Process Safety and Environmental Protection

Rok 2016, Volume 103

September 2016 – Part B

Yik Teeng Leong, Raymond R. Tan, Irene Mei Leng Chew. *Superstructural approach to the synthesis of free-cooling system through an integrated chilled and cooling water network*. Pages 273-290.

Chillers are major energy consumers in industrial facilities. They are indispensable in such industries as semiconductor fabrication, food processing, and plastics manufacturing, among others. Previous studies aimed at improving the energy efficiency of chilled water systems have focused on optimizing the performance of individual chillers. However, an alternative method to recover energy is to perform system-wide water source/sink integration using a superstructural approach. In our previous study, several schemes for chilled and cooling water systems (CCWS) with hub topology were proposed for energy savings. The main contribution of this study is in the development of a methodology to achieve energy savings by introducing free cooling in an integrated superstructure for CCWS. Two examples are used to demonstrate three different scenarios of CCWS with free cooling. It is shown that the integration of free cooling into chilled water system improve the cost and energy saving significantly, and can avoid the need to invest in a new chiller and/or cooling tower to enhance the energy efficiency of CCWS.

- **Keywords:** Eco-industrial park; Free cooling; Superstructure; Process integration; Energy conservation; Centralized hub

Dominic C.Y. Foo, Raymond R. Tan. *A review on process integration techniques for carbon emissions and environmental footprint problems*. Pages 291-307.

Sustainability has become a major focus for industrial sectors and government agencies in the global community. In particular, climate change is now seen as the most critical environmental problem of the world. Various techniques have thus been developed in the past decades to guide planners to reduce greenhouse gas emissions at various scales, ranging from plant-level combustion emissions to regional or national carbon footprints. Process integration techniques that were previously developed for energy, mass and property integration have now been extended to various emission and environmentally-constrained problems, taking into account footprint metrics that measure environmental impacts other than global warming. This paper discusses the historical evolution of the recently developed process integration techniques for various emission- and footprint-related problems, along with their contributions and limitations. Some recent applications for specific countries are also reviewed.

- **Keywords:** Emission reduction; Pinch analysis; Footprint; Optimization

M.D. Víctor-Ortega, J.M. Ochando-Pulido, A. Martínez-Ferez. *Ion exchange system for the final purification of olive mill wastewater: Performance of model vs. real effluent treatment*. Pages 308-314.

Olive mill wastewater (OMW) is a highly pollutant effluent which can be pretreated through an advanced oxidation process. OMW after this secondary treatment (OMW-2ST) presented high sodium and chloride concentrations, responsible for its high conductivity. In this context, two ion exchange (IE) resins were examined (Dowex Marathon C and Amberlite IRA-67) for final OMW-2ST purification. As this effluent is extremely seasonal and deteriorates within few days, the main parameters affecting IE process were previously optimized with lab-made model OMW-2ST. Then the optimum operating conditions were tested with real OMW-2ST. Evolution of conductivity was evaluated as a function of recirculation time to study the effect of resins disposition and resins dosages and compared with both OMW-2ST. Equilibrium was reached in 10 and 20 min for model and real OMW-2ST, respectively. Furthermore, continuous mode experiments were carried out in to investigate the evolution of conductivity as a function of operating time. Breakthrough time was lower for real versus model OMW-2ST (120 vs. 147.5 min). Minimum 10 g L−1 resin dosage ensured 74% and 78% removal efficiencies, thus fulfilling irrigation water legal requirements and rending the production system cost-effective and environmentally respectful. Finally, model OMW-2ST is confirmed as good simulating media to reproduce IE processes.

- **Keywords:** Ion exchange; Olive mill effluent; Purification; Resin dosage; Simulating media; Wastewater reclamation

Gbemi Oluleye, Megan Jobson, Robin Smith. *Process integration of waste heat upgrading technologies*. Pages 315-333.

Technologies such as mechanical heat pumps, absorption heat pumps and absorption heat transformers allow low-temperature waste heat to be upgraded to higher temperatures. This work develops a comprehensive Mixed Integer Linear Program (MILP) to integrate such technologies into existing process sites. The framework considers interactions with the associated cogeneration system (in order to exploit end-uses of upgraded heat within the system and determine their true value), temperature and quantity of waste heat sources and of sinks for the heat upgraded as well as process economics and the potential to reduce carbon dioxide (CO2) emissions. The methodology is applied to an industrially relevant case study. Integration of heat upgrading technologies has potential to reduce total costs by 23%. Sensitivity analysis is also performed to illustrate the effect of changing capital costs and energy prices on the results, and demonstrate the model functionality.

- **Keywords:** Industrial waste heat; Mechanical heat pump; Absorption heat pump; Absorption heat transformer; Site cogeneration system; Mixed integer linear programming

Feifei Yang, Yongzhong Liu. *Evaluation and integration of energy utilization in a process system through material flow analysis coupled with exergy flow analysis*. Pages 334-347.

It is of significant importance to evaluate energy consumption and to optimize configuration of energy utilization in process systems. A comprehensive approach based on material flow analysis (MFA) and exergy flow analysis (EFA) is proposed to evaluate energy consumption and integrate energy utilization of a process system, in which energy-consuming devices and exothermic devices exist simultaneously. By using the

proposed approach, the energy consumption of streams in the process system is evaluated by energy consumption distribution, and the energy efficiency of the system is improved by both the improvement of local sub-systems and the integration of energy utilization of the entire system. A natural gas purification plant with a processing capacity of 200 × 104 m3/d is taken as the case study to demonstrate the detailed implementation of the proposed approach. Results show that the streams with high energy consumption intensity are indicators of energy-intensive sub-systems, and energy conservation of these sub-systems can dramatically reduce the energy consumption of the system. In this case study, after the process improvement, the energy consumption of the desulfurization sub-system reduces by 9.62%, and the energy consumption of the exhaust gas treatment sub-system reduces by 21.02%. Furthermore, after the integration of heat exchange network of the entire system, the energy consumption of the system reduces by 2.16 × 105 kW. By these from the part to the whole strategies, the total energy-saving can reach 1.07 × 106 kW in the system. The proposed approach can be used for effectively identifying the bottlenecks of the energy consumption and improving the energy utilization of process systems.

- **Keywords:** Material flow analysis; Exergy flow analysis; Energy consumption intensity; Energy integration; Natural gas purification plant; Energy consumption distribution; Heat recovery

S. De-León Almaraz, M. Boix, L. Montastruc, C. Azzaro-Pantel, Z. Liao, S. Domenech. *Design of a water allocation and energy network for multi-contaminant problems using multi-objective optimization*. Pages 348-364.

In this paper, a solution strategy based on an optimization formulation is proposed for the design of Water Allocation and Heat Exchange Networks (WAHEN) in the process industries. Such typical large problems involve many processes, regeneration units and multi-contaminants. For this purpose, a two-stage methodology is proposed. The first step is the Water Allocation Network (WAN) design by multi-objective optimization, based on the minimization of the number of network connections and of the global equivalent cost (which includes three criteria, i.e., freshwater, regenerated water and wastewater). The ε-constraint method is used to deal with the multi-criteria problem. In a second step, the Heat Exchange Network (HEN) is solved by two approaches, Pinch analysis and mathematical programming (MP). In both cases the HEN structure is found when the minimal energy requirement and the total annual cost are minimized for Pinch and MP, respectively. These results are compared and the best HEN network is then coupled to the WAN to verify the feasibility of the network. A case study including a change of phase among the streams is solved. The results show that this two-step methodology can be useful for the treatment of large problems.

- **Keywords:** WAN; HEN; WAHEN; Pinch; Mathematical programming; Change of phase

Juan Martinez-Gomez, Eduardo Sánchez-Ramírez, Juan José Quiroz-Ramírez, Juan Gabriel Segovia-Hernandez, José María Ponce-Ortega, Mahmoud M. El-Halwagi. *Involving economic, environmental and safety issues in the optimal purification of biobutanol*. Pages 365-376.

Traditionally, the design of a separation sequence for the biobutanol production has been based primarily on economic criteria with little or no consideration to the environmental and safety issues. Since biobutanol is produced from acetone–butanol–ethanol (ABE) fermentation, the process involves several substances that may cause fire and explosion and can lead to negative environmental and health impact. Hence, it is desirable to incorporate safety and environmental issues in the design objectives to determine the

optimal separation route. This work presents an optimization approach for the biobutanol separation process from the ABE fermentation while accounting simultaneously for economic, environmental and safety objectives. The optimization is carried out through a differential evolution with a Tabu search algorithm, where several Pareto solutions are identified and some routes are highlighted to determine the best compensated solutions. In this case, the best economic solution involves elevated values of the Eco-Indicator 99, the best environmental solution incurs high costs, and the safest solution features less separation columns. The most compensated solutions include configurations that represent a balance among the economic, environmental and safety objectives.

- **Keywords:** Safety; Risk assessment; Environmental impact; Biobutanol separation; Solar collector; Multi-objective optimization

Adeniyi J. Isafiade, Michael Short. *Simultaneous synthesis of flexible heat exchanger networks for unequal multi-period operations*. Pages 377-390.

The synthesis of heat exchanger networks has received significant attention in the last four decades due to the rising cost of fossil based energy sources and their attendant greenhouse gas emissions potential. However, most of the methods presented in the literature for heat exchanger network synthesis (HENS) have assumed that plants' process stream parameters, such as supply/target temperatures and stream flowrates, are fixed, hence having a single period of operation. In reality, process parameters vary within certain ranges due to changes in environmental conditions, changes in product quality demand, plant start-ups/shut-downs, and other disturbances which may upset the system. This implies that plants need to be designed to accommodate the aforementioned potential variations in operating parameters. This paper presents a new 3-step approach for the synthesis of flexible heat exchanger networks for multi-period operations with unequal period durations. The first step entails optimising a representative single period network of the multi-period problem. The solution to the representative network is then used to initialise the multi-period network in the second step. In the third step, the resulting network from the second step is redesigned/evaluated to handle unforeseen changes in lengths of periods. The solutions obtained from the newly presented method compare favourably with those in the literature.

- **Keywords:** Multi-period; Flexible; Synthesis; Mathematical programming; Heat exchanger network; Optimisation

Adeniyi J. Isafiade, Michael Short. *Synthesis of mass exchange networks for single and multiple periods of operations considering detailed cost functions and column performance*. Pages 391-404.

Mass exchange network synthesis (MENS) can be used to reduce pollutant emissions into the environment as well as reduce the need for mass separating agents (MSAs). Designing an efficient network using mathematical programming is not a trivial task, due to the fact that the design equations involved are highly non-linear. Chemical plant process parameters also change from time to time due to issues such as changes in environmental conditions, plant start-up/shut-downs, changes in process feed quality, change in product quality demand, and some other disturbance in the system. Such changes in process parameters result in what is known as multi-period operations; hence the synthesised network has to be flexible to handle these changes. In order to circumvent the issues associated with solving non-linear equations in mathematical programming environment, most methods have simplified the cost functions for MENS. Solutions obtained from these methods may not be realistic because the simplified cost functions are based on the assumption that the diameter of a column is 1 m or 2 m and that the capital cost of packed columns are dependent only on the height of the column.

The simplified models do not make provision to check whether the resulting designs are prone to flooding, operate at optimal pressure drops or even whether the ratio of column diameter to size of packing materials would enhance efficient operations. Furthermore the models assumed single period operations for mass exchange network systems. This paper presents a new synthesis method for single and multi-period MENS using detailed cost functions and correlations which check whether selected columns are prone to flooding or not and whether they have optimal pressure drops that ensure efficient separations as well as optimal use of MSAs. The solutions obtained are compared with an existing method that used pinch technology.

- **Keywords:** Mass exchange networks; Mathematical programming; Multi-period; Packed columns; Optimisation; Pressure drop

Gaonv Tu, Zuwei Liao, Zhengliang Huang, Binbo Jiang, Jingdai Wang, Yongrong Yang. *Strategy of effluent recovery technology selection in polyolefin plants*. Pages 405-412.

The conventional methods for recovering effluent gas in polyethylene processes include compression condensing, membrane separation, cryogenic separation systems and pressure swing adsorption. Since the effluent gas content varies with the process, there is no single recovery technic can meet all effluent gas content conditions. Therefore, a systematic strategy is needed to guide the selection of recovery technologies. This article introduces a method to select the best recovery system for certain compositions of effluent gas. After searching the feasible content region for the recovery systems according to the specified concentration of recycle stream and outlet streams, it shows PSA system has the largest feasible region while compression condensation system has the smallest one. In comparison of economic and exergetic performance, the cryogenic separation system shows its outstanding peculiarity to recover the effluent gas. The obtained result is effective in guiding the design of recovery system.

- **Keywords:** Polyethylene; Recovery of effluent gas; Cryogenic separation; Membrane separation; Combined system

Yus Donald Chaniago, Gregorius Rionugroho Harvianto, Alireza Bahadori, Moonyong Lee. *Enhanced recovery of PGME and PGMEA from waste photoresistor thinners by heterogeneous azeotropic dividing-wall column*. Pages 413-423.

Propylene glycol monomethyl ether (PGME) and propylene glycol monomethyl ether acetate (PGMEA) are representative photoresistor thinners used extensively and generated as waste during the display and semiconductor material manufacturing processes. Although the waste thinner is normally retrieved by distillation, the azeotropes of these two thinner components with water limit the distillation performance. In this paper, an extensive design study of enhanced distillation processes was carried out to determine a favorable path for waste thinner recovery. Appropriate thermodynamic models for the design of a waste thinner recovery process were obtained through the regression and validation of experimental vapor-liquid-liquid equilibrium data. An optimal direct sequence using three conventional distillation columns with a decanter was introduced as a base design to overcome the distillation boundary by azeotropes. Several advanced distillation configurations were examined to further improve the energy efficiency of the conventional recovery process. A novel heterogeneous azeotropic dividing-wall column was developed based on process intensification and integration. The proposed enhanced recovery process reduced the energy requirement for waste thinner recovery significantly by 33.1%. The advanced distillation configuration can be an attractive option for improving the economic and environmental efficiency of the commercial waste thinner recovery and recycling processes.

- **Keywords:** Waste photoresistor thinner recovery; PGME; PGMEA; Heterogeneous azeotrope; Dividing-wall column; Process integration

Srinivas Sahan Kolluri, Iman Janghorban Esfahani, ChangKyoo Yoo. *Robust fuzzy and multi-objective optimization approaches to generate alternate solutions for resource conservation of eco-industrial park involving various future events*. Pages 424-44.

Eco-industrial parks (EIPs), typically including industrial plants and companies, provide a promising resource conservation strategy that includes opportunities for material exchange between participating plants and minimizes the consumption of resources. However, when the participating plants in the EIP fail to share data, various possible future events are ought to happen in future. In this paper, we present various robust optimization approaches in order to generate alternate solutions for resource conservation in EIPs through water reuse networks that take various future events into consideration. Three different optimization approaches are discussed and solved in this study. In the first optimization approach, the objective function is set to minimize the overall emergy of the EIP. In the second approach, an emergy-based fuzzy optimization model is presented and the objective function of the model is to maximize the overall degree of satisfaction. Finally, a solution method incorporating the lexicographic optimization and augmented ε-constraint method is proposed in order to solve the multi-objective optimization (MOO) problem, which simultaneously minimizes the overall freshwater consumption and the regenerated water flow-rate. The resulting model is formulated as a mixed-integer linear programming problem taking into consideration two scenarios (EIP reuse network with a regenerator and direct reuse EIP network without a regenerator). The applicability of the proposed optimization approaches is demonstrated by comparison with a literature case study and by comparing the optimal resource conservation results for the two scenarios. The results show that a regeneration unit with a fixed outlet concentration into the base system causes a 15.6%, 9.8%, 21.2%, and 16.2% reduction in the overall emergy, TAC, freshwater, and wastewater, respectively, in comparison to that of direct reuse.

- **Keywords:** Eco-industrial parks (EIPs); Fuzzy optimization; Multi-objective optimization; Lexicographic optimization; Augmented ε-constraint method; Water reuse

Fardin Torkfar, Akram Avami. *A simultaneous methodology for the optimal design of integrated water and energy networks considering pressure drops in process industries*. Pages 442-454.

This paper presents a simultaneous methodology for the optimal design of integrated water and energy networks. Heat transfer coefficients are not constant but are related to the velocity of the streams. Pressure drops in heat exchangers and related power costs are considered. The model is a non-convex MINLP (mixed-integer non-linear program) model, in which the objective is to minimize the total annual costs. To accomplish this task, a new superstructure is proposed that follows the energy and mass streams from sources to sinks, enabling us to consider heat exchange between streams in two separate stages of the HENS before and after mixers. Furthermore, heat recovery from wastewater is considered. The model is solved for two examples, and results are presented with and without pressure drop effects. The optimum velocity and heat transfer coefficients for the streams in the heat exchangers are determined, and the results are in good agreement with the literature. In this way, the model reflects the real situation in industrial networks where thermal and electrical energy and water requirements interact very closely.

- **Keywords:** Simultaneous optimization; Water networks; Energy integration; Superstructure; Pressure drop

C. Font-Palma, O. Errey, C. Corden, H. Chalmers, M. Lucquiaud, M. Sanchez del Rio, S. Jackson, D. Medcalf, B. Livesey, J. Gibbins, M. Pourkashanian. *Integrated oxyfuel power plant with improved CO2 separation and compression technology for EOR application*. Pages 455-465.

An integrated advanced supercritical coal-fired oxyfuel power plant with a novel cryogenic CO2 separation and compression technology for high purity CO2 to suit injection for Enhanced Oil Recovery purposes is investigated. The full process is modelled in Aspen Plus® consisting of: an Air Separation Unit (ASU), an Advanced Supercritical Pulverised Fuel (ASC PF) power plant with a bituminous coal as feedstock, a steam cycle, and a Carbon dioxide Purification Unit (CPU). The proposed CPU process accommodates a distillation column with an integrated reboiler duty to achieve a very high purity CO2 product (99.9%) with constrained oxygen levels (100 ppm). This work presents a detailed analysis of the CO2 separation and compression process within the full power plant, including effective heat integration to reduce the electricity output penalty associated with oxyfuel CO2 capture. The results of this analysis are compared with previous studies and indicate that the combined application of process optimisation in the CPU and advanced heat integration with the power plant offer promising results: In this work a high purity CO2 product was achieved while maintaining 90% capture for a net plant efficiency of 38.02% (LHV), compared with a thermal efficiency of 37.76% (LHV) for a reference simulation of an ASC PF oxy-fired plant with advanced heat integration, providing a lower purity CO2 product.

- **Keywords:** Oxyfuel combustion; Carbon dioxide Purification Unit; Heat integration; Enhanced Oil Recovery; Supercritical power plant; High purity CO2