Integration of Bioreactor and Membrane Separation Processes: A Model Based Approach -
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Integration of Bioreactor and Membrane Separation Processes: A Model Based Approach: Reverse Electro-Enhanced
Dialysis process for lactic acid fermentation

This work is motivated by the need for tighter integration of industrial processes in an attempt to improve process
sustainability. To this end, this work considers a interesting case study around which different systematic approaches are
used or developed to achieve the above goal. The thesis is concerned with the understanding of an integrated bioreactor
and electrically driven membrane separation processes for lactic acid fermentation. This is achieved through a model
based investigation of the individual units and the integrated system. Development of system understanding is the key to
reveal how the system should be designed and operated in accordance with different production goals. The selected case
includes a fermenter and a two stage membrane separation. In the first membrane stage the lactate is exchanged by
hydroxide by means of anion exchange membranes, in a process referred to as Reverse Electro-Enhanced Dialysis
(REED). Unconsumed substrate and biomass are effectively recycled to the fermenter. In the second membrane
separation stage, the lactate is recovered and concentrated as lactic acid using Electrodialysis with bipolar membranes
(EDBM), while sodium hydroxide is regenerated and recirculated. The novelty of the process relies in the specialized
design and operation of the Reverse Electro-Enhanced Dialysis module. The REED design allows removal of the lactate
from the fermentation broth and simultaneously facilitates pH control in the fermenter using hydroxide. Additionally, the
periodic operation of the REED mitigates the adverse influence of the formation of a fouling layer at the membrane
surface. A first principles dynamic model is derived for the REED module to describe the transport of multiple ions through
ion exchange membranes and adjacent boundary layers in a dialytic module. The unknown model parameters are
regressed from experimental data for Donnan Dialysis recovery of different monoprotic carboxylic acids. Static simulation
results agree with previously qualitative predictions of concentration profiles during Donnan Dialysis separation. Further
static simulations under current load conditions are used to evaluate the influence of imposing an external electrical
potential gradient on the ion fluxes and concentration profiles. Results demonstrate the development of asymmetric
concentration profiles, the potential ion fluxes enhancement and the limiting current density constraint. Through dynamic
simulations, the system behavior is investigated under current reversal conditions. Several phenomena are predicted such
as preferable ion transport at the interfaces, transient flux inversion and accumulation/depletion of ions within the
membranes. The combination of those phenomena can explain a loss of current efficiency, which has been experimentally
demonstrated. Diverse numerical issues are encountered during the different type of simulations, and solutions are
proposed. A bioreactor model with unstructured kinetics is proposed which is suitable for integration with the Reverse
Electro-Enhanced Dialysis process. An identifiable set of parameters are estimated from experimental data. The
identifiability analysis is supported by mathematical and statistical tools. In order to investigate the operability of the REED
module, a methodology for control structure design is extended to handle periodically operated systems. As case study,
the pH regulation of the outlet stream of the membrane unit is addressed. Based upon the goal driven analysis, a non
conventional input resetting control structure is designed. The control performance is evaluated through a set point
tracking test. Satisfactory results are obtained regulating the pH and managing the input constraints. The design and
operability of the integrated bioreactor and REED module are investigated using the developed models and control
structure. The study involves two different case studies: continuous lactic acid production and batch production of a starter
culture. Substantial improvements are predicted in productivity and substrate utilization, while design and operability
limitations are discussed. The investigated integrated system is a clear example where a model based approach,
supported by experimental evidence, can bring improvements in the system understanding, and therefore promote the
development of goal driven process design and the process control discipline.

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