Simulation study on the effect of reservoir bottom water on the performance of the THAI in-situ combustion technology for heavy oil/tar sand upgrading and recovery

Muhammad Rabiul Ado^{1,2}

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Abstract

Some of the bitumen/tar sand/heavy oil reservoirs are underlain by bottom water (BW) layer, which often severely affects the performance of thermal EOR (enhanced oil recovery) processes. The effect of bottom water on the performance of the toe-to-heel air injection (THAI) in-situ combustion (ISC) process is investigated through reservoir simulation using CMG STARS simulator. The current study has shown that there is a limit to BW thickness above which the performance of the THAI process is affected even though the combustion front propagated stably. It is found that the thickness of the “basal gas layer” (BGL) depends on how further down into the BW zone the horizontal producer (HP) well is located. From this study, it is found that the critical BW thickness, when the THAI process is implemented in any heavy oil BW reservoir with the wells arranged in an SLD (staggered line drive) pattern, should lie in the range of 50% OL (oil layer) < BW (bottom water) < 100% OL (oil layer). A comparative study between the active and non-active aquifers models shows that the same cumulative volume of water is produced and that over the 715 days of the process, only negligible amount of oil is produced from BWN (i.e. static aquifer model). It is found that in neither of the models does oxygen bypass the combustion front and as in the previous studies, both fronts are restricted to the upper part of the reservoir, within the oil zone. Therefore, it follows that even in the presence of active aquifer (i.e. BWA model), the THAI process still operates stably in terms of combustion front propagation and sustenance. For the combustion initiated at the oil–water (O–W) interface, it is found that controlled gravity override resulted in a high rate of advancement of combustion front at the top of the reservoir. The combustion is observed to not propagate along the BGL, rather, it propagates as though it is initiated at the top of the reservoir. It is shown that the BGL is only formed during the early period of air injection as the combustion gases could not reach the HP well without displacing the water to create initial gas flow pathway into the HP well. It is also observed that initiating the combustion at the oil–water interface results in a massively improved oil recovery rates, most especially when implemented in the DLD (direct line drive) pattern.

Keywords Bitumen/tar sand/heavy oil · In-situ combustion (ISC) · Bottom water · Toe-to-heel air injection (THAI) · Thermal EOR · Reservoir simulation

✉ Muhammad Rabiul Ado, mado@kfu.edu.sa | ¹Present Address: Department of Chemical Engineering, College of Engineering, King Faisal University, P.O. Box: 380, Al-Ahsa 31982, Kingdom of Saudi Arabia. ²Department of Chemical and Environmental Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK.

1 Introduction

Conducting conventional in-situ combustion (ISC) in reservoirs with bottom water (BW) presents multiple challenges. Few laboratory studies of ISC in the presence of BW have been performed. A review carried out by Turta et al. [1] reported 12% oil recovery when BW thickness was 20% of oil layer thickness. Gravity override was observed once one third of the distance separating the two wells (i.e. injector and producer) had been swept by the combustion front. The bottom water, depending on it is thickness compared to the oil layer thickness, could act as a strong heat sink that consumes most of the generated heat. As a result, the low oil recovery could be due to vaporisation of water to steam as a result of significant energy consumption by the BW. Another laboratory scale study showed that a water cut of up to 80% was recorded during the test. Continuous decrease in peak temperature, with corresponding increase in oxygen production, was observed. Maximum CO₂ production was limited to 6 mol% and continuously decreased with increasing oxygen production. The review concluded that for the conventional ISC, combustion propagation in the presence of BW was unstable and could eventually die out. This showed that the excessive water cut indicates that a producer could easily become watered-out as a result of the BW zone acting as a strong source of water, and as a result of the high mobility of the water compared to that of heavy oil. Results from many field scale projects have also not been encouraging. Recovery ranges from 0 to 25% depending on the formation and BW thickness. A numerical modelling of basal combustion performed by Lau [2] showed that almost all the mobilised oil close to the oil/water transition zone drained into the bottom water zone. The oil production was observed to be very small because the producer was located above the oil–water interface. However, he observed an increase in oil production when the horizontal well was drilled at the oil–water contact zone. The study also showed that the BW zone acts as a strong oil thief zone unless if the producer is drilled near the BW zone. Therefore, other techniques need to be explored in order to unlock the vast reserves of untapped heavy oil from reservoirs with BW. One of the techniques with such potential is toe-to-heel air injection (THAI). The THAI process has been extensively studied using laboratory experiments [3–7] and through experimental scale simulations [8–13]. Additionally, the THAI process has been field-tested by Petrobank [14–17] with encouraging results and have been studied at field scale using numerical simulation [18]. However, as reviewed above, no investigation of

the effect of bottom water (BW) on the performance of the THAI process is available in the literature. But with regards to steam-assisted gravity drainage (SAGD) process, Sugianto and Butler [19] have shown that the higher the thickness of the BW compared to that of the oil layer (OL), the lower the cumulative oil recovery. Turta et al. [1] have suggested that the THAI process may work when the BW thickness is less than 10% of that of the OL. They also offered a preliminary screening criterion, which suggested applying conventional in-situ combustion in BW reservoirs when the BW thickness is 25% that of the oil layer. Consequently, the aim of this work is to present the results of the investigation of effect of BW on THAI process using numerical reservoir simulation.

2 Numerical models construction of bitumen reservoir containing a bottom water layer (BWL)

The Athabasca bitumen properties used in all of this work are similar to those detailed in Rabiú Ado et al. [10, 12, 13] and Rabiú Ado [11], and consequently, they are not repeated here. However, some of the important model input parameters are presented in Table 1. Up-scaled kinetics parameters of the thermal cracking and combustion reactions used throughout this work, and which are taken from Rabiú Ado [11], are shown in Table 2 below. All of the models have been developed and run using the Computer Modelling Group (CMG) thermal reservoir simulator, the CMG STARS.

All the following models were run using the same input parameters as given above.

Table 1 Reservoir petro-physical parameters, initial and boundary conditions

Initial reservoir temperature and pressure	20 °C and 2800 kPa
Initial oil and water saturations	$S_{oi} = 80\%$ and $S_{ow} = 20\%$
Porosity	34%
Horizontal and vertical absolute permeability	6400 mD and 3450 mD
VI (Vertical Injector) and HP (Horizontal Producer) well internal diameter	178 mm
Producer back pressure	2800 kPa
Steam injection pressure	5500 kPa
Steam injection rate (Cold water equivalent)	495 bbl day ⁻¹ (CWE)
Air injection rate	20,000 Sm ³ day ⁻¹

Table 2 Up-scaled kinetics scheme and its parameters based on the up-scaling reported by Rabiú Ado [11]

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	180.88	2.425 × 10 ¹¹ (min ⁻¹)
LC → 0.4243 MC	180.95	3.264 × 10 ¹¹ (min ⁻¹)
IC → 77.4563 COKE	174.28	4.969 × 10 ¹¹ (min ⁻¹)
IC + 98.869 O ₂ → 77.456 CO _{1.947} + 46.904 H ₂ O	138.00	2.772 × 10 ³ (min ⁻¹ kPa ⁻¹)
MC + 49.069 O ₂ → 37.075 CO _{1.947} + 25.953 H ₂ O	138.00	2.772 × 10 ⁴ (min ⁻¹ kPa ⁻¹)
LC + 32.025 O ₂ → 14.600 CO _{1.947} + 35.623 H ₂ O	138.00	2.772 × 10 ⁵ (min ⁻¹ kPa ⁻¹)
COKE + 1.22 O ₂ → CO _{1.875} + 0.565 H ₂ O	123.00	1.530 × 10 ⁵ (min ⁻¹ kPa ⁻¹)

IC Immobile pseudo-component, MC mobile pseudo-component, and LC light pseudo-component

Table 3 BWL/OL thickness ratio and location of the HP for models

Model	Thickness of BWL (m)	BWL-to-OL thickness ratio	Depth of HP well below oil–water interface (m)
1A	24	1:1	12
1B	24	1:1	20
2A	36	3:2	18
2B	36	3:2	30

2.1 Limit to oil production due to bottom water layer (BWL) Thickness

Four different models were developed in which the wells were arranged in a staggered-line drive (SLD). Since previous studies by Sugianto and Butler [19] of SAGD have

suggested that more oil may be produced when the HP well is located within the BWL, in the present study, all of the different well positions are located within the BWL. Table 3 shows the BWL-to-OL thickness ratio, and the location of HP below the oil–water interface for the four different models. While the HP in Model 1A (see Fig. 1 below) was located at a distance that represented 50% of thickness of the BWL, for Model 1B, the HP well was located 4 m above the base of the BW. Model 2B had the HP located 6 m above the base of the BW. THAI simulations for the four models in Table 3 (see below) were run under the same simulated conditions as those provided above. Additionally, all the four models under this section made use of non-active (i.e. static) aquifer. The influence of the active aquifer in which there is water in-flow and out-flow is considered in the coming section below.

Fig. 1 Reservoir dimensions and well layout for model 1A which has BWL:OL = 1:1

2.2 Effect of active aquifer

In all the previous reservoir with BWL models, no water source or sink was included to represent simulate the effect of an active aquifer on the THAI process. These reservoir models mimic the situation that below the middle McMurray formation lies a BWL (with a thickness up to 4 m) which is underlain by an impermeable shale layer [15]. With a static aquifer, the mobilised oil that drains into the BWL could be potentially captured and produced. However, for active aquifer systems, if water source and sink wells are present, the oil that drains into the thief zone could be swept away laterally and thus be prevented from entering the horizontal producer HP well. This could, potentially, not only increase the water cut in the produced fluid, but could also result in no oil production. Therefore, to test this possibility, two further models were developed, each with a BWL/OL thickness ratio of 3:4. As shown in Fig. 2, the first model, denoted BWN, had a static aquifer, while the second model, denoted BWA, had an active aquifer, which is represented by water source and sink wells. For the latter (i.e. BWA model), the source and sink wells were alternately placed at the base of the BWL as can be seen in Fig. 2. In each case, the HP well was located 4.5 m above the base of the BWL. Furthermore, in the BWN model (i.e. the static aquifer model), no flow boundary condition is assumed at the base of the BWL while in the BWA model (i.e. the active aquifer model), flow boundary condition is assumed in which water is injected via the source well and oil and water are produced via the sink wells.

2.3 Combustion at the oil–water (O–W) interface

From findings from field operations and numerical studies, Lau [2] highlighted that most of the gas injected into a reservoir with BWL flows along the oil–water interface just below the OL zone. As a result, it forms a “basal gas layer” at the top of the BWL. However, it is conceivable that a “basal gas layer” might only be formed when the HP well is completely in the BWL, and that its thickness depends upon the location of the HP well. Just as in basal combustion, if air is injected into the reservoir, combustion can be initiated and sustained at the oil–water transition zone. This will heat the overlaying oil from below and, hence, mobilise it for production. The combustion could then be propagated in a toe-to-heel manner (as per THAI) rather than in the kind of “long-distance displacement” manner proposed by Lau [2]. The potential benefit of this would be earlier oil production compared to if the combustion was initiated at the top of the reservoir. It could also reduce the fraction of water cut in the produced fluid, as mobilised oil could form a blanket around the HP well. Hence, these theoretical considerations were numerically investigated to assess the likelihood of them affecting field performance. Therefore, two numerical models were developed each with BWL/OL thickness ratio of 3:4. The wells were arranged in a direct line drive (DLD) in model D (see Fig. 3), while they were in an SLD configuration in model S. In both cases, the HP well was 130 m long and was located 1.5 m above the base of the BW. The models were run under the same conditions as in the previous sections.

Fig. 2 Bottom horizontal layers of static and active aquifer models showing the absence (BWN) or presence (BWA) of water source and sink wells (black dots)

Fig. 3 Reservoir model for THAI with the combustion initiated at oil–water interface. Key: green = oil, blue = water, and red = gas

3 Results and discussion

3.1 Limit to the oil production due to bottom water

Previous studies [11] have detailed the improved benefits of operating the conventional THAI process in a reservoir with BWL with horizontal producer (HP) well located in the BWL. However, that exercise was carried out with the BWL thickness kept constant. Also, in the same study, it was shown that the performance of the THAI process is adversely affected by the presence of BW. In the view of the foregoing, the maximum BW thickness above which THAI, in its conventional form, may potentially be inapplicable is determined under this section.

Figure 4 shows the daily oil production rate for the four different models. It is observed that in all

the models except 1A, no oil production takes place either during the 104 days of the pre-ignition heating cycle (PIHC) or over the 2 years of combustion. Even in model 1A, the production begins at 570 days and the maximum production rate never went above $0.315 \text{ m}^3 \text{ day}^{-1}$. As a result, the cumulative oil production, after additional 264 days of combustion, is 50 m^3 only, which is 0.05% OOIP (oil originally in place). This figure is negligible compared to that obtained in the base case (reported in Rabi Ado [11]). As explained earlier, this shows that it took more than a year of combustion time before enough mobilised oil reached, and hence formed a blanket around, the toe of the HP well in model 1A. For the same bottom water layer (BWL) thickness, moving the HP well further down into the BW zone, as is the case in model 1B, leads to a larger volume of oil needing to be mobilised prior to the formation of drained oil blanket

Fig. 4 Oil production rate for larger BWL thickness

Fig. 5 Water production rate for larger BWL thickness

around the toe of the HP well. Since a further increase in the BWL thickness implies an increase in the depth at which the HP well is located, it naturally follows that not enough oil will reach the toe of the HP in models 2A and 2B. That is why no oil is produced in either model.

The HP well in each case is 'watered-out' with the water production rate increasing as the depth, at which the HP is located below the oil–water contact, is increased (Fig. 5). This can be seen as the highest liquid production rate is maintained for much longer (i.e. 104 to 340 days for models 1B and 2B compared to 104 to 250 days for models 1A and 2A) when the HP well is located near the base of the reservoir. The peaked water production rate period from 104 days to point A for models 1A and 2A has been found to correspond with the period of basal gas layer (BGL) formation. The drop in the water rate in each model is observed to be marked by the start of flue gas production. This further supports the earlier explanation that the formation of BGL is due to the lack of a direct gas flow path to the HP well [11]. Similarly, for models 1B and 2B, the peaked water production period (i.e. from 104 days to point B) corresponds to that of BGL formation. These show that the lower the HP well is located into the BW zone, the longer it takes for flue gas communication with the HP well to be established. From point A to 470 days (Fig. 5), models 1A and 2A have the same water rate signifying that the mobilised oil drainage rate into the BW zone is the same. Likewise, models 1B and 2B have the same water rate from point B to 470 days (Fig. 5). Thereafter, the models converged to a common water rate of $18 \text{ m}^3 \text{ day}^{-1}$ until 580 days.

At the end of the 2 years of combustion, it is found that the lower the depth at which the HP well is located, and/or the thicker the BW zone, the more water is cumulatively

produced (Fig. 6). Point C shows the difference the location of HP well, for the same BWL thickness, has on the cumulative water production. This is mainly due to the formation of BGL.

Figure 7 shows that all the mobilised oil drained into the BW zone and for models 1A and 1B (Fig. 7a and b), it will most likely take a very long time (more than 2 years) before any significant oil production begins. Also, when the HP well is located nearer to the base of the BW reservoir (Fig. 7b), more oil will be produced since the process is gravity-driven and the mobile oil has higher potential energy. However, in the case of model 1A (Fig. 7a), significant portion of the mobilised oil will be left sunk in the BW zone, underneath the HP well. The same explanation applies to models 2A and 2B (Fig. 7c and d) except that the HP well must not be located so low that the mobilised draining oil cannot reach, and therefore forms an oil blanket around the toe of the HP well.

As seen in the previous studies [11], the BGL forms only when the HP well is located inside the BW zone. However, in that case, the location of the HP well within the BW zone was not varied. For the same BW thickness of 24 m (Fig. 8a and b), it is found that the thickness of the BGL is determined by how far down, from the oil–water contact, the HP well is located. The thickness of BGL in model 1A is 10.4 m, which is 7 m shorter than that of model 1B. This is because the combustion flue gas has to establish a pathway, which involves forcing the native reservoir bottom water into the HP well, prior to having direct communication with the HP well. This also explains the difference between the $7.98 \times 10^4 \text{ m}^3$ of water produced in model 1A and the $9.99 \times 10^4 \text{ m}^3$ produced in model 1B, at 834 days (Fig. 6). The same applies to models 2A and 2B which have the same BW

Fig. 6 Cumulative water production for larger BWL thickness **Fig. 7** Oil saturation profiles along the vertical mid-plane for **a** 1A at 834 days, **b** 1B at 834 days, **c** 2A at 715 days, and **d** 2B at 834 days

thickness of 36 m but different BGL thickness for the same reason explained above (Fig. 8c and d). In addition, the $9.91 \times 10^4 \text{ m}^3$ of water produced in model 2A and the $1.31 \times 10^5 \text{ m}^3$ produced in model 2B, at 715 days, further explains why there is the difference in BGL thickness (Fig. 6).

In each of the four models, the combustion front propagates in the oil layer (OL) zone only and is restricted to the upper part of the reservoir (Fig. 9). As is the case in the previous sections, the combustion front is forward leaning, further indicating the stability of the THAI process, even when applied to BW reservoir. In addition, the results

Fig. 8 Ternary diagram for models **a** 1A at 834 days, **b** 1B at 834 days, **c** 2A at 715 days, and **d** 2B at 834 days

reveal that regardless of the thickness of the BW zone, no oxygen bypasses the combustion zone. Also, this shows that the BGL, shown in Fig. 8, contains no oxygen.

To summarise, there is a limit to BW thickness above which the performance of the THAI process is severely affected even though the combustion front can be stably propagated. The critical BW thickness, when the THAI process is implemented in a BW reservoir with the wells arranged in an SLD pattern, should lie in the range of $50\% OL < BW < 100\% OL$. However, future work is required to refine this.

The above findings imply that new strategies are needed in order to either stop the mobilised oil draining into the BW zone or improve the recovery even if the oil continues to drain into the BW zone. For this, the temperature profile was checked to see if basal combustion could be used. The temperature profiles show that the drained oil, in each model, is at a high enough temperature (i.e. at least 115°C) to be mobile. It follows that the static aquifer did not take out a significant quantity of heat from the combustion zone. This is because conduction is the dominant mechanism through which heat is transferred to the BW zone. The temperatures along the horizontal plane (oil–water interface) show that combustion can be

propagated at the oil–water contact (OWC) in a similar fashion as in Lau [2]. As a result, it would be used to investigate THAI with HP well located near the base of the BW zone.

3.2 Effect of active aquifer on the performance of the THAI process

In this section, the impact of an active aquifer is analysed and discussed. As explained in Sect. 2.2, the BWL thickness in each model is 75% that of the OL. To recap, model BWN has a static aquifer, while model BWA has an active aquifer which is represented by water source/sink wells at the base of the BW reservoir (i.e. horizontal layer K13). The active aquifer allows the effect of in-flowing and/or out-flowing fluid into or from the BW zone to be simulated.

As with the previous models with BW thickness of $\geq 50\% OL$, no oil production is realised from either of the BWN or BWA models during the 104 days of PIHC. This is because the BW thickness is greater than 50% of the OL thickness, which is in accordance with the findings in the previous sections. The combustion is run for 615 days and during this time, only a negligible amount of oil is recovered in BWN. No oil production is recorded in BWA (Fig. 10).

Fig. 9 3D shape of combustion front for models **a** 1A at 834 days, **b** 1B at 834 days, **c** 2A at 715 days, and **d** 2B at 834 days

Fig. 10 Oil production rate for both active (BWA) and non-active (BWN) aquifers

The maximum oil production rate in BWN is below $0.3 \text{ m}^3 \text{ day}^{-1}$ and the cumulative oil produced is only 35 m^3 at 715 days. This minor difference between the two models is caused by the sealing effect provided by the no flow boundary condition assigned at the base of the static aquifer in BWN model. As a result, the base of the static

aquifer does not allow fluid transmission further down into the underburden (Fig. 11a). This is in accordance with the Petrobank's observation that below the middle McMurray lies BW zone which is underlain by a shale layer [20].

The inclusion of active aquifer in the BW reservoir showed that the mobilised oil, which is dragged into the

Fig. 11 Ternary diagram along the bottom horizontal plane for models **a** BWN, and **b** BWA and along the vertical mid-plane for models **c** BWN, and **d** BWA

BW zone, is not contained. Rather, it sank into the producers, which are used to simulate the active aquifer (Fig. 11b). Observing the oil flux vectors, superimposed on Fig. 11c and d, reveals that the small oil production achieved in BWN model is due to containment. The continuous inflow of oil from the adjacent vertical planes and the no flow boundary at the base of the static aquifer force the mobilised oil towards the toe of the HP. This is signified by the toe-directed oil flux vectors of model BWN (Fig. 11c). In the case of model BWA, the absence of containment allows the continuously gravity-draining oil to sink into the active aquifer, and be produced in the sink wells. This is indicated by the vertically downward-pointing oil flux vectors, around the toe of the HP well (Fig. 11d). The drained oil front (Fig. 11a) is sharper in model BWN than in model BWA (Fig. 11b). This is caused by the use of larger grid-block size in BWA (i.e. nine times bigger than in BWN) to represent the source/sink wells. However, despite this, the results are not affected quantitatively.

Despite the inclusion of active aquifer in BWA model, the HP well in each model is watered-out. The water production rate is approximately the same regardless of whether active or static aquifer is used to simulate the

THAI process in the BW reservoir (Fig. 12). The two models also have the same BGL formation period ranging from 104 to 275 days. Thereafter, model BWN overlies BWA, by up to $70 \text{ m}^3 \text{ day}^{-1}$, until 345 days. This is due to the displacement of the stagnant BW into the HP well. From 345 to 560 days, the displacement of water from the second bottom-most horizontal layer by flue gas causes the water rate of model BWN to lie below that of model BWA by up to $15 \text{ m}^3 \text{ day}^{-1}$. Beyond 560 days, the difference in the water rate is not pronounced. The cumulative water production at 715 days are 7.82×10^4 and $7.90 \times 10^4 \text{ m}^3$ for BWN and BWA respectively. This is a difference of just around 1%. The difference of just 1% goes to show that simulating the reservoir with either active or static aquifer does not affect the overall results in terms of water production.

The two models predicted approximately the same peak temperature (Fig. 13). Therefore, comparatively, both the static and the active aquifers take the same amount of heat from the combustion front. Analysing the combustion front, it is found that in neither of the models does oxygen bypass the front. As in the previous sections, both fronts are restricted to the upper part of the reservoir, within the oil zone. This implies that even in the presence

Fig. 12 Daily water production rate for both active (BWA) and non-active (BWN) aquifers

Fig. 13 Peak temperature for both active (BWA) and non-active (BWN) aquifers

of active aquifer, the THAI process operates stably in terms of combustion propagation and sustenance.

So far, the studies of THAI process implementation in the BW reservoir have shown that for quite thick BW zone (i.e. thickness of > 50% of OL thickness), almost all of the mobilised oil is not recoverable as it drained and get trapped into the BW zone for the case of static aquifer (i.e. model BWN). For the case of active aquifer (i.e. model BWA), the drained oil sank further down or is 'washed away' laterally. However, of note are the facts that all these models were run with the wells arranged in an SLD pattern and the combustion in each model was initiated at the top of the BW reservoir (i.e. in the oil zone around the vertical injectors). Therefore, new models with the combustion initiated at the oil–water contact and with the wells arranged

in both the direct line drive (DLD) and the staggered line drive (SLD) patterns must be run to test if oil production could be increased.

3.3 Combustion at the oil–water interface

The results of operating THAI process with the combustion initiated at the oil–water contact of the BW reservoir are discussed under this section. To recall, even though it has already been stated in Sect. 2.3, the thickness of the BW zone is 75% of that of OL. For the DLD THAI arrangement (i.e. model D), an almost instantaneous oil production occurs at the end of the 104 days of PIHC (Fig. 14). The oil rate rises to a maximum value of $9.4 \text{ m}^3 \text{ day}^{-1}$ at 274 days before dropping slowly to $6.4 \text{ m}^3 \text{ day}^{-1}$ at

Fig. 14 Oil rate for combustion at the oil–water contact

367 days. The cause of the decrease can be attributed to the increase in the displacement of water by the mobilized drained oil thereby forming a mobilized oil blanket around the mobile oil zone. Thereafter, it increases steadily to $16.0 \text{ m}^3 \text{ day}^{-1}$ at 626 days and then the rate rises steeply to a peak value of $26.1 \text{ m}^3 \text{ day}^{-1}$ at 659 days. It then falls sharply and becomes oscillatory, due to the combustion front reaching the toe of the HP well, until 711 days. In the case of the SLD THAI arrangement (i.e. model S), no oil is produced until 510 days after the start of air injection (Fig. 14). This is despite initiating the combustion at the oil–water interface. The oil rate rises rapidly to $16.0 \text{ m}^3 \text{ day}^{-1}$ at 688 days before slowly increasing to $17.3 \text{ m}^3 \text{ day}^{-1}$ at 834 days.

The oil rate shows that operating the THAI process with the wells arranged in a DLD pattern, and combustion initiated at the oil–water interface results in a substantially improved oil recovery rate. The main reason for this is the use of the injector well in direct line with the HP well. However, it is also partly due to the placement of the heel of the injector well closer to the toe of the HP well. This is because, the initiation of the combustion at the oil–water interface in model S also did have too great an effect on the oil rate compared to that achieved when the combustion was initiated at the top of the reservoir (Sect. 3.2, Fig. 10, model BWN). Peaked oil rate in model BWN is only $0.27 \text{ m}^3 \text{ day}^{-1}$ which is 64 times lower than that in model S. Despite that, the oil production response is faster in model BWN compared to model S. Overall, for model D, the closeness of the injector to the HP well has resulted in a rapid creation of mobilised oil blanket around the toe of the HP well. At 714 days of the process, 5300 and 850 m^3 of oil are cumulatively recovered from models D and S respectively (Fig. 15).

In both models D and S, the daily water rate is quite the same during the PIHC. On injecting air, the water rate peaked to $450 \text{ m}^3 \text{ day}^{-1}$ in each model (Fig. 16). However, the peaked rate is sustained for a period of 46 days (i.e. from 104 days to point A) in the case of model D. This is because it becomes easier for the combustion flue gas to create a gas flow pathway to HP well. Where the injectors are laterally away from the HP well, it takes 96 days (i.e. from 104 days to point B) for communication to be established between the flue gas source (i.e. combustion front) and the HP well. From 236 to 711 days, the water rate in model D overlies that in model S because of the gradual displacement of water by the flue gas in the former. It is also because larger amount of water is already displaced during the BGL formation in model S. However, the same cumulative amount of water, $7.84 \times 10^4 \text{ m}^3$, is produced in either model. Also, it is found that regardless of where the combustion is initiated (i.e. at the top of the BW reservoir or at the oil–water interface), the same cumulative amount of water is produced. This is observed by comparing models BWN and S.

Figure 17 shows the 3D shape of the combustion front at two different times: 30 and 608 days after the start of air injection. In both models, the combustion is successfully initiated at the oil–water interface (Fig. 17a and b). It is found that instead of propagating along the oil–water interface in a toe-to-heel manner, and in the process forming the basal gas layer (BGL), the combustion rises rapidly into the oil zone, reaching the top of the reservoir. Then, controlled gravity override causes the combustion front to advance at faster rate at the top of the reservoir thereby forming a forward leaning front (Fig. 17c and d). The larger pressure at the base of the reservoir, and the decrease in density of the injected

Fig. 15 Cumulative oil production for combustion initiated at the oil–water contact **Fig. 16** Water rate for combustion initiated at the oil–water contact

air because of passing through the combustion swept zone, force the air to buoyantly rise to the top of the reservoir. Initially, the air was directed towards the heel of the injectors before flowing axially due to no flow overburden boundary condition (i.e. toe-to-heel). Once at the combustion zone, the air is completely consumed resulting in no oxygen production and hence stable THAI operation. This can be seen by observing the gas velocity vectors superimposed on the ternary diagram shown in Fig. 18. Since the injector wells in model S are placed on the adjacent vertical planes, it is easier to visualise the gas flow pattern of model D, which is shown in the right column of Fig. 18 as (e) to (h). On leaving the combustion front, the flue gas flow is restricted to the top of the reservoir during the early stage of air injection. As the

combustion zone expands, the gas flow area increases such that the whole reservoir thickness is occupied.

Figure 18 shows the gradual development of the BGL over time. One month after the start of combustion (Fig. 18a), the HP well is still fully submerged in the BW preventing the flue gas from being produced to the surface. This resulted in water displacement forming the first layer of BGL just beneath the oil–water interface. The same applies to model D (Fig. 18e). Around 5 months into the combustion period, the flue gas in model S (Fig. 18b) is in direct communication with the nearly the entire length of the HP well. In this situation, the BGL thickness is the same as the vertical distance separating the HP well from the oil–water interface. As a consequence, the BGL can be said to be fully developed as further inflow of gas does

Fig. 17 Shape of combustion front after 1 month from the start of air injection for models **a** S, and **b** D, and at 711 days for models **c** S, and **d** D

not increase its thickness as shown by Fig. 18c and d. The same applies to model D (Fig. 18f) except that the BGL is in direct contact with the heel of the HP well only and thus thinner in size. This is because of the formation of a direct gas flow path from the toe of the injector to the BGL. Therefore, under this condition, the BGL is only partially developed and additional inflow of gas will displace more water to increase its thickness as depicted by Fig. 18g and h. This further supported the earlier explanation as to why curve D overlies S from 236 to 711 days (Fig. 16). It is also found that the BGL does not have to be fully developed before flue gas production begins.

Comparing models D and S in terms of oil displacement into the BW zone, it is found that oil blanket is quickly formed around the toe of the HP in the former (Fig. 18e) while it requires more than a year of air injection in the case of latter (Fig. 18c). This is because the combustion has to expand laterally before the oil at the top middle part of the reservoir, directly above the toe of the HP well, is mobilised and drained. Once the oil blanket is formed, the continuous advancement of combustion front and drainage of oil lead to the formation of mobile oil zone (MOZ) separating the BGL from the combustion zone (Fig. 18d and h). This, in addition to what is found earlier, partly explains why the combustion does not propagate along the BGL zone. Instead, the deduction that is made

from these results is that the BGL is only formed as the combustion gases generated during the early period of air injection could not reach the HP well. It could be suggested that alternating injection and production could be employed so that the BGL is formed prior to initiating the combustion. This kind of operating strategy, even though not tried on the THAI process, did not work when attempted by Lau, [2] on Basal Combustion process. However, it may work when implemented in the THAI process but only during the early stage of combustion, before the MOZ provides sealing effect. Also, this strategy will result in excessive oxygen production.

In summary, initiating the combustion at the oil–water contact results in improved oil recovery rates, most especially when implemented in a DLD pattern. However, the combustion does not propagate along the BGL rather it rises and propagates as though it is initiated at the top of the reservoir.

4 Conclusions

The current study has shown that there is a limit to BW thickness above which the performance of the THAI process is severely affected even though the combustion front propagated stably. The oil production is heavily delayed to

Fig. 18 Ternary diagrams along the vertical mid-plane and at different times for models S **a–d** and D **e–h**. Key: green = oil, red = gas, and blue = water

the extent that no oil is produced in all the models over the 834 days except in model 1A. It is found that the thickness of the 'basal gas layer' (BGL) depends on how further down into the BW zone the HP well is located. From the study, it is found that the critical BW thickness, when the THAI process is implemented in any heavy oil BW reservoir with the wells arranged in an SLD pattern, should lie in the range of $50\% \text{ OL} < \text{BW} < 100\% \text{ OL}$. However, future work is required to establish this.

The comparative study between the active and non-active aquifer models show that the same cumulative volume of water is produced and that over the 715 days of the process, only negligible amount of oil is produced from BWN. It is found that in neither of the models does oxygen bypass the combustion front and as in the previous studies, both fronts are restricted to the upper part of the reservoir, within the oil zone. Therefore, it follows that even in the presence of active aquifer, the THAI process still

operates stably in terms of combustion front propagation and sustenance.

For the combustion initiated at the oil–water interface, it is found that controlled gravity override resulted in a high rate of advancement of combustion front at the top of the reservoir. The combustion is observed to not propagate along the 'basal gas layer', rather, it propagates as though it is initiated at the top of the reservoir. It is shown that the 'basal gas layer' is only formed during the early period of air injection as the combustion gases could not reach the HP well without displacing the water to create initial gas flow pathway into the HP well. It is also observed that initiating the combustion at the oil–water interface results in an improved oil recovery rates, most especially when implemented in the DLD pattern.

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Compliance with ethical standards

Conflict of interest The author declares that there is no conflict of interest.

References

1. Turta AR, Coates R, Greaves M (2009) In-situ combustion in the oil reservoirs underlain by bottom water. Review of the field and laboratory tests. In: Canadian international petroleum conference 2009, Petroleum Society of Canada
2. Lau E (2001) Basal combustion-A recovery technology for heavy oil reservoirs underlain by bottom water. *J Can Pet Technol* 40(08)
3. Xia T, Greaves M (2002) Upgrading Athabasca tar sand using toe-to-heel air injection. *J Can Pet Technol* 41(08)
4. Xia T et al (2002) THAI process-effect of oil layer thickness on heavy oil recovery. In: Canadian international petroleum conference
5. Xia T, Greaves M, Turta A (2005) Main mechanism for stability of THAI-Toe-to-Heel Air Injection. *J Can Pet Technol* 44(1)
6. Greaves M, Xia TX, Turta AT (2008) Stability of THAI (TM) process - Theoretical and experimental observations. *J Can Pet Technol* 47(9):65–73
7. Zhao R et al (2018) Optimization of well spacing to achieve a stable combustion during the THAI process. *Energy* 151:467–477
8. Greaves M, Dong L, Rigby S (2012) Simulation study of the toe-to-heel air injection three-dimensional combustion cell experiment and effects in the mobile oil zone. *Energy Fuels* 26(3):1656–1669
9. Greaves M, Dong L, Rigby S (2012) Validation of Toe-to-Heel air-injection bitumen recovery using 3D combustion-cell results. *SPE Reserv Eval Eng* 15(1):72–85
10. Rabi Ado M, Greaves M, Rigby SP (2017) Dynamic simulation of the Toe-to-Heel air injection heavy oil recovery process. *Energy Fuels* 31(2):1276–1284
11. Rabi Ado M (2017) Numerical simulation of heavy oil and bitumen recovery and upgrading techniques. In: Department of chemical and environmental engineering 2017, University of Nottingham
12. Rabi Ado M, Greaves M, Rigby SP (2018) Effect of pre-ignition heating cycle method, air injection flux, and reservoir viscosity on the THAI heavy oil recovery process. *J Pet Sci Eng* 166:94–103
13. Ado MR, Greaves M, Rigby SP (2019) Numerical simulation of the impact of geological heterogeneity on performance and safety of THAI heavy oil production process. *J Petrol Sci Eng* 173:1130–1148
14. Petrobank (2017) Whitesands experimental project IETP Annual report 2008 [cited 2017 20 October]. Available from: <http://www.energy.alberta.ca/3040.asp>
15. Petrobank. Whitesands experimental project IETP Annual Report 2009 [cited 2017 20 October]. Available from: <http://www.energy.alberta.ca/3261.asp>
16. Petrobank. Petrobank Reports Q2 2013 Financial Results and Operational Update. 2013 [cited 2014 20 May]. Available from: <http://www.petrobank.com/news>
17. Petrobank. Petrobank Announces Q1 2014 Financial and Operating Results. 2014 [cited 2014 20 May]. Available from: <http://www.petrobank.com/news>
18. Greaves M, Dong LL, Rigby SP (2012) Determination of limits to production in THAI. in SPE heavy oil conference Canada. Society of Petroleum Engineers
19. Sugianto S, Butler R (1990) The production of conventional heavy oil reservoirs with bottom water using steam-assisted gravity drainage. *J Can Pet Technol* 29(02)
20. Petrobank (2010) Annual progress report (2008) for white sands experimental project

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