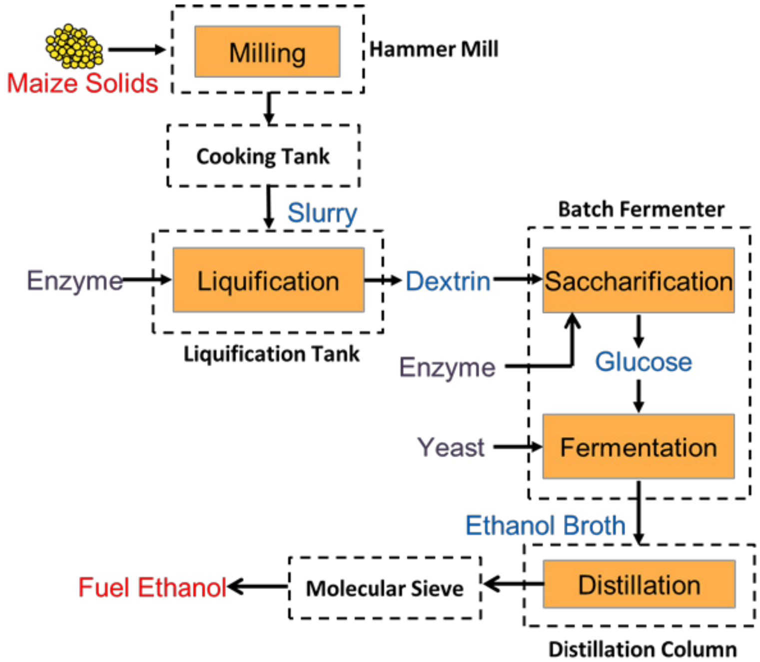
Batch Control and Trajectory Optimization in Fuel Ethanol Production

Ethanol produced from fermentation of biomass-derived sugar is increasingly used as a transportation fuel, either neat or in petrol blends. As the world's largest biofuel producer, the U.S. produced more than 57 billion liters of ethanol in 2012, and the number will increase to 136 billion liters by 2022. Most of the ethanol in the U.S. is produced from maize-based plants, and more than 90% of the plants make use of the dry mill process, which involves four steps: milling, liquification, simultaneous saccharification and fermentation (SSF), and distillation. The SSF process, which is conducted in a batch fermenter, is considered the most important part of the entire production process. SSF breaks down dextrin into dextrose and converts dextrose into ethanol.



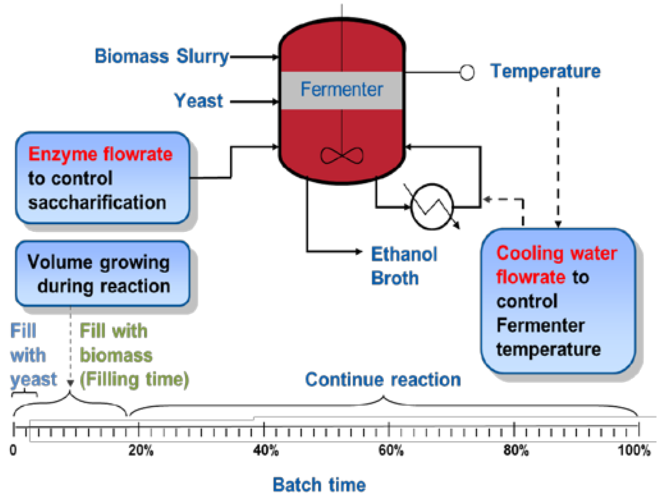
Flow chart of dry mill process

Current Progress

Fuel ethanol production is a $43 billion industry that contributes more than $8 billion in taxes to state, federal, and local governments. Researchers generally acknowledge that there is a gap between the theoretical maximum yield and the yield achieved in process plants. Therefore, even a low-percentage yield increase would result in hundreds of millions of dollars in profits. The most economic approach to increasing ethanol yield is to optimize operation of the SSF process during a batch.

Challenges

1. Modeling: A better understanding of the process represented by mathematical models is required. If models are derived from first principles, they usually consist of coupled ordinary differential equations (ODEs) resulting from component and energy balances.
2. Optimization: A major objective of batch control is for the manipulated variables to follow reference trajectories that maximize a performance index (e.g., the ethanol yield at the end of the run). However, there is no steady state and thus there are no constant setpoints over the course of a batch. Hence, a rigorous optimization strategy is required for control purposes.



Overview of SSF process and timeline of batch operation

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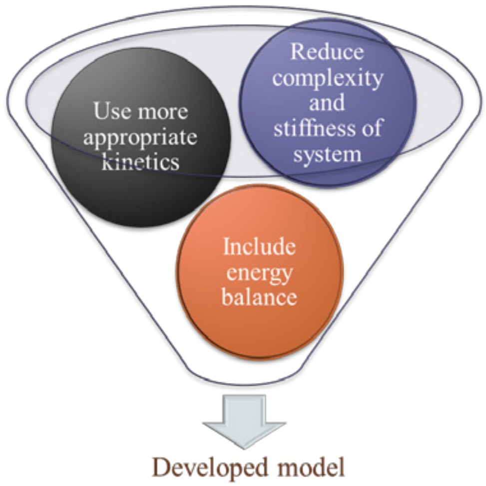
Modeling of SSF Process

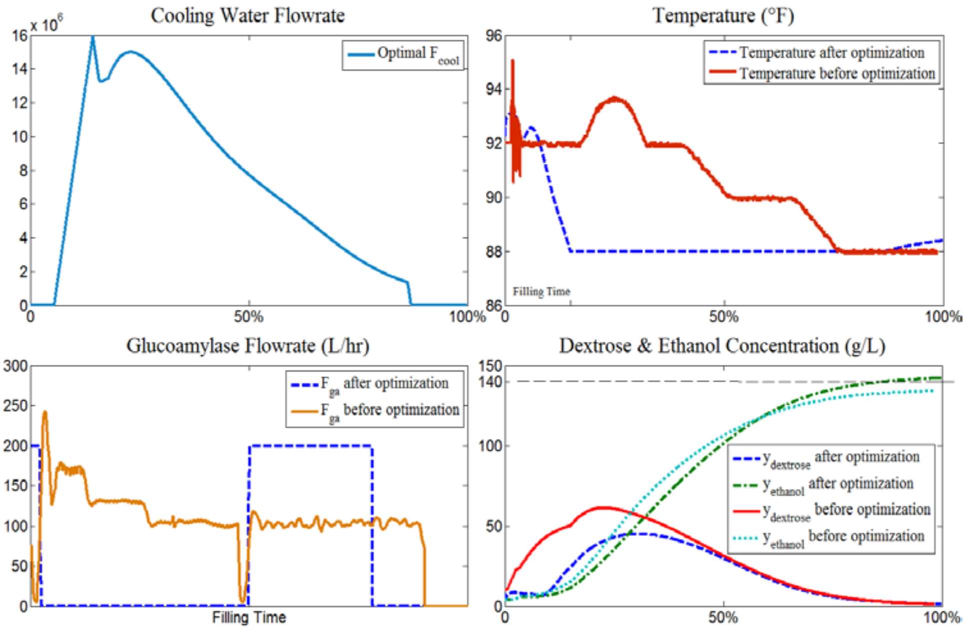
Existing models of the SSF process consist of dynamic balances of components such as the concentrations of yeast, dextrose, ethanol, and other substances. Three aspects have been investigated to improve the process model.



Three aspects to improve a model

Trajectory Optimization

Maximizing the final ethanol yield is the key driver for researchers and engineers to find better control solutions for this process. This objective can be achieved by numerically computing the optimal setpoint trajectory of the controlled variables. A model composed of nine ODEs (eight component balances and one energy balance) and five path constraints is used here for illustration purposes. A simultaneous approach, which discretizes both the manipulated variables and the model, is used for the solution of the optimization problem.



Optimal input profiles and simulation results after optimization

Future Work

More input variables, such as length of the fermentation process, could be considered for trajectory optimization.

Additionally, complex models that incorporate intermediate and branch reactions could be considered for trajectory optimization, whereas a simpler model could be used for fast model-based online control.

Results and Discussion

The optimal temperature profile has a high temperature during the filling phase and favors a low temperature for the remainder of the batch. The optimal enzyme addition profile indicates that glucoamylase should be injected into the fermenter toward the end of the filling phase rather than continuously during the entire phase. The dextrose concentration after optimization is well controlled within a reasonable range, and the ethanol concentration is increased after optimization by as much as 7%. Furthermore, relaxing the lower bound of the temperature constraint increases ethanol production by 11%. However, considering that a discrepancy always exists between the model and a real plant, these research findings will have to be validated in a plant setting.

For more information: W. Dai, D.P. Word, and J. Hahn, Modeling and dynamic optimization of fuel-grade ethanol fermentation using fed-batch process, Control Engineering Practice, 2013.