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

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December, 2020
Outline

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

• List of 22 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
Key Messages

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. Both technical and economic validity of the THAI process is underway to be proved by the current field testing in a staggered line drive (SLD) configuration.

4. THAI is a “stumble upon” process. In developing an ISC process after SAGD and/or 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)

Short-distance displacement, SAGD (HIHP)

Short-distance displacement -THAI case exemplification (VIHP)

Vertical Injector (VI)
Vertical Producer (VP)
Horizontal Injector (HI)
Horizontal Producer (HP)
Vertical Producer (HP)

Courtesy of University of Bath
SAGD; the first SDOD process.
Flowing distance: 20-50 m

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

Horizontal Injector

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

Horizontal Producer
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.; \( \approx 900 \text{m}^3/\text{day} \)
• Balol, and Santhal India; \( \approx 1000 \text{m}^3/\text{day} \)
• Several Projects, China
• BSOC-Bellevue, USA; \( \approx 50 \text{m}^3/\text{day} \)

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)

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)

In this schematic, we see the process of Toe-to-Heel Air Injection (THAI) in a heavy oil field. The injection well injects air into the formation, which reacts with the heavy oil to create a combustion zone. The coke zone forms as a result of the reaction, and the MOZ (middle oil zone) is directly influenced by this process.

- **Air** is injected into the field, creating a combustion zone.
- **Coke zone** forms as the reaction progresses, surrounding the MOZ.
- **MOZ** (middle oil zone) is directly influenced by the combustion process.
- **Heavy residual/coke** moves with the ISC (injection-sweeping-combustion) front, and there is local plugging at the 'Toe' and 'Heel' areas.

Steady operation of THAI (2 self-healing features) is indicated, suggesting that the process has stable and continuous benefits.
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

Start-up region
Initial ISC front

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)

Initial pseudo-linear ISC front

Horizontal Producer

Start-up region

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

Gas Analysers

Air

N₂

H₂O

Controller

Computer

A/D interface

D/A interface

3-D cell

Heating elements

Gas/Liquid Separation

Samples

Gas Analysers
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 THAI and CAPRI processes.]

THAI: 50,000 cp to 10,000 cp (5 times)

CAPRI: 10,000 cp to 100 (100 times)

Oil visc: 1 million $\rightarrow$ THAI $\rightarrow$ 1,000 $\rightarrow$ CAPRI $\rightarrow$ 50

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)
  - CMG simulation- Collin Card 2005 presentation (with a hardware to block O2 short-circuit). Other CMG studies, unpublished.
  - 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
Field Testing of THAI

Starting in 2006; there have been 6 pilots/projects in 3 countries (Canada-2, China-2 and India-1); 15 years of field experience.

- 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
23 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 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
23 Ways that THAI is Superior to Conventional ISC - Continued

14. Works even for slightly lower permeability (dirty sands), where both conventional ISC and SAGD are not applicable
15. Produces free hydrogen
16. 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
17. Produced oil contains less pollutants (metals, Sulphur and Nitrogen)
18. Produced oil is of better quality (related to less pollutants and a better SARA composition); easier to upgrade to pipeline specifications
19. THAI emulsions are less rebellious; easier to treat
20. THAI well configuration can be easily amenable to the development of catalytic THAI (CAPRI) style processes
21. Having lower heat losses THAI can be easier sustained even in reservoirs with lower temperature, where conventional ISC sustainability is more challenging
22. Similar to SAGD, it produces oil a relatively long period after cessation of injection
23. When applying enhanced spontaneous ignition (ESI) based on steam injection pre-heating, there is an additional method for ignition time estimate in connection with hydrogen and CO 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, Air + H₂O, etc.

Reaction zone

Combustion zone

Oil banking in the cold region

Swept zone

Cool zone

Bird’s eye view

(a pattern and its surroundings)

One cannot predict where the ISC front is going!

University of Waterloo

(Courtesy of M. Dusseault)
2. Gravity is fully accounted
(Vertical 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
(stream lines are not along the stratification; they bend towards horizontal producer)

- Injection well
- Combustion zone
- Coke zone
- MOZ
- Producer well
- Air
- Micro-layer of high K
- ‘Toe’
- ‘Heel’
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

– As we go for \( h > 8-10 \) m the VCF decreases significantly, as it has happened in Balol heavy oil reservoir in India

By applying THAI (starting in 2016), 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 O$_2$ 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)

- O$_2$ 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 O$_2$ B/T both at excessively high air injection rates (130,000sm$^3$/day) and excessively low air injection rates (5,000sm$^3$/day) in the field tests carried out so far; a proper design of the start-up region is very important to this effect.

- Moreover, there is no O$_2$ 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 in Canada, 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 normal, being 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 with bottom water, there are very infrequent situations of LTO occurrence, 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 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 (potentially negative) related 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 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 profiles along the horizontal section of the producer P1 - until December 2010

Velocity of ISC =17cm/day
(along the horizontal section)
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 up-dip.
- Several adjacent patterns located updip is the recommended solution.
- Always, horizontal producers (HP) with their horizontal section perpendicular to the strike are needed; they should be toe-up HP. 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 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 (H$_2$) and methane

- H$_2$ is generated by the coke gasification and water-gas shift (WGS) reactions taking place on an extended burning surface during THAI; due to short-distance oil displacement feature, it is preserved until the gases arrive at the surface.

- 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 calculated apparent atomic hydrogen-carbon ratio (from the composition of combustion gases) to account for coke gasification and water-gas shift reactions.

- At this time, the degree of correlation of H$_2$ generation with intensity of oil upgrading is not fully elucidated.
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.

- H₂ 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” (H₂+CH₄+C₂⁺+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 is reflected by comparative 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.
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.
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 a problem!
- There are several ways that the catalyst can be set up, when oil flows into the horizontal section of producer (gravel packing, pre-packed, 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. Having lower heat losses, THAI can be easier sustained even in reservoirs with lower temperature, where conventional ISC sustainability is challenging.

In reservoirs with temperature less than 22 0C, applicability of conventional ISC (C-ISC) *often* is questionable, as its sustainability is challenging due to the premature oxygen breakthrough in the producers, leading to the termination of the process; to avoid that, pre-heating before application of C-ISC may be necessary. Also, some more restrictive air flux requirements may be necessary for C-ISC to remain sustainable.
22. Similar to SAGD, it produces oil a relatively long period after cessation of injection

- This was demonstrated by the Kerrobert THAI Project and THAI piloting in Balol Field, India
- In Kerrobert, 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
- In Balol Field, India, the production continued for up to 2-3 months after cessation of injection
- From this point of view it resembles SAGD, which is another gravity drainage process assisted by gas-liquid segregation.
23. When applying enhanced spontaneous ignition based on steam injection pre-heating, there is a new, additional method for ignition time estimate in connection with hydrogen and CO 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 \((H_2)\) is produced during THAI application; the oil viscosity \textit{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 it may stabilize at lower levels afterwards. At the same time, the hydrogen production takes off only after the ISC front is fully developed.
- Therefore, the composition of gases produced in THAI process is richer in information about spontaneous ignition, as compared to the case of conventional ISC, where this method cannot be applied. It is important to recognize the significance of \(H_2\) and CO productions and their timing.
Summary of the 23 ways that THAI is superior to conventional ISC (C-ISC)

- Full control of propagation direction
- Better use of gravity
- SDOD for oil and LDOD for oxidation leading to high sustainability; no premature O₂ breakthrough
- Larger applicability spectrum in terms of reservoir temperatures
- More robust in application including for air injection stoppage
- Partial upgrading of the oil with better quality of produced oil; hydrogen generation and capture
- Not a complete damaging of the production well at the ISC front interception
- Less operating problems, except sand influx, which seems to be a problem in both processes
Five key-conditions for the THAI or a THAI-like process to work

1. High permeability (K) pathway at the bottom of the layer (horizontal producer, or “simple wormhole” or even disk-fracture)
2. Vertical air injector (s) has to be located within the drainage area of the toe of the horizontal producer
3. Proper anchoring of the ISC front to the toe of corresponding horizontal producer or high K pathway
4. 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
5. 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.
### 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)

Note: For reservoirs with temperature less than 22 0C, it may require pre-heating.

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

- 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 gas-over-bitumen (GOB) 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 key-crucial rules (for THAI application) 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 ?