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Design of Circular Economy Plants - The Case of the Textile Recycling Plant

Athanassios Nikolakopoulos[a*], Foteini Barla[a], Antonis Kokossis[a]

[a] *National Technical University of Athens, Department of Chemical Engineering, Heroon Polytechneiou, 9, Athens, 15780, Greece*

nikolako@mail.ntua.gr

Abstract

The present paper presents a coordinated application of established and original Process Systems Engineering technologies to the solution of a new problem arising within the Circular Economy concept. This is the design of the Textile Refinery; a new biorefinery type that uses waste textiles as feedstock to close the circle of the chemically or naturally derived feedstock fibres economy, aiming to provide a holistic response to the largely overlooked waste textile management problem. The proposed solutions promote and are reinforced by the concept of Industrial Symbiosis, which enables synergies and provides with sustainability characteristics the whole exercise. New, as well as conventional process synthesis, process modelling and process integration techniques are implemented to steepen the learning curve for the design problem, while economic evaluation reveals weak points to be confronted in the iterative process design procedure. Solutions are currently tested at pilot scale and improved through a feedback loop, while scale-up technologies are in place to industrialize the complete process.

Keywords: Circular Economy, Textile Biorefinery, Process Design, Industrial Symbiosis.

1. Introduction

Circular Economy (CE) converts linear production lines into closed loop, renewable-looking paradigms that save materials and promote sustainable development. McKinsey & Company estimates that by undertaking CE opportunities, an additional turnover of $1 trillion and 100,000 new jobs could be created by 2025 (Nguyen et al., 2014). Ellen MacArthur Foundation (2013) forecasts that only the EU manufacturing sector could reach a net annual material cost savings of $280 billion. The global textile and non-apparel industry is among the top ten manufacturing economic activities attaining a market value of €0.82 trillion. In 2008, 24 million tonnes of cellulosic and 39 million tonnes of synthetic fibres were sold globally (Oerlikon report, 2009). Despite industry's great economic value, the textile industry is among the most polluting ones. To only cultivate 1 kg of cotton; 16 g of pesticides, 460 g of fertilizer and 22 m3 of water is consumed (Saleem et al., 2010). In EU alone, 10 million tonnes of textile waste are produced each year (EASME, 2015). Specifically, in France, Germany, UK, Nordic countries, USA and Japan, the total post-consumer textile waste going to landfill is estimated 0.6, 1.9, 0.6, 0.1, 0.4, 0.9 million tonnes respectively.

The paper explains the development of a Circular Economy plant for the textile industry. The approach develops gate links between textile materials with commodity and specialty products and chemicals. Materials include the entire range of options, namely cotton, polyethylene terephthalate (PET), polyamide (PA) and woo. They can be respectively decomposed into glucose, amino-acid solutions, PET monomers (ethylene glycol and terephthalate acid) and PA oligomers. The process eventually produces bio-ethanol, adhesives used in the wood-based panel production, PET bottles and PA-derived value added chemicals (caprolactam, amylamine, hexanoic acid etc.). The decomposition of natural and synthetic textile fibres is achieved through patented chemistries with emphasis on chemical and enzymatic hydrolysis. The paper applies an integrated, multilevel approach. (1) Lab chemistries have been translated into integrated flowsheets in the course of a collaborative project that involves several industrial partners, research institutions, textile collectors, sorting companies and end-users (RESYNTEX, 2015). (2) Modelling work has been to scale up design processes namely reactions and separations. Experimental data include reaction kinetics, thermodynamic and equilibrium data. (3) The work further addresses water and energy integration using model-based optimisation. Significant challenges in operations have been identified upon process flowsheeting and modelling; such as the uncertainties in the feedstock composition and total inflow, technology transfer from batch to continuous mode due to the process nature and properties of intermediate and end products as well as the scaling up task.

2. Process design approach for textile recycling plants

Due to the diverse nature of fibrous waste, a variety of waste management practices and technologies must be coordinated in an integrated plant in order to increase the rate of recycling (Wang, 2006). Setting aside direct reuse of used textiles, and the pure mechanical treatment for new fibre production, which account for a considerable fraction of the total textile waste volume (Adivarekar and Pisal, 2009), the combination of mechanical followed by chemical and/or biochemical treatment requires a special attention from a process design point of view. This is attributed to the fact that, although chemical or biochemical decomposition of the individual textile constituents (cotton, polyester, wool etc.) into valuable products, such as bioethanol (Chen, 2016), polyamide oligomers (Nemade et al., 2011) and polyethylene terephthalate (PET) oligomers is proven to be technically feasible (Chen, 2016; Khajavi et al., 2006), no real-world application combines the technologies required to address the chemical treatment of waste textiles in a holistic way. To surpass the fragmented nature of the chemical processing of textile wastes, a holistic process design approach has to be followed that addresses all aspects of the design procedure with a scope to deliver a conceptual design that features robustness and viability. Such an approach has been put into practice in the course of the European research project RESYNTEX (2015) with a scope to transfer into industrial scale the processing methods to promote textile recycling and re-use via chemical and biochemical pathways. RESYNTEX aims to create a new circular economy concept for the textile and chemical industries. Using industrial symbiosis, it aims to produce secondary raw chemicals and materials from unwearable textile waste.

The design problem of chemical and biochemical processing of waste textiles bears similarity with that of multiproduct 2nd generation biorefineries. There, the feedstock is also waste in the form of residual biomass and there are also several common products, like for instance 2G bioethanol and proteins. On the other hand, process design theory, tools and technology, has evolved during many years having the petrochemical as a main field to apply and test innovative solutions. Conventional chemical process industry demonstrates a steep learning curve and has reach sophisticated levels of operation, intensification and profitability. The first attempt to capitalize on this rich knowledge heritage to expedite the evolution of 2G biorefineries was made through the major

European research project BIOCORE (Biocore, 2014). There, the process design arsenal included state-of-the-art synthesis, flowsheeting and process integration technologies combined into a holistic framework for the selection of optimal processing paths and the production of integrated process designs to reach maximum efficiencies. The experience, lessons learned and conclusions of BIOCORE are now transferred to the RESYNTEX project for realizing the design of an industrial scale "textile-refinery".

For a grassroots design of a chemical textile recycle process the challenges are high because sustainability must be attained at all levels (environmental, economic and social). To this end, the process designs must meet environmental targets but at the same time ascertain a profitable operation. Economic evaluation is therefore added to the process design scheme. Also, industrial scale blue prints of the process are being developed based on information produced at experimental level or by small scale pilots of the individual processing stages. This calls for additional implementation of scale up technology, while innovative solutions must be also implemented to achieve minimum waste production and maximum reuse of resources, particularly energy and water. The process design task is broken down into the following general parts that work collaboratively to reach the end goal; Process synthesis, Process flowsheeting, modelling and simulation, Process integration, Economic evaluation, Waste management and recycles, Scale-up and Industrial Symbiosis analysis that eventually leads to Industrial Integration.

Several new tools and methods have been added recently to the process design arsenal by recent research projects (Mountraki et al., 2011; "RENESENG - EU research project - 607415," 2013) and are ready to be used for the development of the textile refinery; For the synthesis task these include models and platforms for the screening and evaluating alternative processing paths for high throughput analysis (Tsakalova et al., 2015, 2012).

3. Challenges in process synthesis, process modelling and process integration

Process engineering models have been developed to combine the experimental background in RESYNTEX, process engineering evidence at pilot unit processes and new developments at the demonstration site. The models establish basic mass and energy balances for the various hydrolysis, solvolysis, solubilisation and de-polymerization processes (proteins, cellulose, PA, PET, ethylene glycol). Process flowsheeting makes use of commercial software and is extended to include equilibrium data, reaction kinetics, and mass transfer. Additional models address waste treatment processes, solvent extraction, and alternative separation processes that bear advantages and promise. The models incorporate important design parameters (residence times, substrate purity/concentration, pH, viscosity etc.) as they are required to configure terms of integration with the overall flowsheet. Optimization techniques are applied over these parameters for maximizing efficiency and minimizing costs. All models are validated by the real-life pilot process.

In the area of process modelling and simulation, new approaches are implemented for developing surrogate process models to reduced complexity, enabling the possibility of using detailed synthesis optimization models (Nikolakopoulos and Kokossis, 2016). On the other hand, new challenges arise such as the property analysis and simulation of the discoloration processes. During simulation, complex kinetic expressions must be simplified but reflect in sufficient detail the actual reaction steps, while mechanical separation processes are inevitably linked to biochemical and thermochemical upstream processes, adding difficulty in the modelling process.

Process designs are optimized to improve the use of raw materials, energy and water and process integration is applied with a combined use of targeting, process synthesis and mathematical optimization capitalizing on extensive industrial experience in the field. Process synthesis applies a superstructure approach to review options for different reactor configurations, options to separate proteins and polyamides in semi-batch operations motivated by their small flows in comparison with cellulose and polyesters, options to deviate from the simple mixing vessels using macro-mixing of intermediates and feed streams, and possibilities to integrate reaction and separation at a single vessel (in all cases where reaction is reasonably slow and comparable with the mass transfer kinetics). Process integration supports a global perspective to waste savings offering options for central and distributed management. Targeting sets the scope to match and improve efficiencies for energy and water (Pinch, Water Pinch), explaining efficiency bottlenecks, modifications required to improve targets, means to re-use and regenerate water and solvents, as well as means and technologies appropriate to treat waste.

A significant challenge emerging by the need to operate at batch or mixed-batch-and continuous mode is that of exploiting the full potential of energy and material integration. There, sophisticated efforts to produce time-scheduled batch campaigns include the solution of multi-objective Jobshop-like scheduling problems aiming to minimize the time span of production cycles and the at the same time fully exploiting synergies between processes that can be accomplished either by synchronization or by using additional energy and/or material storage media. A first indication of the maximum potential is provided by assuming continuous mode of operation throughout the plant.

4. Process economics and Industrial Symbiosis analysis

Economic evaluation assesses trade-offs between capital and operating costs setting preferred levels of integration and minimizing annualized costs, while investment analysis is pursued by considering different economic criteria (i.e. payback times, NPV, IRR) and evaluate the impact of raw materials, process technologies and integration schemes. The work assesses break-even points of investment disclosing sensitive economic parameters. Cost models assess capital investment as a function of industrial scale and capacity. Costing makes use of commercial software and process models that include equipment costs, operating costs (raw materials, utility costs, labour), piping, maintenance and installation. Due to several pieces of non-conventional equipment, costing is achieved through intense collaboration with industrial partners. Similar collaboration evaluates relative values of intermediates and products as a function of composition and content.

Novel process integration models have been developed for assessing alternatives and achieving maximum efficiencies in energy and water use (Kokossis et al., 2014; Koufolioulios et al., 2014; Nikolakopoulos et al., 2016a; Nikolakopoulos and Kokossis, 2016). Also, early stage capital cost estimation has been new made possible using new shortcut economic evaluation tools (Tsagkari et al., 2016a, 2016b). Finally total waste management and recycle technology has been produced to enable the development of designs for processes with minimum environmental impact (Mountraki et al., 2016; Nikolakopoulos et al., 2016b; Nikolakopoulos and Kokossis, 2016). All previous technologies are currently collaborating for producing optimal designs of the sustainable textile refinery that will operate seamlessly in the context of the circular economy integrated within the textile industry and market.

At a higher-level Industrial Symbiosis analysis assesses the potential of the business concept to function as a waste bio-refinery. Such analysis considers upstream and downstream stages studying aspects that include logistics (upstream), uncertainties in raw materials and markets (upstream/downstream), variabilities of feed composition and fibre origin (upstream), value chains supported by the key production stages (downstream) and options to build scale via integration with other CPIs (upstream/downstream). It involves concept-based optimization models extended with stochastic terms featuring degrees of freedom for the design layout, the product portfolios, and the supply chain network. The optimization in turn assesses the impact of transportation costs and logistics, product portfolios and valuable valorisation paths, the impact of uncertainties and variations in the design layout, and the integration opportunities with other industries.

5. Conclusions and future work

The paper proposes a holistic approach for the design of textile biorefineries that coordinates the use of process synthesis, process modelling and process integration combined with feedback from pilot and experimental processes and the indications of the economic evaluation and investment analysis. It also describes how the textile refinery will be integrated into a broader Industrial Symbiosis scheme. Several challenges have to be addressed in the future, notably the production scheduling and the integration of heat and material flows in batch mode operation, which is inevitable due to the solid nature of the material and the utilization of high temperature and pressure at some of the thermochemical unit processes involved.

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References

H. Nguyen, M. Stuchtey, M. Zils, McKinsey & Company, 2014. Remaking the industrial economy.

Ellen MacArthur Foundation, 2013. Towards the Circular Economy, Opportunities for the consumer goods sector report.

The Fiber Year 2008/09, A World Survey on Textile and Nonwovens Industry, Issue 9, May 2009, Oerlikon report.

A. Saleem, S. Camp, G. Calrk, L. Duane, A. Haight, 2010, Life Cycle Analysis and Systainability Report. Levis Strauss & Co. Jeans, ENVS 195, Sustainability Science, http://www.uvm.edu/~shali/Levi.pdf, last accessed 27/10/2016.

European Commission, EASME, 2015. Giving textile waste a second lease of life in the construction industry, https://ec.europa.eu/easme/en/news/giving-textile-waste-second-lease-life-construction-industry, last accessed 28/10/2016.

EU Research Project RESYNTEX 2015, A new circular economy concept: from textile waste towards chemical and textile industries feedstock. Project ID: 641942. http://www.resyntex.eu/

Adivarekar, R.V., Pisal, S., 2009. Reuse and recycling of textile solid wastes. J. Text. Assoc. 70, 118–126.

Biocore, 2014. EU research project FP7-241566 http://www.biocore-europe.org (accessed January 2017).

Chen, Y., 2016. Recycling methods of waste textiles in Japan. Wool Text. J. 44, 60–64.

Khajavi, R., Mrjalili, M., Motlagh, F., Rashidi, A.S., 2006. Recycling of cotton/polyester fabric with chemical and biochemical methods for producing paper fibers, in: Proceedings - International Fiber Conference 2006: Extreme and Aesthetic Textiles, IFC 2006.

Kokossis, A.C., Tsakalova, M., Pyrgakis, K., 2014. Design of integrated biorefineries. Comput. Chem. Eng. 81, 40–56. doi:10.1016/j.compchemeng.2015.05.021

Koufolioulios, D., Nikolakopoulos, A., Pyrgakis, K., Kokossis, A., 2014. A mathematical decomposition for the synthesis and the application of total site analysis on multi-product biorefineries, Computer Aided Chemical Engineering. doi:10.1016/B978-0-444-63433-7.50076-6

Mountraki, A., Tsakalova, M., Panteli, A., Papoutsi, A.I., Kokossis, A.C., 2016. Integrated Waste Management in Multiproduct Biorefineries: Systems Optimization and Analysis of a Real-Life Industrial Plant. Ind. Eng. Chem. Res. 55, 3478–3492. doi:10.1021/acs.iecr.5b03431

Mountraki, A.D., Nikolakopoulos, A., Pyrgakis, K.A., Mlayah, B.B., Kokossis, A.C., 2011. BIOCORE - On a paradigm for the design and synthesis of real-life biorefineries, in: 11AIChE - 2011 AIChE Annual Meeting, Conference Proceedings.

Nemade, A.M., Mishra, S., Zope, V.S., 2011. Chemical Recycling of Polyamide Waste at Various Temperatures and Pressures Using High Pressure Autoclave Technique. J. Polym. Environ. 19, 110–114. doi:10.1007/s10924-010-0249-1

Nikolakopoulos, A., Faskiotis, D., Kokossis, A., 2016a. Cascade Models for Targeting and Synthesis of Total Water Networks. Chem. Eng. Trans. 52, 943–948.

Nikolakopoulos, A., Faskiotis, D., Kokossis, A., 2016b. Integrated Transhipment Models for Synchronous Screening of Treatment Technologies and Targeting of Fresh Water and Recycle Flows, Computer Aided Chemical Engineering. doi:10.1016/B978-0-444-63428-3.50124-7

Nikolakopoulos, A., Kokossis, A., 2016. A Problem Decomposition Approach for Developing Total Water Networks in Lignocellulosic Biorefineries. Process Saf. Environ. Prot. in press. doi:10.1016/j.psep.2016.12.007

RENESENG - EU research project - 607415 [WWW Document], 2013. URL http://www.reneseng.com/ (accessed January 2017)

Tsagkari, M., Couturier, J.-L., Kokossis, A., Dubois, J.-L., 2016a. Back Cover: Early-Stage Capital Cost Estimation of Biorefinery Processes: A Comparative Study of Heuristic Techniques (ChemSusChem 17/2016). ChemSusChem 9, 2515. doi:10.1002/cssc.201601167

Tsagkari, M., Couturier, J.-L., Kokossis, A., Dubois, J.-L., 2016b. Early-Stage Capital Cost Estimation of Biorefinery Processes: A Comparative Study of Heuristic Techniques. ChemSusChem 9, 2284–2297. doi:10.1002/cssc.201600309

Tsakalova, M., Lin, T.-C., Yang, A., Kokossis, A.C., 2015. A decision support environment for the high-throughput model-based screening and integration of biomass processing paths. Ind. Crops Prod. 75, 103–113. doi:10.1016/j.indcrop.2015.05.035

Tsakalova, M., Nikolakopoulos, A., Kokossis, A., 2012. On the systematic synthesis screening and integration of real-life biorefineries, in: AIChE 2012 - 2012 AIChE Annual Meeting, Conference Proceedings.

Wang, Y., 2006. Recycling in Textiles. Woodhead Publishing.