Digital Open Science Index
International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering Vol:14 No: 10, 2020

Digital Open Science Index, Energy and Power Engineering Vol:14, No:10, 2020 waset.org/publication/10011506

Investigation about Mechanical Equipment Needed to Break the Molecular Bonds of Heavy Oil by Using Hydrodynamic Cavitation

Mahdi Asghari

Abstract**—**The cavitation phenomenon is the formation and production of micro-bubbles and eventually the bursting of the micro-bubbles inside the liquid fluid, which results in localized high pressure and temperature, causing physical and chemical fluid changes. This pressure and temperature are predicted to be 2000 atmospheres and 5000 °C, respectively. As a result of small bubbles bursting from this process, temperature and pressure increase momentarily and locally, so that the intensity and magnitude of these temperatures and pressures provide the energy needed to break the molecular bonds of heavy compounds such as fuel oil. In this paper, we study the theory of cavitation and the methods of cavitation production by acoustic and hydrodynamic methods and the necessary mechanical equipment and reactors for industrial application of the hydrodynamic cavitation method to break down the molecular bonds of the fuel oil and convert it into useful and economical products**.**

Keywords**—**Cavitation, hydrodynamic cavitation, cavitation reactor, fuel oil.

I. INTRODUCTION

INCREASING demand for global and regional markets for lighter compounds and more valuable and lower economic value of heavy compounds extracted from crude oil, the study of new methods of stylization has become important. Conventional processes of converting fuel oil to more valuable products such as catalytic cracking, are performed at high temperatures and pressures; so, the initial costs of building the relevant units and energy consumption will be very high [1]. One of the most effective and efficient methods in improving the quality of heavy crude oil products is the use of energy produced by the phenomenon of cavitation (bubbling) to break various bonds between molecules of heavy crude oil compounds [2].

Cavitation equipment is a new and promising multi-state reactor in which very high energy is produced locally and with high density due to the formation and disintegration of bubbles [3]. Cavitation is a phenomenon composed of the formation, growth, and dissolution of microbubbles or cavities that occur at short intervals and result in the release of high-density energy (1 to 10^{18} Kw.h/m^3). Eventually it creates several thousand atmospheres of pressure and several thousand degrees Kelvin temperature locally, these effects are observed at millions of points in the reactor. Cavitation also leads to the formation of reactive free radicals and an increase in mass transfer rate due to turbulence created during the flow of liquid [4].

In general, cavitation is classified into four types based on production methods:

1. Acoustic cavitation: The difference in pressure in a liquid as a result of the use of ultrasound sound waves with an intensity of 16 KHz to 100 MHz, chemical changes caused by cavitation due to the passage of ultrasonic waves are called sonochemistry.
2. Hydrodynamic cavitation: This type of cavitation is produced by the pressure difference caused by changes in velocity. For example, cavitation is created by the exchange of pressure and kinetic energy under the influence of the reactor geometry, such as the passage of current through the orifice plates, the venturi, and etc.
3. Optical cavitation: This type of cavitation is created by high-intensity optical photons (lasers).
4. Particle cavitation: This type of cavitation is created by the radiation of elementary particles such as protons.

Among the various methods of cavitation production mentioned above, hydrodynamic and acoustic cavitation are scientifically and industrially superior due to the ease of operation and ease of production of the required cavitation intensity [4], [9].

In this paper, we will review the methods of cavitation production by acoustic and hydrodynamic methods and the equipment and mechanical reactors required for the industrial use of hydrodynamic cavitation to break the molecular bonds of heavy petroleum compounds.

II. CREATING CAVITATION USING ULTRASONIC WAVES

The energy produced by cavitation using ultrasonic waves is one of the most effective and best ways to improve the quality of heavy oil products. In general, the effects of acoustic bubbling can be summarized by the growth, oscillation, and explosion of microbubbles in the environment. In this type of bubbling, pressure changes in the liquid are usually caused by the propagation of sound waves (usually 16 KHz – 100 MHz). Sound waves with high ultrasonic frequencies are generated by piezoelectric transducers or magnetic transformers. These waves create high amplitude and frequency and an alternating pressure field, and as a result, part of the liquid is exposed to high and low-pressure cycles, which, if their amplitude is large enough, may cause bubbles to burst [1], [5], [6], [18].

Fig. 1 shows the stages of bubble expansion and compaction and finally, its explosion due to ultrasonic wave compression

---

Mahdi Asghari is Head of Planning, Control and Maintenance Methods of Tabriz Oil Refining Company, PhD. Student of Tabriz Islamic Azad University, Tabriz, Iran (phone: 0098914-412-5018; e-mail: m.asghari1980@gmail.com).

cycles. A bubble can grow in semicircles created by the sound field. Through unilateral penetration, steam and gas are transferred into the bubble until the bubble reaches its critical value and the bubble disintegrates. At the site of the explosion, the temperature will reach more than 5000 °C and the pressure will reach several thousand atmospheres, leading to physical and chemical effects on the surrounding fluid [6], [7].

Bubbles created by ultrasound can show different behaviors. Bubbles may form larger bubbles when they collide, a process called "merging." In a fluid with a saturated vapor solution, a bubble can grow in several acoustic cycles, which is called "correction diffusion". If the bubbles grow large enough to float, they may leave the system in that area without doing anything special, which is called "degassing". Bubbles, after becoming a certain size with an unstable diameter, often explode violently and with a lot of energy, and the bubbles may split after an explosion and become smaller bubbles that explode when they explode and fragment. Bubbles, light, and sound waves are emitted, which is called a "glowing sound" event, and these tiny bubbles will re-enter the cycle (Fig. 2) [7].

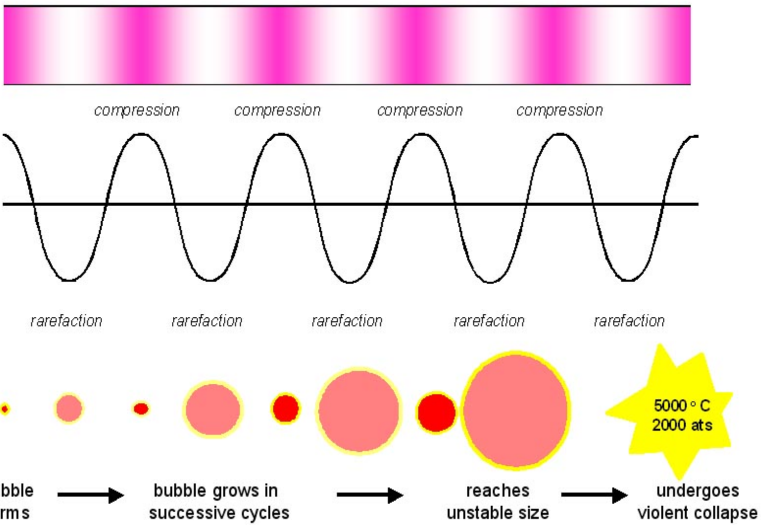

Fig. 1 Expansion, compaction, and disintegration of bubbles due to compressive bursts of ultrasonic wave

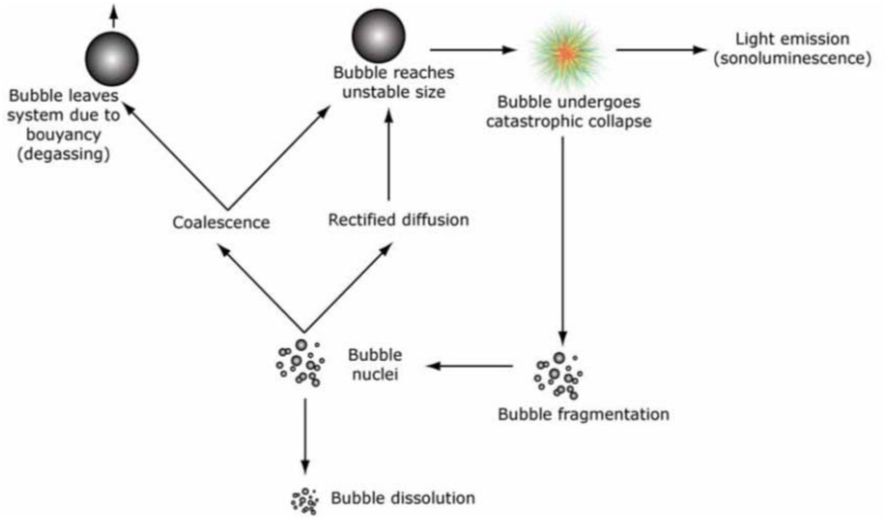

Fig. 2 The behavior cycle of bubbles created by ultrasonic waves

A technology called NexGen is a new technology to upgrade and lighten heavy crude oil by creating cavitation (bubbling) using ultrasound to break long hydrocarbon chains. In this process, heavy crude oil with hydrogen obtained from the pure water is mixed and heated to 200 °C, then the mixture is passed through an ultrasonic wave production reactor and after breaking the long molecular chains by creating cavitation caused by ultrasonic waves, the crude oil is upgraded, dehydrogenated and sent to the distillation unit. The ability of this technology to upgrade and lighten heavy oil from 8° to 42° API with input energy of 20 KWh/bbl has been proven. A capacity of 10 thousand barrels per day NexGen Heavy Oil Upgrade Unit is currently operating in Edmonton city (Alberta, Canada); about $45 million has been spent on the installation of this unit. Fig. 3 shows the process flow of the upgrading heavy oil by NexGen technology by creating cavitation (bubbling) by ultrasound [8].

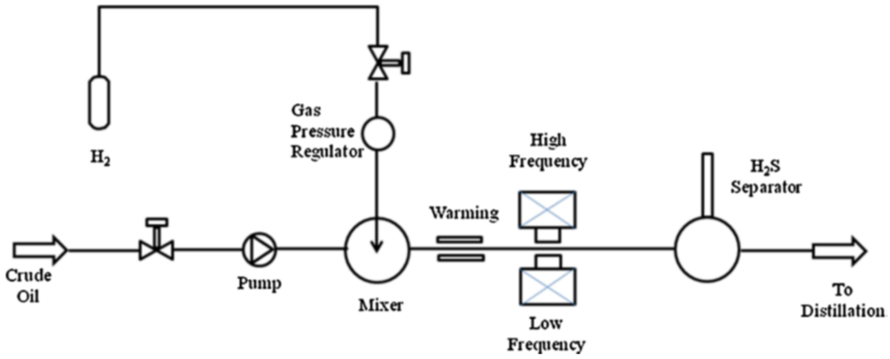

Fig. 3 Process flow of the heavy oil upgrade by NexGen technology

III. Creating Cavitation by the Hydrodynamic Method

Cavitation by hydrodynamic method due to the ability to improve energy efficiency and the capacity of this method to work on a larger scale, can be replaced by the method of cavitation by ultrasonic method (ultrasound). Most efforts to exploit this statement are through practical experiments. However, the short history of hydrodynamic cavitation still lacks basic guidelines for understanding this method. From an engineering point of view, applied cavitation should be done to save energy. Comparison of energy efficiency of hydrodynamic cavitation reactors with ultrasonic cavitation reactors shows that the intensity of energy production due to the explosion of bubbles created by ultrasonic cavitation reactors is higher, but hydrodynamic reactors have higher energy efficiency due to bubble production volume (cavitation production intensity) than the ultrasonic reactors, and on an industrial scale, the hydrodynamic cavitation method is more energy-efficient than the ultrasonic cavitation method [9], [10].

Hydrodynamic cavitation is simply produced using an orifice plate, venturi, throttle valve, high-pressure homogenizer, or high-speed homogenizer. The pressure-velocity relationship of the fluid can be deduced by the Bernoulli equation. With the help of this equation, significant functional effects are discovered. If the control valve is suitable, the pressure around the bottleneck (the distance between the flow separations on the sides) decreases below the threshold pressure (usually the average vapor pressure in operating conditions), resulting in bubbles. Then, as the average velocity of the liquid jet decreases, as a result, the pressure increases, causing bubbles to burst and a significant amount of energy to be released locally. The high turbulence intensity of the downstream fluid flow depends on the magnitude of the pressure drop and the recycling pressure rate, and in general, it can be said that it depends on the geometry of the narrowed duct and the fluid condition such as the degree of turbulence. Turbulence intensity has a profound effect on cavitation intensity, so by controlling the geometry and operating conditions of the reactor, the intensity of cavitation required for optimal chemical and physical changes can be produced with maximum energy efficiency (Fig. 4) [10].

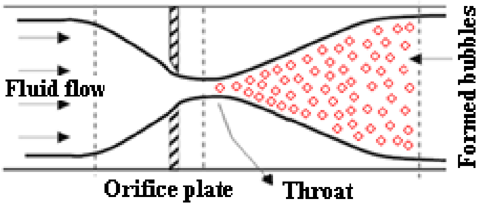

Fig. 4 Fluid flow from inside the orifice plate and creating hydrodynamic cavitation

A dimensionless number is known as the cavitation number, which is usually related to the flow conditions with cavitation intensity, which is obtained from (1):

$$C_v = \frac{P_2 - P_V}{\frac{1}{2}\rho V_0^2} \tag{1}$$

P_2 is the downstream flow back pressure, P_V is liquid vapor pressure, and V_0 is liquid velocity in the narrowed part of the duct and ρ is the density of the fluid. The cavitation number at the beginning of the cavitation that is known as the initial cavitation number is C_v . In general, the onset of cavitation occurs at C_v equal to 1, and the effects of cavitation in $C_v < 1$ will be significant. Cavitation at higher cavitation numbers (in the range of 2 to 4) may occur due to the presence of dissolved gases or some impurities. It is proven that the cavitation number (C_v) depends on the flow geometry and will usually increase with an increase in the size of the narrowed conduit or an increase in the size of the tube relative to the velocity of the fluid. However, cavitation can occur at the highest cavitation number for maximum reactor utilization, but the flow and geometry conditions should be adjusted so that the cavitation number is in the range of 0.1 to 1 [10].

IV. Structure of Hydrodynamic Cavitation Reactors

Selecting an optimal design of hydrodynamic cavitation reactors to maximize the effects of cavitation and achieve an effective operating cost is important. For this purpose, we examine the types of hydrodynamic cavitation reactors:

A. High-Pressure Homogenizer

The system commonly used for hydrodynamic cavitation is a high-pressure homogenizer. The system consists of a double-walled tank plus a high-pressure reciprocating pump with a one-way valve with several stages of the throttle or choke valve. The liquid is pumped from the double-walled storage tank by a high-pressure reciprocating pump. After passing through a one-way valve, the fluid first reaches a throttle valve, in which the pressure reaches more than 70 bar. Then to further increase the pressure, the fluid goes to the throttle valve of the second stage, in this stage, the fluid pressure increases to more than 700 bar, after the fluid passes through the throttle valve of the second stage, returns to the double-walled tank. Bubble-forming conditions begin after the second stage of the throttle valve when the fluid suddenly passes through the larynx at high pressure; sudden evaporation causes bubbles to form. The severity of cavitation depends on the amount of upstream pressure as well as the type of second stage throttle valve. As the pressure in the throttle valve increases, the temperature of the fluid increases, which must be cooled between the two walls of the double-walled tank with cooling water to maintain and bring the fluid temperature to ambient temperature. The main disadvantage of high-pressure homogenizer reactors is that there is no precise control over the volume of cavitation activity and the magnitude of the pressure pulses generated at the end of the cavitation. Fig. 5 shows a high-pressure homogenizer flow loop [4], [9], [10].

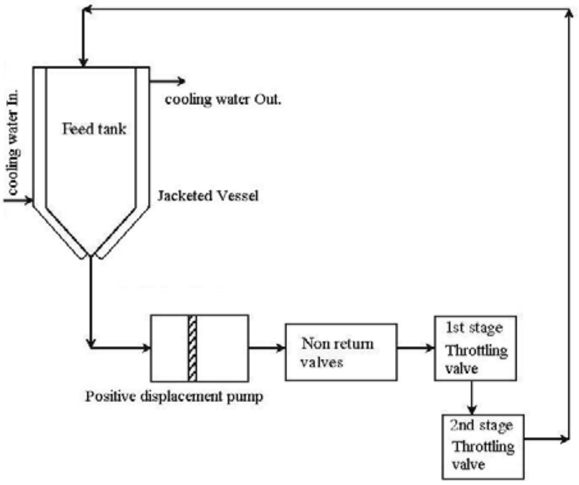

Fig. 5 Flow loop in a high-pressure homogenizer to create hydrodynamic cavitation

B. High-Speed Homogenizer (Rotary Pulse Device)

The cavitation phenomenon can also be produced in rotating equipment. When the speed of the rotating blade tip reaches a critical speed, the local pressure around the rotating blade decreases and reaches below the vapor pressure of the liquid, which results in the production of steam-like bubbles. The liquid then moves away from the rotating blade and moves to the sides. The liquid pressure is restored according to the velocity head; because of this, the bubbles move towards the liquid mass and are destroyed by high energy production. There is a critical rotational speed to start cavitation in the high-speed homogenizer. It should be noted that energy consumption in this type of reactors is much higher and the flexibility of design parameters is much less compared to reactors used to create cavitation with minimum pressure such as Orifice or Venturi. These devices operate at a rotational speed of 4,000 rpm to 20,000 rpm. A high-speed homogenizer usually consists of at least one rotor-stator (moving and stationary parts), the surface of each of which has teeth or similar holes. Moving and stationary parts are usually multi-stage in terms of the number of radial layers or multi-stage in the longitudinal direction of the reactor. The distance between the perforated plates of the fixed part (radial layers) in the rotary pulse or high-speed homogenizer is usually 6 mm and the distance between the perforated plates of the moving part and the plates of the fixed part is between 0.5 mm to 2 mm. The rotational speed of the high-speed homogenizer rotor can be changed by changing the voltage of the electric motor connected to it [4], [6], [9], [10].

In a test and study conducted in 2011 on the crude oil mixture of the oil fields of Basra and Kirkuk in Iraq using a high-speed homogenizer (rotary pulse device) with a speed of 7610 rpm for 10 minutes, the following results have been obtained: the API degree has been increased from 29 to 40, the flash point has been reduced from 75 °C to 54 °C and the pour point has been reduced from -10 °C to -32 °C, and most importantly, the value extraction of middle distillate products has increased from 30% to 39%. Fig. 6 shows the moving and fixed part of a four-stage radial high-speed homogenizer and Fig, 7 shows a four-stage high-speed homogenizer along the length of the reactor [6].

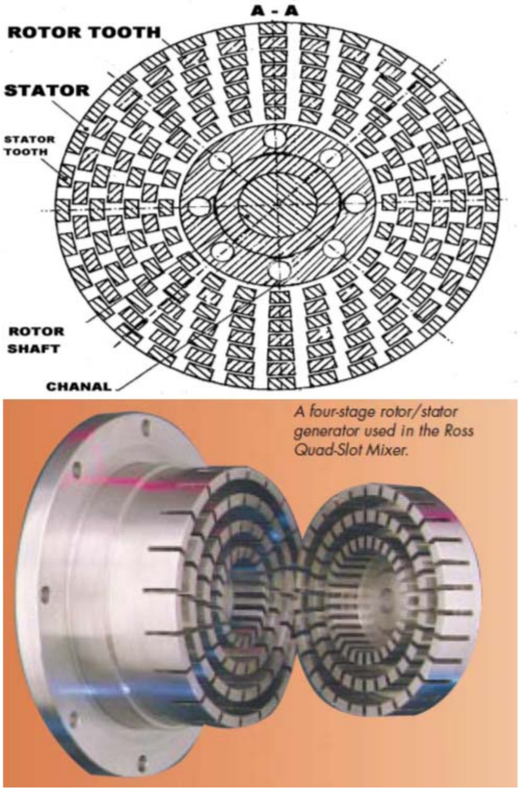

Fig. 6 Moving and fixed part of a high-speed four-stage radial homogenizer

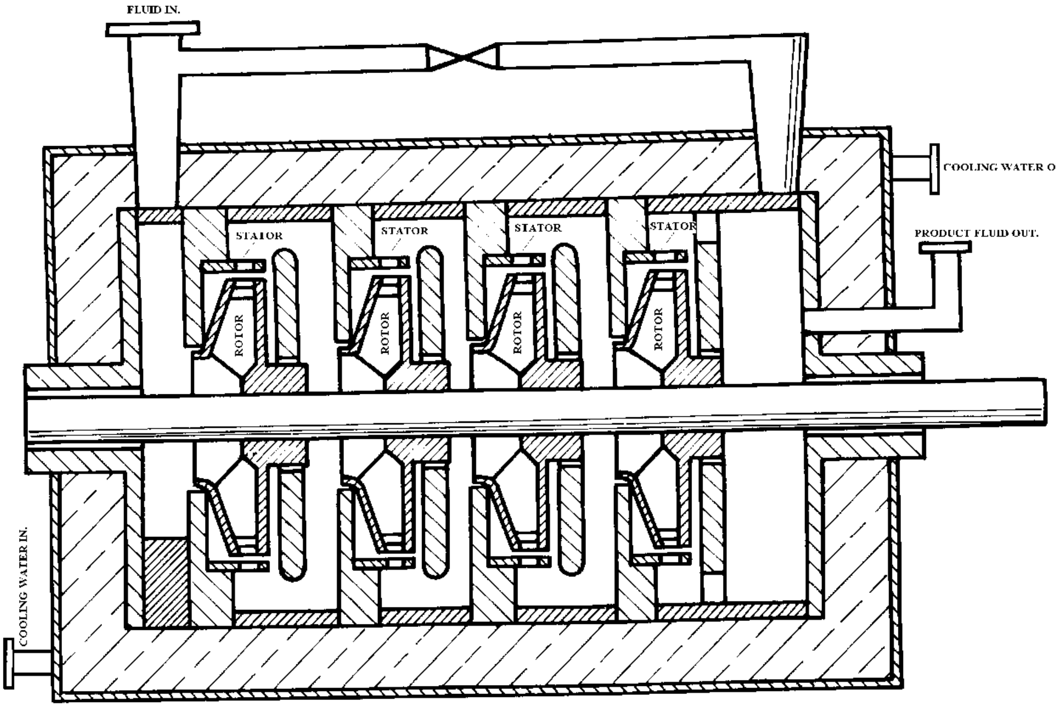

Fig. 7 High-speed four-stage homogenizer along the length of the reactor

C. Hydrodynamic Cavitation Reactor Based on Orifice Plates

In this type of reactor, the fluid flow passes through the main line and reaches the orifice plate or set of orifice plates with narrowed ducts, where suddenly the flow velocity increases due to the decrease in the flow area and the pressure decrease. When the pressure falls below the liquid vapor pressure, bubbles begin to form. The flow diagram of the cavitation generated by the reactor based on the orifice plates is shown in Fig. 8 [4], [9], [10], [12]-[14].

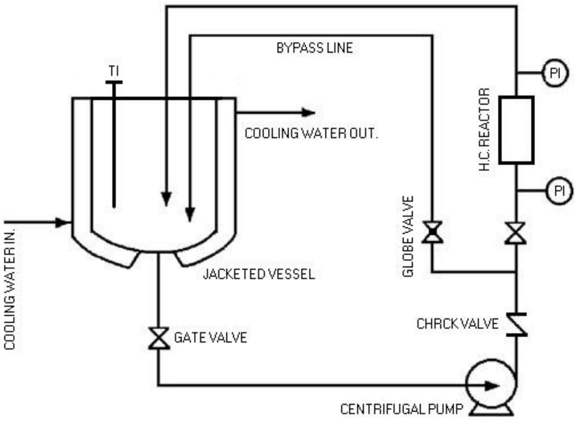

Fig. 8 Flow diagram of Cavitation generation by the reactor based on the orifice plates

The narrowed part of the duct can be a venturi, or an orifice with a single hole, or a set of orifice plates with multiple holes. The holes of the orifice plate can vary in the number of holes, diameter, and shape. The difference in diameter and arrangement of the holes helps to achieve different intensities of cavitation and also the number of cavitation events that occur in the reactor. Therefore, this type of reactor shows considerable flexibility in terms of operating conditions (inlet pressure control, flow rate, and inlet temperature) and geometric conditions (different arrangement of holes on the orifice plate). Depending on the type of application and operating conditions and geometry selected in the hydrodynamic cavitation reactor with the help of orifice plates, maximum cavitation effects are possible with minimum energy consumption [4], [10]. Fig. 9 shows the types of hydrodynamic cavitation reactors using the Orifice and Venturi plates. The number, diameter, and shape of the holes in each reactor are different [11]-[15].

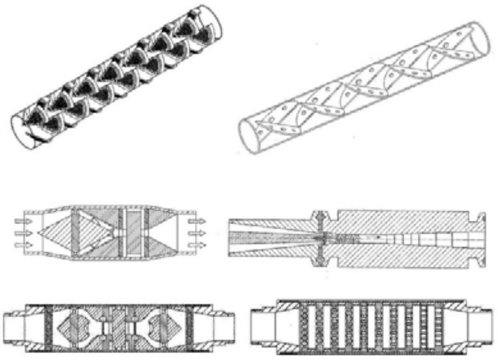

Fig. 9 Types of hydrodynamic cavitation reactors with multi-stage orifice and venturi plates

V. CONCLUSION

A comparison of the results obtained for the magnitude of temperature and pressure in the ultrasonic cavitation process with the conditions used in thermal and catalytic cracking shows that the cavitation process can be a good alternative to conventional methods with high-energy consumption. The most important advantages of the cavitation process are the lack of need for energy supply and external heating of the feed, short operation time, and its cost-effectiveness [1]. Also, a comparison between the energy efficiency of hydrodynamic cavitation reactors and ultrasonic cavitation reactors has shown that the intensity of energy production due to the explosion of bubbles created by ultrasonic cavitation reactors is higher, but hydrodynamic reactors have higher energy efficiency due to bubble production volume (cavitation production intensity). Among which Orifice plate-based reactors and high-pressure homogenizer reactors can have industrial applications (Fig. 10) [3], [4], [8], [17].

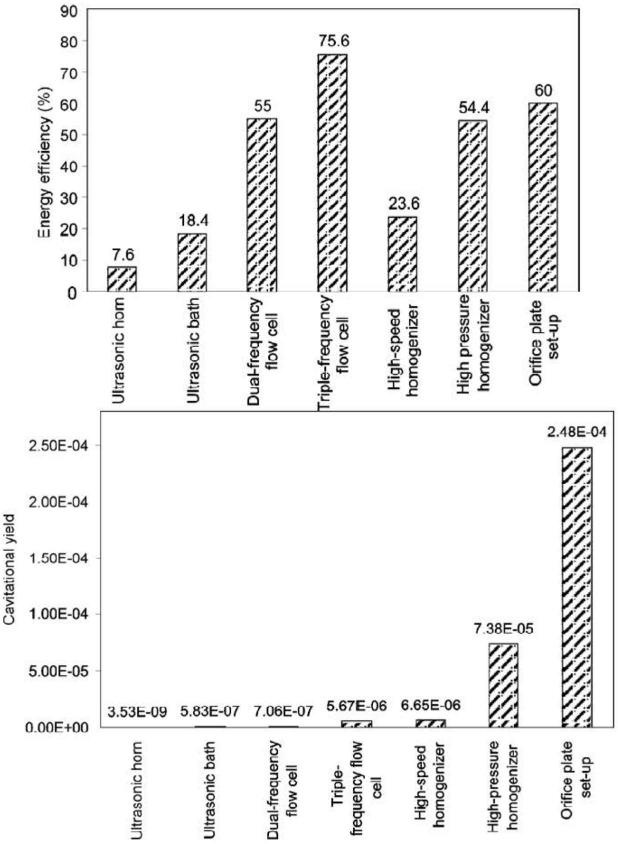

Fig. 10 Comparison between energy efficiency and produced bubbles efficiency with different cavitation generation methods

Today, the possibility of breaking the carbon chains of hydrocarbons by the process of hydrodynamic cavitation and the profitability of this method on an industrial scale has been proven, so the need to design and manufacture multi-stage cavitation equipment to upgrade heavy petroleum compounds is felt [17].

Refinery heavy fuel oil with a kinematic viscosity of 72 cST @ 100 °C is composed of hydrocarbons with long carbon chains, especially alkanes, cycloalkanes, and aromatics, among which the highest amount of energy is needed to break the carbon chains of aromatic compounds. It is equal to 610 KJ/mole, which can be obtained by using the multi-stage hydrodynamic cavitation reactors [1], [16], [17].

In a practical experiment performed using a hydrodynamic cavitation reactor for only 15 minutes on the distillation tower residue in Pennsylvania light crude oil at the Bradford Refinery in the United States, the following results were obtained: Viscosity was reduced by 50% and the API rating has been increased by 1% and the hydrocarbon cut in the kerosene range has been achieved by 5% by volume, with the economic profit of this upgrade operation estimated at $1 per barrel in 2013 [18].

At present, due to the high production capacity of fuel oil in most of the world's old refineries, the profit margins of refining activities have been drastically reduced. On the other hand, the initial costs of constructing fuel oil conversion units to more valuable products, such as the RFCC unit, are very high. So, it is recommended to study and implement the use of alternative methods such as the use of the multi-stage hydrodynamic cavitation technology to upgrade and convert fuel oil into more valuable products.

REFERENCES

[1] Raisi, Zohreh, Naderifar, Abbas, “Assessing the ability of cavitation phenomenon to lighten Iran's heavy oil without energy consumption”, The First International Conference on New Approaches to Energy Conservation, pp. 1,2,3,8, Niroo Research Institute, Tehran, 18 to 19 Dec. 2011

[2] Niazi, Shahram, Hashemabadi, Seyed Hasan and Mirarab Razi, Meysam, “CFD Simulation of Acoustic Cavitation in a Crude Oil Upgrading Sonoreactor and Prediction of Collapse Temperature and Pressure of Cavitation Bubble”, Chemical Engineering Research and Design., Vol. 92, PP. 166 (2014)

[3] Mauro, Capocelli, Marina, Prisciandaro and Amedeo, Lancia and Dino, Musmarra, “Comparison Between Hydrodynamic and Acoustic Cavitation in Microbial Cell Disruption”, Chemical Engineering Transactions., Vol. 38, PP. 13,17,18 (2014)

[4] Gogate, R., Parag, Tayal, K., Rajiv and Pandit, B., Aniruddha, “Cavitation: A Technology on The Horizon”, Current Science., Vol. 91, PP. 35,39,40,41,45 (2006)

[5] Mason, J., Timothy and Lorimer, P., John, “Applied Sonochemistry: Uses The Power Ultrasound in Chemistry and Processing”, 1rd ed., Wiley-VCH Verlag GmbH, Weinheim Germany, (2002)

[6] Hmood, R., Ghufran, “Upgrading of Basrah-Kirkuk Blend Crude Oil Using Mechanical-Acoustic Effect”, Master Degree of Science in Chemical Engineering, University of Technology, Iraq, PP. 18~26,28~31,60~80, 2011

[7] Leong, Thomas, Ashokkumar, Muthupa and Kentish, Sandra, “The Fundamentals of Power Ultrasound a Review”, Acoustics Australia., Vol. 39, PP. 54~56 (2011)

[8] Costaned, C., Luis, Munoz, A.D., Jose and Ancheyta, Jorge, “Current Situation of Emerging technologies for Upgrading of Heavy Oils”, Catalysis Today, PP. 257~258 (2014)

[9] Gogate, R., Parag and Pandit, B., Aniruddha, “A Review of Imperative Technologies for Wastewater Treatment: Oxidation Technologies at Ambient Conditions”, Advances in Environmental Research, Vol. 8, PP. 503,506~514,540~542 (2004)

[10] Gogate, R., Parag, “Hydrodynamic Cavitation for Food and Water Processing”, Food Bioprocess Technol, Vol. 4, PP. 997,1000,1001,1009 (2011)

[11] Gordon, Roman, Gordonitsky, Igor and Promtov, Maxim, “Cavitation Generator”, United States Patent No: US 7,762,715 B2, (2010)

[12] Gordon, Roman, Gordonitsky, Igor and Promtov, Maxim, “Multi Stage Cavitation Device”, United States Patent No: US 8,042,989 B2, (2011)

[13] Maslak, Dominik and Botz, W., Dirk, “Cavitation Reactor”, United States Patent No: US 2012/0222744 A1, (2012)

[14] Mcguire, Dennis “Hydrodynamic Cavitation Device”, United States

Patent No: US 2013/0088935 A1, (2013)
[15] Mcguire, Dennis and Jakhete, Sanjeev “Portable Hydrodynamic Cavitation Manifold”, United States Patent No: US 2011/0305104 A1, (2011)
[16] Gordon, Roman, Gordonitsky, Igor and Promtov, Maxim and Grichko, Varvara, “Flow through Cavitation Assisted Rapid Modification of Crude Oil”, United States Patent No: US 2010/0101978 A1, (2010)
[17] Nesterenko, A.I. and Berlizov, Yu. S. “The Possibility of Cracking Hydrocarbons with Cavitation, a quantitative Energy Assessment”, Chemistry and Technology of Fuels and Oils, Vol. 43, PP. 1~4 (2007)
[18] Zamilov, Fomitchev, Max I. “Heavy Crude Oil Upgrading with Hydrodynamic Cavitation”, Quantum Vortex Inc., PP. 1~8 (2013)

Digital Open Science Index, Energy and Power Engineering Vol:14, No:10, 2020 waset.org/publication/10011506