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Article

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Reducing energy consumption during bitumen separation from oil sand

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Abstract

Oil sands, found in Canada, Venezuela, USA and Russia, contain bitumen, water, clay and some metals. Two different methods of producing oil from oil sands exist: open-pit mining and in situ. Approximately 20% of oil sands are recoverable through open-pit mining.

After oil sand is mined, bitumen is separated from solids and water within the bitumen production facilities. The process of bitumen separation consists of 3 main steps. (1) Hot/warm water is added to the oil sands producing a slurry that can be pumped to the processing plant through hydrotransport pipelines which connect ore preparation to the main extraction facility. These large-diameter pipelines can be several kilometers long, providing the additional time and shear required to break down the lumps of mined oil sands. (2) After hydrotransport pipeline oil sand slurry enters flotation facility where bitumen is gravity separated from the coarse solids producing an intermediate bitumen froth product. (3) Then solvent is added to the froth, to reduce the bitumen viscosity and to remove remaining water and fine solids.

In addition to efficiency concerns, this separation process suffers from high operating cost due to a number of factors such as the energy needed for heating the water, the energy consumed by the cyclofeeder and the energy consumed by hydrotransport. The other problem of hydrotransport is extensive wear since the slurry contains quartz sand particles which are extremely abrasive.

In the present study, an alternative technology based on cavitation jets is suggested. It is found that jets can separate bitumen at low temperatures (5–6 °C) and cavitation jet technologies have the potential to replace hydrotransport.

A series of nozzles were designed for low intensity cavitation at high cavitation numbers ($\sigma=0.37 - 0.46$) to test different types of cavitation generators. It was shown that selfresonating nozzle shows significantly better results than conventional nozzles and conventional nozzles with passive control.

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Keywords: Bitumen separation; Cavitation; Cavitation jet; Hydrodynamic jet; Jets; Energy; Sustainability

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Nomenclature

d	Jet's diameter
f	Resonance frequency
V	Jet's mean velocity
ν	Water kinematic viscosity
Re	Reynolds number ($V \cdot d / \nu$)
S	Strouhal number ($f \cdot d / V$)
P_a	Ambient pressure
P_v	Vapor pressure
ΔP	Pressure drop across the nozzle
σ	Cavitation number $(P_a - P_v) / \Delta P$

1. Introduction

1.1. Oil sands

Oil sands (also called tar sands) are one of the main Canadian resources. The estimated volume of bitumen (extremely heavy crude oil) in Canada is 400 billion cubic meters with 12% or 48 billion cubic meters estimated to be recoverable [1]. Oil sands are the mixtures of very heavy crude oil with sand, clay, water, stones and some other minerals. Tar sands must be mined or recovered in situ (mining in place). Usually it takes two tons of mined oil sand to produce one barrel of synthetic crude oil. Oil Sands are hydrophilic, each grain of sand is surrounded by a film of water about 10 nanometers thick and then by a bitumen envelope. The oil sand particles are firmly bonded together, are random in shape and very abrasive [2].

The Athabasca deposit is the only oil sand deposit with reserves which can be surface mined. There are several companies, including Suncor Energy Inc., Syncrude Canada Ltd., Imperial Oil and Canadian Natural Resources Ltd. involved in oil sand mining in the Athabasca region, north of Fort McMurray. The Canadian government is going to spend billions of dollars for both the in-situ and mining projects from 2018 to 2038 [3].

Before the oil sands can be mined, the top layer of muskeg and vegetation must be removed. The next layer, which is the mixture of clay, sand and rock, is removed by trucks and placed in previously mined areas. The next layer is the deposit of oil sands, this layer is 40 to 60 m thick. Truck-and-shovel method is used for oil sand transportation; the oil sands are moved to the dump pits by the trucks each carrying 400 tonnes load. The dump pits also include the feeder/crusher system. After that hydrotransport technology is used as a first separation step. During this process the oil sands are crushed and mixed with hot water (50–80 °C) in a cyclofeeder. This slurry is fed at high speeds into a pipeline and transported to the extraction plant. The plant could be many kilometers away. One of the major energy expenses in this technology is the heating of the slurry, since in general the hotter the slurry the better is separation process, especially during the winter where oil sand contains ice. Another problem is the pipeline wear because, as was mentioned above, the sand is extremely abrasive [4].

1.2. Cavitation and bitumen separation

In most of the studies related to separation of bitumen using cavitation, ultrasound is used to create cavitation bubbles. Experiments by Bodine [5] and Sadeghi et al. [6] have demonstrated that ultrasonic energy allows more efficient bitumen extraction from tar sands and thus has the potential for reduced energy consumption in oil sands mining technology. A combination of a solvent and sonication with frequency between 0.5 to 2 kHz was used by Davis and Paul [7]. Experimental results showed that this combination resulted in a 20% increase of oil recovery. The total recovery, if recycling was used, increased to 88.2%. Bitumen extraction from tar sand under the effect of ultrasound and alkaline reagents was studied by Abramov et al. [8]; a pilot separation plant based on ultrasound cavitation was built for this purpose. Recently, a process for the simultaneous recovery and desulfurization of bitumen in oil sand using hydrogen peroxide (H_2O_2), tetrahydrofuran (THF), and ultrasound at 45 °C was studied by Okawa et al. [9].

The main problem with utilizing the ultrasound cavitation technology is the difficulty of transducers tuning and high equipment costs. Also, the acoustic setup is very sensitive to environmental changes and has scalability difficulties. An alternative method of producing cavitation is by utilizing cavitation jets. Potentially, they should be less sensitive to the environment and fluctuating flow parameters. Cavitation in this case starts in the low pressure cores of turbulent vortices, which are generated in the submerged jet's shear layer. Experimental studies of cavitation jets show that the origin of the cavities varies from point to point, even at inception. This happens because of the random nature of turbulence. It was determined from the cavitation noise that cavitation inception occurred at cavitation number $\sigma = 0.55$. Flashes of cavitation were observed at $\sigma = 0.7$ [10].

Bozak et al. [11] suggested to supply a slurry to a mixing chamber of a jet pump. The extreme mixing and pressure drop causes cavitation bubbles to develop inside of chamber, which implode on solid particles to enhance the separation of the bitumen from the solid particles. The potential problem of this method in large scale process could be the high rates of erosion since the slurry with quartz sand particles is accelerating inside the jet pump and must reach high velocity in order to generate hydrodynamic cavitation. To avoid this problem, Bukharin et al. [12] suggested to supply hydrodynamic jet to the vessel which contains mixture of water and oil sand. In this case, cavitation occurs in the vessel without collapsing on the walls and high speed slurry flow is not going through the nozzle. The effect of slurry on a bitumen separation process based on cavitation jets was studied by Bukharin and Vinogradov [13]. It was shown that the cavitation occurred at increased slurry densities, and results for cavitating and non-cavitating jets were compared to validate the effect of cavitation.

In the present study, different types of cavitation jet nozzles were tested to assess optimal nozzle for potential applications in bitumen separation processes based on hydrodynamic jets.

2. Experimental setup and experimental procedures

2.1. Experimental setup

The experimental setup used in this study was very similar to the setup used by Bukharin and Vinogradov [13] with slight modifications to connect new cavitation nozzles. Simplified schematics of the setup is shown in Fig. 1.

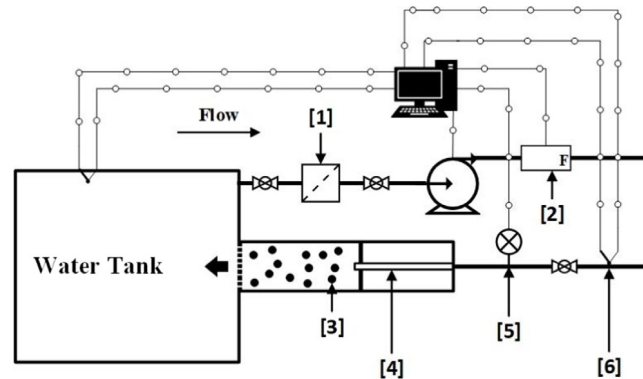


Fig. 1. Experimental Setup, simplified diagram. 1 – filter, 2 – flowmeter, 3 – oil sand sample, 4 – cavitation nozzle, 5 – pressure sensor, 6 – thermocouple.

Centrifugal pump (11.9 kW) was used for pumping water (Fig. 1) at 551.6 kPa pressure inside the nozzle and a $0.003155 \text{ m}^3/\text{s}$ flow rate according to the pump performance curve at 3450 RPM. AC Tech MC3000 Variable Frequency Drive was used to control the pump speed. Upstream from the pump, water circulated through a filter to avoid pump blades damage from sand particles. Flow rate was measured with KROHNE electromagnetic flowmeter (accuracy: $\pm 0.2\%$ from $0.031545 \text{ m}^3/\text{s}$ of FS). Validyne P305D differential pressure transducer was used for pressure measurements (accuracy: 0.5% from 1380 kPa FS with reference to atmospheric pressure). K-type thermocouples were used in the system to measure the temperature. The thermocouples were calibrated with Omega Dry Block Probe Calibrator (CL950A-M-220) (accuracy: $\pm 0.8 \text{ }^\circ\text{C}$). Water was supplied to the cavitation nozzle which was located inside transparent acrylic pipe. Part of the acrylic pipe was blocked with fine metal mesh (200 holes per

linear 0.025 m) on the exit and with the metal disk from the side of the nozzle to avoid recirculation regions. The experimental volume was equal to 21 195 cm³ (a cylinder with 30 cm length and 30 cm diameter). A picture of the setup is shown in Fig. 2. National Instruments DAQ was used to collect the data and LabVIEW as programming language.



Fig. 2. Experimental setup.

2.2. Cavitation nozzles

For every particular application, an optimal cavitation nozzle should be designed. The main goal of this study is to compare different nozzle geometries to assess what is the best design for low temperature bitumen separation process. The range of cavitation numbers which was used in this set of experiments was 0.37 up to 0.46 which is considered extremely high for cavitation erosion efficiency. The reason behind low intensity cavitation regime is that cavitation can potentially damage the equipment as well as the nozzle itself. Therefore, in the present study highest possible cavitation numbers were considered to investigate lowest limits of cavitation erosion efficiency.

The first type of nozzle considered for bitumen separation is the self-resonating nozzle which was tested in by Bukharin and Vinogradov [13]. This type of nozzles was designed and produced first in Tracor Hydronautics to increase the deep-hole mechanical bit drilling rates. It was shown that conventional non-resonating cavitating jets could provide improved rates of drilling but their cavitation inception limits (at about 1220 m deep with a nozzle pressure drop of 13.8 MPa) stimulated the development of methods to produce jet cavitation at greater depths [14]. For this purpose, several nozzle design concepts were developed and tested. They were labeled “STRATOJET” (STRuctured Acoustically Tuned Oscillating JET) and produced effective cavitation in depths two to six times deeper than conventional drill bit nozzles [15]. The self-excitation is achieved hydroacoustically to produce discrete organized ring vortices when the excitation frequency matches the predominant natural frequency of the non-excited jet. An example of structured jet is shown in Fig. 3.

STRATOJET nozzle was compared to non-resonating nozzles with extended diffusers. In general, there are two main concepts of cavitation nozzles design. The first type of nozzles utilizes the maximum technologically possible pressure difference and jet speed. Usually such nozzle’s design is close to de Laval nozzle or Venturi tube profile.

The main idea of the second type of the nozzles is to maximize cavitation effect and minimize discharge coefficient. This can be achieved by manufacturing and installing different obstructions inside the nozzle as well as by sharp transition from pipe to diffuser which is preferable in the case of high cavitation numbers. Similar nozzle design was used for water wells cleaning and showed good performance at high cavitation numbers (0.1–0.3).

In Fig. 4, it can be seen that cavitation is occurring inside the bronze nozzle and destroys it after 5 h of water well cleaning. New nozzle is from the left and nozzles after 5 and 3 h of operation are from the right.

This is normal process for soft materials such as bronze at high ambient pressure when drilling or cleaning is occurring on large depths. For higher cleaning efficiency, cavitation must be incepted inside the nozzle therefore if

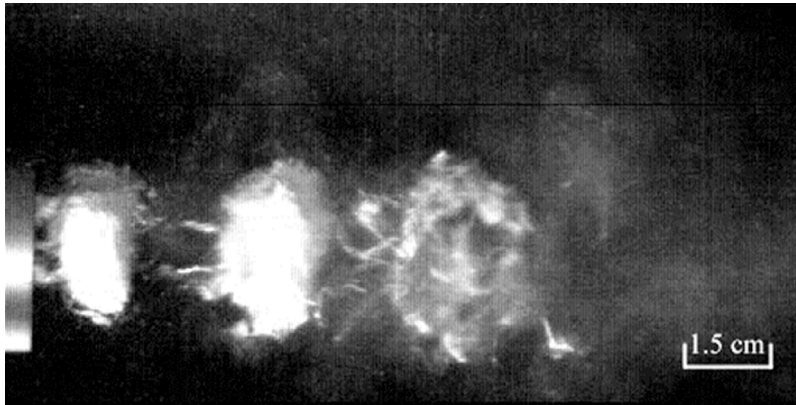


Fig. 3. Self-resonating jet (2000 fps). $Re = 3.1 \times 10^5$, $St = 0.34$, $\sigma = 0.37$. Picture was done in the lab during self-resonating nozzles tests.



Fig. 4. Cavitation erosion inside bronze nozzles.

the material is soft and with poor inside surface finish cavitation inside the nozzle destroys the nozzle much faster. At the same time bronze nozzles are much cheaper in production and in some applications are more economic than stainless steel nozzles or nozzles made out of titanium alloys. In the present study these nozzles were scaled up to accommodate the pumping power and since ambient pressure was close to atmospheric nozzles were not affected by cavitation erosion. Schematics of the bronze nozzles which were used in this study is shown on [Fig. 5](#).

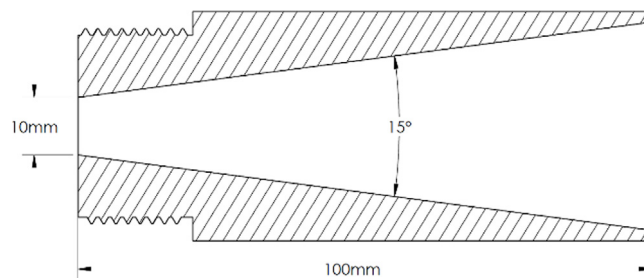


Fig. 5. Cavitation nozzle schematics.

4 nozzles were manufactured using this design (shown in [Fig. 5](#)), diameter of the nozzle inlet was varied from 10 mm to 17 mm (10 mm, 13 mm, 15 mm, 17 mm) and angle of diffuser from 10° to 20° . A fifth nozzle which

has a similar design (Fig. 6) was manufactured. The only difference as compared to other nozzles is the notches inside the diffuser to create more cavitation bubbles.

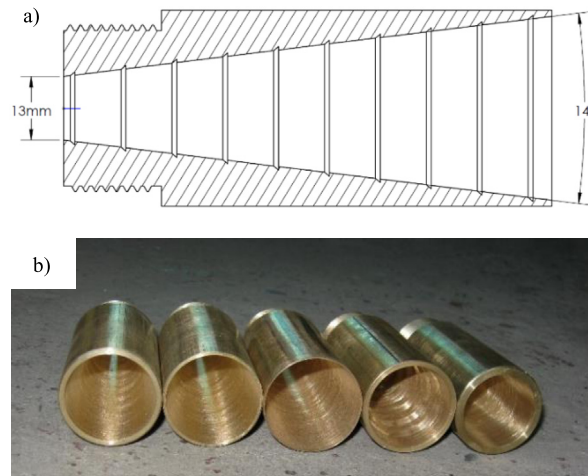


Fig. 6. (a) Cavitation nozzle schematics. Passive flow control. (b) Manufactured nozzles.

3. Results

Preliminary experiments were conducted to assess cavitation activity. Hydrophone (Reson TC 4032) was placed near the jet and sound intensity was measured. The results are shown in Table 1.

Table 1. Average sound intensity.

Nozzle	Sound intensity
STRATOJET	76 dB
Standard, 10 mm	86 dB
Standard, 13 mm	79 dB
Standard, 15 mm	72 dB
Standard, 17 mm	69 dB
Passive control, 13 mm	93 dB

The Oils sand samples used in this study were provided by Syncrude Canada Ltd. The content of bitumen in the mixture was 6%–20% according to material safety data sheet. It was shown by Bukharin et al. [12] that bitumen content in these samples was around 14% in average. 2500 g samples were placed inside the acrylic pipe and subjected to cavitation jets for 3 h. The duration of experiment was sufficient enough to squeeze the separated bitumen through the mesh into the tank. The bitumen was floating to the surface of the tank (Fig. 7) from which it was then collected, dried for 48 h under the fume hood, and then weighed. Temperature was varying from 12 °C to 23 °C during bitumen separation tests.

From Table 1 it can be seen that sound intensity is higher in case of 13 mm nozzle with notches. That can be explained with higher cavitation activity. In general, noise level is higher in case of diverging nozzles. Separated bitumen in grams is shown in Fig. 8. It is interesting to note that STRATOJET nozzle performed significantly better than diverging nozzles despite of lower cavitation noise. This could be related to additional hydrodynamic pulsating jet's effects. It was also found that vortex rings carry organized cluster of cavitation bubbles. This effect is not observed in case of non-resonating nozzles. These results would confirm that organized cluster of bubbles has higher erosive potential. Also pressure pulsations and higher shear can affect separation rates.

4. Conclusion

Six cavitation nozzles were tested for bitumen separation. It was shown that self-resonating nozzle demonstrated better performance even though passive control nozzle showed much higher cavitation activity according to



Fig. 7. Separated bitumen on the surface of the tank.

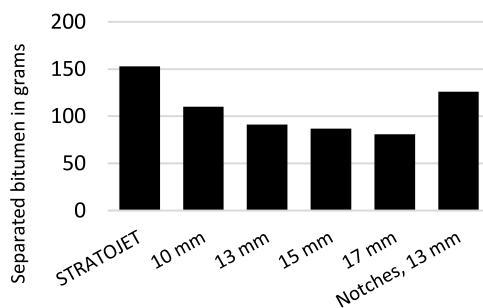


Fig. 8. Collected bitumen.

hydrophone noise measurements. Water temperature was varying from 12 °C to 23 °C which is significantly less than conventional process and thus cavitation jets can potentially replace hydrotransport and reduce energy consumption for bitumen separation.

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