A HIERARCHICAL APPROACH TO THE DESIGN IMPROVEMENTS OF INTEGRATED BIOREFINERIES

By

Omar Yasser Mohamed Abdelaziz

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Chemical Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Under the Supervision of

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Title of Thesis:

A hierarchical approach to the design improvements of integrated biorefineries

Key Words:
Biorefinery; Organocat; Jojoba oil; Pinch Analysis; Bioeconomy

Summary:

In this work, a systematic approach is proposed for improving basic/existing biorefinery designs. This approach is based on enhancing the efficiency of mass and energy utilization of such configurations through the use of a hierarchical design procedure that involves the state-of-the-art process integration. Aspen Energy Analyzer® software is adopted to analyze and improve the energy performance of the processes heat exchange networks (HENs). Mass integration strategies are utilized to design better recycle/reuse mass exchange networks (MENs). The proposed approach is applied on two novel biorefinery plants to boost their material and energy efficiencies.

As a first case study, an improved design of a new pre-processing biorefinery called Organocat is developed. An improved HEN with minimum energy consumption of 4.5 $MJ/kg_{dry\ biomass}$ is designed. An optimal recycle network with zero fresh water usage and minimum waste discharge is also constructed leading to a more attractive Organocat process as a promising building block of a future bioeconomy. In the second study, a basic design of a jojoba oil biorefinery that produces jojobyl alcohols as value-added products and fatty acid methyl ester (FAME) as co-product is modified. An improved HEN with minimum energy consumption scenario that reduces the cooling utilities by 27% and the heating utilities by 100% is designed, making the process more competitive and economically justifiable. The introduced hierarchical approach is applicable to other biorefining processes for the efficient-use of material and energy.

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Dedication

"And say: O my Lord! Advance me in knowledge"

THE HOLY QURAN (20:114)

To my parents and my sister, with love and gratitude

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Nomenclature

MTHF	Methyltetrahydrofuran
EF	Energy factor for heating/cooling
$\sum Q$	Summation of process energy requirement for heating/cooling (kW)
Q_{Target}	Energy target for heating/cooling (kW)
MF	Material factor for fresh use/waste discharge
$\sum \Delta M$	Summation of material fresh use/waste discharge (t/h)
ΔM_{Target}	Material target for fresh use/waste discharge (t/h)
EP	Energy potential
MP	Material potential
HEN	Heat exchange network
MEN	Mass exchange network
MSA	Mass separating agent
ΔT_{min}	Minimum temperature approach (^oC)
GCC	Grand Composite Curve
CW	Cooling water
MPS	Medium pressure steam
LPS	Low pressure steam
CCI	Capital Cost Index
AF	Annualization factor
ROR	Rate of return
PL	Plant life
TCI	Total Cost Index
OCI	Operating Cost Index
T_s	Supply temperature (^oC)
T_T	Target temperature (^oC)
FAME	Fatty acid methyl ester

Abstract

The integrated biorefinery approach for the production of value-added chemicals and biofuels from various waste feedstocks has attracted much attention recently. Biorefineries convert biomass into bio-based products that can replace other common products produced by petroleum refineries. In the concept of biorefining, the economic competitiveness of such processes is highly dependent on the process energy efficiency and material recovery. Establishing an economically viable and energy efficient biorefinery scheme is a significant challenge.

In this work, a systematic approach is proposed for improving basic/existing biorefinery designs. This approach is based on enhancing the efficiency of mass and energy utilization of such configurations through the use of a hierarchical design procedure that involves the state-of-the-art process integration. Aspen Energy Analyzer® software is adopted to analyze and improve the energy performance of the processes heat exchange networks (HENs). On the other hand, mass integration strategies are utilized to design better recycle/reuse mass exchange networks (MENs). The proposed approach is applied on two novel biorefinery plants in order to boost their material efficiency and energetic performance.

Lignocellulosic biomass has emerged as a potentially attractive renewable energy source. Processing technologies of such biomass, particularly its primary separation, still lack economic justification due to the energy intensive nature. As a first case study, an improved design of a novel pre-processing biorefinery called Organocat is developed. An improved HEN with minimum energy consumption of 4.5 $MJ/kg_{dry\ biomass}$ is designed. An optimal recycle network with zero fresh water consumption and minimum waste discharge is also constructed leading to a more attractive Organocat process as a promising building block of a future sustainable bioeconomy.

In the second case study, an improved design of a novel jojoba oil biorefinery is developed. This plant produces jojobyl alcohols as high value-added products and fatty acid methyl ester (FAME) as co-product. The cold and hot utilities are calculated to be 7.4 MW and 2 MW, respectively for the production of 2300 metric tons per annum of jojobyl alcohols. An improved HEN with minimum energy consumption scenario is further designed. As estimated, the designed HEN reduces the cooling utilities by 27% and the heating utilities by 100%, making the process more competitive and economically justifiable. The introduced hierarchical approach is applicable to other biorefining processes for the efficient-use of material and energy.

Chapter 1 : Introduction

One of the most important challenges facing humanity nowadays is the need for a sustainable development that accommodates the growing demands for natural resources while leaving future generations with the opportunities to notice their potential. This challenge is typically important for the chemical process industries that are characterized by the massive consumption of natural resources. To efficiently address this challenge, it is mandatory for industry to adopt the concept of sustainable design, which involves process design activities that lead to economic growth, environmental protection, and social progress for the current generation without compromising the potential of future generations to have an ecosystem that meets their own needs [1].

The problem of depleting fossil fuel sources and the increased global environmental concerns towards reducing anthropogenic greenhouse gas emissions tend to highlight the importance of renewable resources. Taking into consideration the environmental impact urged by the tremendous growing energetic consumption of fossil fuels and, to some extent, even by renewable energy sources is crucial. In this context, the objective is to minimize the global demand on energy supplies and to save energy, either by increasing the efficiency of current material and energy resources or by producing new sustainable energy sources [2].

1.1. The path forward towards next generation process and product systems

Biorefineries are expected to produce several product lines similar to those currently produced from fossil sources but in a more sustainable manner. The biorefineries typically convert biomass into value-added chemicals and fuels that can replace other common products produced from fossil resources. Biorenewables can evidently replace common fossil carbon feedstock, if the annual production of biomass can satisfy the future global carbon demand.

The integrated biorefinery concept has emerged as a potentially attractive alternative towards decreasing dependency on petroleum and fossil fuels. An integrated green biorefinery is an approach that efficiently optimizes the utilization of biomass towards the production of biofuels, biomaterials, and bioenergy for short and long term sustainability [3].

It is expected in the coming decades that the transition from the current fossil-based to the future bio-based economy will evolve continuously [4]. The easily accessible regenerative feedstock like plant oils, sugar, and starch will consequently be transformed first into the common traditional products. A non-stop changeover to more complex biorenewable feedstock’s like agricultural residues, industrial wastes, green plants, wood, or algae will take place. Eventually, the traditional petrochemical product tree will be replaced by a bio-based alternative.

1.2. Motivation and objective of the work

Integrated biorefineries are normally complex structures of many equipment and process/utility streams. The synthesis and the design of integrated biorefineries are generally complex and open problems of a considerable scale and comprehensive interactions [5]. They require generation and screening of many pathways and optimization of miscellaneous objectives besides intense energy requirements. The shift towards the green economy has lately encouraged manufacturers all over the world to cut CO_2 emissions and increase energy efficiency [6]. Accordingly, improved process concepts and designs are inevitable in order to achieve material and energy efficient and economically attractive biorefinery process designs leading to a future sustainable bioeconomy.

Such processes typically include several stages, such as fractionation, product purification, solvent recovery, and enzymatic hydrolysis. Both energy sources and cooling utilities are substantially consumed. Materials including solvents and fresh water are also necessary to perform the different relevant processing stages of the unit. Because of their complex configuration, biorefineries contain a large number of process streams and this require many exchanger units to provide the heating and cooling requirement, in addition to the material separating equipment. This complex nature interaction provides potential opportunities for improvement in terms of material and/or energy efficiency.

Motivated by this fact, any existing unit or basic design of biorefinery plant can be modified aiming at increasing its energy efficiency and reducing the flows of external utilities and fresh solvents/materials, while minimizing the total annualized costs of modifications and operation. To address such objectives, a hierarchical approach outlining a systematic procedure is to be proposed in this work. The proposed approach will be further applied on two novel second-generation biorefinery plants in order to enhance their material efficiency and energetic performance.

1.3. Organization of the thesis

The remainder of this thesis is organized according to the following outline. Chapter two provides a detailed survey of the previous studies in the area. Chapter three introduces the proposed systematic approach and discusses its major features and findings. In chapter four, an application of the developed approach on a novel biorefinery called Organocat is presented. In chapter five, another novel Jojoba oil biorefinery plant is analyzed and improved through the introduced approach, representing another application of the procedure. Finally, conclusions and results analysis of the proposed approach and its applications are discussed.