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Integration of Renewable Energy into Mass, Heat and Regeneration Network Synthesis

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This paper presents a new synthesis method for optimally integrating mass exchange networks, involving regeneration, with solar thermal energy, so as to reduce the quantity of water used in mass exchange operations, while simultaneously reducing the environmental impact associated with the use of fossil based energy sources. The problem in this paper involves gaseous streams from which ammonia has to be removed using water as the mass separating agent. The ammonia rich lean stream is then sent to a regenerator where steam stripping is used to remove the ammonia, after which the lean stream, which is now somewhat free of ammonia, is recycled back to the network of mass absorbers for further ammonia absorption from the gaseous streams. The stage-wise superstructure is adopted, however it is extended by including models to account for primary mass exchange, regeneration and heat exchange subnetworks. Other extensions include the addition of model equations to determine optimal solar panel area and heat storage vessels. The example considered demonstrates the benefits of the integrated approach.

1. Introduction

The chemical process and allied industry is faced with myriad challenges among which are the need to selectively remove species from solutions, reduce emissions of pollutants (including greenhouse gases) into the environment, minimise use of energy, especially those of fossil origin, as well as minimise use of scarce natural resources such as water. The goal is to accomplish all of these in a cost effective and sustainable manner. There have been attempts to overcome these challenges, however, most of these attempts have involved tackling the aforementioned issues either individually or sequentially using methods which are heuristic based, e.g. Pinch Technology, or mathematical programming based. The paper by Liu, et al. (2013) involves the synthesis of mass exchanger networks (MENs) for multicomponent systems, however, no consideration was given to possible regeneration of the mass separating agents (MSA) or the benefits of simultaneously integrating the MEN with heat exchanger network (HEN). Isafiade and Fraser (2007) on the other hand studied MENs involving single components with the inclusion of possibilities for regeneration of the external MSA using Pinch Technology. Consideration was given to the energy associated with the regeneration process in determining the total annual cost (TAC) of the resulting network. This scenario was then extended by Isafiade and Fraser (2009a) through the use of a mathematical programming approach. Although these studies explored the benefits of combining the synthesis of heat and mass exchanger networks, however, the additional benefits that would be obtained if renewable energy, such as solar thermal, is integrated in the network, was not investigated. Recently, a host of papers presented studies involving the integration of renewable energy into process network synthesis. Such studies include the paper by Sharan and Bandyopadhyay (2015) where multiple effect evaporators were integrated with solar thermal energy, the work of Isafiade, et al. (2016) where solar thermal energy was integrated with multi-period process heat demand with opportunities for heat storage, and the paper by Nemet, et al. (2015) where solar thermal panel area as well as heat storage vessel sizes for integration with various process heat demand were targeted using a sequential technique. Other studies that also involved integration of renewable energy, in the form of solar thermal, include the paper by Atkins, et al. (2010) which also used a sequential approach for solar heat integration with a diary process heat demand, and that of Walmsley, et al. (2014) which involves integration with heat recovery loop considering both series and parallel arrangements. It is worth stating at this point that the cases where solar thermal energy has been integrated with processes has mostly involved direct heat exchange processes. Scenarios where solar thermal energy is integrated with mass exchange and regeneration operations that can be enhanced through simultaneous synthesis with heat exchange networks has not been considered. Hence this paper presents a synthesis method for scenarios where the mass exchange process in a mass exchange network synthesis, involving regeneration of at least one of its MSAs, is enhanced through integration with solar thermal energy with opportunities for thermal heat storage in a heat exchange network.

2. Problem statement

The problem addressed in this paper is stated as follows: Given a set of rich streams (R) having flowrates (G) from which species such as SO_2, CO_2, NH_3, etc., are to be removed so as to reduce their compositions from supply values y^s to target values y^t. Available for this removal are a set of lean streams (S), which comprise both process and external lean streams (i.e. mass separating agents, MSA). The process lean streams have supply and target compositions expressed in the equivalent equilibrium rich stream phase as y^{*s} and y^{*t}, while they have maximum available onsite flowrate (L^u). Given also are as set of regenerants (RG), such as steam, monoethanolamines/diethanolamines, etc., having supply and target compositions z^s and z^t, and flowrate (V), which can be used to strip the absorbed specie from the external lean stream exiting the primary mass exchange network. Note that the regenerant flowrate (V), the supply and target compositions (y^{*s} and y^{*t}) of the external lean streams in the primary MEN as well as its flowrate (S), are all variables to be optimised. In order to enhance the absorption and stripping processes in the primary MEN and regeneration network respectively, hot utilities (HU) and cold utilities (CU), which can be generated from both non-renewable, e.g. coal, oil, etc., and renewable sources, e.g. solar thermal, are available for the purpose of heating and cooling the external lean stream to the optimal mass exchange temperatures in the primary mass exchange and regenerating network, respectively. Also given are the costs associated with each unit of the external lean streams, utilities and mass exchange equipment, as well as global horizontal irradiation (GHI) and ambient temperature of the local environment where the plant operates at various time periods (P). The aim is to synthesise a cost optimal network of mass and regeneration network, where both the primary mass exchange and regeneration operations are enhanced by an optimally integrated heat exchanger network having opportunities for use of both renewable and non-renewable energy while considering the potential for heat storage.

3. Methodology

Since the problem statement involves heat and mass exchanger networks, the methodology adopted entails a combination of the heat exchange stage-wise superstructure, presented by Yee and Grossmann (1990) where hot and cold streams are made to participate in a set of defined intervals for the purpose of heat exchange, and its mass exchange equivalent, presented by Szitkai, et al. (2006) where rich and lean streams are made to participate in a set of defined intervals for the purpose of mass exchange. This kind of combination is known as combined heat and mass exchange network synthesis (CHAMENS). Beyond just the combination of these two existing models, additional model equations and updates to the existing stage-wise superstructure models is done in this paper. The additional equations include formulations to account for the optimal size of solar panels to capture heat to be used for both direct and indirect heat integration in the network. For the indirect heat integration, which involves use of solar heat as hot utilities at periods when solar irradiation is unavailable or insufficient, formulations are included in the model to simultaneously determine the optimal tank size for thermal heat storage. Furthermore, for cases where the mass exchange operations are continuous processes, integrating solar thermal heat, whose availability is non-continuous and unpredictable, requires that the existing stage-wise models for HENS and MENS be updated to handle such cases. In this paper, the existing HENS and MENS stage-wise superstructures are extended to handle the problem statement of this paper by including the index ‘p’ to account for periods of availability/non-availability of solar irradiation. For the purpose of simplification, the HENS and MENS stage-wise superstructures are not shown in this study, the reader is referred to the papers by Yee and Grossmann (1990) and Szitkai, et al. (2006) for the details. Since the model equations build on existing multi-period stage-wise superstructure models for HENS and MENS, the details of these are also not shown in this paper. The reader is referred to the papers by Verheyen and Zhang (2006) for the HENS model equations and to Isafiade and Fraser (2009b) for the MENS model equations. It is worth stating that a multi-period version of the stage-wise superstructure for MENS is not well developed as its multi-period HENS counterpart, furthermore a combination of these two superstructures together with a regeneration network, as will be presented in this paper, has not been previously presented in the literature. This paper will show the key new set of model equations for the combined multi-period HENS, MENS and regeneration superstructures. Figure 1 is a schematic representation of combined MEN, HEN and regeneration exchanger network (REN). As can be seen in the figure, the link between the REN and the MEN are the lean streams that need to be heated/cooled to optimal mass absorption and stripping temperatures. The model equations are described next.

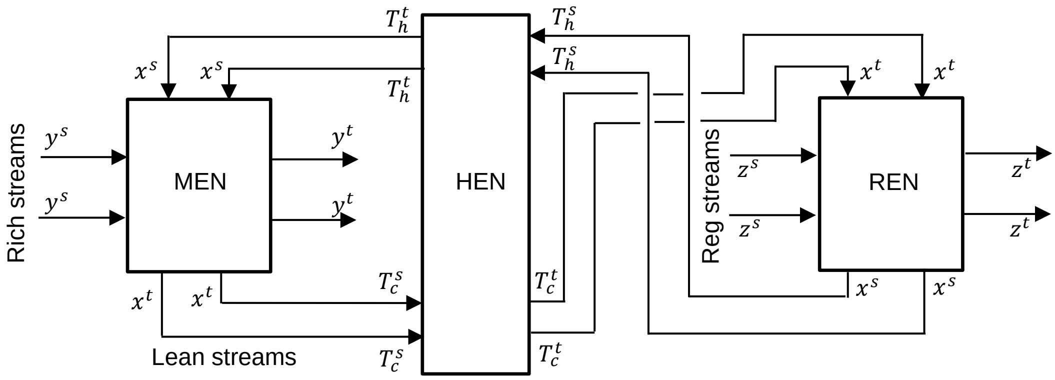

Figure 1: Schematic of a combined heat, mass and regeneration network

3.1 Model equations

Representative maximum heat exchanger area and maximum mass exchanger height

Since the model approach adopted in this paper is the use of the multi-period concept to represent time periods in each day of a year where solar irradiation is available/unavailable, the heat and mass exchangers need to be designed to be big enough so as to efficiently transfer heat/mass at the various time periods of operations. Equation 1 represents the maximum heat exchanger area $A_{i,j,k}$ (m^2), which will exchange heat $q_{i,j,p,k}$ (kW) between the same pair of hot stream i and cold stream j in any time period p of operation in interval k. Equation 2 represents the maximum packed height $H_{r,s,k}$ (m) for the absorber column which will exchange mass $M_{r,s,p,k}$ (kg/s) between the same pair of rich stream r and lean stream s in any time period p of operation in interval k. The equivalent for the regeneration column is shown in Equation 3.

$$A_{i,j,k} \geq \frac{q_{i,j,p,k}}{(LMTD_{i,j,p,k})(U_{i,j})} \tag{1}$$

$$H_{r,s,k} \geq \frac{M_{r,s,p,k}}{(LMCD_{r,s,p,k})(Kw)} \tag{2}$$

$$H_{s,rg,k} \geq \frac{M_{s,rg,p,k}}{(LMCD_{s,rg,p,k})(Kw)} \tag{3}$$

In Equation 1, the variable $LMTD_{i,j,p,k}$ (°C) is the logarithmic mean temperature difference for match i,j,p,k in time period p, while the parameter $U_{i,j}$ is the overall heat transfer coefficient between hot and cold streams i,j. In Equation 2, $LMCD_{r,s,p,k}$ is the logarithmic mean composition difference for match r,s,p,k in time period p, while the parameter Kw is the lumped mass transfer coefficient.

Representative maximum solar panel area and thermal storage vessel

Just as was done for the representative heat and mass exchangers in terms of their required sizes, the solar panel needs to be designed to be big enough to capture the maximum possible amount of heat in a cost-efficient manner irrespective of the amount of solar irradiation available. It should be known that it is assumed in this paper that solar irradiation is available at fixed time period p of each day. This fixed value is taken as the average value of actual historical global irradiation (GHI) values for the local environment concerned. The panel area model is shown in Equation 4. Note also that the panel are $ASC_{i,j,k}$ is designed in such a way as to not only capture heat for use at the time period p where solar irradiation is available, but to also capture additional heat to be stored in thermal storage vessels for use at other time period p where solar irradiation is unavailable. Again, just like the solar panel, the volume of the heat storage vessel $VTS_{i,j,k}$ is designed to be big enough to store sufficient heat for use at time period p where solar irradiation is unavailable. The model equation is illustrated by Equation 5.

$$ASC_{i,j,k} \geq \frac{q_{i,j,p,k}}{\eta_0(GHI_p) - a_1(T_c - Ta_p) - a_2(T_c - Ta_p)^2} \quad (4)$$

$$VTS_{i,j,k} \geq \frac{q_{i,j,p,k}}{C_p\rho(T_i^s - T_i^t)} \quad (5)$$

In Equation 4, η_0 is the efficiency factor of the solar panel (76.4 %), GHI_p is the global horizontal irradiation for the time period p in the local environment where the plant is situated, a_1 and a_2 (1.53 W/(m^2·°C) and 0.0003 W/(m^2·°C) respectively), which are experimental constants, are called the thermal loss coefficient, Tc (90°C) is the average of the inlet and outlet capture fluid temperature to the solar panel, Ta_p (32°C) is the ambient temperature for the time period p in the local environment where the plant is situated, Cp (4.2 kJ/(kg·°C)) is the specific heat capacity of the thermal storage fluid, while ρ (1,000 kg/m^3) is its density, T_i^s and T_i^t (50°C and 110°C) are the supply and target temperatures of the storage fluid in the storage vessel.

Overall combined objective function

The objective function comprises a sum of the annualised capital costs and annual operating costs. The capital cost comprises cost of process heat exchangers, cost of utility exchangers, costs of packed mass absorbers in the primary MEN, costs of regenerating column in the regeneration network, costs of solar panels and costs of thermal storage vessels. The operating cost comprises costs per unit of hot and cold utilities, costs of lean streams and costs of regenerant. It should be known that the cost of the lean stream being regenerated is actually a make-up cost (assumed to be zero in the example considered) since the stream is being recycled within the network, hence it's not used on a once through bases. Equation 5 below illustrates this combined objective function.

$$\begin{aligned}
min\Bigg\{ \Bigg\{ \sum_{p \epsilon P} \Bigg[& \left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p} \cdot \sum_{i \epsilon HP} \sum_{j \epsilon CU} \sum_{k \epsilon K} CUC_j \cdot q_{i,j,p,k} \right) + \left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p} \cdot \sum_{i \epsilon HU} \sum_{j \epsilon CP} \sum_{k \epsilon K} HUC_i \cdot q_{i,j,p,k} \right) \\
& + \left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p} \cdot \sum_{r \epsilon R} \sum_{s \epsilon S} \sum_{k \epsilon K} LSC_s \cdot L_{s,p} \right) + \left(\frac{DOP_p}{\sum_{p=1}^{NOP} DOP_p} \cdot \sum_{s \epsilon S} \sum_{rg \epsilon RG} \sum_{k \epsilon K} RSC_{rg} \cdot V_{rg,p} \right) \Bigg] \Bigg\} \\
& + \Bigg[AF_{HE} \left(\sum_{i \epsilon HP} \sum_{j \epsilon CP} \sum_{k \epsilon K} CF_{i,j} \cdot y_{i,j,k} + \sum_{i \epsilon HP} \sum_{j \epsilon CP} \sum_{k \epsilon K} AC_{i,j} \cdot A_{i,j,k}^{ACE} \right) \\
& + AF_{MA} \left(\sum_{r \epsilon R} \sum_{s \epsilon S} \sum_{k \epsilon K} CF_{r,s} \cdot x_{r,s,k} + \sum_{r \epsilon R} \sum_{s \epsilon S} \sum_{k \epsilon K} MAC_{r,s} \cdot H_{r,s,k}^{HCE} \right) \\
& + AF_{RC} \left(\sum_{s \epsilon S} \sum_{rg \epsilon RG} \sum_{k \epsilon K} CF_{s,rg} \cdot w_{s,rg,k} + \sum_{s \epsilon S} \sum_{rg \epsilon RG} \sum_{k \epsilon K} RAC_{s,rg} \cdot H_{s,rg,k}^{HRCE} \right) + AF_{SP}(ACSC_{i,j} \cdot ASC_{i,j,k}) \\
& + AF_{ST}(ACTS_{i,j} \cdot VTS_{i,j,k}) \Bigg] \Bigg\}
\end{aligned}$$

$$\forall \ i \epsilon HP;\ j \epsilon CP;\ s \epsilon S;\ rg \epsilon RG;\ p \epsilon P;\ k \epsilon K \quad (6)$$

In Equation 6 DOP_p is the average time duration for which solar irradiation is available and unavailable in each day, NOP is the number of solar irradiation availability/unavailability time periods considered for each day, CUC_j and HUC_i are costs per unit of cold utility j (1.3 \$/(kW·y)) and hot utility i (136 \$/(kW·y)), LSC_s and RSC_{rg} are the costs per unit of external lean stream s (0 \$/(kg·y)) and regenerating stream rg (20,867 \$/(kg·y)) $L_{s,p}$ and $V_{rg,p}$ are the flows of external lean and regenerating streams in time period p respectively, AF_{HE}, AF_{MA}, AF_{RC}, AF_{SP}, AF_{ST}, are the annualisation factors for heat exchangers, mass absorbers, regenerating column, solar panels, and thermal storage tanks (0.2/y in all cases) respectively, $CF_{i,j}$, $CF_{r,s}$, $CF_{s,rg}$, are fixed charges for heat exchangers (8,333.3 \$/y), mass absorbers (0 \$/y) and regenerating columns (0 \$/y), $y_{i,j,k}$, $x_{r,s,k}$, $w_{s,rg,k}$ are binary variables indicating the existence or otherwise of heat exchangers, mass absorbers and regenerating columns respectively, $AC_{i,j}$, $MAC_{r,s}$, $RAC_{s,rg}$, $ACSC_{i,j}$, $ACTS_{i,j}$ are the cost per unit area for heat exchangers (641.7 \$/m^2), cost per unit height for mass absorbers (6,180 m), cost per unit height for regenerating columns (6,180 m), cost per unit area for solar panels (100 \$/(m^2·y)) and cost per unit volume for thermal storage tank (50 \$/(m^3·y))

4. Example

The example considered in this paper comprises five gaseous rich streams from which ammonia is to be absorbed in packed columns so as to achieve some specified target concentrations. Available for the absorption are three water based lean streams, two of which are process lean streams while the third is an external lean stream. The external lean stream can be regenerated through steam stripping in a packed column. Since absorption is enhanced at lower temperatures while stripping is enhanced at higher temperatures, the external lean stream, which has the opportunity of being regenerated, is made to operate in the absorption column at 20°C while the steam stripping operates at 100 °C. Two time periods were considered, where period 1 which is the time of availability of solar irradiation spans 8 h of a d, while period 2 which is the time of no solar irradiation spans 16 h of each d. Table 1 shows the problem data. In Table 1, m is equilibrium constant (5.82 for regenerating stream in Table 1), while Reg means regenerating. Since the model is a mixed integer non-linear program (MINLP) it was solved using DICOPT in General Algebraic Modelling Systems (GAMS) environment. DICOPT works in conjunction with CPLEX and CONOPT. The MENS and HENS stage-wise superstructures applied to the example both had 3 stages each while the REN had only one stage. The combined model equations, which have 709 single equations, 560 single variables and 48 discrete variables, was solved in 6 s of CPU time. It is worth stating that the scenarios considered in solving the example is not exhaustive so as to simplify the solution process. CHAMENS problems of this nature have so many competing variables as well as scenarios which have to be investigated in order to get the best network not only in terms of economic criteria but environmental impact criteria as well. Apart from the usual variables in the traditional stage-wise individual HENS and MENS models, additional variables that come to play in this CHAMENS context are the optimal absorption and stripping temperatures as well as the optimal supply and target compositions of the lean streams, especially the external lean stream. In solving this example, fixed temperatures were selected for absorption and stripping which are 20°C and 100°C, while 3 sets of absorption column supply x^s and target x^t compositions where investigated for optimality for the external lean stream. It is the intention of the author of this paper to consider all of these variables simultaneously in a more detailed model in future studies. Two options of hot utilities are considered, the first is utility obtained from solar energy while the second is utility obtained from fossil fuel. The set of solutions obtained at the 3 sets of external lean stream absorption supply and target compositions investigated are shown in Table 2. For each set of supply and target compositions shown in this table, investigations were carried out to see what maximum price that the fossil based utility source can have beyond which it will no longer be economically viable, i.e. the fossil utility price that will make the model select solar thermal energy in favour of utility obtained from a fossil source. This has the potential to be more beneficial economically and environmentally since utility obtained from solar thermal energy requires very minimal operating cost compared to that of a fossil based source. Investigations of this nature would go a long way in helping government and stakeholders determine how to price utilities from both fossil sources and renewable sources so as to make the renewables economically competitive. A flowsheet representation of one of the solutions in Table 2 (TAC = 159,076 $/y) is shown in Figure 2.

Table 1: Problem data for the example considered

Rich Streams	G Kg/s	y^s	y^t	Lean streams	L Kg/s	m	x^s	x^t	Reg stream	z^s $\times 10^{-6}$	z^t $\times 10^{-6}$
R_1	0.02	0.0800	0.0065	S_1	2.4	1.2	0.0017	0.0071	RG_1	1.031	3.436
R_2	0.04	0.0800	0.0025	S_2	1.9	1	0.0025	0.0085			
R_3	0.35	0.0110	0.0025	S_3	∞	1.029	∞	∞			
R_4	0.15	0.0100	0.0050								
R_5	0.50	0.0080	0.0025								

Table 2: Total annual costs for the example considered

x^s $\times 10^{-5}$	x^t $\times 10^{-4}$	Maximum fossil hot utility price ($/(kW·y))	Total annual cost ($/y)
4.859	6.803	143	136,517
3.887	6.803	131	151,538
1.944	8.746	135	159,076

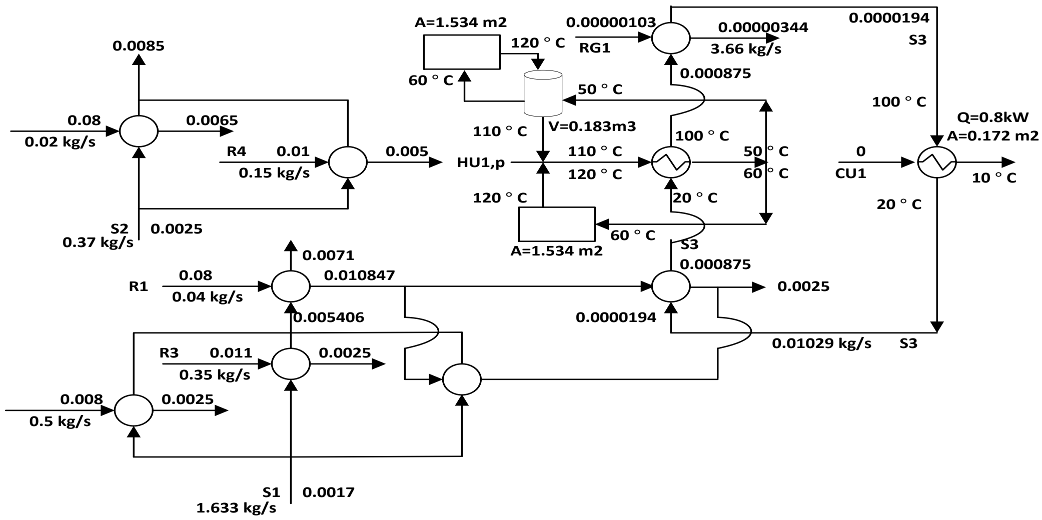

Figure 2: Representative flowsheet solution at a TAC of 159,076 $/y

5. Conclusions

An extension to existing CHAMENS methods has been presented in this paper. The new method includes the integration of renewable energy in the form of solar thermal while considering its time variability and opportunities for heat storage. Although the solution approach adopted is not exhaustive, the model however can be used to gain preliminary insights into CHAMENS when integrated with renewable energy. Key issues not considered by the model include simultaneously determining the optimal absorption and regeneration temperatures within the columns, variable column diameter, pressure drop in columns and seasonal variation of GHI and ambient temperature. However it is hoped that these issues will be considered in future studies.

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