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Chapter

Ablation of Oil-Sand Lumps in Hydrotransport Pipelines

Mahshad Pazouki and Sayeed Rushd

Abstract

Oil-sand ore is a kind of heavy crude oil found primarily in Canada. The surface mining of this petroleum resource requires expensive 400-ton capacity trucks to transport the ore to the slurry plant. The slurry prepared with the crushed ore is usually conditioned in a hydrotransport pipeline prior to extracting bitumen. As the elimination of the mammoth trucks has a tremendous economic and environmental incentive, it is of industrial interest to employ new processes capable of conditioning oil-sand right at the mine face. This would demand an accelerated rate of conditioning compared to what is achieved at present in the industry. One of the significant steps of the conditioning process is oil-sand lump ablation (OSLA). An understanding of the fundamental concepts associated with OSLA is essential to achieve any industrial-scale change in the current conditioning method. A number of parameters such as temperature, lump size, pipe diameter, pipe length, flow rate, and shear influence the ablation process. The current chapter introduces the concept of OSLA. It also includes a comprehensive review of the most important models available to predict the ablation rate and the scope of future works.

Keywords: heavy oil, bitumen, transportation, conditioning, ablation rate, modeling

1. Introduction

About 15–20% of the Canadian oil-sand reserve containing 140 billion barrels of bitumen can be found at a depth less than 75 m, where surface mining is economically feasible [1]. The remaining 80–85% buried at higher depths can possibly be recovered with underground-type mining employing in situ techniques. The Great Canadian Oil Sands, now known as Suncor Energy Inc., developed an open-pit mine, a hot water extraction plant and an upgrading complex in 1967. Their operation was followed in 1979 by Syncrude Canada Ltd.'s open-pit mine at Mildred Lake. Currently, Suncor Energy Inc., Syncrude Canada Ltd., Albian Sands Energy Inc., and Canadian Natural Resources Ltd. employ surface mining [1–3].

A typical surface mining operation, as shown in **Figure 1**, includes the following steps [1, 2]:

1. Removal of overburden using shovels and trucks

2. Mining oil-sand with hydraulic or electric shovels

3. Transport of oil-sand ore from the mine face to the crushers with trucks
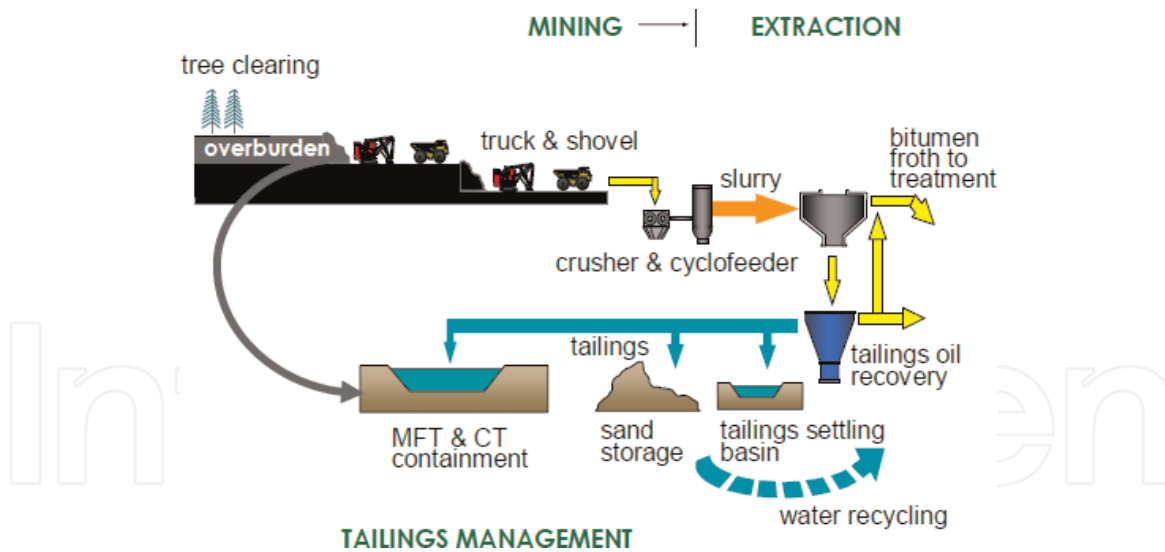
Figure 1.
Major steps for bitumen recovery in surface mining operation [1].

4. Crushing of large oil-sand lumps into smaller parts

5. *Oil-sand conditioning*

6. Gravity separation of bitumen froth

7. Diluted froth treatment to separate water and solids

8. Supplemental solvent recovery from tailings

9. Dewatering and concentrating the tailings

Among the above mentioned steps, *oil-sand conditioning* is probably the most important phase that can further be divided into three stages [1, 3]:

i. Oil-sand lump ablation or size reduction

ii. Liberation of bitumen from sand grains

iii. Aeration of bitumen droplets

Oil-sand ore carried from the mine with conveyors was originally conditioned with rotating drums or tumblers [1]. Investigations into the possibility of replacing conveyors and tumblers with pipelines began at the Syncrude Research Center in the early 1980s [3, 4]. The idea was based on the examination of the pipelines transporting tailings from the separation vessels to the tailing ponds. Subsequently, a large-scale prototype of an oil-sand hydrotransport system known as the extraction auxiliary production system was commissioned in 1993. It became a successful commercial unit that could digest up to 5000 ton of oil-sand per hour. Since then, hydrotransport pipelines are being used in other commercial extraction plants to simultaneously transport and condition oil-sand ore. Roughly 60, 000 ton of oil-sand flowing as slurry of about 60 wt% solids is digested per hour to produce ½ million barrels of bitumen per day at present [3, 5]. Commercial applications of hydrotransport pipelines enabled the conditioning process to be carried out at considerably lower temperatures [6]. Syncrude Aurora now operates their 5 km hydrotransport line at 35–40°C [7].

The use of hydrotransport pipelines improved the oil-sand conditioning at lower temperatures [1]. As the efficiency of the conditioning process significantly influences the final recovery of the bitumen, achieving an efficient method for the conditioning has always been the target among oil-sand producers [1, 3]. In addition, reducing the production cost and greenhouse gas emissions has also been ongoing targets in the industry [1]. Continued process improvements have led to more economic bitumen production process and reduced environmental footprint [8]. Presently, oil-sand companies aim to eliminate the use of expensive trucks to transport the ore to the slurry plant by conditioning the oil-sand slurry at the mine face [2]. This kind of onsite conditioning would demand a consequent reduction of pipeline length, which would potentially cause incomplete conditioning and could especially affect lump ablation [2]. In order to resolve the problem, an accelerated conditioning process would be required. Before implementing any significant changes in the oil-sand conditioning, a better understanding on the fundamentals of OSLA must be developed.

As the first step of conditioning, the crushed and screened oil-sand lumps (size range, 50–150 mm) are ablated or digested inside the hydrotransport pipeline [9]. The ablation occurs due to the dual effects of heat transfer and mechanical energy [6]. Generally, bitumen acts as a glue to hold the matrix of sand grains together. It should be mentioned that the viscosity of bitumen is a strong function of temperature. As a result, the viscosity of the bitumen on the surface layer of the lump reduces considerably as an oil-sand lump is exposed to the hot slurry medium. The softened surface layer is then sheared away due to the shearing inside the hydrotransport pipeline, and, thereby, a new lump surface is exposed to the hot medium. The new surface undergoes the same mechanism. This process repeats itself to the point that the entire lump is ablated. The heat transfer from the slurry and the contacts of a lump to neighboring lumps as well as the pipe wall control the rate of ablation [10]. The parameters that mostly affect OSLA can be identified as temperature and composition of the slurry, size and temperature of the initial lump, and mechanical shear imparted to the lump [1, 11].

The current chapter aims to contribute to the better understanding of the lump ablation process. It would assist to identify the important parameters that affect the OSLA and to recognize the way in which each one of these parameters influences the ablation process. The oil-sand conditioning process can be improved by changing one or more of these factors to achieve accelerated ablation and conditioning as required. Previous studies of oil-sand lump ablation are also described, and important areas not covered by those investigations are identified. In addition, some background theory needed in the development of improved ablation models is introduced.

2. Effects of operating parameters on ablation

As mentioned previously, the ablation of oil-sand lumps is the result of two important phenomena: heat transfer and shear forces [1]. Any factor that affects these phenomena would have an effect on the ablation process. The most important of this kind of parameters, viz., slurry temperature, initial lump size, pipeline diameter, and pipeline velocity or shear stress, are discussed here.

2.1 Slurry temperature

Since the commissioning of the first commercial oil-sand mining and bitumen extraction operation, attempts to reduce bitumen production costs and environmental impacts have driven process improvements and flowsheet changes [6]. One

way to reduce both simultaneously is to operate the process at a lower slurry temperature. Slurry temperature is effectively the most important parameter in the extraction of bitumen from Athabasca oil-sand, as it affects all three steps of oil-sand conditioning, i.e., oil-sand lump ablation, bitumen liberation, and air attachment.

Bitumen, because of its high viscosity, holds the mixture of sand grains and fine minerals together within an oil-sand lump [6]. The viscosity of bitumen decreases sharply with increasing temperature as shown in **Figure 2**. Since the viscosity is above 10^5 mPa.s at room temperature (T = 20°C), bitumen looks like a solid, and it is essentially impossible to separate bitumen from the sand grains at this tempera-ture. When the temperature increases to 50°C, bitumen viscosity reduces by more than one order of magnitude, i.e., to the order of 10^3 mPa.s. The separation of bitumen from sand grains occurs relatively quickly at such temperature. Lower viscosity of bitumen must be attained in order to reduce the lump size and liberate bitumen from sand grains efficiently [6, 12]. It should be mentioned that froth quality and bitumen recovery are also dependent on slurry temperature as the temperature influences the air bubble-bitumen attachment. Although oil-sand pro-ducers ultimately wish to operate hydrotransport pipelines at low temperatures due to the reduced operating costs and environmental impacts, they are well aware that a balance between bitumen recovery and temperature reduction must be attained. At this point, operating temperatures between 40 and 55°C are common in the industry [6].

2.2 Initial lump size

The heat transfer to an oil-sand lump is an important factor in ablation process [13]. The thickness of the layer softened and ablated away is equal in essence for all lump sizes under comparable thermal conditions. Therefore, the fraction of lump mass that is removed decreases as the lump size increases. In other words, the time necessary for complete digestion of a lump increases with the initial lump size [1].

2.3 Pipeline diameter

Pipeline diameter is a key parameter in the ablation of an oil-sand lump. For a specific slurry flow rate, more energy is dissipated in a pipe having smaller
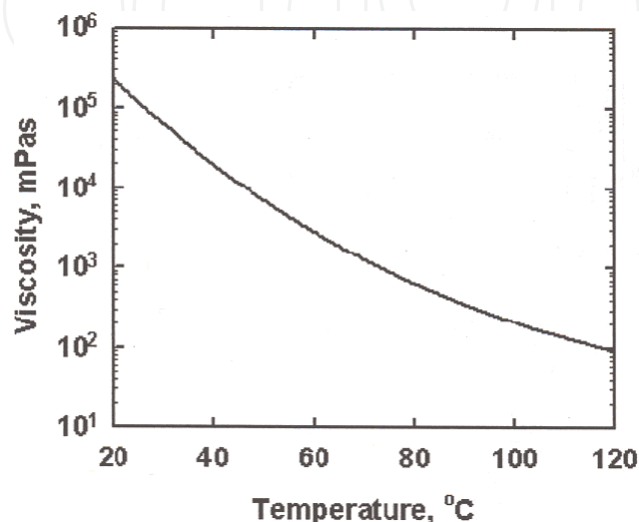
Figure 2.
Viscosity of Athabasca bitumen as a function of temperature [1].

diameter, and this leads to the higher interparticle shear stresses [1]. The relationship between energy dissipation and pipe diameter can be expressed as follows [14]:

$$\overline{\varepsilon} = \left(2f_f V^3\right)/D \tag{1}$$

where,

$\overline{\varepsilon}$ is the volumetric average of energy dissipation in the pipeline (m²/s³), V is the bulk velocity (m/s), D is the pipe diameter (m), and f_f is the Fanning friction factor.

According to Eq. (1), energy dissipated in a pipe inversely varies with the diameter of the pipe. Consequently, higher energy dissipation, i.e., higher ablation rate, is expected in smaller pipelines. On the other hand, the residence time of an oil-sand lump inside a smaller pipe will be shorter as the bulk velocity is higher in the pipe for a constant slurry flow rate. A shorter residence time is likely to result in a lower ablation rate [1]. A balance must be sought between the residence time and the energy dissipation in order to achieve an acceptable ablation rate. That is, the pipeline diameter should be optimized for a specific flow condition.

2.4 Shear stress

An oil-sand lump moves at a different velocity than the surrounding slurry and contacts with the pipe wall as well as other lumps present in the slurry. The difference in the velocities results in a shear stress on the lump surface [1]. In a pipeline, the shear force acting on the lump surface is expected to increase with increasing mixture velocity and concentration. Higher slurry concentrations promote particle-particle interactions and particle-wall interactions [1, 3]. Thus, all steps of the oil-sand slurry conditioning process depend on the slurry velocity in a hydrotransport pipeline [5]. However, more research has been conducted to study the effect of shear exposure on bitumen liberation and bitumen aeration than lump ablation. Clearly, this area demands further investigations.

3. Examples of previous studies

Important examples of previous experimental and modeling studies on lump ablation are briefly discussed in this section. The parameters considered in each study are summarized, and the parameters that need further investigations are identified.

3.1 Traynis wheel test stand

Traynis [15] studied the grinding or crushing of coal particles using a wheel test stand (WTS). It was experimentally demonstrated that the pressure losses for slurry in a WTS agree quite well with that in a horizontal pipeline. This agreement was a result of the similarities in energy dissipation mechanisms of moving solid particles in both systems. The mechanism of energy dissipation was found to determine the process of the particle crushing.

Most of the tests reported in [15] were completed using a WTS made of a 200-mm diameter pipe. Three runs were repeated with another WTS made of 300-mm diameter pipe to investigate the effect of pipe size on particle crushing or grinding. Pipes were polished using abrasive materials like quartz to ensure that the pipe wall was smooth when the experiments were started. The apparatus was filled up to 1/3 of the total volume with a mixture of water and coal. For each run

using the smaller WTS, 10–40 kg of coal was loaded. Coal particles from two different hydraulic mines were used for the experiments. At certain time intervals, the degree of size reduction of the coal particles was determined by measuring the particle size distribution of the remainder of the particles. To reconfirm that the WTS system was representative of the horizontal pipeline, a number of experiments were replicated by circulating slurry in 4 and 1.3-km long pipelines. The effects of slurry velocity and concentration, pipe diameter, coal particle size, existence of abrasive rocks, pipe length, and mechanical properties (strength and hardness) of the coal particles on the size reduction of the coal particles were investigated. The outcomes of the experimental investigation can be summarized as follows:

1. The results obtained using short pipelines (∼10 km) agreed with those of the wheel test stand experiments. However, transporting the coal particles for a long distance (>20 km) resulted in faster crushing. This is probably because the mixture passed through the feed pump many times. It caused more rapid size reduction of the coal particles. The effect was more evident when the initial coal particle size was large.

2. The slurry velocity was changed from 1.8 to 6 m/s for experiments with different coal types. In all cases, velocity had an insignificant effect on the crushing of coal particles.

3. Slurry concentrations were varied from 1:16 to 1:2 (mass of solid, mass of liquid). These experimental runs showed that size reduction of the coal particles was independent of slurry concentration.

4. The pipe size of the wheel test stand did not affect the extent of size reduction of the coal particles.

5. For coal particles having initial diameters in the ranges of 3–6 or 50–100 mm, the degree of size reduction was only affected by the initial particle size. For particles smaller than 3 mm, increasing the initial particle size resulted in more visible increase in the intensity of crushing.

6. The existence of abrasive rocks, which were 50–100 mm in diameter initially but were crushed to the 3–6 mm size range in the slurry, caused more rapid size reduction of particles. Considerable crushing was observed within the first 15 km.

7. The crushing rate was higher in the first few kilometers of the pipe, and it decreased as coal particles moved along the pipeline. This must be because of the fact that shear stress decreases as particle size decreases, which would be expected when the particle slip velocity decreases. Rounding of the edges of the particles within the first kilometers of the pipe might be another reason for reduction of the crushing rate with pipeline length.

8. Experiments using coal particles with initial size in the range of 6–13 mm showed that as the strength factor of the coal particles increased, the crushing rate decreased. Strength factor is an indicator of the grindability of the coal particles.

One of the strengths of this study is that it introduces a new experimental method for studying the mass loss of solid particles. In addition, this is the only

study done on the effect of slurry velocity and concentration on the particle mass loss in slurry pipelines. However, one cannot directly apply the results of this research to oil-sand hydrotransport pipeline. This is because the nature of coal particles is very different from oil-sand lumps. Coal is a brittle organic sedimentary rock that contains varying amounts of carbon, hydrogen, nitrogen, oxygen, and sulfur [16]. On the other hand, oil-sand contains bitumen, sand grains, clays, and small amount of water, and the viscosity of bitumen highly varies with temperature [1]. As coal is brittle, coal particles tend to break down into smaller particles when they are exposed to the shear forces. However, mass loss from oil-sand lumps occurs by gradual mass removal from the surface of the lump. The amount of mass loss from an oil-sand lump depends on many parameters, although temperature seems to be the most important factor. Thus, one cannot study oil-sand lump ablation without considering the slurry temperature. Additionally, because the nature of the two materials is different, the effect of slurry concentration and velocity on their mass loss can be expected to be different.

3.2 Law et al. experimental study

Law et al. [17] examined the ablation of frozen mixtures of water and paraffin wax (octadecane) with solid particles such as kaolinite clay, titanium oxide, aluminum powder, and sand. Because the ablation of oil-sand samples was complex, they chose to study the ablation of less complex materials. This investigation was conducted with the purpose of obtaining information from a well-controlled system and applying it for designing the rotating drums, which were used for oil-sand lump ablation at that time. A turbulent axisymmetric water jet, whose velocity varied between 1.7 and 2.8 m/s, was used. The temperature of the jet was changed from 32 to 60°C depending on the material being tested. The water temperature was chosen based on the sample's melting point, which was 26–29°C for octadecane. Cylindrical samples (L = 150 mm, d = 11 mm) were manufactured and immediately frozen in liquid nitrogen. The samples were then placed in front of the jet using a sliding platform. The sliding platform was moved up and down by using a stepping motor. Before the start of the experimental run, the front of the sample was placed in-line with a certain point called the melt front pointer. During an experimental run, the sample was never moved from this point. Instead, the sliding platform was lowered at a speed equal to the ablation rate of the frozen sample. The downward movement of the sliding platform against time was recorded and plotted. The slope of this line, for each set of the experiments, was considered to be the ablation rate. It was observed that for each operating condition, the slope of the plotted line remained constant with time. The results of this study can be summarized as follows:

1. For all samples, an increase in the jet temperature increased the ablation rate. For instance, ablation rate of lumps made from octadecane and 60 (vol%) sand at V = 2.8 m/s and T = 60°C was equal to 4.4×10^{-3} m/s, whereas it was equal to 3×10^{-3} m/s at T = 50°C.

2. Increasing the jet velocity from 1.7 to 2.8 m/s increased the ablation rate equivalent to that of raising the jet temperature by approximately 10°C (from 50 to 60°C). This is because surface shear stress on the sample is proportional to V^2.

3. Addition of solid particles to the samples affected the ablation rate in a complex way. The effect depended on the type of the solid particles and the lump material because thermal conductivity of the solid particles was different, so the heat transfer coefficient within the sample differed depending

on the solid particles. In the case of octadecane-kaolinite samples, at a certain jet velocity and temperature (V = 2.06 m/s, T = 50 and 60°C), ablation rate gradually increased for solid content up to 17 vol%, and, for solids content beyond 17%, the ablation rate increased significantly. The reasons for this observation were mentioned to be the increase of the heat transfer area due to the roughening of the melting surface and the ablation of the sample as clusters instead of layers at high solid contents. That is, ablation can also depend on the type and components of the oil-sand ore.

Although this experimental study could provide a good indication of the way different parameters influence ablation, the study had some limitations such as:

i. Viscosities of the samples were significantly different from that of bitumen.

ii. Sample was stationary and was exposed to water only from one face.

iii. Ablation with only water was investigated.

iv. The number of experimental runs using samples manufactured with sand particles was very limited.

More investigations need to be conducted on actual OSLA using a system that better represents the actual conditioning medium. These experiments are necessary to develop a predictive model applicable for all operating conditions.

3.3 SRC experimental study

In 1996, an experimental study on the ablation of actual oil-sand lumps was conducted at the Saskatchewan Research Council (SRC) Pipe Flow Technology Centre™ [10]. Lump ablation at various operating conditions were investigated by loading a certain amount of lumps to a 264 mm pipe loop using a feeder close to the pump discharge. At certain time intervals, lumps were trapped with a basket before discharging into the storage tank. The trapped lumps were weighed and put back into the loop. The SRC experiments showed the following results:

1. For all types of the oil-sand lumps, the time or pipeline length required to reach a certain ablation rate was strongly dependent on the slurry temperature. As shown in **Figure 3**, the time required for the complete ablation at T = 50°C was one third of that at T = 30 and 18°C for soft lumps. It is worth noting that the effect of temperature on the ablation rate was found to be qualitatively similar for various oil-sand ores [1, 10].

2. The ablation rate was faster for lumps with lower initial temperature at higher slurry temperatures (T = 30 and 50°C)

This experimental study is very valuable, as it is the first available research on the ablation of actual oil-sand lumps. However, the research did not include the effects of important parameters such as slurry velocity and concentration on ablation.

3.4 Masliyah ablation model

Masliyah ablation model (model 1) was developed for the ablation of oil-sand lumps based on the fact that crushed oil-sand lumps and sand particles form a moving layer at the bottom of the pipe, while the fine solids—water blend known as

the carrier fluid, exist within the whole pipe cross section [1, 6, 10]. The height of the bottom layer reduces with axial position along the pipeline when lump size reduces. It was assumed that the heated surface layer of the lump peeled off because of the shear stress inside the pipe. This process was presumed to repeat up to the point when 95% of the lump mass would be removed. The SRC two-layer model was used to estimate the velocities of top and bottom layers of the flow. An average value of the shear stress on the lumps was calculated using the slurry viscosity and the axial flow velocity [1, 6]. The model was validated with the data available in [10]. The predicted effects of mixture velocity, pipeline diameter, slurry temperature, initial lump size, slurry density, and pipeline length are discussed as follows [1]:

1. Raising the slurry velocity does not cause any significant enhancement in the oil-sand lump ablation rate. As shown in **Figure 4**, the beneficial effects of increasing velocity are offset by the reduced residence time of the lump.

2. The rate of lump digestion reduces with the increasing pipe diameter at T = 25°C (**Figure 5A**). As a result, longer pipelines are needed for complete ablation. At T = 50°C, however, the effect of pipe diameter is not very
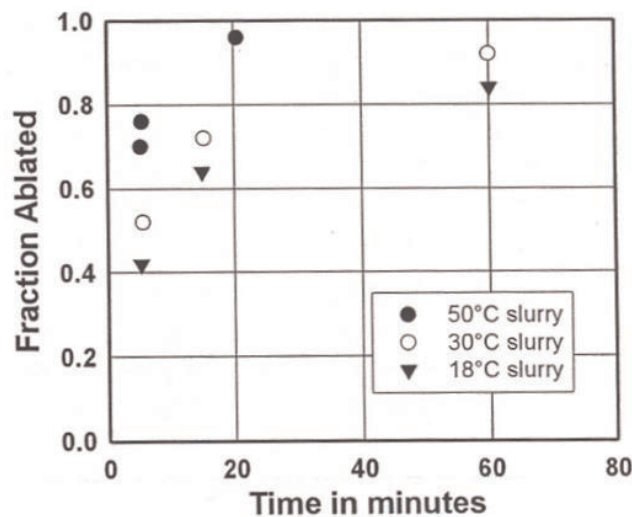

Figure 3.
SRC Experimental results showing the effect of slurry temperature on the ablation time of soft lumps [10].
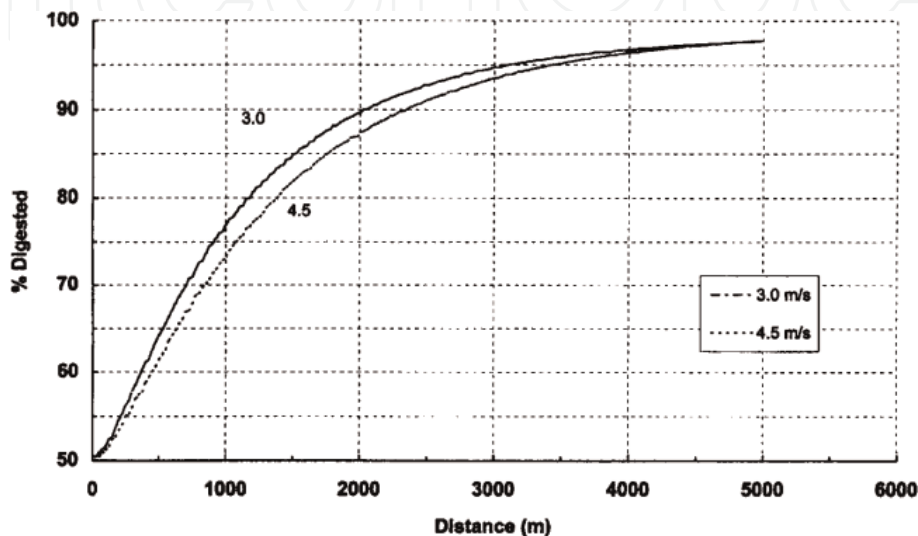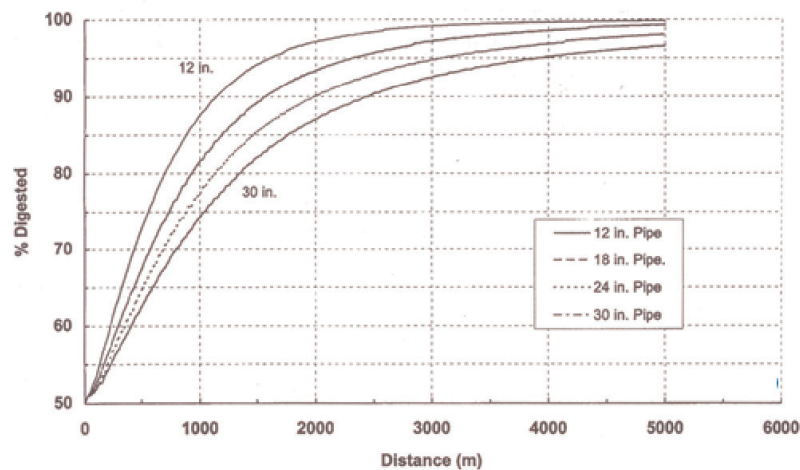

Figure 4.
Effect of mixture bulk velocity on the oil-sand lump ablation (T = 50°C; T_{oL} = 5°C; d = 20 mm) [1].

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significant (**Figure 5B**). This is probably because heat transfer is the dominant factor in the ablation of an oil-sand lump. At a higher temperature, the viscosity of the bitumen and the surface shear stress required for consequent removal of the soft surface layer reduce significantly.

3. Increasing the slurry density increases the ablation rate at a fixed temperature (**Figure 6**). This is because an increment in slurry density is caused by a reduced water flow rate, i.e., an increased residence time. For the same reason, ablation rate reduces with decreasing slurry density.

4. Smaller oil-sand lumps ablate more rapidly (**Figure 7**). A given mass of oil-sand ore in the form of smaller lumps is digested much faster than the same mass of ore in the form of larger lumps due to the larger surface area of the former.

Although model 1 is one of the pioneer models that can be used for industrial-scale ablation of oil-sand lumps, it has a number of limitations. Some of the limitations are identified as follows:

i. Only one set of experimental data was available for validating this model. The data was also limited to a certain pipeline size and a set of velocities.

(A)
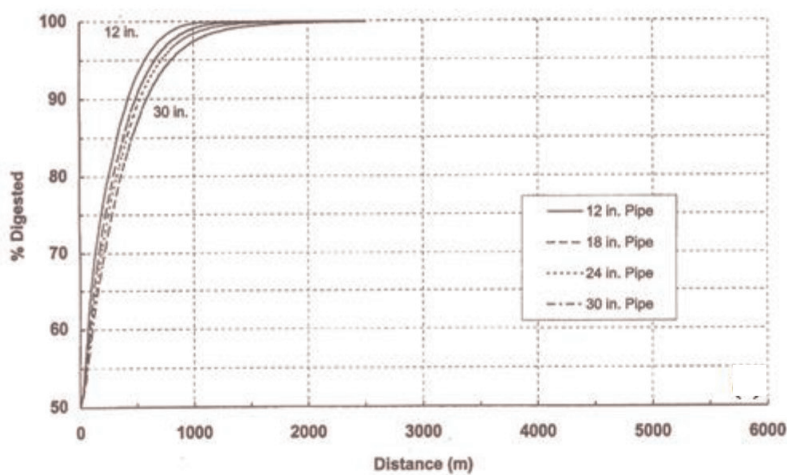
(B)

Figure 5.
Effect of pipe diameter on the ablation of oil sand lumps (T_{oL} = 5°C; V = 3.8 m/s; ρ_m = 1550 kg/m³; d = 20 mm): (A) T = 25°C; (B) T = 50°C [1].

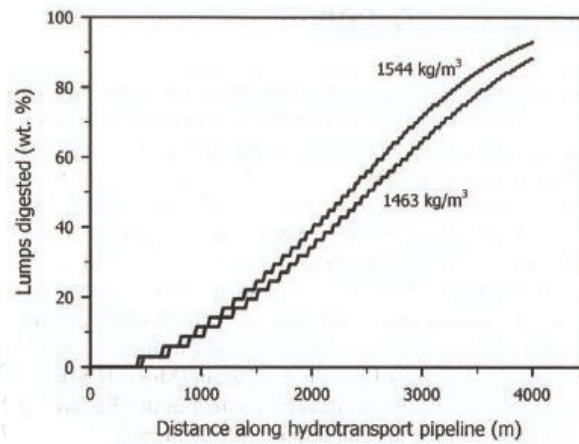**Figure 6.**
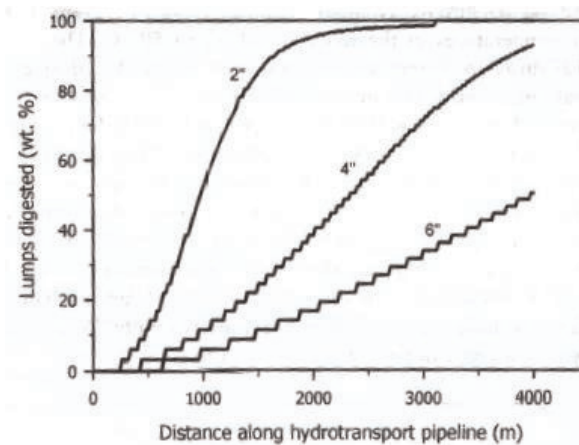*Effect of slurry density on the ablation of oil sand lumps (T_{oL} = 0°C; D = 710 mm; d = 100 mm and T = 40°C) [1].*

Figure 7.
Effect of initial lump size on the ablation of oil-sand lumps (T_{oL} = 0°C; D = 710 mm; ρ_m = 1548 kg/m³ and T = 40°C) [1].

   ii. A part of the model, namely, the method of estimating surface shear force on the lumps is yet to be verified.

   iii. The version of the SRC two-layer model used for the modeling is out-of-date. The SRC model has been improved lately. However, the improvements were never integrated into model 1.

   iv. According to model 1, the bulk velocity was used to calculate the shear stress acting on the oil-sand lumps. However, the velocity of the lumps in slurry is about 90% of the bulk velocity. This means, the relative velocity causing the shear stress on the lump is likely to be only 10% of the velocity. Therefore, the shear stress used in Model 1 might be overestimated.

3.5 Eskin et al. ablation model

   Eskin et al. model (Model 2) was developed for the ablation of a spherical oil-sand lump using a hypothesis similar to that of Masliyah model [13]. The following assumptions were used for the purpose:

   1. The effects of shear stresses and heating were integrated with respect to a surface critical temperature. The critical temperature remained constant

during the ablation and was related to the minimum adhesive strength of the bitumen. This model-specific temperature was determined using the experimental results available in [17].

2. The lump was considered to retain its spherical shape during ablation.

Based on the assumptions, the complex phenomena were simplified as a one-dimensional heat conduction problem for a shrinking sphere. The critical temperature was used as an input to the applied convection boundary condition. A correlation between the reduction of sphere size and the critical temperature was found by simplifying the boundary condition-based equations. The heat conduction equations were also included in the model. The model was applied to study the effect of lump size and initial temperature on OSLA.

Although the fundamental concepts used for model 2 agree with general hypothesis of how individual oil-sand lumps ablate, the way of integrating shear stress to a critical temperature is debatable. Moreover, the effects of slurry velocity and slurry concentration on ablation cannot be investigated with the model. Most importantly, the model was never validated against any experimental data.

3.6 Pazouki study

Pazouki [18] applied an innovative method by using strain gauge technology for online tracking of the mass loss of the anchored oil-sand lumps. Four small strain gauges looped in a full-bridge circuit were used for the measurements. The new method also allowed measuring the drag force on ablating and non-ablating objects. The accuracy of the drag force measuring technique was evaluated by comparing the measured drag force with the calculated drag force on the number of smooth spheres in water.

As part of the experiment, an idealized oil-sand lump was anchored in a basket at the height of $40D_L$, where D_L is the diameter of the cylindrical lump. Artificially manufactured oil-sand lumps were used for the experiments. Slurries (C = 0.15 and 0.30) were prepared by mixing pre-weighed industrial quartz (d_{50} = 0.190 mm) with water. The flow temperature was adjusted using a double-pipe heat exchanger located in the vertical section of the pipeline loop. DASYlab 10.0 software was used to the readings of strain gauges, temperature, and flow meter.

In addition to experimentation, Pazouki [18] also developed a new modeling approach. The overall outcomes of this study can be summarized as follows:

1. The online measurement method and the experimental apparatus built at SRC provide the opportunity to test OSLA at many different operating conditions. The strain gauge measurement method also enables measuring the drag force on the ablating oil-sand lump.

2. The data obtained using the artificially produced oil-sand lumps were repeatable.

3. The OSLA was enhanced significantly with the increasing flow temperature. Heat transfer played a more important role for ablation in the slurry where surface shear stresses can be expected to be lower.

4. The slurry velocity was found to affect OSLA appreciably. The ablation rate increased with V^n, where n = 2–4.7. The value of n was a function of temperature.
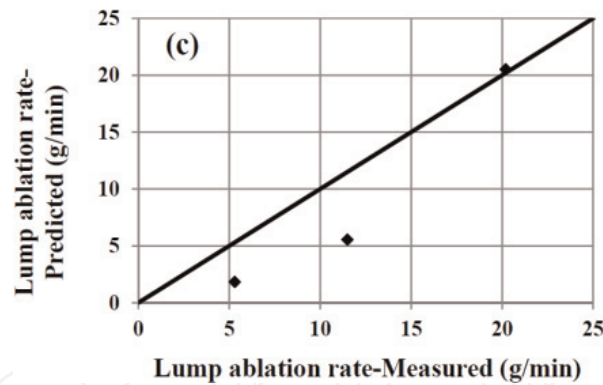
Figure 8.
Comparison of measured and predicted ablation rate for slurry (C = 0.30) at T = 45°C [18].

5. Ablation in water occurred at a slower rate than that in the slurry. However, an increase of slurry concentration from 15 to 30% at T = 30°C reduced the ablation rate. This reduction was most likely related to the turbulence modulation in slurries that could affect both shear force and heat transfer.

6. For the range of concentrations used for the study, the slurry concentration did not have a significant influence on the ablation of oil-sand lumps.

7. The drag force acting on a lump depended on the slurry concentration.

8. The equivalent fluid model was found to be most appropriate for simulating the drag force. In this model, the slurry is treated like a single-phase fluid with density and viscosity related to the solid concentration.

9. The proposed model demonstrated the ablation rate to be a primary function of surface shear force and temperature. In the model, the effect of temperature was implemented as the change in the bitumen viscosity.

10. The model was validated with respect to the experimental measurements. An example of the validation results is presented in **Figure 8**. In course of the validation, it was found to better predict the ablation rate than other existing models.

Even though the study advanced both experimentation and modeling of OSLA, it suffers from the similar limitations of previous studies. It neither clarifies the procedure to apply the experimental findings to the actual hydrotransport pipelines nor verifies the model with industrial-scale data.

4. Theory and modeling

In order to estimate the ablation rate of the oil-sand lumps inside the hydrotransport pipeline, the shear stress acting on the lumps and the temperature profile of the lump at different times must be determined. The most relevant models for the estimation are follows:

1. SRC two-layer model

2. Shear stress decay law

The benefits and drawbacks of each model are discussed in the subsequent sections.

4.1 SRC two-layer model

Recall that an early version of SRC model was used to estimate the shear stress acting on the oil-sand lump(s) in model 1. If one intends to use a similar approach, it would be advisable to use a more recent version of the model. The theory behind the development of the SRC two-layer model is explained in this section. Also, the validity of this approach for calculating the shear stress acting on a lump is discussed.

In a slurry pipeline similar to the hydrotransport pipeline, fine particles (particles <0.074 mm) are considered to augment the viscosity and density of the suspending liquid, i.e., the carrier fluid. The coarse particles that are suspended by fluid turbulence are assumed to be at a constant volume fraction throughout the flow domain. The other part of the coarse particles, that is, the fraction not effectively suspended by fluid turbulence, is supposed to transmit the immersed weight to the pipe wall. These particles are found in the lower layer and contribute Coulombic or sliding bed friction [11]. The continuous concentration profile of the coarse particles was simplified to a step-change, i.e. two layers for the purpose of writing force balance equations. The velocity within each layer was assumed to be constant. **Figure 9** shows the idealized concentration and velocity distributions.

The SRC two-layer model was developed using mass and force balances for the two layers of the slurry. The force balance produces an equation for the axial pressure gradient in horizontal slurry as a function of friction losses in top layer, bottom layer, and the interface between the layers [19].

To estimate the ablation rate of an oil-sand lump, the actual shear stress on the lump needs to be estimated. If one assumes an oil-sand lump is located at the interface between the two layers, the surface shear stress acting on this lump can be assumed to be equal to the shear stress at the interface. The shear stress at the interface is calculated using the following correlation [11]:

$$\tau_{12} = \frac{1}{2}f_{12}(V_1 - V_2)|V_1 - V_2|\rho_1 \tag{2}$$

where ρ_1 denotes the slurry density in the upper layer and f_{12} is the interfacial friction factor that can be estimated from a modified Colebrook friction factor equation:

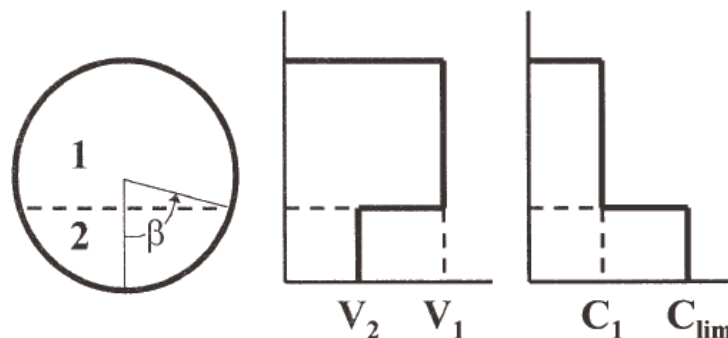$$f_{12} = \frac{2(1+Y)}{\left[4 \log_{10}(D/d) + 3.36\right]^2} \tag{3}$$

Figure 9.
Idealized concentration and velocity distributions used in the SRC two-layer model [19].

where Y is the 0 for d/D < 0.0015 and Y is calculated using the following equation when 0.0015 < d/D < 0.15:

$$Y = 4 + 1.42 \log_{10}(d/D) \tag{4}$$

Equation (4) has been formulated based on the data taken at Archimedes number, $Ar < 3 \times 10^5$.

It is inferred from Eq. (2) that the shear stress acting on a lump is proportional to $(V_1 - V_2)^2$. Calculating the velocity of the layers using the SRC two-layer model shows that V_2 is substantially small compared to V_1 and $(V_1 - V_2)$ is approximately equal to the slurry bulk velocity (V). On the other hand, other research conducted at the Saskatchewan Research Council showed that the velocity of a large particle in horizontal slurry flow was about 0.9 V. That is, the shear stress on the oil-sand lump would be proportional to $(0.1 \, V)^2$, which is considerably smaller than $(V_1 - V_2)^2$. In other words, the shear stress calculated using Eq. (2) might overestimate the shear stress acting on an individual lump.

4.2 Shear stress decay law

In order to estimate the effects of slurry velocity and concentration on OSLA, a simplified approach can be taken instead of using complex two-layer model. The following assumptions are necessary to apply the method:

1. The oil-sand lump is stationary compared to the slurry flow in the hydrotransport pipe.

2. Slurry flow has reached steady state.

3. Slurry density is constant throughout the pipe.

Based on the assumptions, the local shear stress where the solid particle is located in the hydrotransport pipeline can be estimated using the shear stress decay law [11]:

$$\tau_{rz} = \frac{2s \, \tau_w}{D} \tag{5}$$

where s is the distance from pipe axis (m), τ_{rz} is the shear stress at y (Pa), τ_w is the pipe wall shear stress (Pa), and D is the pipe diameter (m).

For a known value of the wall shear stress, the shear stress at any radial position of the pipe can be calculated using Eq. (5). However, calculating the wall shear stress for a hydrotransport pipeline is complex as wall shear stress and flow density are not constant around the pipe.

Flow is not uniform throughout the cross section in a hydrotransport pipeline at all. Significant concentration and velocity gradients can exist, particularly, if operating velocity is just higher than the deposition velocity (V_c) [10]. However, the concentration profile was found to be nearly uniform for highly concentrated settling slurries at velocities significantly higher than V_c, and, for these slurries, Coulombic friction was also found to be negligible relative to kinematic friction [19]. Moreover, Coulombic friction is typically negligible as long as the particle diameter is not too large ($d_{50} \leq 0.3$ mm), and the mixture velocity is high (say, $V > 2V_c$) [11]. It is therefore worthwhile to consider the so-called kinematic friction loss component of the SRC pipe flow model [Eqs. (6) and (7)] to calculate the wall shear stress

for such systems [10, 11]. Using this model, the kinematic friction loss component is determined so that it accounts for the friction associated with the flow of the carrier fluid, the friction related to particle collisions and the tempering effect of near-wall lift. If the Coulombic friction can be assumed to be negligible, then only the kinematic friction is important, and the τ_w can be calculated using the following equations [10, 11, 20]:

$$\tau_w = 0.5\ V^2 \left(f_f \rho_f + f_s \rho_s \right) \tag{6}$$

$$f_s = \lambda^{1.25} \left[A\ Ln\left(d^+\right) + B \right] \tag{7}$$

for d + $\leq$ 21: $A = -1.1 \times 10^{-4}$ and $B = 4.2 \times 10^{-4}$
for d + $\geq$ 21: $A = -5.6 \times 10^{-5}$ and $B = 2.6 \times 10^{-4}$

$$d^+ = \frac{d\ v^* \rho_f}{\mu_f} = \frac{d\ \left(f_f/2\right)^{0.5} V\ \rho_f}{\mu_f} \tag{8}$$

$$\lambda = \left[\left(\frac{C_{max}}{C}\right)^{1/3} - 1 \right]^{-1} \tag{9}$$

The estimation of kinematic friction provides a tool for realistic assessment of the effects of slurry velocity and concentration on the local shear stress. To

Term	Value
D (mm)	103
s (mm)	20
ρ_f (kg/m^3)	1000
μ_f (Pa.s)	0.001
d_{50} (mm)	0.120
ρ_s (kg/m^3)	2650

Table 1.
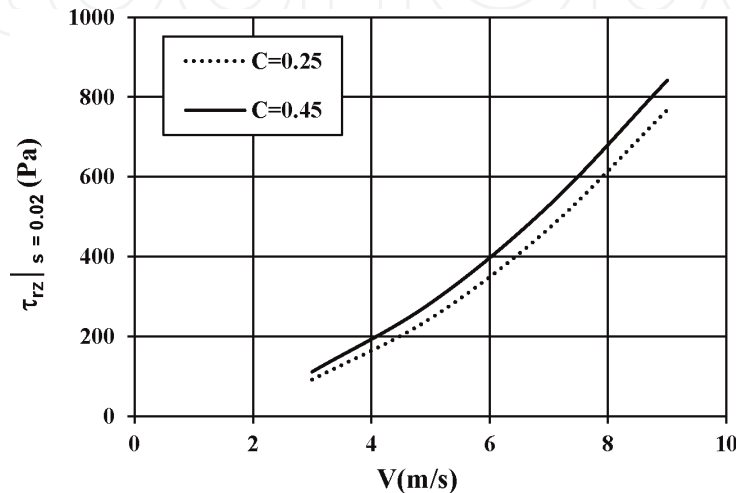*Input parameters for estimating shear stress inside a pipe.*

Figure 10.
Pipeline local shear stress at different slurry velocities and concentrations.

demonstrate the application, a model system is considered here. The system properties are chosen on an arbitrary basis and outlined in **Table 1**.

The local shear stress is shown in **Figure 10** as a function of mixture velocity for two different solid concentrations. The graph indicates that, for a solid particle placed 20 mm from the center of a 103 mm pipe, the surface shear stress on the particle increases substantially at higher mixture velocities. It should be noted that the graph indicates the effect of velocity and concentration on shear stress qualitatively. The results do not represent the actual shear stress on the oil-sand lumps. This example shows the application of shear stress decay law for a simplified case, where the solid particle is stationary. However, in the actual hydrotransport pipelines, oil-sand lumps move along the pipe axis. In order to estimate the shear stress acting on the lump, the slip velocity of the lump must be considered.

5. Conclusions

A limited number of studies on the ablation of large particles exist in open literature. Among these studies, only a few looked at the effect of velocity and concentration on the ablation. Slurry concentration and velocity were experimentally demonstrated to have minimum effect on the grinding or crushing of the coal particles [15]. The effect of slurry velocity on OSLA was also shown to be insignificant with the application of model 1 [1]. Interestingly, increasing velocity was found to cause a considerable increase in the ablation rate for stationary samples [17, 18]. An estimate of pipe local shear stress based on a simplified application of shear stress decay law likewise shows that increasing slurry velocity enhances the shear stress inside the pipeline. That is, the velocity is likely to have a positive impact on OSLA. However, an increase in slurry concentration appears to have a more substantial effect on the increase of local shear stress at low slurry velocities. Rigorous investigations are required to clarify the impacts of slurry velocity and concentration on OSLA. To the best of authors' knowledge, no significant research has been done until now to study the effect of slurry velocity and concentration on the ablation of actual oil-sand lumps. Also, a publicly available model that can estimate the ablation rate of the oil-sand lump as a function of shear stress forces is not available to date, although such a model is highly required for engineering usage in the industry.

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Other declarations

A part of the manuscript is adapted from the first author's PhD dissertation.

Nomenclature

A	area (m^2)
Ar	Archimedes number ($-$)
C	solid volume concentration ($-$)
D	pipe diameter (m)
D_L	lump diameter (m)
d_p	particle diameter (m)
d_{50}	mean particle diameter (m)
d^+	dimensionless particle diameter ($-$)
f_f	Fanning friction factor ($-$)
f_s	solid friction factor ($-$)
L	length (m)
R	radius (m)
s	distance from pipe center (m)
s^+	dimensionless distance from pipe center ($-$)
T	temperature (°C)
T_{0L}	lump initial temperature °C
t	time (s)
V	bulk velocity (ms^{-1})
V_s	solid object velocity (ms^{-1})
V_c	deposition velocity (ms^{-1})
v	local velocity (ms^{-1})
μ	viscosity (Pa.s)
ρ	density (kgm^{-3})
τ	shear stress (Pa)
τ_w	wall shear stress (Pa)
τ_{wp}	wall shear stress on solid object (Pa)

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