International Journal of
Environmental Sciences & Natural Resources
ISSN: 2572-1119

Juniper Publishers
key to the Researchers

Review Article
Volume 19 Issue 3 - May 2019
DOI: 10.19080/IJESNR.2019.19.556015

Int J Environ Sci Nat Res

Hydrodynamic Cavitation – A Promising Technology for Biomass Pretreatment

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Submission: April 26, 2019; **Published:** May 23, 2019

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Abstract

Biomass pretreatment is a highly expensive process used in bioethanol production from lignocellulosic feedstocks. The existing pretreatment methods are not commercialized due to two significant bottlenecks faced by the bioethanol industry such as higher operating cost and capital investment. Hydrodynamic cavitation technology is successfully demonstrated in the diversified fields. Hydrodynamic cavitation or its combinations is a viable technology for biomass pretreatment. This technology requires lesser energy inputs in terms of thermal or electrical energy as compared with other energy-intensive pretreatment methods. Other advantages of this technology are simple in reactor construction and easy to upscale. The combined hydrodynamic cavitation with alkali or biocatalyst showed positive results for different lignocellulosic biomass feedstocks. There is more scope for this technology to adopt in commercialization scale in both bioethanol and biorefinery industries.

Keywords: lignocellulsic biomass; Biomass pretreatment; Hydrodynamic cavitation

Introduction

The cavitation means the phenomena of millions of cavities generated and collapsed in milliseconds and thus dissipating huge magnitudes of energy. Hydrodynamic cavitation, acoustic cavitation, Optic cavitation, and particle cavitation are the four methods classified based on cavitation production mode. Among them, the the first two methods, hydrodynamic cavitation and acoustic cavitation were tried for biomass pretreatment studies due to its simple operation. The hydrodynamic cavitation (HC) is more energy efficient than acoustic cavitation [1,2]. HC can be produced by supplying the liquid at a constant pressure via a constriction arrangement (orifice plate or venturi tube) and energy lost due to a pressure drop at the constriction. This can indirectly help in increasing the liquid velocity, thus helps in collapsing of bubbles in the liquid. In order to generate the cavities, the liquid pressure should reach below the liquid's vapor pressure. The collapse of cavities takes place immediately after pressure recovered.

Application of hydrodynamic cavitation has been found to be adequate for different applications, i.e. biomedical, wastewater treatment [3-6], water treatment [7], biogas production [8,9], cell disruption [10], reactants mixing in chemical reactors [11], biodiesel production [12-18], volatile compound removal [19], delignification of wheat straw for paper pro duction [20], 2,4-dinitrophenol compound degradation [21], 2,4,6-trichlorophenol degradation [22]. Most of the existing pretreatment methods are not commercialized at large scale due to higher energy inputs and capital investment, safety aspects and difficult to upscale. HC technology can handle the large volume of the chemical reactants. Also, there is more scope for application of HC technology to reduce overall processing cost, which indirectly reduces biofuel price. This paper briefly discusses the recent developments in HC technologies in the biomass pretreatment process.

Biomass Pretreatment

Biofuels can be produced from biomass feedstocks via thermochemical or biochemical biomass conversion technologies. Among the liquid biofuels, bioethanol is recommended for blending with petrol to run the spark ignition engines. First generation bioethanol production technology is successfully implemented at commercial scale in different countries. Because of simple and efficient technology, the fermentable sugars from sugar/starch crops is quickly recovered and used for bioethanol production via a fermentation process. As compared to these crops, the lignocellulosic biomass (LCB) feedstocks have a complex cell wall structure to protect the fermentable sugars. Generally, the LCB feedstocks comprise 75% of carbohydrates (40-50% of cellulose, 25-30% of hemicellulose) and up to 25% of lignin. The conversion of cellulose and hemicellulose sugars available in the LCB feedstocks into fermentable sugars is a difficult task due to lignin binding. The LCB feedstocks into bioethanol production via biochemical conversion technologies involve three stages. Firstly, the biomass undergoes the pretreatment to break the lignin barrier. Secondly, the hydrolysis process used for cellulose and hemicellulose sugars to produce fermentable sugars. Lastly, the production of bioethanol from these sugars can be done by the fermentation process. There are no efficient technologies available for pretreating the LCB feedstocks. Biomass pretreatment is an essential process for cellulosic ethanol production. Currently, physical, chemical, biological and combined pretreatments (two or more) are the primary techniques employed. In comparison to individual pretreatment method, combined pretreatments are focused much more attention due to its improved pretreatment performance.

Discussion

HC technology for biomass pretreatment

Several researchers have involved in developing an efficient method to pretreat the different LCB feedstocks via physical or chemical or physicochemical or biological or combination of two or more methods. Recent review paper covers various aspects (including merits and demerits) of different biomass pretreatment methods *viz.*,

a) physical (mechanical extrusion, milling, microwave, ultrasound, pyrolysis and pulse electric field),

b) Chemical (acid, alkali, ozonolysis, organosolv, ionic liquids, and eutectic solvents)

c) physicochemical (steam explosion, liquid hot water, etc.) and

d) biological (fungi, bacterial and archaeal) methods [23].

Based on the conclusion drawn from the literature review, the current biomass pretreatment methods used for LCB feedstocks were the more complicated process, energy intensive and difficult to upscale. The primary reason may be due to the involvement of higher energy inputs (electrical/thermal energies) and processing cost. In order to overcome these issues, HC technology can be combined with other pretreatment methods for the effective pretreatment of LCB feedstocks.

In order to improve pretreatment efficiency, HC can be combined with existing chemical or biological methods. At the time of the cavitation process, dissociation of the water molecule into OH- and H- produced at higher pressure and temperature conditions. The OH- radicals generated in the cavitation process are more reactive, which can play an essential role in oxidization of lignin molecule. Orifice plate and venturi tube are commonly used in the reactor to produce HC. There is no mechanism used for mixing of reactants in the reactor. The radicals formed in the reaction can be used to enhance the pretreatment performance. Depending on the reactor geometry and configuration, the biomass pretreatment in HC reactor was done in two ways. One method uses biomass kept in HC zone and chemical solution (water + catalyst) as working fluid to pass through biomass (HC zone) for several times using closed loop arrangement. Another method uses biomass slurry as working liquid and sent to HC zone several times through closed loop circulation [24]. The results of a comparative study showed that performance of alkali biomass pretreatment in HC reactor with an orifice plate was better in terms of energy requirement, lignin reduction and bioethanol yield than ultrasound cavitation method [25]. The pretreatment was done by keeping reed biomass in the HC zone and working fluid is circulated for the reaction period. Higher lignin reduction was achieved as 35-42% under optimal conditions of 11.8% biomass loading, 3.0% NaOH and reaction 41.1min (Table 1). Another study on combined HC and alkaline pretreatment to pretreat the sugarcane bagasse using HC reactor with an orifice plate showed maximum lignin removal as 60.4% in 44.48min [26]. Further enzymatic hydrolysis shows that yield from pretreated biomass was higher than raw (82%) and alkaline treated biomass (30%). Another similar study showed maximum lignin was 51.52 % in 30 min [27]. This might be due to differences in biomass types, reactor geometry configurations, operating and optimal conditions used in the experiments. A combination of alkali and HC was used to pretreat the sugarcane bagasse feedstock for bioethanol production via simultaneous saccharification and fermentation (SSF) process [28]. Among the different alkaline catalysts used (NaOH, KOH, Na_2CO_3, $Ca(OH)_2$), the combined NaOH-HC pretreatment achieved the highest amount of ethanol production (17.26 $g.l^{-1}$). Results of the combined HC and hydrogen peroxide pretreatment of sugarcane bagasse showed 95.4% of cellulosic fraction digestibility was reached under optimal conditions (0.29M of NaOH, 0.78% (v/v) of H_2O_2, 9.95min.) [29,30]. They also reported that bioethanol yield from pretreated biomass by *Scheffersomyces stipites* NRRL-Y7124 in a bubble column reactor was achieved as 31.50 $g.l^{-1}$ Nakashima et al. [31] studied a comparative pretreatment using a reactor with a venturi tube and ultrasonication for combined HC with catalyst (sodium percarbonate) to pretreat the corn stover biomass. The biomass slurry (water +biomass powder +chemical solution) was used as a working liquid and continuously re-circulated via a venturi tube for the reaction period. They found that the biomass pretreatment efficiency in the HC method was higher than the ultrasonication method. The combined HC and enzymatic (HCE) method were evaluated as corncob pretreatment by using biomass slurry (buffer + biomass powder +enzyme) as working liquid and continuously re-circulated via orifice plate for the reaction period [24]. They found the highest lignin reduction (47.4%) under the optimal conditions (biomass loading: 5%, enzyme loading: 6.5U g^{-1} of biomass and reaction time: 60min.). Hence, application of HC in biomass pretreatment has gained interest when compared to conventional methods of pretreatment *viz.*, higher removal of lignin, easy accessibility of cellulose for saccharification, less energy consumption, simple geometric configuration, construction and easy to scale up.

How to cite this article: Ramesh Desikan, Kiruthika Thangavelu, Sivakumar Uthandi. Hydrodynamic Cavitation – A Promising Technology for Biomass Pretreatment. Int J Environ Sci Nat Res. 2019; 19(2): 556015. DOI: 10.19080/IJESNR.2019.19.556015

Table 1: Comparison of combined HC with different catalysts to pretreat the various lignocellulosic biomass feedstocks.

S. No.	Parameters	Kim et al. [25]	Hilares et al. [26]	Nakashima et al. [31]	Madison et al. [30]	Hilares et al. [28]	Kiruthika et al. [24]
1	Cavitational device used	Orifice	Orifice	Venturi	Venturi	Orifice	Orifice
2	Orifice hole dia (nos) / throat dia	Ø=1 mm, (27)	Ø=1mm, (27)	throat Ø = 3.6 mm	throat Ø = 5.72 mm	Ø =1mm, (16)	Ø =2mm, (27)
3	Operating temperature, °C	77	64	30	22	70	30
4	Inlet pressure, kPa	500	300	-	370	300	50
5	Feedstock used	Reed	Sugarcane bagasse	Corn stover	Sugarcane bagasse	Sugarcane bagasse	Corncob
6	Feedstock size	10mm	4.7mm	0.25mm	10 mesh size	4.7mm	≤ 212µm
7	Biomass loading, %	11.8	4.24	4	1	--	5
8	Catalyst	3.0% NaOH	0.48M NaOH	0.4mol/L of Na_2CO_3, 0.6mol/L of H_2O_2	$Ca(OH)_2$ -0.1g/g of dry biomass	0.3M NaOH	Laccase Enzyme: 6.5U g^{-1} of biomass
9	Working fluid	Water + catalyst solution	Water + catalyst solution	Biomass slurry (water + catalyst +biomass powder)	Biomass slurry (water + catalyst +biomass powder)	Water + catalyst solution	Biomass slurry (water + catalyst +biomass powder)
11	Duration, min.	41.1	44.48	60	120	30	60
12	Lignin removal, %	35-42	60.4	-	36	51.52	47.44
13	Energy consumption,	3.65MJ kg^{-1} of biomass	--	9.4 kJ/g sugar	752kJ/g sugar	--	1.35MJ kg^{-1} of biomass

Factors affecting the HC pretreatment

The bubble size describes the intensity of cavitation and grows at low pressure or high temperature [32]. As compared to smaller bubbles, larger bubbles collapsing with a higher intensity would have significant effects on reactants used in the chemical process. For instance, collapsing of vast numbers of bubbles using the process can deconstruct the biomass structure. In the case of working fluid with highly viscous nature and low vapor pressure, more energy is required to produce cavitation. Furthermore, the size and reactor geometry can also affect the pretreatment efficiency [33]. The cavitation number Cv is a measure of resistance to cavitation. A higher value of Cv indicates cavitation will not take place and vice versa. Low cavitation number can increase the cavitation intensity, which can be achieved by reduce the pressure or increase the flow rate of the working fluid [33]. Sometimes the bubbles may combine to form a larger bubble at low cavitation numbers, and they may be carried away with the liquid. This would lower the effectiveness of the cavitation process [34]. The significant parameters affect the intensity of cavitation during the biomass pretreatment are particle size, catalyst activity, inlet pressure, temperature and diameter of the orifice plate.

Conclusion

Recently, HC technology is a good candidate among the other pretreatment methods for pretreating the LCB feedstocks. The large-scale application of this technology has potential to reduce pretreatment process cost. In comparison with the HC process, the combined (HC and other pretreatment methods) biomass pretreatment can increase the overall performance of the pretreatment process. HC technology can also offer a possibility for continuous biomass pretreatment process. The viability of technology can be judged based on their technical, economical and life cycle assessment aspects. Application of HC process on the deconstruction of biomass should be validated in both batch and continuous mode of operations. For above-said reasons, optimization of process parameters and their interactions on overall pretreatment efficiency must be studied in detail for different LCB feedstocks.

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