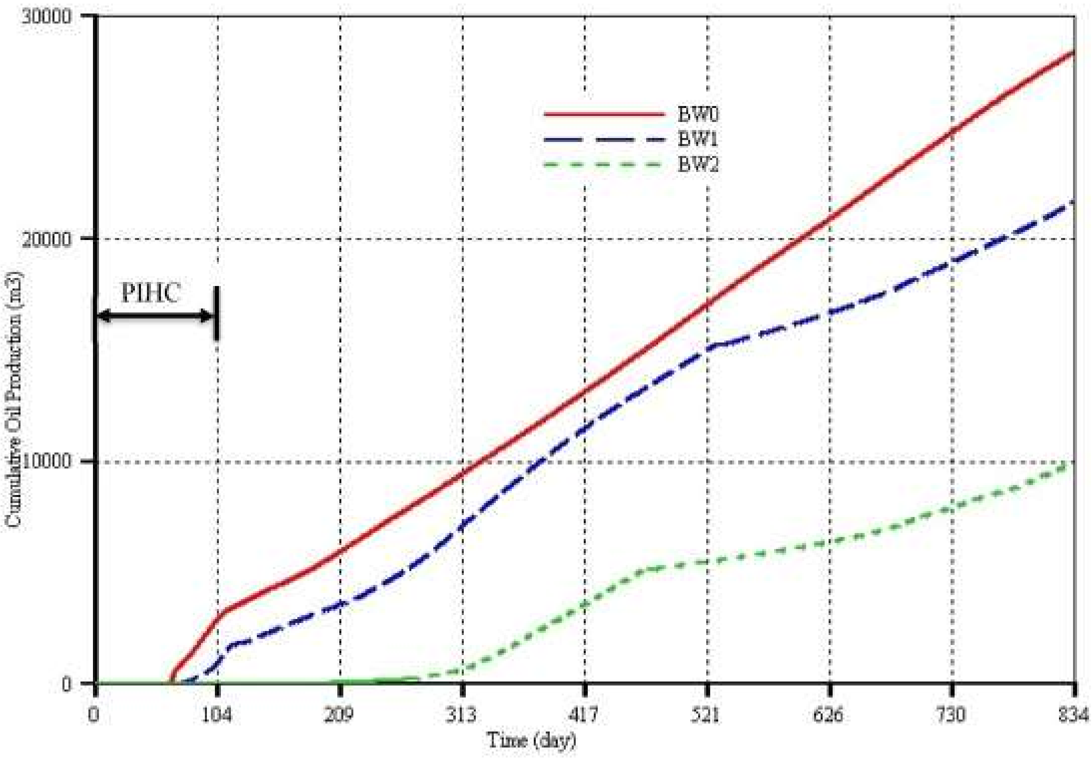

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Fig. 4. Cumulative oil production in THAI in reservoir models with different BW thickness. The double-headed arrow indicates the PIHC.

3.4. Shape of the combustion fronts

The shape of the combustion front is delineated by the leading edge of the oxygen profile (though this is only approximate, unless oxygen concentration is zero). During operation of the THAI process, the two models, BW1 and BW2, had similar shapes of the combustion front, which propagated stably and were restricted to the upper part of each reservoir, within the oil zone, as can be seen in Fig. 5a and b. Since in both cases, the combustion front did not reach the toe of the HP, the volume of the reservoir swept is the same, implying that the thickness of the BWL did not noticeably affect the burning efficiency in the combustion front. This may be because of the presence of accumulated drained-oil around and just below the toe region of the HP well. Along the vertical mid-plane, the combustion fronts, regardless of the thickness of the BWL, had approximately the same areal sweep as can be seen in Fig. 5c and d. The combustion fronts in both cases were forward-leaning, indicating stable propagations. Nevertheless, oil production depended significantly on the thickness of the BWL.

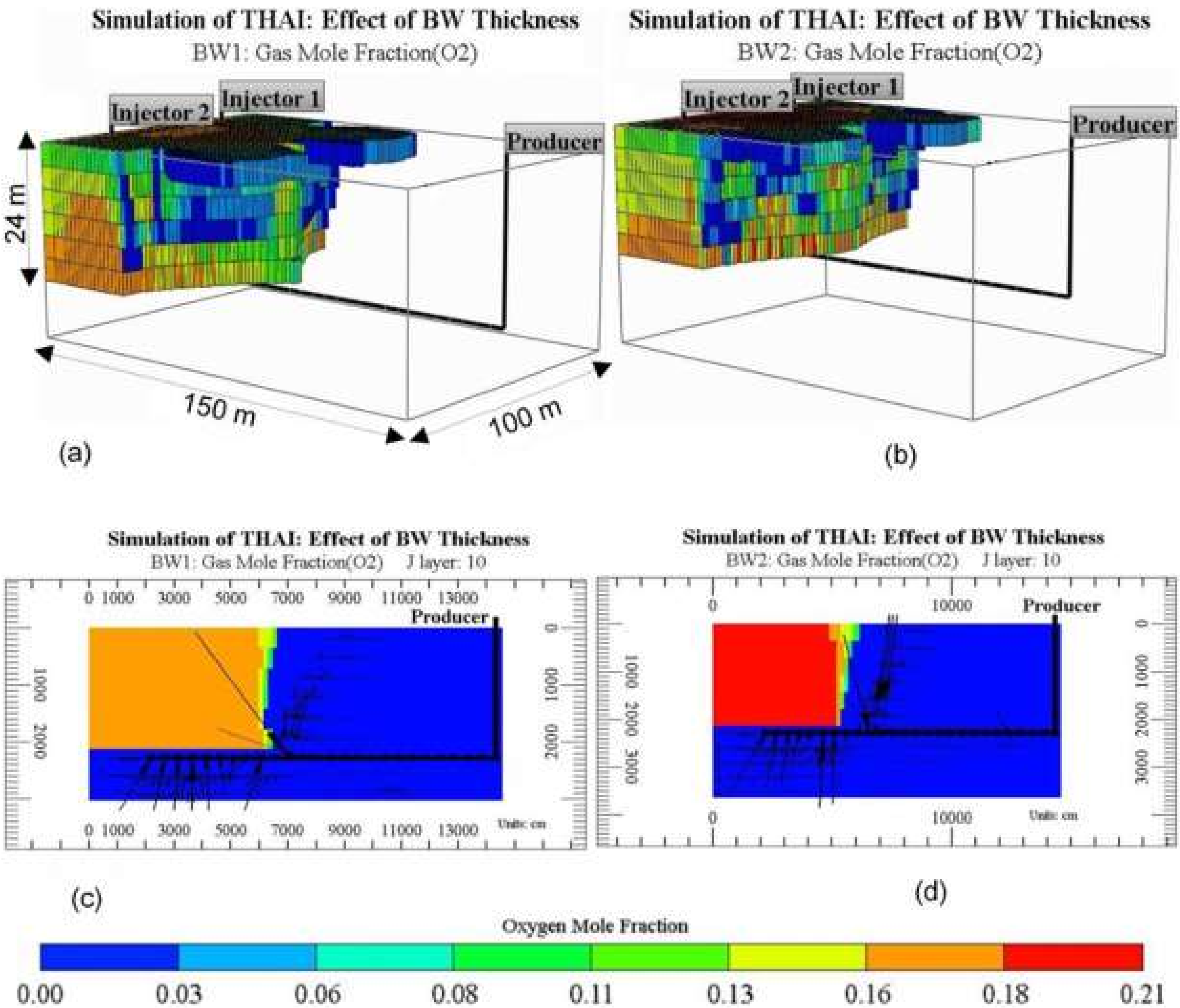

Fig. 5. The three-dimensional shape of the combustion front for the BW1 (a) and BW2 (b) models, and oxygen mole fraction profile along the vertical mid-plane for BW1 (c) and BW2 (d) models. Each is shown after two years of combustion. The arrows shown are oil flux vectors.

3.5. Fluid distribution and oil saturation profiles

Since THAI is a gravity-stabilised oil recovery process, it should be expected that the mobilised oil flow would be downward directed in such a way that the presence of the HP well near the base of the reservoir would enhance the oil recovery rates, and, hence, increase the quantity of oil recovered. However, it has been observed that this is not always the case where the reservoir contains bottom water. Despite placing the HP well at the oil-water interface in both models BW1 and BW2, a significant quantity of the mobilised oil in either of the two cases was not recovered. Rather, the oil drained into the BWL regardless of the thickness of the latter (see Fig. 6). As a consequence, water was displaced from the BWL, and because of the higher mobility of water compared to that of the oil, the former was produced. That is why oil production only began when the height of the accumulated mobilised oil in the BWL equates to that of the displaced water from the BWL. Therefore, as seen in Fig. 4, the thicker the BWL, the longer it takes before oil production begins in the THAI process.

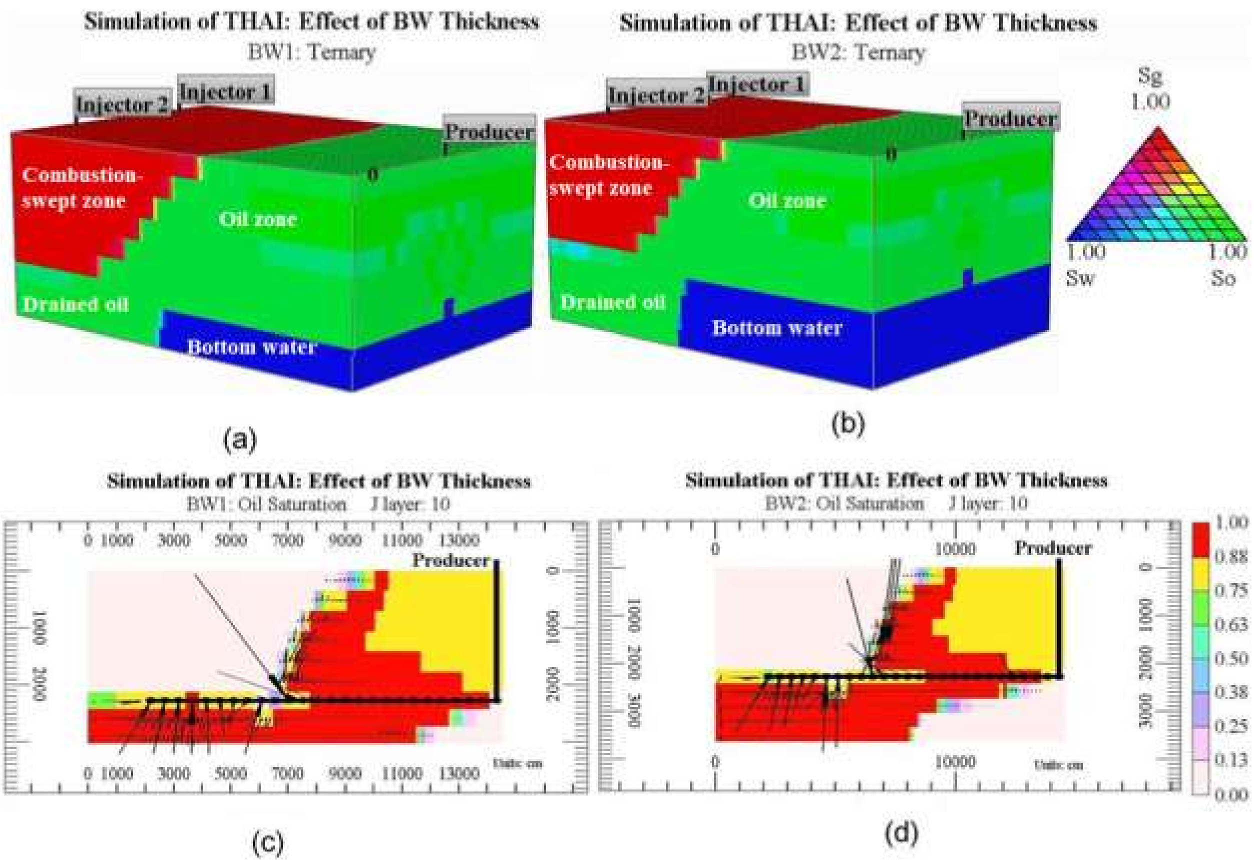

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Fig. 6. Ternary diagrams for BW1 (a) and BW2 (b), and oil saturation profiles along the vertical mid-plane of models BW1 (c) and BW2 (d), all after two years of operation. The singled-headed arrows represent the magnitude and direction of the oil flow.

From the ternary diagrams (Fig. 6), it can be seen that the drained oil cannot be produced with the THAI process implemented in the conventional form. This is because the accumulation of the drained oil is below the HP. The upward directed vectors, shown superimposed on the oil saturation profiles along the vertical mid-plane, reveal that some of the oil that drained into the BWL does flow upward into the HP (Fig. 6). However, closer inspection revealed that the cause of this is the continuous gravity drainage of oil from the parallel vertical planes laterally-adjacent to the vertical mid-plane. The energy transferred from the inflowing mobile oil, from either side of the vertical mid-plane, forced the drained mobile oil to flow upward into the HP well. Comparing the oil saturation profiles of BW1 and that of BW2 in Fig. 6 shows that a larger quantity of oil is lost to the BWL of the latter. This is reflected in the oil production rates (Fig. 2) and the cumulative oil recovered (Fig. 4).

3.6. Temperature and viscosity distributions profiles

The three dimensional temperature profiles for both models BW1 and BW2 exhibit similar characteristic shapes as seen in Fig. 7, with main part of the combustion zone residing in the upper portion of the oil layer zone. Furthermore, they both showed that there is heat transfer into the BWL especially in the region where the drained oil accumulated (Fig. 7). As a result, the heat was predominantly transferred via convection. Inside the BWL, the temperature of the drained oil ranged from 136 to 252 °C, thereby implying that the oil should still be mobile (Fig. 7a and b). From the oil viscosity profiles for models BW1 and BW2 in Fig. 7c and d, the combustion of the affected zone where the oil had some mobility, can be observed. Broadly, the viscosity of the drained oil in both models ranges from 1.26 to 1580 cp (some 3 to 4 orders of magnitude less than that of the original bitumen). These values show that the oil is mobile since the typical viscosity of the THAI produced oil from the field was 10^3 to 10^4 cp (Petrobank, 2009; Turta, 2018).

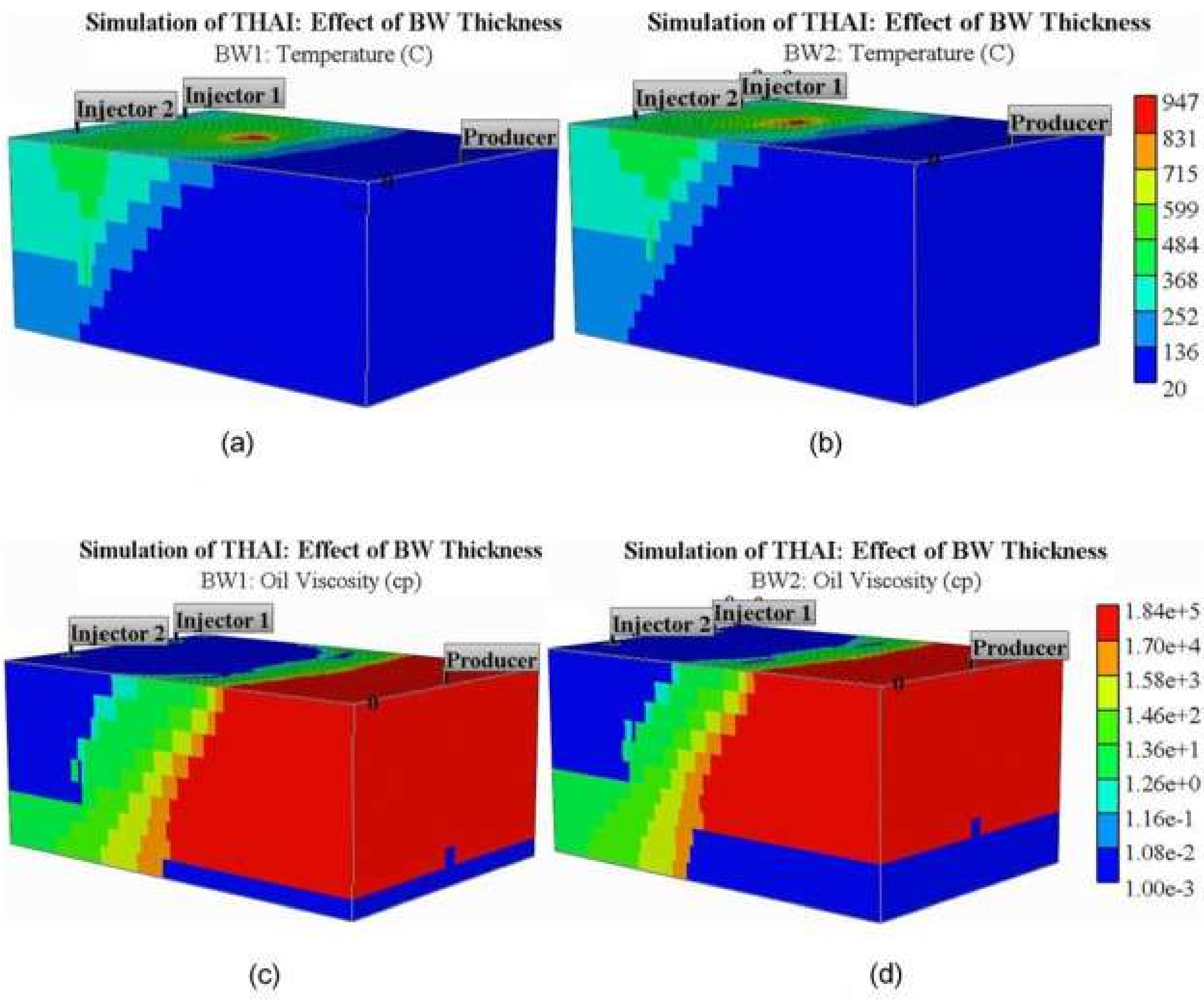

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Fig. 7. Three-dimensional temperature profile for models BW1 (a) and BW2 (b), and the three-dimensional viscosity distribution for BW1 (c) and BW2 (d) all after two years of simulated operation.

Therefore, it is safe to infer that, if the THAI process is to be run until all the oil inside a reservoir with a BWL is fully mobilised (i.e. viscosity is reduced to mobility level), then at least 25% OOIP for the case of BW1 or 50 %OOIP in the case of BW2 will not be produced. It will remain trapped in the BWL zone. Therefore, these findings suggested that a new strategy is required to maximise the oil production rates and lower the water production rates to optimum levels.

4. Conclusions

This work reports numerical simulation results of the THAI process for heavy oil recovery when applied to a reservoir containing bottom water layer (BWL). The bottom water zone is assumed inactive (i.e. the aquifer is considered static) in this study. It is found that the combustion front propagates stably with no oxygen bypassing the combustion front that could have resulted in it exiting the reservoir via the BWL zone as seen experimentally in conventional in situ combustion process. Furthermore, it is found that the oil recovery is affected by how large the thickness of the BWL zone is, and the severity of such is determined to be proportional to the thickness of the BWL. This study also shows that there is a period of low oil production rate which corresponds to oil displacement into the BWL zone which in turn causes a surge in water production rate. The practical implication of this is that prolonged period of low oil production rates will expose companies and/or investors to higher risk due to the oil market volatility. It is also revealed that the height of the mobilised displaced oil into the BWL equates to that of the displaced and replaced water thereby implying that when the BWL thickness is 50% that of the OL, less than 50% of the mobilised drained oil will be recovered when the entire reservoir is swept by the combustion front. As a result, new strategy is needed to enhance the oil production and hence recovery rates. As a future design study, to allow capturing and producing the mobilised drained oil from the BWL thief zone, it is proposed that the horizontal section of the HP well should be located below the oil-water interface. This way, it is anticipated that an optimum balance between water cut and oil recovery can be established.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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