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CAVITATING JETS IN THE OIL AND GAS INDUSTRY

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Аннотация. Кавитация – это явление образования парогазовых пузырей в жидкости, когда давление падает ниже критического уровня. Пузыри (каверны) перемещаются из области низкого давления в области высокого, схлопываются и генерируют высокое давление и температуру.

Кавитация может приводить к разрушению материалов, и это может использоваться в инженерных приложениях. Она может приводить к разрушению труб и оборудования. Но эрозионная способность кавитации может использоваться и полезно.

В данной работе рассмотрена теория кавитации, использование кавитации в различных инженерных направлениях, особенно в нефтяной и газовой промышленности.

Проанализированы различные аналитические и экспериментальные данные о кавитации и кавитационных струях.

В работе рассмотрены различные направления использования кавитационных струй в актуальных производственных процессах, аспекты проектирования кавитационных насадков, реальный опыт использования кавитационных гидродинамических струй в различном нефтегазовом оборудовании.

Ключевые слова: кавитация, кавитационные струи, битуминозный (нефтяной) песок, бурение, флотация, очистка отложений.

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Annotation. Cavitation is a phenomenon of bubble formation in the liquid flow regions where the pressure drops down to some critical value. When such bubbles move to the region with higher pressure they collapse and locally produce high pressures and temperatures.

Cavitation can damage any material, which is why it is usually undesirable in engineering applications. It can damage pipeline components, it can also cause noise, vibrations and pumps efficiency losses. But at the same time destructive cavitation properties can be used in a peaceful way.

The aim of this paper is to provide some cavitation theory background and review cavitation engineering applications, specifically applications of cavitating jets in oil and gas industry. As far as we know there are now reviews in such application area and this makes this paper different from the other reviews devoted to cavitation and cavitating jets. This review contains some applications where cavitating jets are used in actual industrial processes and some interesting applications on the stage of concept proof. It also contains some aspects of cavitating nozzles design and can be really useful for newcomers in the field of hydrodynamic jets engineering.

Keywords: cavitation, cavitating jets, oil sand, drilling, flotation, scale cleaning

1. Introduction

1.1 *Cavitation*

Cavitation is a phenomenon of formation and collapse of gas and vapour bubbles in a flowing liquid, in a region where the pressure of the liquid falls below some critical value. With additional pressure drop, small bubbles can coalesce and form caverns (Sedov, 1976). In general, liquids in nature and liquids which are used in engineering contain rigid particles and dissolved gases, called nuclei, which reduce cavitation inception requirements. For example, in the case of ordinary tap water the pressure critical value is equal to the water vapour pressure at the given operating temperature (Knapp et. al, 1970). Theoretical calculations based on the simple spherical bubble model show that the maximum pressure generated would be about 110 MPa and the maximum temperature would be 4×10^4 times the ambient temperature. Of course, in reality those numbers will be smaller, because of many factors, for example diffusion of gas from the liquid into the bubble and the effect of liquid compressibility, but such calculations show the potential of the cavitation to generate extremely high pressures temperatures and even shock waves (Brennen, 1995). Thermal effects play an important role in the final stage of bubble collapse when its contents are highly compressed. The elapsed times are of the order of microseconds, and it can be assumed that the noncondensable gas in the bubble behaves adiabatically. The adiabatic calculations show that the gas temperature in the bubble center can rise up to 8800 ºC (Tomita and Shima, 1977). Another very interesting effect during the collapse of cavitation bubbles is the development of a re-entrant jet caused by the asymmetry, such as the presence of a nearby solid boundary. Due to asymmetry one side of the bubble will accelerate inward more rapidly than the opposite side and, as a result, will produce a high-speed re-entrant microjet which will penetrate the bubble and be directed toward the boundary. Other asymmetries, such as gravity, can also cause the formation of these re-entrant microjets (Plesset and Chapman, 1971). The microjet can also be formed because of the asymmetry caused by the proximity of other neighbouring bubbles in a finite cloud of bubbles (Chahine and Duraiswami, 1992). The speed of this jet can be hundreds of meters per second and sufficiently high to create a pressure which is enough to melt the material (Lauterborn and Boll, 1975).

The above described phenomenon of a violent bubble collapse near solid surfaces, resulting in highly localized, large-amplitude shock waves (and noise), microjets and high temperatures in the fluid at the point of collapse is the cause of damage to solids, surfaces and material degradation.

1.2 *Vortex cavitation. Cavitating jets*

In vortex cavitation, cavitation bubbles can be found in the cores of vortices formed in the zones of high shear. For example, vortex cavitation may appear on the blade tips of ships' propellers and it may also occur on the boundaries of submerged jets. As an example let us consider a submerged jet of water being forced through a hole into a water tank. As the jet appears from the nozzle, a free shear layer is established. The thickness of this shear layer grows with the distance from the nozzle outlet (Rouse, H., 1966) At high Reynolds numbers, the jet becomes unstable and turbulent. Turbulent motion starts to spread, engaging surrounding liquid. The resulting mixing region has a constant maximum velocity and it spreads into the surrounding liquid and into the jet. A zone of fully developed flow follows after the boundary shear layer diffuses into the jet centerline. The continued diffusion reduces the maximum velocity and gradually dissipates the jet energy. Cavitation will start in the low pressure cores of turbulent vortices, which were generated in the shear zone (Young, 1989). Cavitating jets are commonly used for cleaning, cutting, digging and peening. They are generated by special nozzles which are called cavitating nozzles. Here we would like to review some applications of cavitating jets in the oil and gas industry.

1.3 *Cavitating nozzles*

The design and quality of cavitation nozzles are very important because cavitation nozzles define the efficiency of cavitating jets. Birkhoff and Zarantonello (1957) after the series of experiments came to conclusion that the best erosion effect can be achieved by utilizing nozzles which consist of two sections. The first section is conical and equal approximately 2–3 outlet diameters, the second one is cylindrical. Vulis and Kashkarov (1965) reported that the optimal cone angle for cavitating nozzles was 13-14 ºC and the optimal length of cylindrical section was 3–5 outlet diameters. The examples of such cavitation nozzles can be seen in Figure 1.

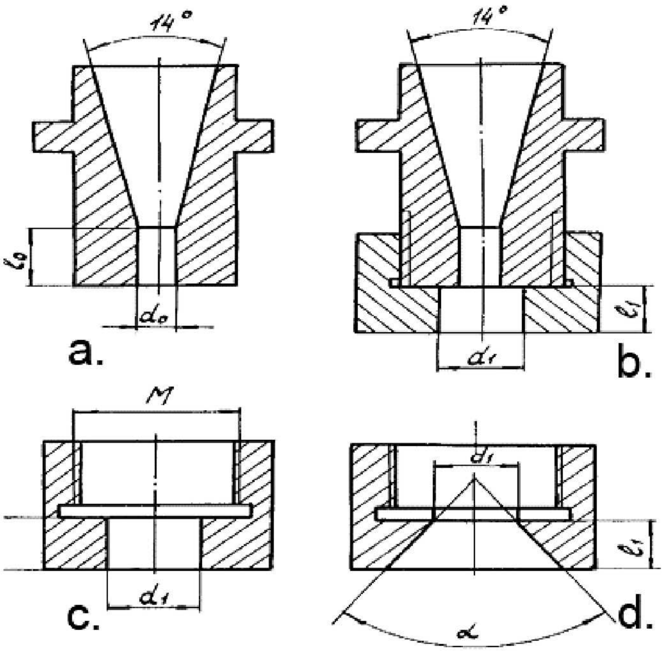

Figure 1 – Cavitation nozzles with two sections. Different combinations of cylindrical and conical sections:
a – nozzle; b – nozzle with cylindrical attachment; c – cylindrical attachment; d – cone attachment

There are many different cavitating nozzles exist for different applications not only in oil and gas industry (for example (Vickers, 1982), (Whaling, 1986), (Ivannikov and Ivannikov, 2004), (Kondratiev et al, 2009)). In general, analysis of patents devoted to cavitating nozzles and their efficiency in different cases starting from 1950 to present shows two main concepts of cavitation nozzles design. The first type of the nozzles utilizes the maximum technologically possible discharge coefficient (the ratio of the mass flow rate at the discharge end of the nozzle to that of an ideal nozzle which expands an identical working fluid from the same initial conditions to the same exit pressures). In this case jet destructive property is mostly characterized by hydrodynamic jet impact. Usually such nozzle design is close to de Laval nozzle Figure 2.

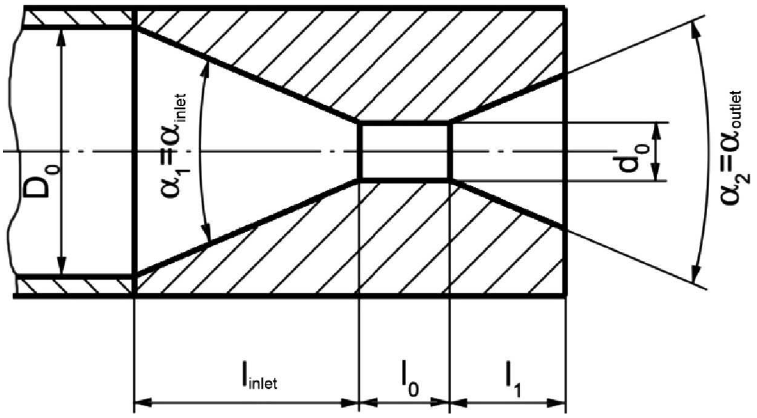

Figure 2 – First type cavitation nozzle design

The main idea of the second type of the nozzles is to utilize cavitation effect and minimize discharge coefficient. This can be achieved by manufacturing and installation of different impacts inside the nozzle which generate more cavitation bubbles. The schematics of such nozzle is shown in Figure 3.

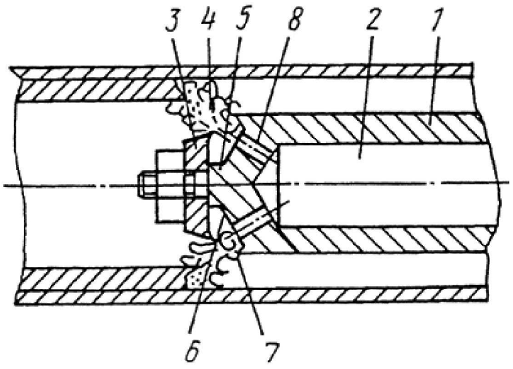

Figure 3 – Example of second type cavitating nozzle design:
1 – nozzle body; 2 – nozzle channel; 3 – disk deflector; 4 – sharp edge; 5 – cylindrical belt; 6 – cone part;
7 – sharp edge; 8 – cylindrical part

For destruction of different materials with high pressure jets it is necessary to design and manufacture nozzles of both types because very often it is impossible to predict what type will be more preferable in each particular case.

There are other cavitating nozzles design parameters which should be taken into account such as nozzle finish and material. This is important because wrong material and rough finish can cause cavitation erosion inside the nozzle and destroy it too fast. It should be noted here that in all cases cavitating nozzles are “eating” themselves (Figure 4) and like all other tools they are wearing with time, but the correct design help them to work much longer. Each particular case needs the individual approach because of the cost and difficulties of production. For example bronze is much more convenient for nozzle manufacturing process than titanium (2 out of 3 drill bits are braking in titanium nozzles manufacturing process) but titanium is much stronger. We usually use bronze nozzles for relatively small pressure applications and prototype tests in which we do need more than 24 operating hours.

Figure 4 – Cavitation nozzles wear (bronze)

2. Applications of cavitating jets in the oil and gas industry

2.1. *Scale removal*

Deposition of scale inside wellbores is causing millions of dollars in damage every year. The scale in oil fields can be formed because the produced water becomes oversaturated with scale components when two incompatible waters such as reservoir water and sea water meet downhole or it forms directly from the water which is naturally contained in reservoir rocks. Any water production or injection in the gas or oil well is creating a possibility of scale formation. In the North Sea and Canada, where entire regions are disposed to scale, it is recognized as one of the main production problems. It can reduce formation porosity and permeability, it can block flow in the pipes, and it can damage downhole completion equipment. Some mineral scales such as calcium carbonate ($CaCO_3$) can be dissolved with acids but common hard scales such as barium sulphate ($BaSO_4$) are extremely resistant to both chemical and mechanical removal (Crabtree et. al, 1999). The effect of scale, for example, was really fast and devastating in one of the wells in the Miller field (North Sea), where the production fell from 4770 m^3/d to zero in 24 hours (Brown, 1998).

Another scale problem is natural radionuclides from the U-238 and Th-232 series which are contained in rocks and are carried out on the surface during oil production. Radioactive materials are accumulating in the form of salt sedimentations and the main component of such scale is radioactive barium sulphate $Ba(Ra)SO_4$, which contains isotope radium-226. This isotope is extremely dangerous to the health and can cause cancer (Cuthill and DeCook, 1993).

According to «Rosneft-Stavropolneftegaz» (Russia) report (Pecherica et. al, 2005) in 1998 500 tonnes of metal equipment (pipes, fittings, valves, etc.) which contained the scale with natural radionuclides Th-232, Aa-226, Aa-228, K-40, accumulated on its territory. Specific activity of such equipment is mostly defined by the content of Ra-226 and varies from 20 Bq/g to 230 Bq/g. A pipe with 5 cm diameter and 9.5 m length can contain 2–4 kg of salt sedimentations. The crystals of $Ba(Ra)SO_4$ inside the pipe are shown in Figure 5.

The cleaning of scale, especially radioactive scale, is a very difficult problem. During the cleaning of radioactive scale it is important to insulate the process to avoid the appearance of radioactive dust and material leakage, it is also important to automate the process and organize waste utilization. Omelyanyuk (2008) suggested using cavitating jets for such cleaning processes generated by nozzles specifically designed for such applications. An example of the cleaning setup is shown in the Figure 6. The setup consists of three main parts: high pressure pump (50–70 MPa) system, pipe holding system with rotating mechanism, and the mechanism for translational motion of cavitating nozzle, filtration and storage system.

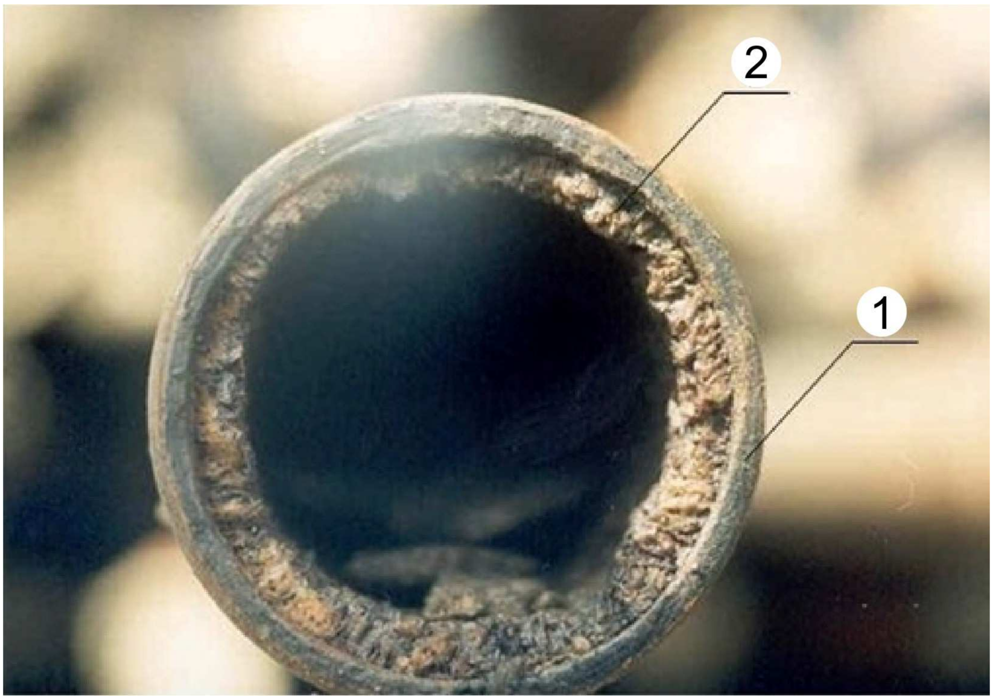

Figure 5 – $Ba(Ra)SO_4$ scale inside the «Rosneft-Stavropolneftegaz» pipes:
1 – pipe (diameter = 73 mm); 2 – scale

«Rosneft-Stavropolneftegaz» uses 3 setups of such type and successfully applies cavitating jet technologies for scale cleaning. The average cleaning time for 9.5 meters long pipe with 0.0635m diameter (2.5 inches) is 8–22 minutes, the radioactive background after the cleaning process is normal. Before cavitating jets conventional jet technology was used, with the same pumps cavitation jet technology was 20 % more efficient. The technology is also suitable for cleaning pipes inside the well, using high pressure pipes or coiled tubing.

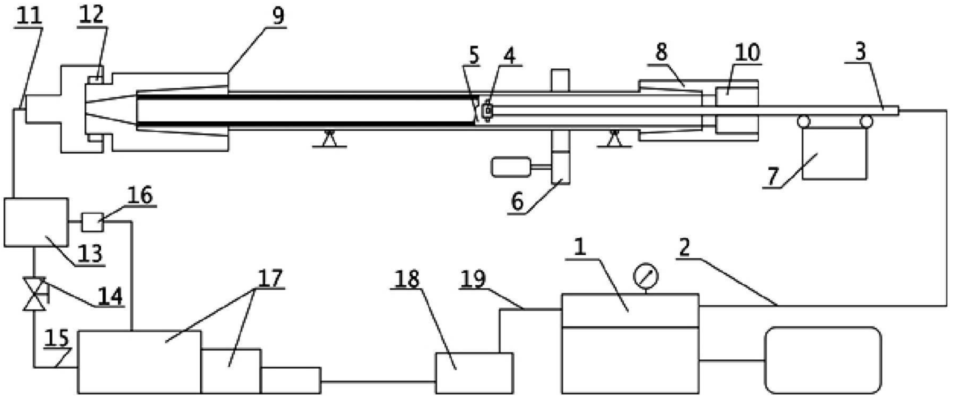

Figure 6 – The scheme of the stationary cleaning setup for removing a radioactive scale from the pipes:
1 – high pressure pump; 2 – flexible high pressure hose; 3 – high pressure pipe; 4 – cavitating nozzle; 5 – cleaned pipe; 6 – rotation mechanism; 7 – pipe moving mechanism 3; 8, 9 – pipes nipple and coupling; 10,12 – sealing; 11 – outlet; 13 – dispenser; 14 – valve; 15 – pipeline; 16 – safety valve; 17 – filtering system; 18 – fine filter; 19 – pump inlet

2.2. *Bitumen separation and deep hole drilling nozzles*

Oil sands are one of the main Canadian resources, the estimated volume of bitumen (extremely heavy crude oil) in place is 400 billion cubic meters with 12 % or 49 billion cubic meters estimated to be recoverable. This volume is comparable to the proven conventional oil reserves of Saudi Arabia (Government of Alberta, 2007). Oil sands (also called tar sands) are the mixtures of very heavy crude oil with sand, clay, water, stones and some other minerals. Conventional crude oil can be pumped from the ground or it can flow naturally but 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, Figure 7 (Carrigy ,1963)

The oil sand particles are firmly bonded together, they are random in shape and are very abrasive. The oil sand from Syncrude Ltd. North Mine can be seen on Figure 8.

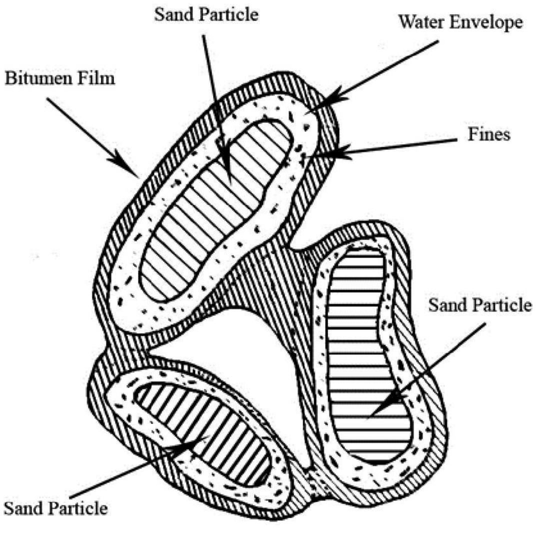

Figure 7 – Oil sand composition

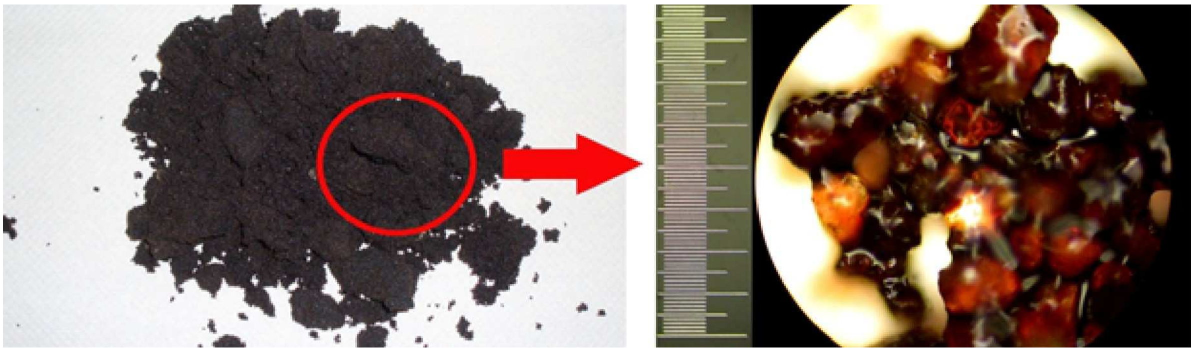

Figure 8 – Oil sand sample under the microscope. The value of one scale division is equal to 10 microns

The Athabasca deposit is the only oil sand deposit with reserves which can be surfacemined. There are several companies, including Suncor Energy Inc., Syncrude CanadaLtd., Shell Canada Ltd., Canadian Natural Resources Ltd. and Albian Sands Energy Inc. involved in oil sand mining in the Athabasca region, north of Fort McMurray. The Canadian government is spending billions of dollars for both the in-situ and mining projects. (McRory, 1982).

A review of present oil sands mining technology is given in (National Energy Board, 2000). 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 meters 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 ^{o}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 and another problem is the pipeline wear because, as was mentioned above, the sand is very abrasive. Vinogradov et. al (2011) suggested to use cavitating jets in bitumen separation processes, self resonating STRATOJET nozzles were used for that purposes. Such nozzles were 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 1,220 m deep with a nozzle pressure drop of 13.8 MPa) (Conn et. al., 1981) stimulated the development of methods to cause jet cavitation at greater depths. 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 (Chahine et. al., 1989). The self-excitation is achieved hydroacoustically and it transforms the jet shear layer into discrete organized ring vortices when the excitation frequency matches the jet's preferred value Figure 9, which is the predominant natural frequency of the non excited jet. This can be obtained by supplementing the final jet forming nozzle with various types of acoustic chambers, such as organ-pipe tubes or Helmholtz chambers, which are tuned to resonate at the desired frequency. It was proved that such cavitation jets can separate bitumen at any temperature even at 5–6 ^{o}C and cavitation jet technologies have the potential to replace hydrotransport. Some more results in this area can be found in (Bukharin et. al., 2012).

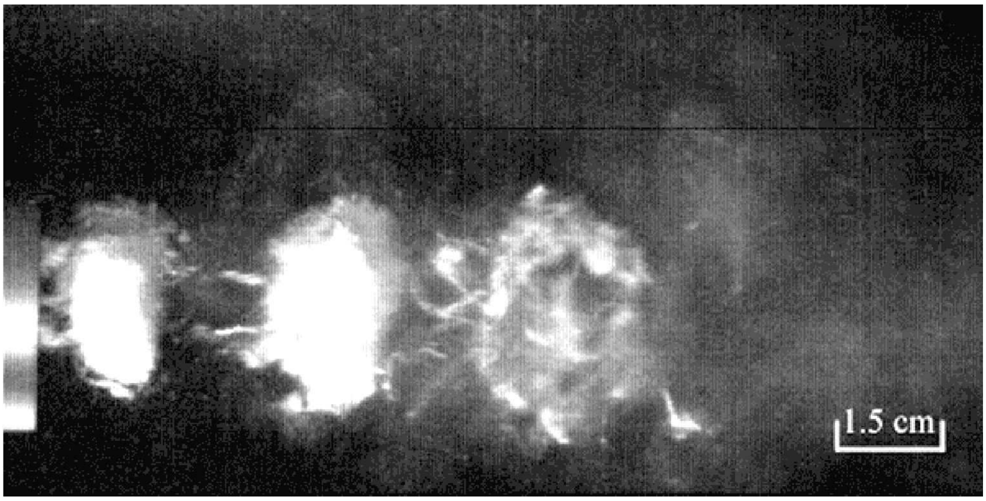

Figure 9 – Cavitation vortex rings moving along the jet periphery. Each ring carries a cluster of cavitation bubbles
(The picture from University of Calgary Laboratory, made by Nikolay Bukharin with high speed camera)

2.3 *Cleaning of gas blower cooling system*

During operation of heat exchangers the scale forms on the different surfaces, it consists of salts, products of corrosion, etc. In Northern America billions of dollars are spent to fight this problem (Vilhelmson, 2005). In gas pipeline applications this problem occurs in piston gas blowers in which internal cooling system is used and shell-and-tube heat exchangers are used in lubrication system.

Scale (Figure 10 (Omelyanyuk et. al, 2008)) produces the heat spots in the cylinder-piston system especially in the power cylinder bush in the region of connection with exhaust windows as a result the power cylinder bush deforms and breaks, the piston, oil-control and compression rings collapse, it causes exhaust break into gas compressor housing. Scale also dramatically increases corrosion rates and blocks cooling system pipes. The replacement of power cylinder bush, piston head, oil-control and compression rings is very expensive process that is why it is very important to clean the scale in gas motocompressor cooling systems in time. There are several methods of scale cleaning such as chemical, mechanical (drilling), electrohydropulse (hydraulic hummers) (Baltahanov and Ivanov, 1997) hydrodynamic (high pressure jets), etc. Each of them has its strengths, weaknesses and limitations. One of the most widely used methods in oil and gas industry is hydrodynamic method when high pressure jets are used (Bila V.J., 1993). Of the possible ways to use hydrodynamic technology is to clean the scale with cavitating jets. Cavitating jets were successfully used by Russian company «Kubangazprom» and it was demonstrated that cavitating jets can be 50 % more efficient than conventional jet technologies (Omelyanyuk et. al, 2008).

Figure 10 – Fragment of scale which was removed from power cylinder bush. Diameter of the coin is 19.45 mm

2.4. *Column flotation. Cavitation tube sparger*

2.4.1 *Column flotation*

Froth flotation is a flexible method for particles separation, which is based on ability differences of air bubbles to attach to mineral surfaces in slurry. The particles with attached bubbles are carried to the surface where they are removed and the other particles that remain completely wetted stay in the liquid. Flotation requires a machine for mixing and dispersing air in mineral slurry while removing the froth product. These machines are then connected and form flotation circuit. Conventional flotation cells consist of a tank with mixer designed to disperse air into the slurry. Such machines are relatively simple, the particles are carried into the froth along with the water making up the bubble films and hydrophobic particles can break free from the froth and can be removed along with the hydrophilic particles. Conventional flotation cells are usually assembled in multi-stage circuits (Hartman, 1992). Column flotation was designed to provide the improvement of froth flotation. In principle this is a flotation circuit arranged vertically, the slurry is flowing downward and the air bubbles float upward in countercurrent flow (Degner and Sabey, 1988; Eberts, 1986; Idlas et. al, 1990). The prototype of column flotation cell was patented by Callow in 1915 (date of patent submission), it was a pneumatic flotation cell which used sparging through the porous bottom (Callow, 1921) and the first countercurrent column flotation device was designed by Robert Towne and Frederick Flinn in 1914 (date of their patent submission) (Towne and Flinn, 1919). Callow's pneumatic flotation machines were widely used in industry in 1920's and 1930's, but the absence of effective air spargers for generation of sufficiently small bubbles and poor developed automated control systems forced to replace them by the impeller-type flotation devices. Column flotation devices were re-introduced for mineral processing in the late-1960's in Canada by Boutin and Wheeler (1967). At the end of 1980's column flotation had became a well established technology in the mineral industry.

2.4.2 *Cavitation sparger*

The conventional cells impeller-type mixers are not suited for use in flotation columns, because they need long shafts or rotating seals. Originally the bubbles were produced by sintered ceramic air diffusers which produced very fine air bubbles, but such setup suffered from plugging problems that is why it was replaced by cloth and perforated rubber (Dobby et al., 1985; Boutin and Wheeler, 1967) and later by various types of external bubble generators (McKay et al., 1988; Rubinstein, 1995). To maximize the bubble surface area generation, Canadian Process Technologies Inc. has developed an industrial sparging system based on hydrodynamic cavitation. In this application it is useful to stabilize the bubbles avoiding their collapse, for this purposes chemicals such as frothers are used. Small bubbles (picobubbles) which are generated by such cavitation sparging nozzles have better attachment properties than large bubbles because of their lower ascending velocity and rebound velocity from the surface. Klassen and Mokrousov (1963) showed that flotation recovery can be improved by combining flotation by mechanically generated bubbles and by gas nuclei from air supersaturation. Picobubbles on the particles surfaces promote the attachment of air bubbles because the interaction between the bubbles is better than interaction between bubbles and solid surfaces. Picobubbles are playing the role of secondary collectors enhancing particles attachment properties. As a result such combined flotation scheme reduces reagent cost. Picobubbles enhance particle collection an increase in flotation yield up to 15 wt %, a frother dose reduction of 10 %, and a collector dose reduction of 90 %. Zhou et al. showed that hydrodynamic cavitation significantly increased flotation kinetics of silica and zinc sulfide precipitates. Canadian Process Technologies of Vancouver, BC, Canada, has developed column flotation for oil/water separation (VOSCell) and, in partnership with Eriez Magnetics of Erie, PA, USA, has also developed column flotation for fine coal recovery (CoalPro). In 2002, the decision was made to advance column flotation technology in the Athabasca Oil Sands. Column flotation where among others cavitating spargers were used has been shown to offer significant improvements over conventional mechanically agitated flotation cells in secondary bitumen recovery (http://cpti.bc.ca/).

2.5 *Utilization of Cavitation for Environmental Protection. Dispersing Spilled Oil*

Accidental crude oil spills from oil tankers have damaged natural ecosystems in the Gulf of Mexico, France, the Galapagos Islands and other places all over the world. Mechanical recovery of oil is the most desirable operation in these cases to protect the environment. However, the recovery sometimes becomes difficult and the dispersing of oil is another solution in such a case and chemical dispersants are used. The obvious problem of chemical approach is that they can also cause some environmental problems. Kato, 2003 suggested to use cavitating jets for solution of this problem because the dispersing effect of cavitation is well known and widely used, Kato, 2000. It was shown that that the cavitating jet was a very promising method of dispersing spilled oil.

3. Conclusion

The review of cavitating jets applications in oil and gas industry was given. We can note that the main application of cavitating jets is cleaning and cutting but engineers in absolutely different industrial areas of Petroleum Engineering are trying to apply its interesting properties in solution of very wide range of problems. As we mentioned in abstract this review can be really useful for newcomers in the field of hydrodynamic jets engineering and contains references on main fundamental literature.

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