22 Ways Toe-To-Heel Air Injection (THAI) Process is Superior to Conventional In-Situ Combustion

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Outline

• Introduction; Status of THAI/CAPRI processes
  – Laboratory work
  – Simulation
  – Field testing

• List of 21 ways that THAI is superior to conventional in-situ combustion (ISC)

• Discussion of the List

• Higher complexity in application of THAI in staggered line drive (SLD) configuration

• THAI application: four-key conditions; screening criteria and THAI as a “stumble upon” process
1. Compared with conventional in-situ combustion (ISC) THAI process offers a good control on the propagation direction of the ISC front with a short-distance oil displacement feature, taking full advantage of gravity segregation.

2. Technical validity of the THAI process has been proved by its field testing in a direct line drive (DLD) configuration.

3. THAI is a “stumble upon” process. In developing an ISC tertiary process after SAGD and steamflooding or in drilling a horizontal production well in a conventional ISC process, it is mandatory to clearly understand the THAI mechanisms.
Long-distance & Short-distance Oil Displacement Processes

Long-distance displacement, the conventional IOR/ISC (VIVP)

Vertical Injector (VI) ➔ Vertical Producer (VP)

Horizontal Injector (HI)

Horizontal Producer (HP)

Short-distance displacement, SAGD (HIHP)

Short-distance displacement - THAI case exemplification (VIHP)

Vertical Injector (VI) ➔ Horizontal Producer (HP)

Courtesy of University of Bath
SAGD; the first SDOD process.

Flowing distance: 20-50 m

Note: Compared to 200-500m in the LDOD processes.

Steam Chamber

Horizontal Injector

Oil with reduced viscosity drains (mobile oil zone-MOZ)

Horizontal Producer

Unswept zone
Staggered Line Drive (SLD) and Direct Line Drive (DLD) Configurations in THAI Process

Bird’s eye view

SLD

DLD

Start-up region

Horizontal producers
Conventional ISC Process; Its Status

Current commercial operations:
  • Suplacu de Barcau, Ro.; ≈ 900m³/day
  • Balol, and Santhal India; ≈ 1000m³/day
  • Several Projects, China
  • BSOC-Bellevue, USA; ≈ 50m³/day

ISC Pilots:
  • Petrochina, China:
  • Pacific Rubiales Energy, Colombia:

Note: The key for success: operation of a peripheral line drive starting from the uppermost part of reservoir.
Main Problems of Conventional ISC

• Flow of oil through the cold region, involving:
  - either exceedingly high pressure drops (drastic reduction of the air flux / injectivity problems)
  - or an intensive channeling of the ISC front.

• Lack of control on the direction of the ISC front propagation

• Negative effect of gas-liquid over-riding (burn zone at the top, on a very narrow zone)

• Very negative effect of reservoir heterogeneity (stratification effects)
3-D View of THAI in DLD and SLD Configurations

Direct Line Drive (DLD)  Staggered Line Drive (SLD)

Start-up region

Note: SLD has a better sweep efficiency, therefore is always more efficient
Schematic of Toe-to-Heel Air Injection (THAI) (Modified from University of Bath)

Steady operation of THAI (2 self-healing features)
THAI: Configuration and Operation
(according to the USA patent: 5,626,191/1997)

Line drive operation (2 distinct phases):

1. Generation of a quasi-linear, ISC front and its propagation inside the start-up region

2. Then, ISC front is anchored at the toe of horizontal producer and propagated from the toe to the heel of horizontal producer

Note: The first phase includes the generation of hot communication and ignition (separately or lumped together)

Legend:
VI=vertical injector

Initial ISC front
Start-up region

Horizontal Well Producer
THAI: Direct Line Drive (DLD) Configuration. Two ways of starting the first phase of the process (communication and ignition)

**Patent recommended** - full initial ISC front between injectors and then connection with the toe of HP

**Local linking and local ISC fronts**: just VI-HP link (radial front, initially)

Note: Patent recommended approach is always better (better sweep efficiency)
Laboratory Set up
of University of Bath, UK

- Air
- N₂
- H₂O

Gas Analysers

Controller

A/D interface

D/A interface

Computer

3-D cell

Heating elements

Gas/Liquid Separation

Samples

Gas Analysers

Laboratory Set up of University of Bath, UK
Statistics - Lab tests

• More than 100 laboratory tests conducted in 3D models at University of Bath (U of B), UK in 12 consecutive years; more than 75 million has been spent for these

• Other THAI tests and quasi-THAI tests have been done voluntarily or involuntarily by Petrobank and ARC; they confirmed the findings of U of B.

• All the aspects have been investigated, except communication phase
THAI for Wolf Lake Oil and Athabasca Bitumen. Laboratory tests.

**Thermal** upgrading during dry and wet THAI using Wolf Lake oil (viscosity 50,000 mPa.s)

THAI and catalytic THAI (CAPRI) for Athabasca Bitumen

![Graph showing API point of the produced oil over time for dry and wet THAI and CAPRI processes.](image1)

THAI: \[50,000 \text{ cp}\] to \[10,000 \text{ cp}\] (5 times)

CAPRI: \[10,000 \text{ cp}\] to \[100 \text{ cp}\] (100 times)

![Graph showing oil viscosity over time for various processes.](image2)

Oil visc: \[1 \text{ million}\] \(\Rightarrow\) THAI \(\Rightarrow\) \[1,000 \text{ cp}\] \(\Rightarrow\) CAPRI \(\Rightarrow\) \[50 \text{ cp}\]

Courtesy of U. of B.
Numerical Simulation of THAI
(by 10 organizations and at least 6 PhD and MSc theses)

• Simulation of laboratory tests
• Limited simulation of field tests
• Main simulations and their limitations/merits:
  – Coates, ARC 2001 (with a hardware to block O2 short-circuit)
  – Initial University of Bath work (generally, overestimate of the oil rate) Period 2000-2011
  – Schlumberger, 2007: Simulation of a Field THAI test using different well configurations
  – Petrobank Energy and Resources. After 2009-2010
  – Surcolombian University, Neiva, Colombia. After 2008
  – Sharif University, Iran 2008 (carbonate formations)
  – Texas A and M University, H. Rahnema, PhD-2012-13 (excessively LOW oil rate-not conform with reality)
  – Brazilian, 2012 ( MSc Thesis); best estimate of a generic field oil rate
  – A T EOR Consulting (excessively LOW oil rate - not conform with reality)
  – Current University of Bath along with U of Birmingham and Nottingham (generally very good estimate of oil rate in a lab test, some advancements in the simulation of a field test) 2012-2017
Starting in 2006; there have been 6 pilots/projects in 3 countries (Canada-2, China-2 and India-1); 15 years of field experience.

- **Canada:** Whitesands Pilot, Alberta (Athabasca oil sands) 2006-2011 and Kerrobert Project, Saskatchewan (2009 – on going)
- **China:** Shuguang pilot (Liaohe oilfield), and Fengcheng pilot, Xinjiang oilfield in the provinces of Liaoning and Xinjiang, respectively. Period: 2012 present (last one it is probably an ongoing project)
- **India:** Balol and Lanwa Fields in Gujerati State; Start: December 2016 – ongoing

Note: All in all, 22 well pairs (VI-HP) have been used in these field tests.
Underground upgrading of the produced oil in Kerrobert THAI Pilot operation

Source: Petrobank Corporate Presentation, January 2012
22 Ways that THAI is Superior to Conventional ISC (when applied to normal heavy oil reservoirs)

1. Full control on propagation direction (in-built guidance)
2. Gravity is fully accounted for
3. Almost non-flow through the cold regions (short-distance displacement); enables the preservation of most of in-situ oil upgrading (production of partially upgraded, low viscosity oil)
4. It is much less sensitive to the permeability’s heterogeneity of reservoir (mainly stratification)
5. The way is designed and operated, it displays a better vertical conformance factor mainly for oil formations with thickness larger than 10-12m
6. Flow blocking with the displaced oil – cooled down ahead of the in-situ combustion (ISC) front is avoided
7. Heat losses to the adjacent formations are slightly smaller (more concentrated burned volume)
8. Premature O2 break-through in the production well never occurs; extremely robust process due to a longer residence time of oxygen molecules in the hot region, by far more extended than in conventional ISC
9. Better burning quality. Unlike conventional ISC, there are no low temperature oxidation (LTO) reactions. However LTO reactions are a natural part of initiation of ISC by spontaneous ignition
10. More robust/stable vis-à-vis the temporary interruption of air injection and vis-à-vis sudden, significant increase of air injection rate
11. By far less damaging to the production wells; only the toe region is usually damaged, not entirely as in conventional ISC
12. Easier to monitor and control, as temperature measurements in the horizontal section of horizontal producers are very helpful, almost for the entire life of the project
13. Although line drive is preferred, it can be operated in separate patterns
13. Works even for slightly lower permeability (dirty sands), where both conventional ISC and SAGD are not applicable
14. Produces free hydrogen
15. As it produces some methane and C2+ gas hydrocarbons, the higher content of fuel gases (H2, C1+ and CO) in the produced gas requires less make up fuel gas for incineration of combustion gases
16. Produced oil contains less pollutants (metals, Sulphur and Nitrogen)
17. Produced oil is of better quality (related to less pollutants and a better SARA composition); easier to upgrade to pipeline specifications
18. THAI emulsions are less rebellious; easier to treat
19. THAI well configuration can be easily amenable to the development of catalytic THAI (CAPRI) style processes
20. Similar to SAGD, it produces oil a relatively long period after cessation of injection
21. When applying enhanced spontaneous ignition (ESI) based on steam injection pre-heating, there is an additional method for ignition time determination in connection with CO and hydrogen variation before and after generation of the full ISC front.

Note: normal heavy oil reservoirs assume reservoirs of good porosity and permeability
Conventional In Situ Combustion (ISC) and THAI
1. Control of propagation direction

Cross-section view

Air, \( \text{Air} + \text{H}_2\text{O} \), etc.

Combustion zone

Reaction zone

Oil banking in the cold region

Swept zone

Cool zone

One cannot predict where the ISC front is going!

Bird’s eye view

(a pattern and its surroundings)

University of Waterloo

(Courtesy of M. Dusseault)
2. Gravity is fully accounted
(vertically section visualization)

Conventional ISC  THAI

Burned zone
3. Underground Upgrading in THAI Process

Steady operation of THAI (2 self-healing features)
4. Avoiding Channeling and Blocking occurring in Conventional ISC

- Pattern of flow of oil is very advantageous
- Does not involve oil flow via cold region, such that either exceedingly high pressure drops (drastic reduction of the air flux / injectivity problems) cannot occur
- Also, an intensive channeling of the ISC front is not developed as seen in the next slide.
5. Less sensitive to stratification
6. It displays a better vertical conformance factor mainly for oil formations with thickness larger than 10-12m

In case of conventional ISC:

- For a good *vertical conformance factor* (VCF) the ideal thickness \((h)\) of oil formation is 5-8 m for conventional ISC
- As we go for \(h>8-10m\) the VCF decreases significantly, as it happened in Balol heavy oil reservoir in India

By applying THAI, this allowed to revive new regions on Balol reservoir, where commercial conventional ISC has been applied for 20 years.
7. Heat losses to the adjacent formations are slightly smaller

- More concentrated burned volume
- In conventional ISC this burned volume usually is not compact (it is fragmented) and extends from the ISC front to the production wells for most of the time of the project
- This advantage was first determined by the Chinese investigators of the THAI process
- This helps in a better stability of the process to the air injection stoppages
8. No premature O₂ break-through (B/T)

- THAI process (mainly DLD-THAI) is a short-distance process for oil flow, while being a long-distance process for burning/oxidation, which takes place on a large burning surface, adjacent to mobile oil zone (MOZ)

- O₂ is consumed long before its arrival in the horizontal producer; there are coke gasification and water gas shift reactions generating hydrogen

- There have been no O₂ B/T both at excessively high air injection rates (130,000sm³/day) and excessively low air injection rates (5,000sm³/day) in the field tests carried out so far

- Moreover, there is no O₂ B/T even when operating a very abrupt, large increase of air injection rate

- This is a very solid, field-based conclusion from both THAI Whitesands Pilot and THAI Kerrobert project, where the apparent atomic hydrogen-carbon ratio (AAHCR) has been in the range of 1-2 for all the steady-state situations.

- However in both pilots, AAHCR was higher than 2 during the initiation of ISC by enhanced spontaneous ignition assisted by injection of a steam slug for pre-heating.

- LTO reactions are a natural part (for a few months) in two situations:
  - Initiation of ISC by spontaneous ignition
  - After a long period of air injection interruption

- For application of THAI to heavy oil reservoirs there are very infrequent situations of AAHCR>2, when ISC front may leave the oil zone and penetrate at the water-oil interface, therefore related to low control on the process.
10. More robust vis-à-vis the temporary interruption of air injection and vis-à-vis sudden, significant increase of air injection rate

- Even a 4 month-interruption in air injection did not lead to the loss of the ISC front; resuming the ISC process was very easy. This was clearly established in Canadian THAI pilots/projects.

- However, there are other reasons to pay attention to other effects due to air injection interruption.

- Even a sudden increase of air injection from 10,000 sm$^3$/day to 30,000-40,000sm$^3$/day did not result in an $O_2$ break-through.
11. Less damaging to the production wells

- Very high temperature first in the toe region and then experienced closer and closer to the heel

- Statistics of horizontal producers damaging in Kerrobert THAI Project; just partial (mainly toe region for 2 out of 12 producers)

- For conventional ISC 15%-20% of production wells are usually damaged and have to be replaced by new wells
12. Easiness of MONITORING. WhiteSands pilot. Bottomhole temperatures (BHT) profiles along the horizontal section of the producer P1 - until December 2010

V=17cm/day
13. Although line drive is preferred, it can be operated in separate patterns

- However, the evaluation of incremental oil recovery becomes a problem when the pattern is not located updip.
- Several adjacent patterns located updip is the recommended solution.
- Always, toe-up horizontal producers (HP) are needed (HP with their horizontal section perpendicular to the strike).
- Great attention to the sizing of the start-up region!
14. Works even for slightly lower permeability (dirty sands), where both conventional ISC and SAGD are not applicable

- Injectivity is better as THAI it is a short-distance oil displacement method
- Oil flows through the mobile oil zone (MOZ), which has high temperatures (100-250 °C)
- Thin shale intercalations (up to 1-2 m) are not a problem; they are penetrated vertically
- However, sand influx can happen in some cases (probably for extremely fine sand)

Note: For extremely low permeability (fractured or non-fractured) the process has not been tested yet.
15 and 16. Produces free hydrogen (H2) and methane

- H2 is generated by the coke gasification and water-gas shift reactions taking place during ISC
- Methane is produced by methanation process. It is practically impossible to differentiate this methane from that dissolved originally in the oil
- Methods have been established to correct the value of apparent atomic hydrogen-carbon ratio calculated from the composition of combustion gases
- At this time, the correlation of H₂ generation with intensity of oil upgrading is not fully elucidated
The higher content of fuel gases ($H_2$, $C1^+$ and CO) in the produced gas requires less make up fuel gas for incineration of combustion gases.

- $H_2$ is in the range of 1.5-4%, sometimes reaches 10-16%.
- Methane is in the range of 2-3% sometimes reaches 5-6%.
- CO can be as low as 0.2-0.3% and as high as 1.5-2%, depending on kinetics; not easy to predict in advance.
- Total “fuel gas” ($H_2+$CH$_4$+$C_2^+$+CO) is in the range of 5-9% (average 7%).
Produced oil contains less pollutants (metals, sulphur and nitrogen). It is of better quality (related to less pollutants and a better SARA composition); easier to upgrade to pipeline specifications.

- Sulphur reduction: 20%
- Metals reduction: 70-80%
- Nitrogen reduction: 70-80%
- Oil quality improvement as reflected by SARA analysis of original oil and of the THAI-produced oil
- Upgrading to pipeline specifications and then processing of the partially upgraded oil in refineries is by far easier; a financial effect for this however has not been evaluated yet. See Prof. Murray Grey presentation for this particular INFO.
19. THAI emulsions are less rebellious; easier to treat

- Emulsions are extremely rebellious in conventional ISC; the very fine water droplets are very difficult to remove (to strip them out); emulsion treatment is expensive and time consuming for determining the best recipes

- No emulsion problems have been reported so far in the 7 THAI pilots/projects worldwide
20. THAI well configuration is easily amenable to the development of catalytic THAI (CAPRI), or similar processes

- CAPRI = CAtalytic Upgrading PRocess In-situ
- Enhanced upgrading (twice) in CAPRI
- The pre-made at surface liners containing the catalyst in an annular have already been tested in the Whitesands Pilot; extra 3 API points obtained…but poisoning of the catalyst was rapid!
- There are several ways that the catalyst can be set up, when oil flows into the horizontal section of producer (gravel packing, etc)
- The research on CAPRI is still in an incipient phase although in UK there have been systematic investigations for 10 years (University of Birmingham and University of Nottingham)
21. Similar to SAGD, it produces oil a relatively long period after cessation of injection

- As demonstrated by the Kerrobert THAI Project
- For a period of 6-month of “on & off air injection” the oil production was still obtained such that the Project activity (oil production) did not cease
- From this point of view it resembles SAGD, which is another gravity drainage process assisted by gas-liquid segregation
22. When applying enhanced spontaneous ignition based on steam injection pre-heating, there is an additional method for ignition time determination in connection with CO and hydrogen variation before and after generation of the full ISC front.

- This specific method is characteristic to the heavy oil reservoirs with high viscosity, where hydrogen is produced during THAI application; the oil viscosity *probably* should be higher than 1000cP.

- It is based on the simple fact that CO% is higher before the full ISC is formed, i.e. during the LTO reactions predominance, while stabilizing at lower levels afterwards. At the same time, the hydrogen production takes off only after the ISC front is fully developed.
Summary of 22 ways that THAI is superior to conventional ISC

- Better control of propagation direction
- Better use of gravity
- SDOD for oil and LDOD for oxidation; no premature O2 breakthrough
- Partial upgrading of the oil with better quality of produced oil; hydrogen generation and capture
- Less operating problems
- Not a complete damaging of the production well at the ISC front interception
Four key-conditions for the THAI or a THAI-like process to work

1. High permeability (K) pathway at the bottom of the layer (HW, or “simple wormhole” or even disk-fracture)

2. Proper anchoring of the ISC front to the toe of corresponding horizontal producer or high K pathway

3. Existence of self-healing features in the advancement of the displacement front (along the high K pathway); local plugging being the one and controlled gravity segregation being the second

4. Existence of a hot region and a relatively colder region, as somebody goes along or parallel to the high K pathway, with a forward tilting of ISC front, making up the separation between these two regions.

![Diagram of ISC front with HOT and COLD regions]
Preliminary Screening Criteria for Application

Conventional ISC

- Depth > 150 m
- No fracturing.
- No gas cap present.
- No bottom water present (less than 20% thickness of the oil zone)
- Net pay thickness > 3 m
- Permeability > 50 md
- Oil viscosity < 5000 mPa.s.
- Porosity, fraction > 0.18 (if reservoir temperature is low)

THAI Process

- Depth > 150 m
- No fracturing.
- No extensive gas cap present
- No bottom water present (or less than 40% thickness of the oil zone)
- Net pay thickness > 6 m
- Permeability > 200 mD
- Oil viscosity > 200-300 mPa s
- Water cut < 70-80%
- Porosity, fraction > 0.2
Sweet Spots and Recommended Reservoir Conditions for THAI Application

- Sweet Spot: as a follow up to a conventional ISC operation, except in cases where the layer thickness < 5-6m; conversion of conventional ISC operations in THAI operations (successful experience acquired in this area)

- Recommended Reservoir Conditions (where SAGD is not applicable), in a first step without bottom water:
  - Depth > 1000m
  - Layer thickness < 10-12m
  - Dirty sands
  - Low pressure bitumen reservoir in a GOB, i.e. gas-over-bitumen situation; depth > 150m is a prerequisite

- Other situations: as a post-SAGD process, the best process to be field tested is still work in progress.
THAI as a “Stumble Upon” Process

• Recent good field results proved applicability of conventional ISC as a tertiary process after steam flooding; Jurassic Badawoan Field, China and Suplacu de Barcau, Romania; incremental oil recovery more than 20% OOIP and a good value for AOR (2,200-3,000sm³/m³), in both cases. A line drive operation was utilized.

• Both THAI applications after steam floods and those to be proposed as a follow up to SAGD will have to obey the 4 crucial rules from the previous slide. Also, drilling of any production horizontal wells in a conventional ISC project has to obey the same 4 rules presented in the previous slide

• Therefore, in many situations, when using horizontal producers in thermal projects, willy-nilly, the specialists have to get familiarized with THAI mechanisms
THANKS

? THAI or Conventional ISC ?

END