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A Review of Intensification Technology Hydrodynamic Cavitation in Biodiesel Production

Lai Fatt Chuah*[a], Nor Hasni Osman[a], Abdul Kafi[a], Kasypi Mokhtar[b], Anuar Abu Bakar[c], Nizamuddin Zainuddin[a], Mohd Azhafiz Abdullah[b], Misaal Maruf[d], Shahrul Miza Mahmud[e], Keng Bin Loke[b]

[a]School of Technology Management and Logistics, Universiti Utara Malaysia, Malaysia
[b]Faculty of Maritime Studies, Universiti Malaysia Terengganu, Malaysia
[c]Faculty of Ocean Engineering Technology, Universiti Malaysia Terengganu, Malaysia
[d]Synergy Marine Group, Singapore
[e]Nautica Ship Management Sdn Bhd, Selangor, Malaysia
johnfatt2000@yahoo.com

The quest for energy is an essential aspect of industrial and economic progress. As the demand for energy rises, various sources, including coal, fossil fuels, wind, solar, nuclear, natural liquid gas etc., become necessary. Biodiesel exhibits comparable characteristics to conventional diesel oil, enabling its utilization in diesel engines without requiring substantial engine modifications. Biodiesel stands out as a potential alternative fuel due to its carbon footprint reduction and environmentally friendly qualities, such as being green, clean, renewable and biodegradable. This makes biodiesel a promising option to address the diminishing reserves of fossil fuels. This paper presents a review of the evolving hydrodynamic cavitation technology's application in the synthesis of biodiesel. The review assesses the differences between hydrodynamic cavitation and advanced hydrodynamic cavitation techniques in biodiesel production. This hydrodynamic cavitation field demonstrates the capability to achieve a biodiesel conversion of 96.5 wt.% or higher, meeting both ASTM D6751 and EN 14214 standards. A SWOT analysis was performed to assess the efficacy of advanced hydrodynamic cavitation in biodiesel production. The insights derived from this analysis could potentially inspire future advancements in this novel intensification technology.

1. Introduction

The global population is estimated at approximately 8 x 109 as of 2024 (Worldometers, 2024). The expansion of the economy and industry, encompassing sectors such as transportation (Kweon et al., 2023), construction, agriculture, power plants, mining, etc., heavily relies on fossil fuels. This reliance contributes to elevated carbon levels, leading to the emission of greenhouse gas (GHG) and contributing to global warming. In 2022, global energy consumption reached approximately 178,899 x 109 kWh (Our World in Data, 2023). The breakdown of this consumption includes oil (29.6 %), coal (25.1 %), natural gas (22 %), hydropower (6.3 %), traditional biomass (6.2 %), nuclear (3.7 %), wind (3.1 %), solar (1.9 %) and other sources (2 %) (Our World in Data, 2023). The GHG emissions resulting from the variable pricing of fossil fuels have prompted individuals to explore renewable and sustainable fuel alternatives (Boldyryev et al., 2023). Approximately 38.5 x 109 t of carbon dioxide emissions originated from various sectors, with the power industry accounting for 38.1 %, transportation for 20.7 %, industrial combustion for 17.0 %, buildings for 8.9 %, industrial processes for 8.4 %, fuel exploitation for 6.6 % and other sectors for 0.4 % in year 2022 (Statista, 2024). Between 2010 (20.3 x 109 L) and 2022 (57.2 x 109 L), worldwide biodiesel consumption experienced a rapid 1.8-fold increase (Sonnichsen, 2024a). The leading global biodiesel producers, in descending order (estimate), include Indonesia (30 %) (Sonnichsen, 2024b), the EU (26.3 %) (REN21, 2023), the United States (15.8 %), Brazil (9.8 %) and other contributors (18.2 %) (Manprasert, 2018). According to REN21 (2023), the global demand for biodiesel volume is estimated at approximately 1,538 x 109 L, constituting only about 3 % of the current global biodiesel production.

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Biodiesel commonly recognized as fatty acid methyl ester emerges as a sustainable and eco-friendly substitute for traditional fossil fuels. It is derived from the reaction between oil and methanol in the presence of a catalyse under optimized operating parameters. Noteworthy characteristics include biodegradability, cleanliness, renewability, environmental friendliness, harmlessness and lubricity (Samani et al., 2021). Biodiesel closely mirrors the properties of petroleum diesel, enabling its direct use in internal combustion diesel engines without significant modifications (Oo et al., 2022). Vegetable oil, in its unconverted state, can be directly utilized through methods such as direct mixing (dilution) and micro-emulsion. While these processes enhance viscosity, they are only recommended for short-term applications due to the risk of incomplete combustion in diesel engines. An innovative approach involves pyrolysis or thermal cracking, utilizing only heat and catalysts to decompose oil (although at a high cost) and synthesize suitable fuel compounds for diesel engines without the need for methanol and oxygen (Gul et al., 2021). Another widely used method is the chemical reaction approach, encompassing transesterification, esterification and interesterification reactions for biodiesel production. Among these, catalytic-based transesterification (utilizing homogeneous, heterogeneous and enzyme catalysts) or non-catalytic-based methods (such as supercritical and co-solvent) stand out as the most promising due to their rapid reaction rates and mild reaction conditions (Gul et al., 2021). Numerous factors impact both the yield and quality of biodiesel, with conversion efficiency being a crucial requirement aligned with ASTM D6751 and EN 14214 standards for commercial sale. Key variables in this process encompass oil to alcohol molar ratios, catalyst loading, reaction time, operating temperature and notably, moisture and free fatty acid contents.

The primary obstacle to the commercial viability of biodiesel production lies in its production costs. To the best of our knowledge, the raw material cost, even when utilizing non-edible sources or incorporating high-quality glycerin recycling (Farvardin et al., 2022), stands out as one of the most significant expenses. This is followed by the cost associated with mixing methods and other factors. While the mechanical stirring method is widely employed by industries to mitigate mass transfer resistance, it suffers from drawbacks such as a low reaction rate, extended reaction time, the need for substantial space and high energy consumption. In pursuit of cost optimization in biodiesel production, recent studies have explored various intensification technologies aimed at enhancing and efficiently overcoming mass transfer resistance between oil and alcohol to replace the conventional approach.

Recent research has delved into intensification technologies, including microwave, ultrasonic cavitation (UC), microtubular mixer, reactive distillation, hydrodynamic cavitation (HC) and others, to identify the most cost-effective means of augmenting the mass transfer rate between oil and reactants. Among them, HC emerges as a highly efficient option, demonstrating approximately 138 times greater efficiency than UC and 253 times greater efficiency than mechanical stirring in terms of energy efficiency for biodiesel production (Chuah et al., 2017). Due to its advantages in energy efficiency as mention ealiert, shorter reaction time and cost-effective setup, HC has become the most promising intensification technology (Samani et al., 2021). For understanding of cavitation formation and mechanisms, refer to the review by Chuah et al. (2017).

Since 2006, HC has been employed in biodiesel production. Figure 1 illustrates that the number of journals related to biodiesel production via HC (111) is comparatively lower than other emerging technologies such as microwave (1,124), ultrasonic (792) and reactive distillation (226), based on a search of article titles, abstracts and keywords in the Scopus dataset as of January 25, 2024. UC and HC methods have garnered significant attention from researchers, reflecting a growing interest in exploring their advantages. Both methods serve as pathways to induce sonochemistry effects.

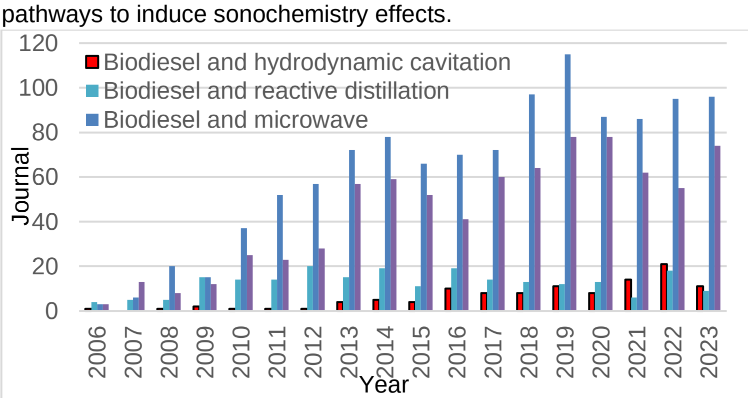

Figure 1: Timeline of published journals on intensification technologies in biodiesel production (Scopus, 2024)

There are four main cavitation types viz. particle-induced, optical, acoustic and hydrodynamic. These phenomena were initially discovered by Leonhard Euler in 1754 (Suslick, K.S., 1990). Among the various types,

UC and HC have gained significant popularity, particularly for their remarkable ability to effectively eliminate mass transfer resistance. HC is considered a more practical option compared to UC, given its ease of setup, along with lower energy consumption and shorter reaction periods (Oo et al., 2021a).
This review aims to highlight the latest innovation in HC viz. dynamic HC, rotational HC generator, rotor stator, shockwave power reactor and advanced rotational HC compared to homogenizer and non-advanced rotational HC, non-rotational HC generator, orifice plate, venturi, nozzle, vortex diode and wedge. Despite numerous studies on conventional HC in biodiesel production since 2006, only a limited number of works have explored advanced HC methods in biodiesel production. Based on the recent publications, only a few review articles delves into advanced HC. Limited research has explored advanced rotational HC and its advantages over conventional method remain relatively low to the best of our knowledge. This underscores a need for deeper comprehension in this field. To address this gap in analysis, the review emphasizes the effectiveness and practicality of advanced rotational HC (Section 2). In Section 3, a SWOT analysis evaluating the advanced rotational HC for biodiesel production is presented, offering insights that could inspire future advancements in this novel intensification technology.

2. Conventional and advanced HC

The efficacy of both conventional and advanced HC in biodiesel production relies on their structural configuration and operating conditions. The innovative rotor-stator intensification technology is particularly suitable for chemical reactions, notably transesterification, owing to its capability for strong shear stress, elongational stress, intense vortex or turbulence, a blend of energy and continuous cavitation (Oo et al., 2021a). A rotor can be designed with various shapes, such as numerous holes on its surface located inside the stator, facilitating high-velocity liquid flow into the gap within the rotor and stator. As the rotor rotates, the static pressure of the liquid inside the holes decreases below the vapor pressure, leading to the generation of cavities within the holes. The cavitation region forms when high velocity liquid impinges upon the rotor's surface, resulting in a reduction of liquid pressure below the vapor pressure (Oo et al., 2021b). In conventional HC, the liquid traverses through non-advanced rotational HC, non-rotational HC generators, orifice plates, venturis, nozzles, vortex diodes, wedges or throttling valves at a sufficient speed and velocity. As the local pressure of the liquid drops below the vapor pressure, the liquid vaporizes, generating vapor bubbles or cavities. These cavities undergo expansion and collapse (compression) due to pressure recovery, releasing a significant amount of energy locally in the form of shock waves. This rapid phenomenon results in a pronounced surge in local temperature and pressure within µs. Among innovative advanced HC, the cavitation generation unit (CGU) takes the form of various teeth and shaped holes strategically positioned on the rotor, be it a cylinder or a circular disc. The CGU induces rotating cavitation at a sufficient rotational velocity. As the rotational velocity increases, the cavities are periodically induced and collapse between the stationary reactor and the rotor's motion. This process yields a notably higher energy release compared to conventional HC. The liquid circulation at high velocity enhances mixing and accelerates the reaction rate, resulting in a substantial reduction in production time and increased efficiency.
The rotating cavitation induces both intrinsic and instability, differing from the intrinsic instability observed in conventional HC (Sun et al., 2023). The advanced HC can be categorized into two types: shear type, where the rotor is within the CGU and interaction type involving both rotor and stator in the CGU. The interaction type of advanced HC demonstrate a robust compressing effect between the two vortexes in the CGU leading to a significant impact and the formation of sheet cavitation (SC) and vortex cavitation (VC). This feature renders the interaction type more conducive to industrial-scale continuous processes. The shear type, lacking interaction between the rotor and stator, experiences a substantial decrease in the relative speed of the liquid resulting in a smaller separation area and lower vortex intensity formed by the CGU (Sun et al., 2023). Based on the Table 1, despite the multitude of studies on conventional HC in biodiesel production since 2006, a restricted number of investigations (around 9 focusing on rotor-stator systems, 1 employing computational fluid dynamics and 3 with homogenizers) have delved into advanced HC methods from 2016 to the present. These publications lack specific information about the hole spacing and distribution pattern on the rotor, critical for designing large-scale reactors and enhancing methyl ester conversion performance. Rotor stator HC methods consistently demonstrate high conversion efficiency across various feedstocks compared to other techniques such as homogenizer HC, mechanical stirring and UC. The intense mixing and shear forces from rotor stator HC promote rapid transesterification, resulting in high biodiesel yields. Rotor stator HC methods need optimized parameters like rotor stator distance, speed and hole dimensions for cavitation. Homogenizer HC offers space-saving design and better separation efficiency, suitable for space-constrained applications.

Table 1: Compilation of prior research findings on advanced HC in biodiesel production

Reference	Feedstock	Method and capacity	Oil to alcohol molar ratio	Time (min)	Conversion (wt.%)	Other
Crudo et al., 2016	Waste cooking oil	Rotor Stator HC + 10 L	1:6 molar ratio, 0.6 wt.% NaOH, 55 °C	15	99	390 L/h flow rate
Abbaszadeh-Mayvan et al., 2018	Waste cooking oil	Rotor Stator HC	1:6 molar ratio	0.5	96.62	25,510 rpm, Dr/Ds=0.73, Dc/Dr=0.06, dc/Δr=0.5
Samani et al., 2021	Safflower seed oil	Rotor Stator HC	1:8.36 molar ratio, 0.94 wt.% KOH	1.06	89.11	1.53 cm rotor stator distance
Oo et al., 2021a	Crude palm oil	Rotor Stator HC	17.7 vol.% methanol, 2.9 vol.% H_2SO_4, 60 °C		91.27	3,000 rpm, 25 L/h, 11.456 to 1.028 wt.% FFA, 0.0264 kWh/L
Oo et al., 2021b	Esterified crude palm oil	Rotor Stator HC	28.6 vol.% methanol, 6.2 g KOH /L, 60 °C		99.163	3,000 rpm, 25 L/h, spherical holes on rotor with D=6.4 mm abd depth=6.2 mm, 0.049 kWh/L
Oo et al., 2022	42 vol.% diesel + 50 vol.% biodiesel + 2 vol.% water + 3 vol.% Span80 + 3 vol.% Tween80	Rotor Stator HC				Nanoemulsion fuel remain stable for 90 d, 4011 rpm, 11.8 L/h, diameter hole=5.8 mm, hole dept=6.4 mm
Farvardin et al., 2022	Waste cooking oil	UC + Rotor Stator HC	1:6 molar ratio, 1.0 wt.% KOH	1	90.45	3,000 rpm, 250 W UC, 21.52 kJ
Oo et al., 2023	Crude palm oil	Rotor Stator HC	20.8 wt.% methanol, 2.6 wt.% H_2SO_4		97.34 vol.%	3,000 rpm, 12.014 to 1 wt.% FFA, hole diameter=5 mm, hole depth=5 mm, 110 ° point angle of cone
Vera-Rozo et al., 2023	Soybean oil	Rotor Stator HC	1:6.5 molar ratio, 1.0 wt.% NaOH, 60 °C	6	97.63	3,415 rpm, hole depth=17 mm, rotor stator distance=3 mm
			1:10 molar ratio, 1.0 wt.% NaOH, 60 °C			2,000 rpm, , hole depth=17 mm, rotor stator distance=3 mm
		Mechanical stirring	1:9 molar ratio, 0.6 wt.% NaOH, 60 °C	120	98.58	200 mL jacketed batach reactor
Mohod et al., 2017	Waste cooking oil	Homogenizer HC	1:12 molar ratio, 3 wt.% KOH, 50 °C	120	97	Rotor diameter=190 mm, 18.5 kW electric motor
Joshi et al., 2017	Esterified waste cooking oil	Homogenizer HC + 0.3 L	1:10 molar ratio, 1 wt.% CaO, 50 °C	30	88	12,000 rpm, stator diameter=25 mm, rotor diameter=17 mm
		Mechanical stirring		120-180	88	
Tarigan et al., 2023	Waste cooking oil	Homogenizer HC	1:1.5 molar ratio, 25 °C	0.5	95.9	Stator =35 mm, rotor r=25 mm
	Esterfied waste cooking oil		1:9 molar ratio, 1 wt.% NaOH, 25 °C	5	91.4	Stator r=35 mm, rotor =25 mm

3. SWOT analysis for advanced HC in biodiesel production

The SWOT analysis findings are illustrated in Figure 2, providing a summarized overview of the review's conclusions. Advanced HC presents strengths such as ample scalability potential, collapse cavities heightened energy release, elongational stress, strong shear stress, formation of SC and VC. The opportunities is potential for scaling up operations. A weakness is the lack of exploration on harvesting energy from periodic cavity induction and collapse, which induces only intrinsic instability. The system must seriously address and mitigate the threatening effects of HC, such as noise, erosion and vibration.

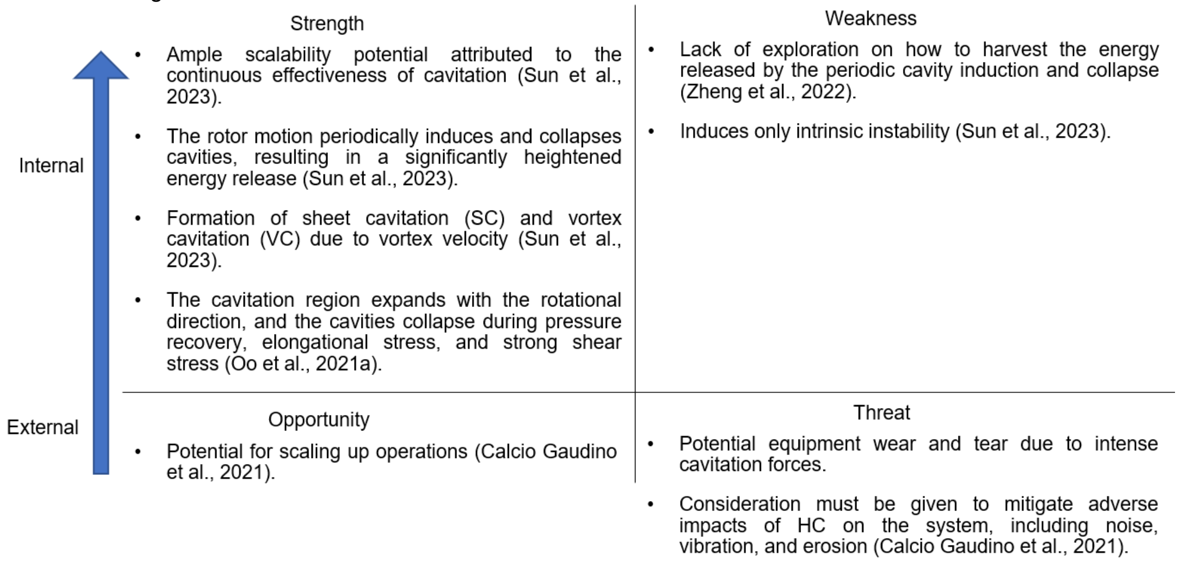

Figure 2: SWOT analysis evaluating the efficiency of advanced HC in biodiesel production

4. Conclusions

The pursuit of sustainable energy sources is pivotal for industrial and economic advancement. Biodiesel emerges as a promising alternative, boasting characteristics akin to traditional diesel oil and contributing to a reduced carbon footprint. This paper extensively explores the application of evolving HC technology in biodiesel synthesis. The HC field demonstrates significant potential, achieving biodiesel conversions meeting industry standards. While this review provides valuable insights, there is still a room for further exploration, particularly in comparing HC with other industrial processes. Investigating how this technology enhances efficiency will be crucial for its widespread adoption and advancement in biodiesel production. Addressing these gaps could drive future developments in this innovative intensification technology.

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