Non-Intrusive Telemetry Applications in the Oilsands: from visible light and x-ray video to acoustic imaging and spectroscopy

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ABSTRACT

While the production, transport and refining of oils from the oilsands of Alberta, and comparable resources elsewhere is performed at industrial scales, numerous technical and technological challenges and opportunities persist due to the ill defined nature of the resource. For example, bitumen and heavy oil comprise multiple bulk phases, self-organizing constituents at the microscale (liquid crystals) and the nano scale. There are no quantitative measures available at the molecular level. Non-intrusive telemetry is providing promising paths toward solutions, be they enabling technologies targeting process design, development or optimization, or more prosaic process control or process monitoring applications. Operation examples include automated large object and poor quality ore during mining, and monitoring the thickness and location of oil water interfacial zones within separation vessels. These applications involve real-time video image processing. X-ray transmission video imaging is used to enumerate organic phases present within a vessel, and to detect individual phase volumes, densities and elemental compositions. This is an enabling technology that provides phase equilibrium and phase composition data for production and refining process development, and fluid property myth debunking. A high-resolution two-dimensional acoustic mapping technique now at the proof of concept stage is expected to provide simultaneous fluid flow and fluid composition data within porous inorganic media. Again this is an enabling technology targeting visualization of diverse oil production process fundamentals at the pore scale. Far infrared spectroscopy coupled with detailed quantum mechanical calculations, may provide characteristic molecular motifs and intermolecular association data required for fluid characterization and process modeling. X-ray scattering (SAXS/WAXS/USAXS) provides characteristic supramolecular structure information that impacts fluid rheology and process fouling. The intent of this contribution is to present some of the challenges and to provide an introduction grounded in current work on non-intrusive telemetry applications - from a mine or reservoir to a refinery!

Keywords: oilsands, non-intrusive, telemetry, process, property, identification, control

1. INTRODUCTION

Canada is the fifth largest hydrocarbon energy producer in the world. The upstream sector is the largest private sector investor in Canada. This ongoing success is based on hydrocarbon resources such as oilsands and industrial processes we still do not fully understand. Each insight regarding the fundamental behaviours and properties of oilsands, heavy oil, and reservoir fluids spurs innovation in production, transportation and refining, reduces industry costs and environmental impacts, and increases revenues, all contributing materially to the Canadian and the global economy. The impact of pure and applied research and development is significant. Greenhouse gas emission intensity, a key indicator of material and process knowledge, has decreased 40 % over the past 20 years. Significant efficiency and environmental gains remain to be tapped.

Heavy oil and oilsands bitumen are ill-defined hydrocarbon resources. Their phase behaviour, and thermophysical and transport properties are complex. Property discovery presents significant experimental and theoretical challenges and opportunities for innovation. Diverse techniques including x-ray transmission videography, small angle x-ray scattering (SAXS), nano-filtration, calorimetry, rheology, spectroscopy, and acoustics, comprise a partial list. Integration of quantitative materials property knowledge and theory from the molecular scale to the nanometer scale to the macro scale is required so that thermophysical properties, transport properties, and phase behaviours identified across these length scales are better understood. The basic and process knowledge obtained is finding applications in both high and low temperature production and refining process operation, and in process and sensor development. Non-intrusive telemetry and sensors can be adapted and deployed to provide thermophysical property or process knowledge across a broad range

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of length scales. The balance of this brief report provides illustrative examples only, in the form of capsule summaries drawn from our research experience and the research experiences of colleagues. It is not exhaustive. The intent is to stimulate discussion and to spur collaboration and innovation on the development and application of non-intrusive telemetry in the oilsands and related fields.

2. PHASE BEHAVIOR AND TRANSPORT PROPERTY DISCOVERY

Within the last 10 years the Oilsands bitumen literature and the hydrocarbon literature in general asserted that oilsands bitumen and heavy oils are single-phase Newtonian fluids and that constituent fractions such as asphaltenes are defined as soluble in toluene and insoluble in n-alkanes.

2.1 The phase behavior of oilsands bitumen and heavy oil

By combining a nanofiltration separation technique[1] with rheometry and calorimetry measurements on the subsamples [2, 3], we were able to show that oilsands bitumen and heavy oil comprise multiple phases with nanoscopic, microscopic and bulk scale phase domains. In the interpretation of the results we were led to hypothesize that one of the phases was liquid crystalline. We were able to demonstrate that this was in fact the case using cross-polarized light microscopy and there by discovered a class of materials and phase behaviors unknown previously and not suspected[4,5]. Oilsands bitumen possesses a minimum of three phases at room temperature[3].

2.2 The phase behavior of oilsands bitumen + diluent mixtures

Conventional view cells cannot be employed to study the phase behavior of heavy oils because they are opaque to visible light, and the typical conditions where data are needed exceed the temperature range normally available. With a variable volume, beryllium walled view cell equipped with x-ray video telemetry, it was possible to overcome these limitations. As a polychromatic x-ray beam is employed, the ratio of K band to L band X-rays can be varied by varying the excitation voltage of the tungsten source. So, in addition to accurate online phase volumes, phase densities, and phase based elemental compositions can be obtained[6]. With this apparatus, shown in Figures 1a and 1b, the phase behaviors of mixtures containing oilsands bitumen and bitumen fractions + water, n-alkanes, hydrogen, and toluene have been investigated, under conditions that simulate production and refining environments, and subsidiary studies included investigation and control of the phase exposure of catalysts on their behavior and reaction outcomes at temperatures as high as 700 K and 30 MPa[7-13]. An example observation is shown in Figure 1c. Counterintuitive results that overturned conventional understanding of the phase behavior of such mixtures have for example included: vacuum residue from oilsands bitumen is soluble in supercritical pentane and that this mixture can possess up to four phases in equilibrium[13]!

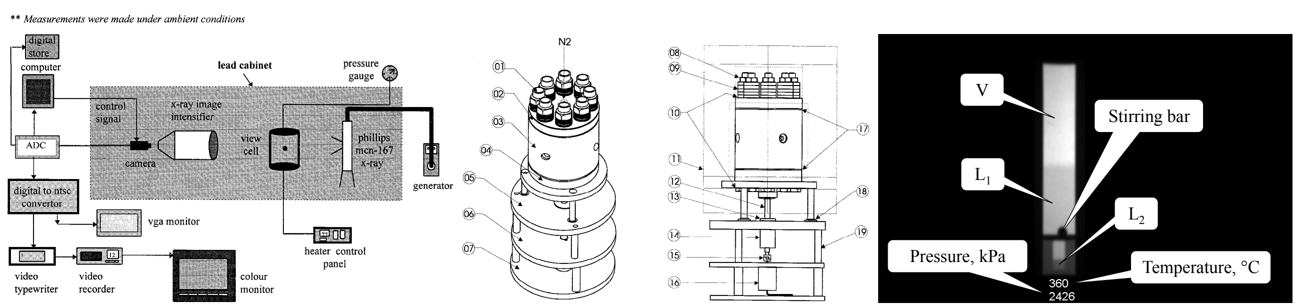

Figure 1. X-ray view cell apparatus. a) schematic[6], b) beryllium walled view cell detail showing aspects of assembly[6], c) example video still showing the operating conditions, and liquid 1 – liquid 2 – vapour (L1L2V) phase behavior of an Athabasca vacuum residue + decane mixture[7].

2.3 Mutual diffusion coefficient measurement

Mutual diffusion coefficients are important properties in oilsands bitumen production and blending. Prior to our contributions based on x-ray transmission tomography the literature was in disarray due to shortcomings in the experimental measurement methods applied and in the interpretation of data obtained from appropriate measurements[14-15]. We have also used the x-ray view cell, Figure 1, to evaluate forced mass transfer at solvent bitumen interfaces[16]. More recently, a microfluidics approach for mutual diffusion measurements has been developed that is based on visible light transmission. This new approach, illustrated in Figures 2a-c, is faster, simpler and equally robust[17].

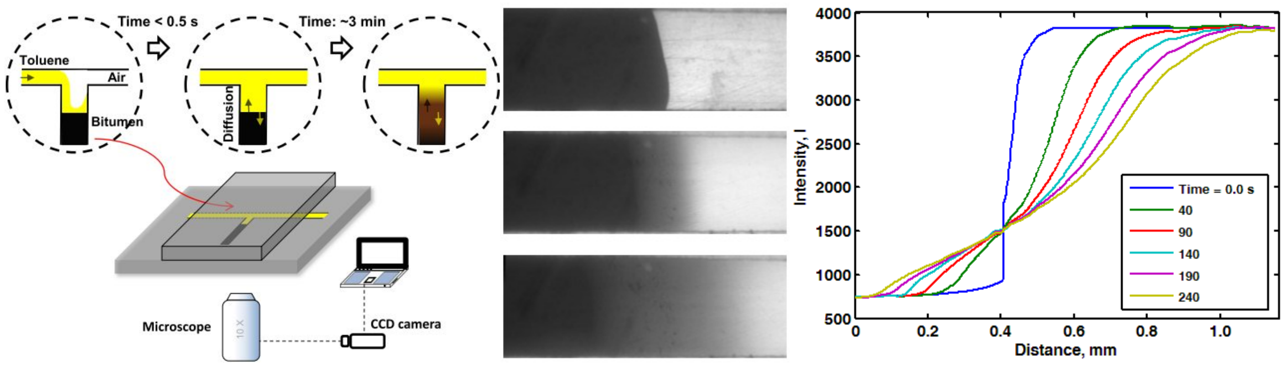

Figure 2. Micro fluidics diffusion measurement cell: a) over all schematic; b) high resolution images showing mutual diffusion of bitumen and toluene in at 650 um wide by 75 um deep teflon microchannel, at time = 0 s (upper image), 120 s (middle image), and 540 s (lower image); c) transmitted light intensity profiles[17].

2.4 Challenging fluid physics concepts – asphaltene solubilty in toluene

Asphaltenes, an important but ill-defined oilsands bitumen and heavy oil fraction comprising 15 to 20 wt % of these resources, contributes significantly to production, transport and refining difficulties associated with them. One broadly held notion is that asphaltenes are soluble in toluene at room temperature. In fact this is built into ASTM standard definitions. This notion was challenged recently by testing the hypothesis that asphaltene behavior in toluene + polystyrene mixtures would be governed by nano particulate behaviours. Polystyrene is a non-adsorbing polymer on asphaltenes. Thus, the only mechanism available for phase separation is depletion flocculation. This mechanism for phase partitioning is only accessible if the asphaltenes in toluene are fully or partially particulate in nature. Visually, the phases are not distinguishable but they are readily distinguished as polymer-rich (upper) and asphaltene-rich (lower) phases based on speed of sound, Figure 3a, or sound wave attenuation measurements, Figures 3b and 3c. Single to two-phase boundaries were identified along with critical points for two mean molar masses of the polymer[18] using an acoustic array technique[19].

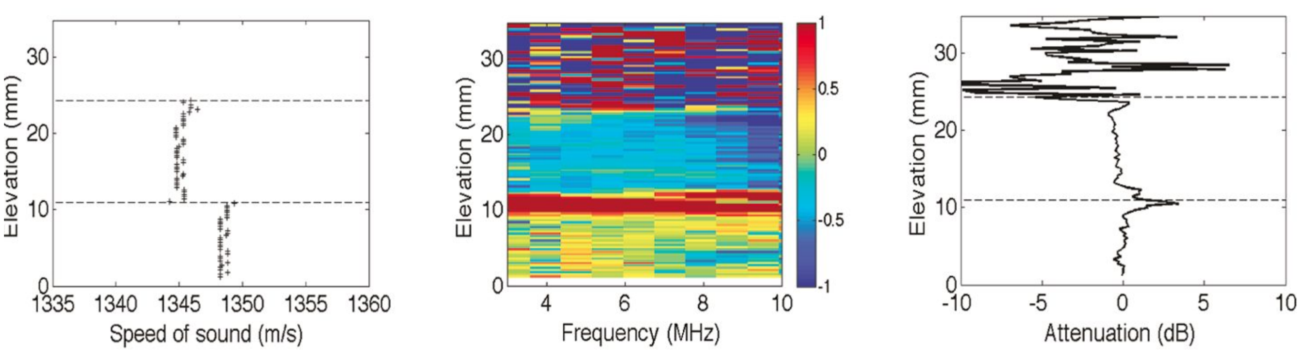

Figure 3. Liquid-liquid (lower) and liquid-vapour (upper) interface elevation identification for a mixture of asphaltenes (14 vol. %) + toluene (83 vol. %) + polystyrene (3 vol. %, molar mass 393,400 g/mole) based on: a) local speed of sound values, b) acoustic wave attenuation spectra difference relative to toluene, c) acoustic wave attenuation difference relative to toluene at 7.9 MHz[18].

2.5 Challenging Fluid Physics Concepts – asphaltene behavior at liquid to liquid-liquid transitions

Oilsands bitumen + diluent mixtures may exhibit complex phase behavior and Athabasca vacuum residue (AVR) + pentane mixtures possess up to four bulk phases in equilibrium[7]. As pentane is added to AVR, there is a transition from one bulk liquid phase to two at ~ 55 wt % AVR. The second liquid phase (L2) grows from the base and comprises ~ 3 volume % of the mixture at 50 wt. % AVR and grows to a maximum of 35 volume % at ~ 42 wt % AVR. The upper liquid phase (L1) is continuous through the L1 to L1L2 transition and using SAXS measurements, we demonstrated that asphaltenes are particulate or primarily particulate in the L1 phase and show that there is a discontinuity in asphaltene aggregation across the transition in the L1 phase[20]. Step changes in the average radius of gyration, Figure 4 a, the surface to volume ratio, Figure 4 b, and the scattering coefficient, Figure 4c, of the level 1 objects at the L1 to L1L2 boundary are apparent. Prior art would suggest that there is a transition from molecular to particulate behavior, and that it would be gradual and not abrupt as shown by the experimental results.

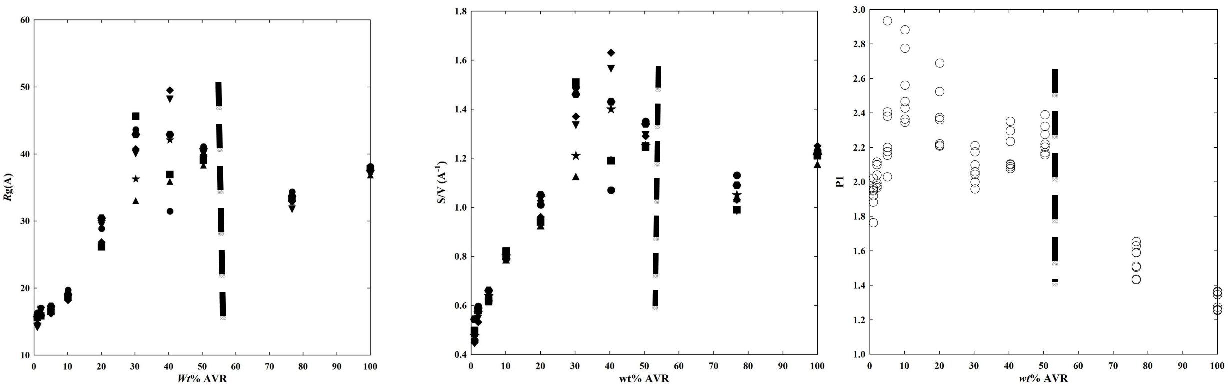

Figure 4. SAXS derived radii of gyration (a), surface to volume ratios (b) and scattering coefficients (c) for level one objects present in pentane + Athabasca vacuum residue (AVR) mixtures. The vertical dashed line shows the boundary between L1L2 two phase behavior (left hand side) and L1 phase behavior (right hand side). SAXS measurements were obtained in the L1 phase at mixture bubble pressures over the temperature range 50 C to 170 C[20].

2.6 Challenging Fluid Physics Concepts – asphaltene definitions

There are two prevalent definitions for asphaltenes in the literature. One is based on oil partitioning with pentane. The other is based on oil partitioning with heptane. These asphaltene subfractions, comprising 14 to 20 wt % of oilsands bitumen depending on the details of the partitioning procedure, differ from one another chemically and physically and both differ from the nanostructured materials in bitumen they are purported to represent. The confusion in the literature arising from misconceptions and poor definition on this topic is significant, and aspects of the field are stymied. The community has begun to tackle this issue[21] and based on recent nanofiltration and coordinated nanofiltration and SAXS studies[22,23], it is becoming clear that heptane based partitioning yields an asphaltene fraction that is unrepresentative of the nanostructured materials in oils and that pentane based partitioning yields an asphaltene fraction that approximates imperfectly the properties of nanostructured materials in oils. As greater clarity is beginning to arise on this topic and researchers describe and resolve the properties of the nanostructured materials directly, concepts such as resin-asphaltene association and "asphaltenes" loosely defined may disappear.

3. PROCESS SENSORS AND INSITU PROPERTY MEASUREMENT

3.1 Interface measurement detection and control

Oil + water emulsions and dispersions arise in diverse laboratory and industrial contexts. Local compositions and the evolution of emulsions or dispersions at interfaces during batch processes are readily monitored using transmitted electromagnetic radiation, whether x-rays or visible light[24] as still or video images. During insitu oilsands bitumen production, bitumen and water are co-produced and then separated in surface facilities. During oilsands mining, the oilsand is mixed with water and subject to further processing to liberate the bitumen from clay and sand. The final unit operation is a separator where bitumen the bitumen effluent leaves at the top of the separator and water + sand effluent leaves at the bottom. There is a middle layer of varying thickness comprising emulsified components at the interface between the two liquids called a rag layer. The separator, a key unit operation ahead of oilsands bitumen upgrading/refining is difficult to control. P.V. Jampana and S.L. Shah won an Alberta Science and Technology award (2010) for their development and implementation of an industrial-scale video-based sensor that uses an edge detection algorithm to automate the operation of this separation process[25,26]. Their test rig is illustrated in Figure 5a. By parsing video still images and applying the edge detection algorithm to the sight glass regions interface elevations are identified, as shown in Figure 5b. The process had been controlled manually and was subject to frequent upsets leading to water and sand entering the upgrader or oilsands bitumen entering the waste/recycle-water treatment system. Their interface monitoring and control technique has been adopted by industry. Their edge detection algorithm has been applied successfully to automate interface detection in the x-ray view cell apparatus[27].

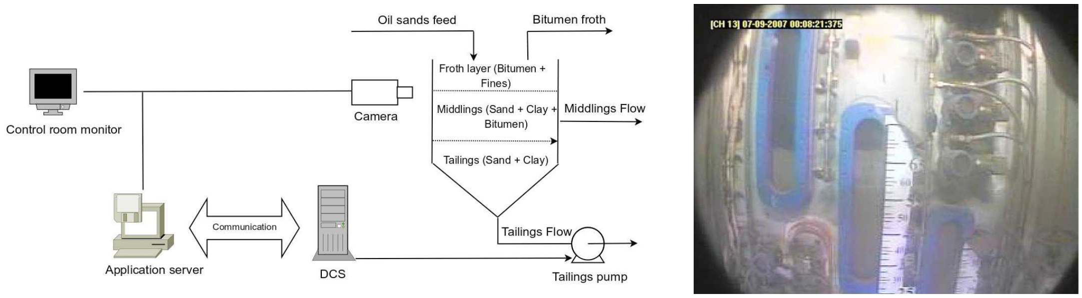

Figure 5. Mined oilsand bitumen/water + sand separator interface level controller plant scale test rig: a) schematic, b) example video still where the sight glasses are trimmed in blue and the interface is the grey to black transition visible in the left and middle sight glasses[27].

3.2 Insitu property measurement

Direct measurement of thermophysical properties is difficult to perform in fluids under pressure. Acoustic measurements can be carried out with a high degree of accuracy including at high pressure, and which presents the advantage of giving access to various derived properties. Acoustic sensors are conveniently small, very sensitive and capable of measuring a variety of properties depending on the wave modes and configurations used. For example, viscosity can be determined from variations in resonance frequency and from bandwidth measurements using up to eight different overtones. The resonance frequency allows an absolute measurement of the viscosity but leads to an accuracy limited to 5% whereas the bandwidth technique works in a relative way and provides an accuracy of 2%[28]. This could prove to be an inexpensive enabling technology that enhances laboratory based phase behavior measurements and it may also find application in the field.

Adaptation of sophisticated logging tools [29] used in vertical, and primarily in high-risk high-value off-shore fields, for typically shallow horizontal well configurations found in insitu oilsands production applications is unlikely. Thus there is room for development of sensors that are inexpensive to produce and operate, as deeper deposits begin to be produced.

3.3 Deposit detection in refining

The formation of coke during the upgrading of oilsand bitumen and heavy oil is an area of significant importance because of its effect on reducing the liquid yield, catalyst deactivation, and fouling of reactor internals and downstream vessels. Coke formation is triggered by reactions such as cracking, polymerization, and condensation, which results in the formation of coke as a new carbonaceous phase. Carbonaceous mesophase is an intermediate phase comprising optically anisotropic spheres surrounded by an isotropic liquid matrix. The mesophase spherules form as a result of the accumulation of layers of oriented polycondensed aromatic hydrocarbons. Once mesophase spheres begin to form, they can coalesce to form larger mesophase domains. These larger domains eventually deposit as coke on the interior surfaces of process equipment. The formation and growth mechanism is indicated in Figure 6a. By hindering or ideally preventing the coalescence process, mesophase domains can be carried out of the process lines and vessels without fouling equipment. Mesophase domain growth can be observed using a microreactor, Figure 6b, equipped with a mixer and a cross-polarized light microscope. The impact of agitation and catalyst addition on mean domain size and size distribution is quantified using standard image analysis software. An example is shown in Figure 6c. Basic knowledge and process monitoring and control applications can be envisioned[30]. It is important to note that modest improvements in process performance, either yields of desired products or the time between shutdowns, have significant economic impacts due to the scale of the industry.

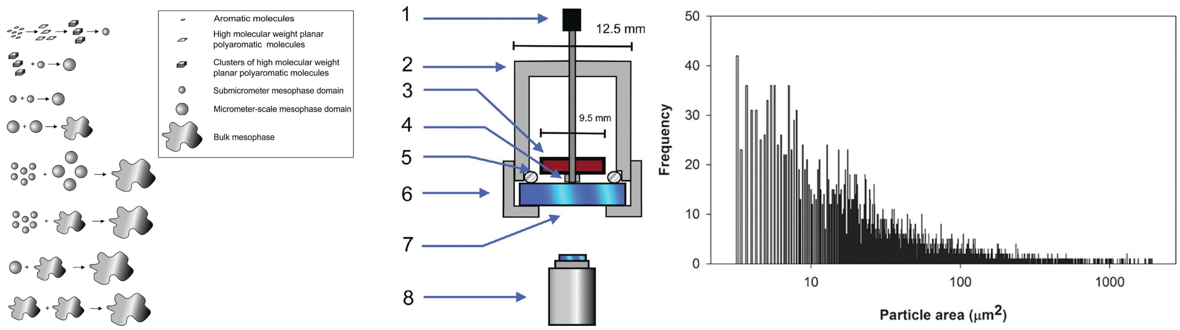

Figure 6. Anisotropic mesophase formation and growth during refining: a) mechanisms for domain formation and growth, b) apparatus schematic (1, thermocouple; 2, steel body; 3, magnet; 4, metal washer; 5, O-ring; 6, bottom nut; 7, sapphire windows; 8, objective lens of microscope), c) example mesophase domain area (number) distribution[30].

3.4 Deposit composition measurement

With the appropriate choice of windows it is possible to apply infrared or RAMAN spectroscopy to obtain information on submolecular structures present in heavy oils[31]. These techniques are well adapted to online or laboratory measurements. While it is possible to detect large differences in composition arising near interfaces[5] care must be taken not to over interpret the data as extrapolation to molecular level information is non-trivial[32]. Further, the nature of the surface –Lewis acid or base – affects the nature of the deposit/surface layer on the fluid side of the window[33]. From a sensor development perspective this is both an advantage and a disadvantage but it does permit inclusion of controls if performed thoughtfully.

3.5 Nanoparticle Association Mechanism Identification

A current thread in our research is to develop a better understanding of how nanoaggregated materials in oilsands bitumen and other hydrocarbon resources associate and disassociate in different solvent, temperature and pressure environments. We are currently engaged in model studies using nanoparticles with well-defined geometries and surface properties, with the objective of understanding the roles of physical entanglement, and pi-pi and hydrogen bonding, in solution that give rise to observed photoacoustic infrared and RAMAN spectra, SAXS, calorimetric and rheological behaviors. Detailed quantum mechanical calculations that discriminate molecular vibration modes, and intermolecular vibration modes[34] are being employed to interpret spectral data. Photoacoustic infrared and RAMAN data for model compounds[35,36] are being reinterpreted to benchmark the computational approach.

4. HIGH-RESOLUTION FLOW MEASUREMENT IN POROUS MEDIA

4.1 Microseismics

Real-time measurement of local composition and movement of organic fluids in porous media presents numerous data acquisition and data processing challenges but is relevant to many fields of science and engineering. Imaging techniques based on X-rays, acoustic or thermo-acoustic devices have been used to study the evolution of the structure of cells and internal organs in biology and biomedical applications or to monitor thermophysical phenomena such as diffusion, catalysis, phase change, and natural gas hydrate formation in chemical engineering. Acoustic techniques are of growing interest as they are often more convenient, cheaper, and have fewer side effects in the case of biomedical applications. While, the data acquisition time required to obtain high-resolution three-dimensional images can be long, current commercial multi-element acoustic devices permit the generation of two-dimensional high-resolution acoustic images from ultrasonic emission from an array of sensors at short time intervals. In principle, it is possible to monitor a physical property as a function of time at small length scales. A micro seismic experimental technique is illustrated in Figure 7a and b. This equipment provides real-time, two-dimensional, high-resolution images of fluid flow within an inorganic porous medium, Figure 7c. The example illustrated provides 40 um resolution for imbibition of heptane in natural sandstone. Data to construct individual images was obtained over 8 minutes, a time period short compared to the time scale of imbibition - two or more hours. The data acquisition time is the subject of ongoing development. The images are processed asynchronously using a supercomputing cluster (WESTGRID) and take approximately 10 hrs of cpu time per image generated. Specific applications of this technique include fundamental understanding of the complex thermophysical and phase behaviour change processes arising in oilsands and heavy oil reservoirs at the undisturbed resource – produced resource interface, and fluid movement in porous media more broadly such as in catalysts and structured media. As the work develops, local composition and flow will be decoupled. Publications are in preparation.

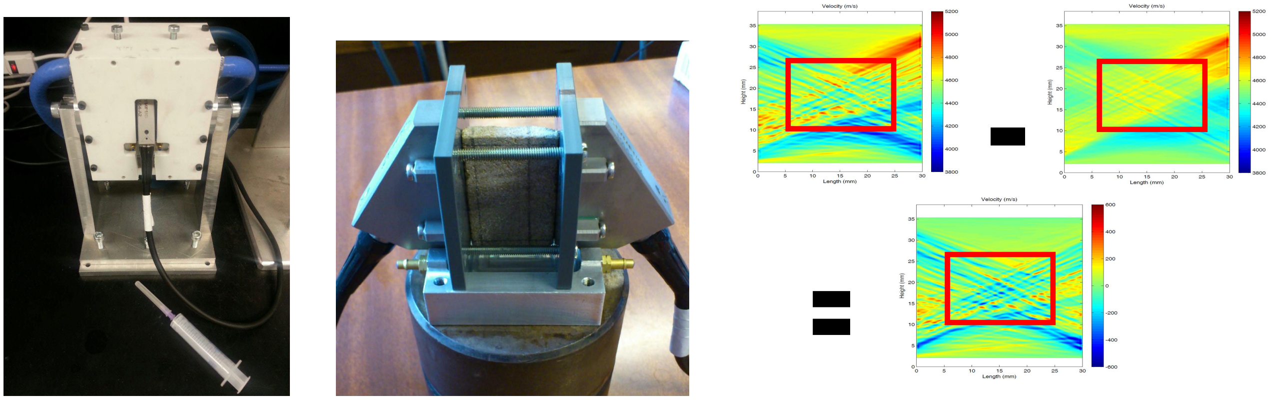

Figure 7. Inbibition of heptane into natural sandstone: a) an image of the cell, b) an image showing the arrangement of the acoustic sensors and the sandstone slab, c) an example illustrating local speed of sound map images and how difference maps are obtained at fixed time by subtracting a map obtained prior to imbibition. Imbibition occurs from the base of the sandstone. The zone within the red box is the focus for study and analysis.

5. SUMMARY

The intent of this report is to highlight physics, chemistry, fluid mechanics and physical properties applications of non intrusive telemetry from submolecular to bulk length scales in the oilsands with an emphasis on diversity of applications rather than on the provision of an exhaustive review. Further the bias in the capsule summaries toward small-scale applications (sensors, local property measurement and discovery, interfacial phenomena) is clear. However, the subject is vast. Large-scale applications arising during oilsands mining operations, from selecting which parts of which mine faces are produced/rejected in real time, to protecting crushers from large objects, to optimizing truck deployment and performance could easily provide a basis for additional reviews. Details related to a number of telemetry applications and technologies are not publicly disclosed. However there are excellent opportunities for further collaborative research and development of non-intrusive telemetry and sensor applications in the oilsands bitumen production, transport and refining sectors.

6. ACKNOWLEDGEMENTS

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