DEPARTMENT

Physics in the oil sands of Alberta

Alberta's petroleum reserves are comparable to Saudi Arabia's, but accessing that oil poses challenges in the physics of fluids and particulates.

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Figure 1

The recent spike in the price of oil to over US$140 per barrel focused worldwide attention on the need for more diverse supplies of fuel from unconventional sources and renewable resources. The oil sands of Alberta, the largest source of unconventional fuel for North America, are also the largest petroleum deposit on Earth. Sometimes called tar sands, they contain an estimated 2.5 trillion barrels of crude oil over an area of more than 140 000 square kilometers, but that oil, called bitumen, is too viscous to be extracted by conventional drilling. Large oil-sands deposits also exist in Venezuela, and smaller ones are found in Utah, western Africa, and Russia, but production from the Canadian deposits is the largest.

Material from a typical commercially viable oil-sands deposit is shown in figure 1. It contains 9%–13% bitumen, 3%–7% water, and 80%–85% mineral solids. Of the solids, 15%–30% are fine particles, predominantly clays, less than 44 μm in diameter. The challenge in production is to separate the bitumen not only from the sand grains but also from the micron- and submicron-sized clay particles. Alberta's bitumen reserves—the amount that can be recovered economically with current and foreseeable technology—are estimated at 172 billion to 315 billion barrels. In comparison, the crude-oil reserves in Saudi Arabia are estimated at 264 billion barrels. Over the past decade, production of crude oil from the oil sands has grown to well over 1 million barrels per day, at a production cost of Can$35 (US$28) per barrel, compared with a few dollars for conventional crude oil of comparable quality.

The Canadian oil sands were formed some 50–100 million years ago, when crude oil was released from shale under the Rocky Mountains and migrated eastward and upward into sedimentary sand deposits in eastern Alberta. There, microbes biodegraded the oil, removing all the low-molecular-weight components and leaving behind the large, complex molecules that make up the dense and viscous bitumen.

Europeans discovered the oil sands in the late 18th century along the banks of the Athabasca River, where erosion had exposed seams of oil sands that oozed bitumen on a warm summer afternoon. In the 1920s Karl Clark, of the Alberta Research Council and the University of Alberta, demonstrated that the bitumen from mined oil-sands ores could be recovered by air-assisted flotation: When a slurry of oil-sands ore in hot water is aerated, bitumen droplets attach to air bubbles and float to the top, leaving the solid particles behind. Clark's method, using water at 75–80 °C, was first commercialized in the late 1960s. It continues to be used today, albeit at a much lower processing temperature.

Mining bitumen

Relatively shallow oil-sands deposits are most economically accessed by mining operations in which the overlying dirt, or overburden, is removed by massive trucks and shovels to expose the oil sands. The goal of mining operations is to remove overburden and extract oil-sands ore in large quantities, process the ore using as little energy as possible to recover at least 90% of the bitumen, and then reclaim the mines to leave a landscape that supports vegetation and wildlife. The technical challenges of the process are related to the physics of oil-sands components, and solving them involves fluid–particle physics, chemistry, and interfacial science.

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Figure 2

The first few steps of the process are illustrated in figure 2. The mined ore lumps are cohesive and can be as large as 1 m. They are first crushed and then mixed with warm water to prepare a 40–55 °C slurry of much smaller lumps. To liberate bitumen from the sand grains, the slurry is pumped through a hydrotransport pipeline (shown in figure 3) for 3–5 km. Turbulence in the pipeline ablates the lumps and separates the bitumen from the sand grains. At the same time, bitumen droplets attach to entrained air bubbles.

Figure 3

The slurry of sand and aerated bitumen then enters a gravity-separation vessel, where the aerated bitumen rises to the top and is skimmed off as froth, while the sand rapidly falls to the bottom together with water carrying clays and fugitive bitumen. The so-called middlings layer, a water suspension of clay particles and residual bitumen, is often re-aerated to allow more bitumen to float to the surface as secondary froth. The physics governing the gravity separation of the components is described in the box at right.

Cleaning the froth

The bitumen froth that is skimmed off in the gravity-separation vessel contains about 10% fine solids and 30% water. The air bubbles entrained in the froth are easily removed by heating or gravity drainage, but the viscous bitumen does not easily give up the fine clays and emulsified water droplets. Diluting the bitumen in a solvent reduces its viscosity and density and speeds the settling of denser solids. However, the emulsified water droplets and fine clays have tiny diameters, so they still settle very slowly. Originally, banks of centrifuges were used to accelerate the settling, but such equipment is expensive to maintain.

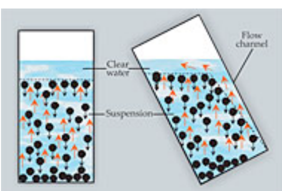

Figure 4

A much more elegant approach uses inclined-plate separators, as shown in figure 4. Sedimentation is slow in a vertical geometry partly because as the solids fall, the liquid that they displace must also rise. But confining the suspension between inclined plates establishes a circulation pattern whereby solids fall along the bottom plate and push the free liquid upward along the top plate. That pattern, called the Boycott effect, was first observed by a physician trying to remove blood cells from plasma samples and now allows the rapid removal of fine clays and tiny water droplets from diluted bitumen froth. Inclined-plate separators also enhance the separation of light and heavy particles, as shown in figure 5.

Emulsified water droplets

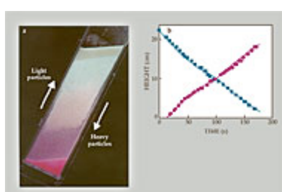

Figure 5

Bitumen contains several components that tend to stabilize the emulsified water droplets 2–10 μm in diameter. The original, natural biodegradation of the bitumen left behind carboxylic acids that act as natural surfactants. While those compounds are beneficial for liberating the bitumen from the sand grains, they also reduce the surface tension of the bitumen–water interface, a process that leads to emulsification of water in the diluted bitumen. The water droplets are stabilized by submicron mineral solids and organic particles that accumulate at the interface, coating each droplet with a skin of fine particles. As illustrated in figure 6, the skin stops the water droplets from coalescing even when they are pushed into contact with each other. The emulsified water droplets in the diluted bitumen are too small to settle easily.

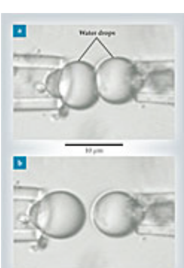

Figure 6

Two approaches are used to promote settling of the water droplets. One method is to add polymers to the diluted bitumen to bind the water droplets together and hence increase their effective diameter. Removing the bound droplets reduces the water content to about 2% and the clay content to about 0.8%. The solvent is then evaporated and recycled, along with any residual water, and the solids remain in the bitumen. However, both water and solids cause problems at later stages. Evaporation of water may seem benign, but any salts that were dissolved in the water are left in the bitumen. The oil-sands ore contains sodium chloride and calcium chloride, which accumulate as the warm water is recycled in the extraction process. After the salts are transferred to the bitumen, they react in downstream refineries to produce corrosive hydrochloric acid. The clays that remain in the bitumen cause problems by depositing in pipelines and refineries.

A recently developed alternative approach is to coagulate, or flocculate, the water droplets, along with any suspended clay particles, by selectively precipitating a portion of the bitumen. Bitumen's largest and most polar molecules, known as asphaltenes, will precipitate when bitumen is diluted with a straight-chain alkane solvent. The aggregates, or flocs, of precipitated asphaltene bind to the water droplets and the remaining clay particles to form larger suspended flocs. Although the flocs are similar in density to the diluted bitumen, the increase in diameter from a 2-μm water droplet to a 100- to 1000-μm floc is sufficient to lead to rapid settling of the contaminants from the mixture.

Tailings ponds

One of the biggest challenges faced by the oil-sands industry arises in the settling and compacting of the tailings, the mixture of sand and clay solids carried in the bottom stream of the gravity-separation vessel. In many cases the tailings are transported to large ponds surrounded by dikes of sand and overburden. In those tailings ponds, the sands settle rapidly, leaving much of the fine clay in suspension. As the fine solids slowly settle out of the water over a period of one to two years, relatively clean surface water is produced and is extensively recycled to form the major part (up to 87%) of the water needed to process the oil-sands ore. Since the water cools off in the tailings pond, it needs to be reheated before it can be used again for bitumen extraction. That is not a problem as long as upgrading operations (described later in "From sand to fuel") are located nearby, since they produce excess thermal energy that is used to heat the water.

The initial sedimentation of the clay particles follows the Masliyah-Lockett-Bassoon equation presented in the box. But as soon as the particles touch each other to form a loose network, the forces between the colloidal particles become too strong for further compaction. As a result, a water-rich sludge containing just 15% solids by volume, or 30% by mass, accumulates in the bottoms of the tailings ponds, where it can remain for decades. The sludge accounts for about half of the net uptake of fresh water used to process the oil sands, or about 1–1.5 cubic meters of water for every cubic meter of crude oil produced.

The sludge poses two problems. First, it accumulates continuously with time, so the ponds need to grow in size and depth: Increasing amounts of land must be disturbed for sludge storage, and more fresh water must be drawn from the Athabasca River, thereby requiring careful management of water inventory. Second, the accumulated sludge is too fluid to bear any weight at all, so it presents environmental concerns. The sludge must eventually be treated to produce a self-supporting solid matrix that can bear weight before the landscape can be remediated to support vegetation and wildlife.

Oil-sands operators have developed several technologies to break down the network of clay particles and densify the sludge. One strategy is to mix the sludge with coarse sand and gypsum (calcium sulfate). The calcium ions bind the clay particles together, while the sand, acting as a press, applies force to them. The result is rapid release of water to produce a solid sediment that can bear traffic and is ready for land reclamation through topsoil addition and grass and tree planting.

Tailings are processed differently when upgrading operations are not in close enough proximity for their excess thermal energy to be used to reheat water. In large vessels called thickeners, flocculants such as polyacrylamides are added to the tailings to bind the fine particles together. The newly formed flocs settle rapidly to produce a paste with a relatively low water content, and the rest of the water can be recycled while it is still warm. Avoiding the heat loss from the water saves about 350 megajoules per barrel of bitumen. Ultimately, the paste may then be filtered or centrifuged and the solids immediately returned to the mine pit for final land reclamation.

Deeper deposits

Oil sands buried under more than about 40 m of overburden cannot be economically accessed by mining operations, but some of the bitumen can be recovered by in situ techniques. For much deeper deposits, steam is injected into wells drilled in the deposits, where it heats the surrounding oil sands to about 250 °C; the heat lowers the bitumen viscosity by orders of magnitude so that it can be pumped to the surface. Two approaches are used: cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD). In CSS, also known as "huff and puff," the steam is injected into a vertical well and left for several days to heat the bitumen. The bitumen and the condensed steam are then pumped out of the same well. When the bitumen stops flowing, the cycle is repeated. The CSS approach is being applied in the Cold Lake region of the Alberta oil sands, where it allows the recovery of about 20% of the bitumen in place.

In SAGD, two L-shaped wells are drilled in parallel, their horizontal segments one above the other, in the lower part of an oil-sands deposit. Steam is injected into the upper well, and the heated bitumen and condensed steam then flow together into the lower well, where they can be pumped to the surface. The recovered water is treated to remove oil and hardness and is heated in boilers to generate steam for reinjection. SAGD can recover 60% of the bitumen in place, but it can be applied only to thick, rich deposits. It is currently used in the Athabasca oil-sands region.

From sand to fuel

Bitumen that has been cleaned of its sand, clay, and emulsified water is still too viscous and contains too many impurities such as sulfur to use as fuel. It is either upgraded (by thermal cracking or hydrogenation) to produce a crude oil desirable for refineries in Canada and the US, or it is blended with solvents and shipped by pipeline to refineries in the midwestern US and Ontario. As bitumen production in Canada has increased, exports have moved further afield to reach refineries along the Texas coast. The majority of gasoline and diesel fuel in western Canada is produced from bitumen, and if you live in the midwestern US, you also probably have products from the oil sands in your gas tank.

The present commercial oil-sands operations are based on the application of a broad range of applied sciences and engineering disciplines. Only through understanding the science of bitumen, sand, clay, and water interactions can we effectively and responsibly recover that Canadian resource.

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Further reading

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