# PORE SCALE PHENOMENA OF HEAVY OIL RECOVERY USING VAPOR EXTRACTION

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## ABSTRACT

The Vapour Extraction Process (VAPEX) for heavy oil recovery is targeted for reservoirs having oil viscosity greater than 10 Pa.s. The pore scale events of heavy oil recovery using the VAPEX process are not yet well developed to the extent of incorporating pore level physics into mathematical models to the point that the observed phenomena can be described mathematically. The primary objective of this paper is to elucidate the pore scale events of gas absorption type of mass transfer during the gravity drainage of live oil in heavy oil reservoirs when employing the VAPEX process by way of documenting pore scale events seen in micromodels of porous media. VAPEX experiments were carried out in micromodels of capillary networks etched on glass saturated with heavy oil, as well as in thin slabs of porous media consisting of glass beads sintered between glass plates and were vapour extracted using butane. The observed phenomena of vapour extraction at the pore scale demonstrate that gravity drainage of heavy oil from a vertically standing heavy oil/VAPEX interface occur in a very thin layer comprised of a monolayer of pores in the direction perpendicular to the interface. This leads to a continuously draining and renewed surface where gas absorption takes place at capillary interfaces in pore bodies and pore throats. The diluted bitumen drains from pores in a hierarchical manner dictated by drainage displacement mechanisms and the interplay of gravity and capillary forces. As oil filled pores with vapour-diluted bitumen drain at the interface, the corresponding volume of oil expelled flows downwards in a film flow regime along the first row of pores adjacent to the VAPEX interface. The periodic nature of draining pores with diluted bitumen and diffusion limiting the gravity drainage, result in a continuously evolving VAPEX interface having a constant shape. As a result, oil production takes place at constant rate that depends on the permeability and height of the porous medium. Observed phenomena in VAPEX demonstrate that oil film flow, snap-off of the liquid films and localized trapping of vapour enhance the mass transfer rate.

## INTRODUCTION

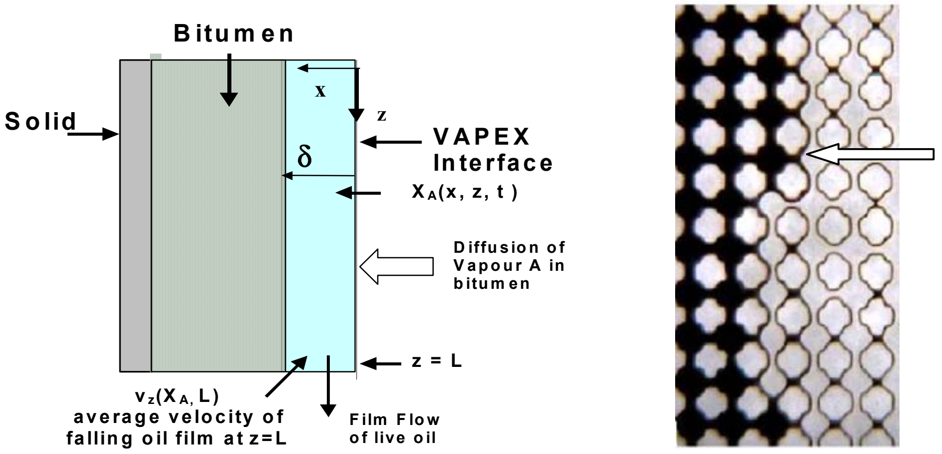
Heavy oil reserves are found all over the world and it is estimated to contain some 4 trillion barrels of oil [1]. Canada possesses over 50% of these reservoirs at 2.4 trillion barrels that are located mainly in Alberta and Saskatchewan ([1], [3]). With over 90% of Canada's total oil resources consisting of bitumen and heavy oil reserves, there is a great deal of interest to oil companies with heavy oil recovery operations to exploit this valuable resource. From the various methods of heavy oil recovery, the steam assisted gravity drainage (SAGD) has been found to be successful in Canada [3]. In order to achieve low enough oil viscosity values, high temperatures are required for the SAGD process, as it is necessary to heat the entire reservoir to sustain operating pressures. As the steam chamber develops in situ by extending vertically and sideways in the zone of steam injection, there is considerable heat loss to the overburden and underburden of the oil pay zone [1]. Because of excessive heat losses, SAGD is not recommended for relatively thin reservoirs. An alternative method to the SAGD is the vapour extraction (VAPEX) process [1-3]. The VAPEX process is considered to be an alternative to the SAGD process to recover heavy oil, both economically and practically. This process involves the injection of a hydrocarbon vapour that is close to its dew point at the reservoir pressure. Reduction in the viscosity of the heavy oil is achieved chemically by way of a diffusion process mechanism and interplay of gravity and capillary forces in draining the solvent enriched oil. Typically, ethane, propane or butane vapour is used as solvent because of their low dew point and good solubility in oil. Based on experimental results reported so far [1-10], up to four orders of magnitude decrease in the viscosity of heavy oil can be achieved in VAPEX. Since the hydrocarbon vapours are selective in solubilizing into the oil phase, they will only affect and mobilize the heavy oil. Theoretically, there will be very little interaction of these vapours with brine and reservoir clays. The nature of the Vapex process operation means that fewer and less expensive equipment is required. For example, the solvent produced along with the heavy oil in the VAPEX process can be readily separated from the produced live oil by a stripping process, recovered and then sent back to the reservoir [3]. The VAPEX process requires a simple stripping operation using steam to strip-off the solvent from the produced live oil by the VAPEX process. The SAGD process requires a lot more handling facilities by comparison to VAPEX process, e.g. a heated de-emulsification tank, water-softening tank, water softening system and compressors for steam injection [3]. Furthermore, once a reservoir has been produced to the economic limit using VAPEX, most of the hydrocarbon vapours can be recovered and re-used in future recovery operations. The VAPEX process has been in use in vertical well systems since 1974, mostly in the "huff 'n puff" process mode [3]. Use of the VAPEX process incorporating horizontal wells was first proposed and investigated by Butler and Mokrys [4] in Hele Shaw cells and in sand packed prototypes, simulating horizontal injection and production wells scenario. The published literature on VAPEX is predominantly based on the pioneering work of Butler and co-workers [1-7] and very few fundamental studies performed elsewhere [8-9].

The main objective of this paper is to illustrate the important features of the VAPEX process seen at the pore scale. The intent is to document a series of flow visualization experiments involving the vapour extraction of heavy oil that had a viscosity of about 80000 cP in capillary network type of micromodels and in slabs of consolidated glass beads. This study aims to provide a better understanding of how VAPEX operates at the pore scale and how the VAPEX interface evolves over time. VAPEX involves primarily the interaction of gravity forces, capillary forces and mass transfer aspects associated with gas absorption on oil films in a porous medium with flow caused by the action of gravity towards a horizontal production well. Near the VAPEX/bitumen interface, the viscosity and diffusion coefficient values in heavy oil recovery using VAPEX can assume values that vary by several orders of magnitude, depending on the concentration of extraction vapour absorbed [8-10].

## THEORETICAL ASPECTS

The VAPEX process involves the absorption of a light hydrocarbon vapour near its dew point by the resident heavy oil or bitumen, as illustrated in Figure 1(a). Assuming the liquid surface is exposed to a light hydrocarbon vapour near its due point, a thin mobile film of diluted bitumen forms near the interface of thickness $\delta$. Based on experimental evidence in our laboratory, for a readily absorbing hydrocarbon "A" in a heavy oil "B", such as propane or butane vapour near the dew point, and for systems when a falling liquid film of diluted bitumen has a length in the range of 0.3m to 2m, an average mass fraction ($X_{A,\,ave}$ ) of 20 – 40 wt. % is established at room temperature [8-10]. Having such a high concentration value of absorbed gas in absorption operations, the heat of absorption is expected to be significant; yet, the effects of this phenomenon have not received proper attention in VAPEX studies so far. The temperature rise near the VAPEX interface due to heat of absorption is expected to be beneficial for heavy oil recovery using the VAPEX process. This subject is presently investigated in our laboratory and is beyond the scope of this paper. Another important feature in vapour extraction of heavy oil is the great variation in the viscosity of diluted oil. In the case of VAPEX using butane or propane in our laboratory to extract heavy oil having a viscosity value of 80,000 cP, the produced live oil was found to have a viscosity of only about 2-5 cP, which is about 4 orders of magnitude smaller [8-9].

At the gas-liquid interface in vapour extraction, the concentration of vapour A in the liquid phase is at its maximum value. At some distance $x = \delta$, the mass fraction $X_A$ ($\delta$, z, t) may be assumed to be negligible and at $x = \delta$, the bitumen is immobile (Fig.1a). For vapour extraction in a falling film over a planar surface by gravity drainage, the average velocity of a falling liquid film of constant density $\rho$ and viscosity $\mu$ is proportional to ($\delta^2/\mu$) [11]. In the case of vapour extraction in porous media, the gas absorption takes place in falling liquid films of diluted oil that are found to be in pores where the diluted oil was displaced by the gas phase. These pores are located in the proximity of the pores being drained. The mass transfer of absorbing vapour takes place across capillary interfaces located in pore bodies and pore throats, as well as in the corners of gas invaded pores where oil films drain. As such, the diffusion distance for gas absorption in such situations does not exceed the dimension of a pore. The classical treatment of mass and momentum transfer developed for the case of gas absorption in dilute systems (see ref.11) is not appropriate for the VAPEX process. The main reason is primarily due to the fact that both the viscosity and the diffusion coefficient are very strong functions of the concentration profile near the interface of the falling film [9].



**(a) VAPEX interface over a film of bitumen** **(b) VAPEX interface in porous media**

Fig.1: Schematic of gas absorption interface in a falling film over a flat bitumen surface and in porous media.

Consider a rectangular slab of a porous medium that is saturated with heavy oil. Imagine that vapour extraction of heavy oil is taking place from one of its faces much like in the schematic shown in Fig. 1(b). The VAPEX interface in this case will be defined by the pores drained adjacent to pores filed by heavy oil. The characteristic length for diffusion in the heavy oil saturated portion of the system is one particle diameter, $d_p$. When the viscosity of oil is reduced sufficiently in the heavy oil saturated pores adjacent to vapour extracted pores, the pores with diluted oil will drain by the interaction of capillary and gravity forces. The pores will drain in a sequence involving pore scale displacement mechanisms that are appropriate for pore-scale drainage type immiscible displacements [12]. As the light hydrocarbon vapour invades a pore, an oil film is left behind in the pore corners because the oil is the wetting phase. The oil films in gas invaded pores were found to be responsible for achieving very high oil recovery efficiency during gravity drainage in conventional oil reservoirs [13]. For the purpose of modelling the VAPEX process, it is important to combine pore scale events along with mass transfer and pore-scale flow dynamics in the vicinity of the VAPEX interface. This problem is currently under investigation in our laboratory.

## EXPERIMENTAL ASPECTS

In our laboratory we have developed capabilities for conducting flow visualisations of immiscible displacements in porous media with applications to oil recovery, including waterflooding experiments, gas flooding - gravity drainage experiments, accessibility of residual oil during miscible solvent injection, and recently for heavy oil recovery studies using the VAPEX process. The porous media models used for flow visualisations of the VAPEX process include:

1. Pore network glass micromodels: They are etched in glass plates and contain several thousands of pores. The micromodels have dimensions as large as 150 mm wide by 300

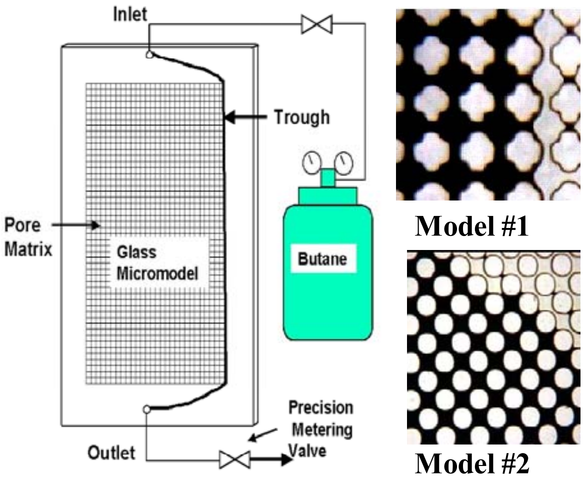
mm long, with equivalent pore throat sizes of 50 μm to 200 μm. When the oil saturated micromodels are oriented to stand vertically, gravity drainage experiments can be carried out and can be used to study heavy oil recovery using butane or propane in the VAPEX process mode. Pressure conditions up to 1 MPa can be used.

2. Prototypes of sintered glass beads between glass plates: These models permit the use of the same medium of a given pore structure to conduct flow visualisations of the VAPEX process and other immiscible displacements under various process conditions. The models can be made to have dimensions as large as 30 cm wide by 60 cm long by 5 mm thick and can be used when placed in an environmental chamber up to pressures of 60 psi. Models of different permeabilities can be made using different sizes of glass beads. Heterogeneities can be incorporated as desirable in the packing stage of model fabrication prior to sintering the glass beads.

Investigations of the VAPEX process for heavy oil recovery using micromodels and other media mentioned above permit flow visualizations which assist in the quantitative comparison of the mathematical model predictions of the VAPEX chamber growth and oil production history with direct experimental evidence.

## Experimental set-up used in Micromodel Experiments

The experimental setup for conducting VAPEX experiments using pore network micromodels etched on glass is shown in Fig. 2. The model is first filled with the heavy oil in an oven at about 80 $^{o}$C by injecting into it heavy oil using a syringe pump. There is no residual water in this experiment for simplicity, because for spreading oil under gravity drainage with residual brine present the recovery efficiency is over 95% [13]. A ditch-like channel (a trough) along one side of the pore network, which is relatively large by comparison to pores, was made in the model so that we can simulate a vertical line source of vapour extraction to simulate the falling film over a vertical plate (see Fig. 2). The micromodel was connected to a butane cylinder maintained at constant temperature in a water bath maintained about 1-to-2 $^{o}$C below the room temperature. Butane vapour was allowed to enter the micromodel at the top and fill the trough on the right of the pore network as shown in Fig. 2. As diluted oil is produced by film flow and gravity drainage in the micromodel, the live oil produced accumulates at the bottom part of the model which is periodically let go from the exit part of the model, by opening the metering valve slightly without allowing the vapour to breakthrough. Throughout the flow visualizations made

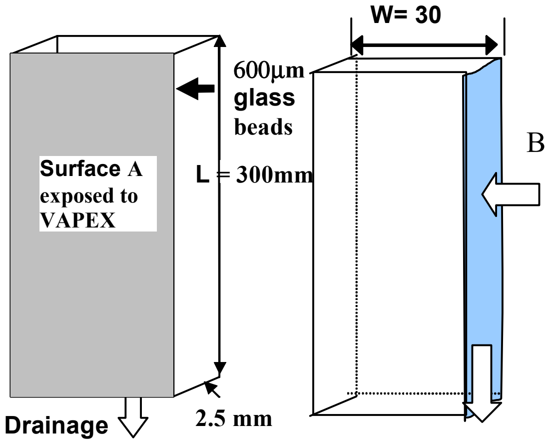


**Model #1**

**Model #2**

Fig. 2: Schematic of VAPEX Experiments

in vapour extraction experiments, the observed phenomena were recorded on video as well as on photographs taken at various stages to document the rate of advance of the VAPEX front into the model. Pore scale phenomena on close-up view were captured using a Cannon video camera with close-up no.4 lenses attached to it. This made it possible to have a region in view that contained a few pores as seen in figures presented in this paper. Two glass micromodels having a square type pore network structure as shown in Fig. 2 were used, identified as Model #1 and Model #2 respectively. The primary purpose was to see the effect, if any, of pore orientation with respect to drainage phenomena and advancement of the VAPEX interface into the bitumen saturated part of the micromodel. Model #1 was 87 mm wide containing 64 pores along its width and it had 97 pores along the vertical orientation. The lattice spacing in this model was 1.36 mm for the center-to-center distance of pores. Model # 2 contained only 25 pores along its width of 100 mm and the center-to-center distance of pores was 3 mm.



(a) Surface A exposed (b) Surface B exposed

Fig.3: Slabs of consolidated glass beads

In addition to VAPEX visualization experiments in glass micromodels, experiments were also conducted in thin slabs of consolidated 600 µm glass beads sandwiched between glass plates. The slabs were about 2.5 mm thick of glass beads (4 to 5 bead diameters), 30 mm wide and 300mm long, as shown in Fig. 3. Using the set-up shown in Fig. 3, two types of experiments were performed to test the hypotheses that: a) pores with diluted bitumen drain at a constant rate adjacent to the VAPEX interface (Fig. 3a), and b) a vertical VAPEX interface advances at a constant rate into the bitumen saturated part of a system as indicated in Fig. 3b. These experiments were conducted by placing the bitumen saturated slabs of consolidated glass bead models in an environmental chamber made from a 63 mm inside diameter Plexiglas tube and exposing the slab surface A or surface B to butane vapour, as indicated in Fig. 3. In this type of experiments, the model is first saturated with heavy oil and placed in the environmental chamber. Subsequently, the air in the housing is displaced by flowing butane vapour for a few minutes at ambient pressure. Following this step, the bleed valve at the bottom of the column is closed, allowing only vapour of butane to enter the system constantly from the butane supply as dictated by the gas absorption requirements on the diluted bitumen at the VAPEX interface that drains under the action of gravity. For large enough models, a mass flow meter is used to monitor vapour uptake as a function of time.

# EXPERIMENTAL RESULTS AND DISCUSSION

## 1. VAPEX Experiments Using Glass Micromodels

Pore scale flow visualizations of the VAPEX process reveal several mechanisms that operate in the vicinity of the VAPEX interface. As indicated by the visualization of photographs depicted in Fig. 4, the VAPEX interface at the boundary of bitumen saturated pores is defined by the continuum of gas invaded pores which is dendritic in nature. Right at the defining VAPEX boundary surface, the pores in Model #1 drain preferentially in the direction of gravity force and form dead-end type of structures that lead to forming peaks and valleys (see Fig. 6). The diluted oil in pores at the interface is displaced from a pore along the interface boundary. The diluted oil flows in the direction of the adjacent pore beneath it if mobility of oil in that pore permits it, otherwise the oil flows counter-current to the direction of pore invasion in film flow manner. The expelled diluted oil flows over the surface pores at the VAPEX interface boundary.

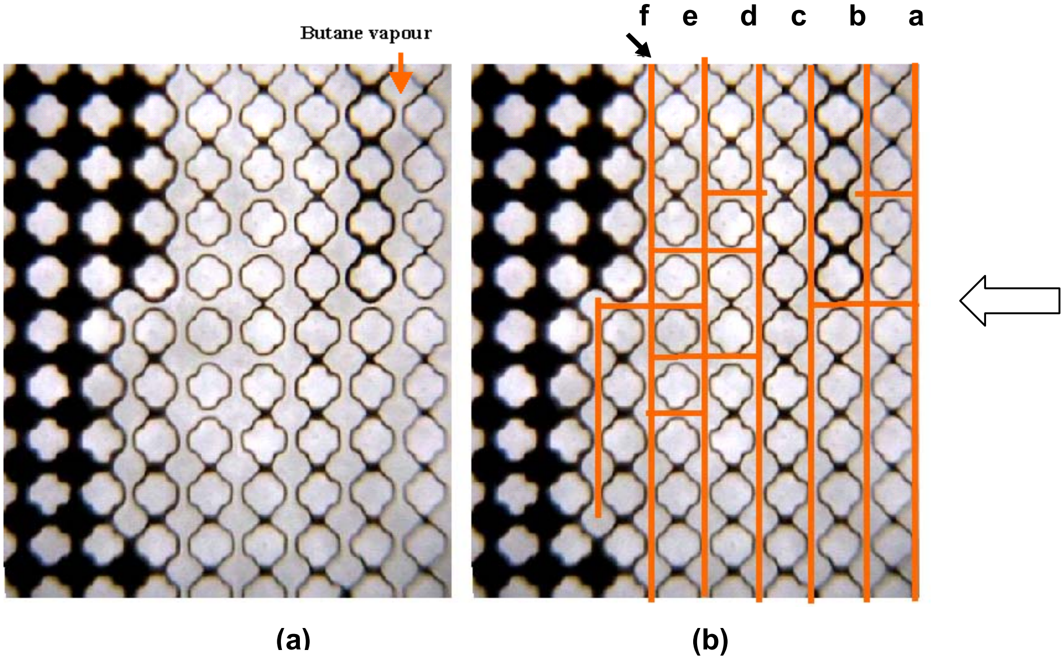


**Fig. 4: (a) Visualization of VAPEX interface and (b) the skeleton of vapour paths near the VAPEX interface in Model #1**

The connectivity of pores invaded by vapour near the VAPEX interface has an oriented structure, as seen by the skeleton of vapour paths shown in Fig. 4b by the light lines drawn to clarify these paths. The skeleton of the vapour pathways at various stages in Model #1 is shown in Fig. 5. This figure shows that the skeleton evolves continuously. The oil films left behind in the VAPEX extracted region periodically form loop structures involving films in gas invaded pores and pore throats filled with diluted bitumen. Capillary instabilities lead to periodic snap-off of interfaces in pore throats containing butane vapour that lead to formation of oriented structures of butane invaded pores that make vapour transfer to the VAPEX/bitumen interface very tortuous. This phenomenon points out that when an inert gas (e.g. nitrogen) may be used along with butane for vapour extraction, it may cause significant reduction in the rate of butane absorption at the front of the bitumen/VAPEX interface, because the non-absorbing gas will keep on concentrating in the vicinity of pathways identified by the first row of pores along the interface (see skeleton line **f** in Fig. 4b). Noteworthy is the fact that the skeleton of the gas phase has the least connectivity near the interface with fork like structures (Fig. 4b, line **f**) while just two pores away from it we see vapour-filled pore pathways with coordination number equal to 3 and 4 (skeleton lines **e** and **b** in Fig. 4b). Formation of dead-end structures that form pathways involving peaks and valleys as illustrated in the sequence of photographs in Fig. 6 is another important feature seen in the VAPEX interface. Also seen in this figure is the phenomenon of oil films connecting throats filled with diluted bitumen and forming loop structures. These loops were seen to orient with the pore structure in Model #1 (Fig. 6) and Model #2 (Fig. 8 and Fig. 10). Experiments in progress with random network pore structure also show loop structures of diluted bitumen filled pores with orientation in the direction of gravity.

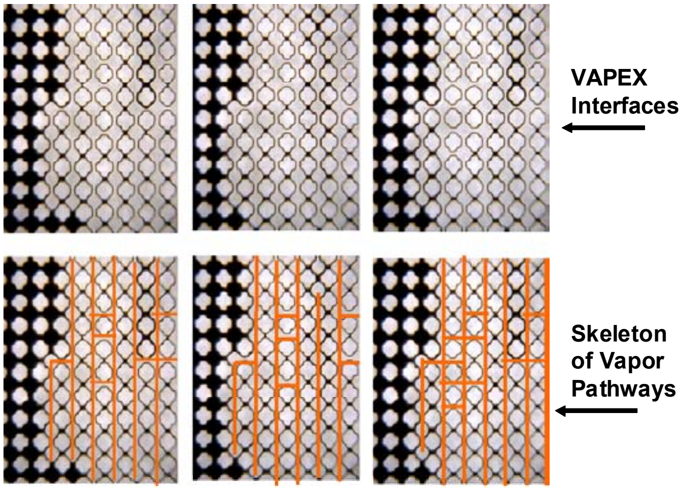


**Fig. 5: Visualization of the skeleton of vapour pathways in Model #1 at increasing times from left to right.**

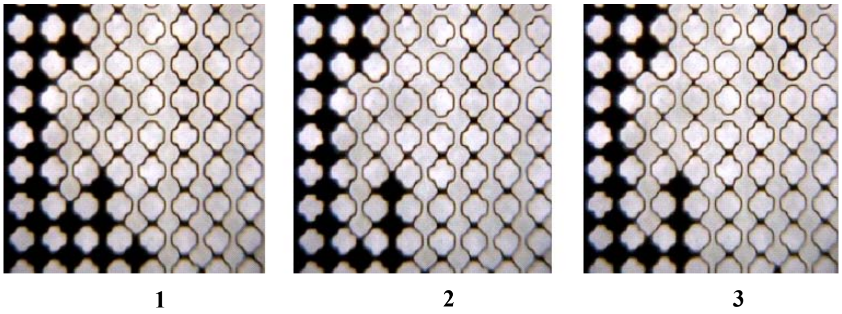


Fig. 6: Formation of peaks and valleys at the front of VAPEX interface.

As vapour enters a pore body by penetrating through the pore throat, the phenomenon of snap-off is a key feature in VAPEX process where pockets of vapour are temporarily entrapped in the pore bodies adjacent to terminal menisci of VAPEX interface. Snap-off is common in pores of high aspect ratio (ratio of pore body size to pore throat size). The photographs in figures 7 and 8 demonstrate that as a terminal meniscus drains a pore, trapped vapour occurs by the snap-off mechanism [12]. These pockets of vapour enhance the dilution of heavy oil just below the terminal menisci at the VAPEX interface. This phenomenon also facilitates in increasing the surface area for mass transfer and reduces the diffusion distance for vapour extraction. As seen in Fig. 7, pockets of trapped vapour in stage A go into solution in stage B, thus reducing the viscosity of the resident heavy oil in pores adjacent to terminal menisci. Visualization results shown in Fig. 8 also demonstrate trapping of vapour takes place by snap-off in vapour filled pores beneath the advancing terminal menisci. As the heavy oil in these pores is diluted to achieve mobility, local mobilization of trapped vapour in diluted oil filled pores is observed. Phenomena of this type cannot happen in VAPEX experiments conducted in Hele-Shaw cells or in other type of porous media models where the particle size used is very large because these models do not involve capillary phenomena.

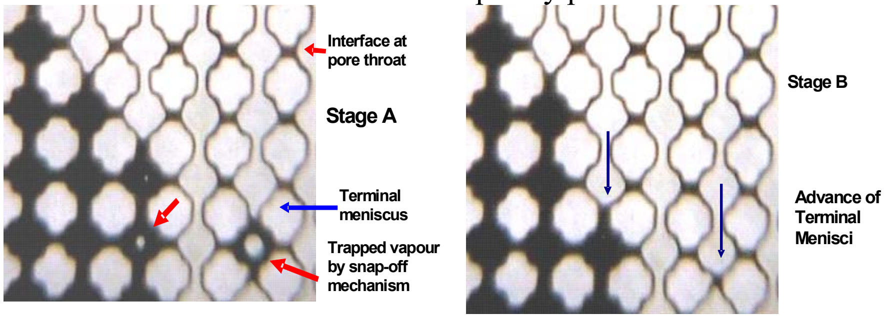
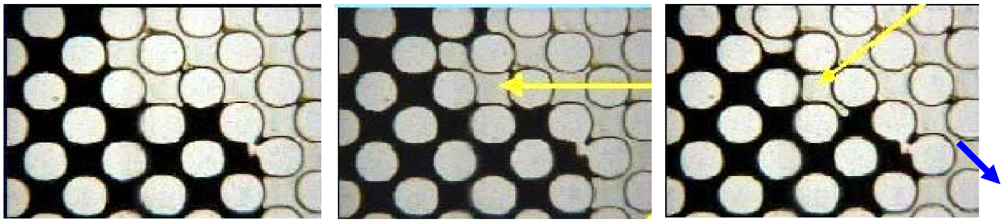


Fig. 7: Visualization of advancing terminal menisci and vapour entrapment.



**t = 0 min** **t = 1 minute** **t = 7 minutes**

Fig. 8: Visualization of pore scale phenomena in VAPEX interfaces in Model #2: snap-off and local mobilization of trapped vapour.

## 2. Macroscopic aspects in VAPEX experiments

The advancement of the VAPEX interface seen on a macroscopic scale in micromodels #1 and #2 is illustrated in Fig. 9 and Fig. 10. We observe that for a line source of vapour injection, the VAPEX interface advances into the bitumen saturated part of the system with a similar geometry. Continuous surface renewal leads to very distinct clear pathways near the interface while loop forming regions in the VAPEX extracted zones consist of diluted oil films of bitumen rich in solvent that swell and drain. The fact that pathways near the front of the interface were drained completely may have to do with the heat of absorption that prevents vapour to condense because of higher temperature established at the VAPEX interface. Swelling of oil films in closed-loop form is also seen away from the interface. Pore orientation is observed to affect the growth-rate of VAPEX interface at the very top of the system (see Fig. 9 and Fig. 10). Similar experiments conducted in slabs of glass beads (shown in Fig. 3b) were observed to exhibit behaviour very similar to that observed in Model #1. Of interest is the velocity at which the VAPEX interface advances at a particular location in the system. The results shown in Fig. 9 illustrate a constant velocity of the VAPEX interface advance, which implies a constant production rate of live oil. This finding is in agreement with results found in previous studies that focused on macroscopic aspects of VAPEX [8-10]. There was no evidence of asphaltenes precipitating out at the pore scale based on results seen in figures 9-10.

Experiments conducted on slabs of consolidated glass beads depicted in Fig. 3a and Fig. 3b respectively have shown to be consistent with the VAPEX experiments conducted in 2-D pore network micromodels. In the case where the widest surface of the slab is the one exposed to vapour extraction, the production rate was maintained constant. This implied that vapour extraction proceeded inwards at constant velocity. Similar behaviour was found when the narrower surface was exposed to vapour extraction as indicated in Fig. 3b. In this case, the VAPEX interface advanced in the direction of diffusion into the slab at constant rate. The shape of the VAPEX interface was similar to that for Model #1 illustrated in Fig. 9. It is reasonable to conclude that phenomena observed in 2-D network models mimic the behaviour of VAPEX extraction seen in 3-D porous media.

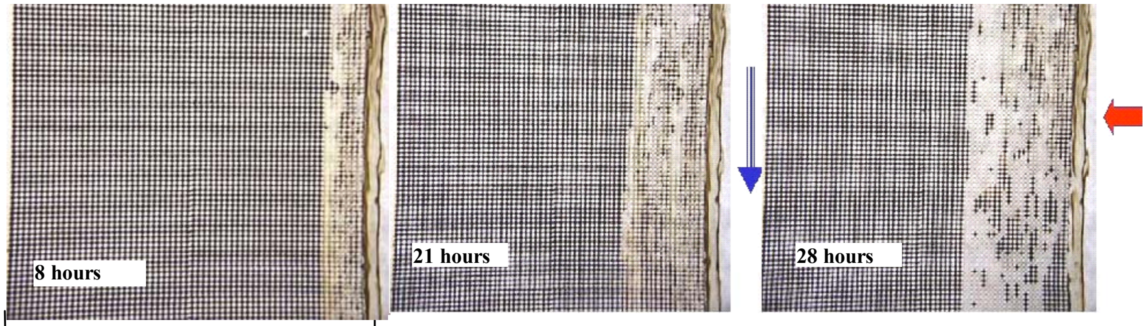


Fig. 9: Evolution of VAPEX Interface in Model #1

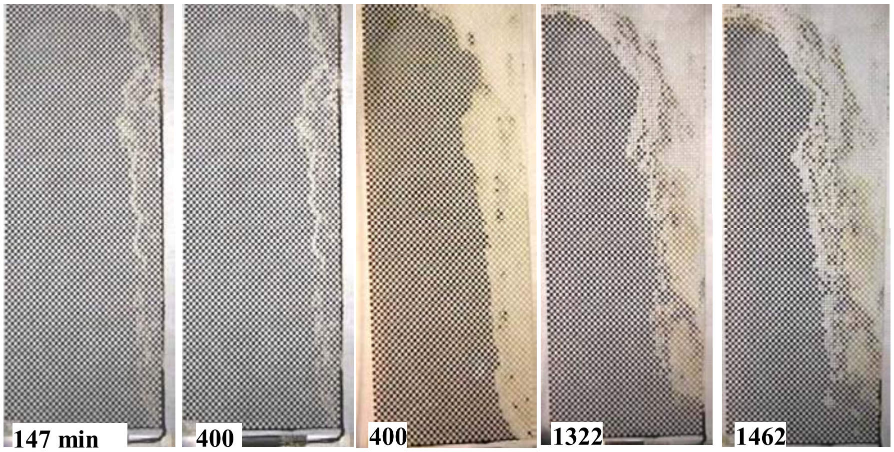


Fig. 10: Sequence of photographs showing the drainage of diluted bitumen and the condensation in the VAPEX extracted part of Model #2 in various stages.
(at 400 min, the model was cleaned free of diluted oil and experiment was restarted again)

**3. Example for predicting production rate in VAPEX**

Consider the application of VAPEX to extract an 80,000 cP heavy oil reservoir which has a 20m thick pay zone, a permeability of 10 Darcy and using a 1000 m long horizontal well. Suppose a VAPEX experiment conducted in a slab of glass beads 30 cm long and 200 Darcy permeability gave a production rate of Q = 0.1 $cm^3$ per cm width per minute in the lab. In systems having the same permeability and different length L, the flow rate of produced live oil was found to be proportional to $L^{0.55}$ [9]. When the length was kept constant and the permeability (K) was varied, the production rate was found to be a function of permeability according to: $Q \propto K^{0.47}$. In scaled prototypes where VAPEX was performed using horizontal wells, it was observed that the vapour percolates to the top of the formation and forms a VAPEX chamber [1, 3, 7-8]. Using the above scaling information and data, assuming two symmetrical surfaces of VAPEX interface develop initially (like a vertical fracture) along the length of a horizontal well, the predicted production rate of live oil for conditions specified after the VAPEX chamber forms is calculated to be 71$m^3$ per day. As the extent of the chamber grows laterally, the surface area for vapour extraction becomes larger and the production rate is anticipated to increase. The volumetric production rate of live oil will contain about 40 wt.% vapour that will be eventually recovered at surface facilities and returned by re-injection to the reservoir for VAPEX. This rate of oil production is considered to be economical for heavy oil recovery [3, 9].

## CONCLUSIONS

Based on the results of pore scale flow visualization of the VAPEX process presented in this paper, the following conclusions can be made:

1. The production rate in VAPEX remains essentially constant for a system of a given length because the geometry of the VAPEX interface remains the same over time.
2. The relatively large pores closest to the VAPEX interface are the first to drain, starting from the top portion of the VAPEX chamber. The snap-off mechanism and pools of diluted oil in the irregular interface enhance the mass transfer rate by way of increased diffusivity of vapour due to the exponential decrease of live oil viscosity with solvent concentration in heavy oil. The accumulation of diluted heavy oil in "valley" locations in the VAPEX interface boundary helps in washing away the "peaks" of the bitumen/VAPEX interface as the diluted oil flows past these locations.
3. Asphaltene precipitation is not seen to occur to a significant extent in the micromodels tested.

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