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Review

Enzymatic hydrolysis of biomass at high-solids loadings – A review

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ABSTRACT

Enzymatic hydrolysis is the unit operation in the lignocellulose conversion process that utilizes enzymes to depolymerize lignocellulosic biomass. The saccharide components released are the feedstock for fermentation. When performed at high-solids loadings (≥15% solids, w/w), enzymatic hydrolysis potentially offers many advantages over conversions performed at low- or moderate-solids loadings, including increased sugar and ethanol concentrations and decreased capital and operating costs.

The goal of this review is to provide a consolidated source of information on studies using high-solids loadings in enzymatic hydrolysis. Included in this review is a brief discussion of the limitations, such as a lack of available water, difficulty with mixing and handling, insufficient mass and heat transfer, and increased concentration of inhibitors, associated with the use of high solids, as well as descriptions and findings of studies that performed enzymatic hydrolysis at high-solids loadings. Reactors designed and/or equipped for improved handling of high-solids slurries are also discussed. Lastly, this review includes a brief discussion of some of the operations that have successfully scaled-up and implemented high-solids enzymatic hydrolysis at pilot- and demonstration-scale facilities.

1. Introduction

Lignocellulose is the largest renewable source of carbon on the planet, as it is the main structural component of plants. Energy from lignocellulosic biomass has been tapped as one possible solution to decrease the United States' foreign dependence on petroleum, as well as serve as a more environmentally friendly source of energy. Lignocellulose can either be processed thermochemically or biochemically, depending on the desired product. The biorefinery concept is thought to be the desired model for biomass processing, where all of the biomass is exploited. The suite of products would be dictated by the market and selected to extract the greatest value possible out of lignocellulose (Fig. 1).

Enzymatic hydrolysis of lignocellulose has long been studied as a method to depolymerize the biomass into fermentable sugars for conversion to biofuels and biochemicals, with a more recent focus on operating at high-solids loadings. It has been suggested that enzymatic hydrolysis conducted at high-solids loadings will be necessary to render the lignocellulosic conversion process more economically feasible. A process is considered "high solids" if the ratio

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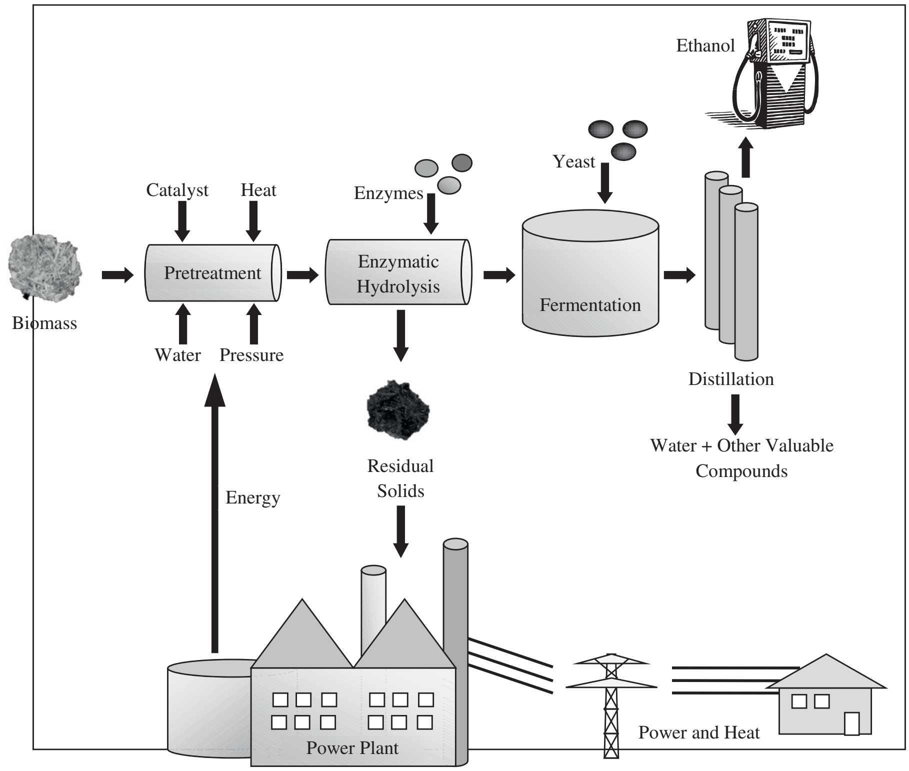

Fig. 1 – Schematic of the biorefinery concept. Lignocellulose enters the conversion process and undergoes pretreatment, enzymatic hydrolysis and fermentation. Distillation produces liquid transportation fuels, as well as other valuable products. The residual solids can be burned to produce energy that can be cycled back into the conversion process or shipped out to the grid for residential or commercial use.

of solids/liquid is such that very little to no free water is present in the slurry [1] or roughly a solids loadings ≥15% (w/w).

Enzymatic hydrolysis performed at high-solids loadings offers several advantages over low- and moderate-solids loadings, the main one being final sugar concentrations are higher [2,3]. In theory, higher sugar concentrations translate into higher ethanol concentrations, which could reduce energy use and costs associated with the distillation process [4,5]. For the purpose of this paper, the term "concentration" refers to the amount of a component dissolved in a given volume of liquid, while the terms "yield" and "conversion" refer to the quantity of a product obtained expressed as a percentage of the theoretical maximum. Distillation is most economical when the ethanol concentration is ≥ 4% (w/w). In order to obtain this ethanol yield, glucose yields must be at least 8% (w/w), which translated into a lignocellulose loading of ≥20% (w/w) for enzymatic hydrolysis [6]. These estimates only account for conversion of cellulose; however, as improvements are made to hemicellulose conversion (hydrolysis and fermentation) technologies that work in combination with cellulose conversion, this initial solids loadings estimate may decrease. Another potential advantage is the reduction of capital and production costs. Smaller equipment and/or fewer reactors can be utilized to produce an equivalent output [7,8]. Fewer reactors also translate into reduced energy demands for heating, cooling and mixing [3,5], although the latter aspect may be a point of contention as increased solids makes effective mixing more difficult. Additionally, less water is needed, which reduces the cost of disposal or treatment of process water.

The goal for this review is to provide a consolidated source of information for the latest technological advances for managing enzymatic hydrolysis at high-solids loadings. Following a brief discussion of the factors limiting enzymatic hydrolysis at high solids, various aspects and approaches pertaining to hydrolysis operating conditions are detailed. Additionally, reactors designed to overcome some of the limitations associated with high-solids hydrolysis, as well as pilot- and demonstration-scale plants operating at high-solids loadings are discussed. Lastly, the authors comment on the envisioned direction for high-solids hydrolysis research, as well as the necessary advances this technology must make to become commercially viable.

2. Factors limiting high-solids enzymatic hydrolysis

As solids loading increases, challenges that were negligible in low-solid systems become more prominent, which has also been noted in high solids pretreatment [9]. One of the major challenges for enzymatic hydrolysis at high solids loading is the lack of available water in the reactor. Water is essential to effective hydrolysis for two reasons: mass transfer and lubricity. Water increases the effectiveness of the enzymatic and chemical reactions, mainly by providing a medium for