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Simultaneous Optimisation of Multiple-Effect Evaporation Systems and Heat Exchanger Network

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In recent work, a general superstructure and a Non-Linear Programming (NLP) model were presented for Multiple-Effect Evaporation Systems (MEESs). This NLP model was combined with a Heat Exchanger Network (HEN) model in order to simultaneously perform optimisation and heat integration of the overall system. The results of a forward-feed evaporation system integrated with hot and cold streams of the evaporation system as well as with the background process were presented. In this paper, the superstructure is extended by including multi-stage flash vessels for improving energy efficiency within the overall system. Additionally, various flow-patterns of heat-integrated MEES are studied. Also, trade-offs between energy and investment costs of heat-integrated MEES are explored for different numbers of evaporation effects in order to determine the optimum number of effects. The proposed Mixed-Integer Non-Linear Programming (MINLP) model of the combined MEES-HEN networks is implemented in a General Algebraic Modelling System (GAMS) and solved simultaneously using a two-step solution strategy. In the first step of the strategy, the NLP model of MEES is solved, providing an initialisation point for solving the MINLP model of the combined MEES-HEN network within the second step. A case study of a milk concentration process is used to illustrate the method. The results show that the forward feed flow-pattern with three evaporation effects is totally integrated with hot and cold process streams from the background process, and the system exhibits the minimum Total Annualised Cost (TAC).

1. Introduction

Evaporation is a unit operation used within process industries in order to evaporate a portion of the solvent (usually water) from a diluted solution (feed stream) and to produce a concentrated solution (McCabe et al., 2005). It is one of the most energy-intensive unit operations used by industry, as large amounts of energy are required to evaporate water from a diluted solution. Evaporation can be used to concentrate various feed streams such as milk, salt water, tomato juice, black liquor and fruit juice, or to produce fresh water within desalination processes. Various methods within evaporation plants have been considered for reducing energy consumption, including Multiple-Effect Evaporation Systems (MEES), vapour recompression systems, flashing condensates, vapours bleeding, and preheating of the feed stream. In MEESs, evaporated water from the previous effect can be used as a heating medium for the upcoming effect. As a result, the overall consumption of energy can be significantly reduced; however, investment costs increase when adding evaporation effects. This highlights the importance of investigating trade-offs between savings in steam and added investment in order to find the optimum number of effects. In addition to multiple-effect evaporation, vapour recompression systems (Walmsley, 2016), including mechanical (Onishi et al., 2017) and thermal compression (Sharan and Bandyopadhyay, 2016b), can be combined with a single and MEESs in order to reduce energy consumption (Périn-Levasseur et al., 2008). Different tools and software packages are used to study various evaporation systems, such as Visual Basic 6.0 (Ruan et al., 2015), Excel (Sharma et al., 2012), Matlab (Kumar et al., 2013), Aspen Plus (Chawankul et al., 2001), and General Algebraic Modeling System (GAMS) (Onishi et al., 2017). In addition, Pinch Analysis and Mathematical Programming (MP) methodologies have been used for heat integration and optimisation of evaporation systems. Previous studies focused on analysis and steady-state simulation of evaporation systems, and computer-based simulators of MEES were developed. Also, design and optimisation of steam economy for various flow-patterns with and without pre-heating were studied. Optimising the number of effects has also been addressed through minimising the Total Annualised Cost (TAC) and maximising the net present value. Most of these studies considered stand-alone evaporators isolated from the background process. However, it should be highlighted that optimal designs obtained in this way can be very different from the optimal designs of heat-integrated evaporators with the background process (Smith and Jones, 1990). Accordingly, Hillenbrand and Westerberg (1988) studied heat integration of a triple-effect evaporation system with streams inside and outside the evaporation system in order to minimise utility consumption and to select approximately the best temperatures for placing evaporator effects. Their research was later extended in order to investigate the liquid flow-patterns of a multiple-effect evaporator system (Westerberg and Hillenbrand, 1988). Simple calculations based on physical insights were performed to estimate the added utility caused by the flow-pattern. Smith and Jones (1990) suggested a procedure for integrating evaporators into the overall process, where the capital-energy trade-off should be explored within the overall system. These were among the first studies related to the synthesis of multiple-effect evaporator systems, but the design of a Heat Exchanger Network (HEN) achieving the minimum utility consumption was not presented. Xiao and Smith (2001) considered heat integration of evaporation systems within the overall process and presented case studies of evaporators integrated with the background process and thermal vapour recompression. Sharan and Bandyopadhyay (2015) developed an analytical methodology to integrate MEES with the background process and showed that energy can be saved if the systems are integrated properly. Also, they focused on selecting appropriate temperatures for evaporator effects in order to minimise energy consumption in the overall process (Sharan and Bandyopadhyay, 2016a). In their work, a case study of corn glucose manufacturing consisting of three evaporation effects and the background process (three hot and three cold streams) was considered. However, the proposed design had 22 heat exchangers and the minimisation of the overall cost of the system was not performed in the study. Recently, Chantasiriwan (2017) investigated distributions of juice heater surface in order to find the optimum performance of the evaporation process within sugar production plants, and found that juice heater surface distribution affects the performance of the evaporation system. Sharan and Bandyopadhyay (2017) analysed a multiple-effect evaporator integrated with a thermo-vapour compressor in a corn glucose manufacturing plant combined with a solar system, and determined the optimal solar radiation and steam temperatures. Onishi et al. (2017) proposed a superstructure and a Non-Linear Programming (NLP) model of multiple-effect evaporation with mechanical vapour recompression for shale gas flow-back water desalination. Different scenarios were investigated, and among all of the processes evaluated, the best option was multiple-effect evaporation with single vapour recompression including thermal integration. It should be emphasised that besides minimisation of utility consumption (cost), the investment cost of the system must be taken into account within an optimisation procedure in order to find appropriate trade-offs between capital and energy. It should also be noted that simultaneous optimisation of heat-integrated MEES with the background process exploring trade-offs between energy and capital cost within the overall system has been rarely addressed in the literature.

The aim of this paper is to present a superstructure-based optimisation approach for simultaneous optimisation and heat integration of combined MEES and HEN networks minimising TAC. The corresponding Mixed-Integer Non-Linear Programming (MINLP) model, together with the applied solution strategy, will be described in the following section.

2. Problem statement

The problem can be stated as follows. Given: i) a set of evaporator effects for concentrating a feed stream including flash vessels; ii) a set of hot and cold streams from the background process; iii) flow-rate, solids concentration, and temperature of feed stream, and a desired concentration of solids within a concentrated product; iv) temperature of fresh steam introduced within the heating chamber of the first evaporation effect; v) a minimum allowed temperature difference between hot and cold streams within MEES and HEN; vi) a residence time of condensate within flash vessels.

It is necessary to perform simultaneous optimisation and heat integration of a combined MEES-HEN network in order to determine an optimal network design minimising TAC which includes operating (hot and cold utility) and investment cost (evaporators, heat exchangers and flash vessels).

3. Superstructure, model and solution strategy

Figure 1 presents an extended superstructure of the previous work (Ahmetović et al., 2016) for a heat-integrated MEES combined with a HEN superstructure (all hot and cold streams could be integrated within the

HEN). Multi-stage flashing of condensate streams is incorporated within the MEES for producing low pressure vapours and improving the steam economy and energy efficiency of the system. In this case, for example, the condensate from the first evaporation effect (E1) is directed to the first flash vessel (V1) in which vapour is generated and mixed with secondary vapour from the first effect and then introduced for heating within the chamber of the second effect (E2). It is assumed that only the latent heat of steam is transferred within each evaporation effect. An initial feed process stream is directed to the MEES in order to produce a concentrated product. Hot and cold streams from the MEES and the background process are directed to a HEN for heat integration. Preheating of a feed stream can be done by condensate streams from heating chambers of evaporation effects, and secondary vapour streams generated within evaporation effects or other hot streams from the background process. The proposed superstructure includes different options of feed flow-patterns (forward, backward, and parallel feed). On the basis of the superstructure presented, a Mixed-Integer Nonlinear Programming (MINLP) model was formulated and combined with a HEN model (Yee and Grossmann, 1990). The objective of the proposed model is to minimise total annualised cost (TAC) of the overall network subject to equality and non-equality constraints related to MEES and HEN networks. The model was implemented in GAMS (Rosenthal, 2015). A two-step solution strategy was used for model solving. A nonlinear programming (NLP) model of non-integrated MEES was solved by BARON in the first step. This provided an initialisation point for the MINLP model of combined MEES-HEN network solved by SBB within the second step of the strategy.

4. Case study

The proposed superstructure, model and solution strategy shortly described within the previous section were used in order to present the results of MEES for the milk concentration process. The MEES is fed with 2.5 kg/s of milk with 10 % solids at 30 °C in order to be concentrated to 40 % solids. Fresh steam at 85 °C is used for indirect heating within the first evaporation effect. The minimum temperature within the last evaporation effect is set to be 40 °C (Bylund, 2015). All other design and operating data for this case study are summarized in Table 1. Investment cost models for heat exchangers, evaporators and flash vessels were obtained by linear approximations of the results obtained from the CAPCOST program (Turton et al., 2009), where a Chemical Engineering Plant Cost Index (CEPCI) for 2015 (556.8) and stainless steel material were used for estimation. Two process streams are available within the background process that can be used to integrate the MEES. Accordingly, the system boundaries are extended and simultaneous optimisation can be performed for the overall plant exploring trade-offs between energy and investment cost. A hot process stream with a heat capacity flow-rate 10 kW/°C is cooled from 82 to 50 °C, and a cold process stream with heat capacity flow-rate 5 kW/°C is heated from 20 to 40 °C (see Figure 2).

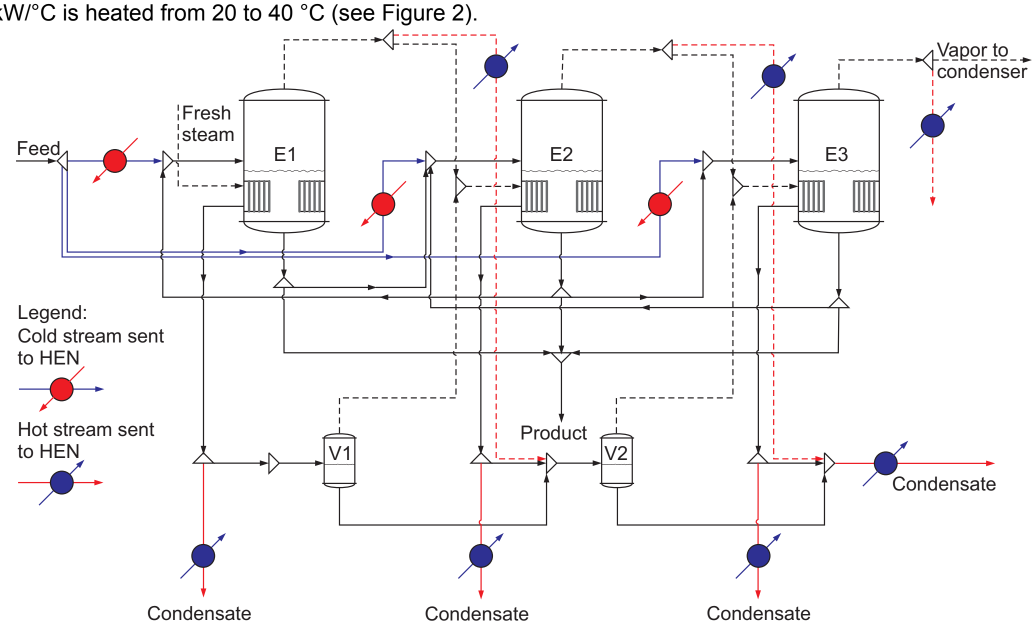

Figure 1: Superstructure of a heat-integrated multiple-effect evaporation system for three effects

Table 1: Data for case study

Parameter	Value
Cooling water inlet and outlet temperatures, °C	10 and 20
Hot utility (fresh steam) temperature, °C	85
Hot utility cost, \$/(kW·y)	382
Cold utility cost, \$/(kW·y)	189
Fixed cost for heat exchangers, \$	117,014.02
Area cost coefficient for heat exchangers, \$/m^2	1,055.6
Fixed cost for flash tanks, \$	12,103.61
Volume cost coefficient for flash tanks, \$/m^3	5,046.19
Fixed cost for evaporators, \$	641,705.1
Area cost coefficient for evaporators, \$/m^2	15,601.7
Individual heat transfer coefficients for process streams, water and utilities, kW/(m^2·°C)	1
Specific heat capacity of condensates, kJ/(kg·°C)	4.2179
Retention time of condensate within the flash tanks, min	5
Plant operating hours, h	8,000
Interest rate, %	8
Equipment lifetime, y	10
Minimum allowed exchange temperature, °C	10

Table 2 shows the optimisation results of MEES consisting of three effects involving different flow patterns integrated with hot and cold streams from the background process without and with flashing condensates from evaporation effects. The results of fresh steam consumption show that improved energy efficiency was achieved by incorporating multi-stage flash vessels within the proposed superstructure (see Figure 1), and that the forward feed flow-pattern was the best from the economic point of view for the cases considered in this study (see Table 2). The model was further solved in order to find the optimum number of evaporation effects for the forward feed flow-pattern. The results presented in Table 3 show that the optimum number of evaporation effects is three, with a minimum TAC of 1,292,048 \$/y. Figure 2 shows the optimal design of a heat-integrated triple-effect evaporation system with hot and cold process streams from the background process. The feed stream is first preheated with condensate streams from evaporation effects and further with the hot process stream from the background process. Accordingly, the initial temperature of the feed stream is raised from 30 to 72 °C, which is close to the temperature within the first evaporation effect (72.51 °C). The overall utility consumption is 0.591 kg/s. Process hot and cold streams are totally integrated with streams from the evaporation system and an appropriate trade-off between energy and capital cost is achieved within the overall network.

Table 2: Results of optimisation and heat integration of different flow-patterns of a triple-effect evaporation system without and with flashing condensates from evaporation effects

Parameter	Forward feed	Backward feed	Parallel feed
Fresh steam consumption, kg/s	0.604	0.671	0.627
	0.591*	0.646*	0.605*
Evaporator investment, \$	4,735,642	4,908,466	5,361,180
	4,738,067*	4,904,963*	5,377,758*
HEN investment, \$	420,494	274,142	516,734
	441,292*	281,634*	521,659*
Flash vessels investment, \$	-	-	-
	27,905*	30,050*	29,781*
Annualised investment, \$/y	768,416	772,361	875,983
	776,036*	777,434*	883,625*
Operating cost, \$/y	528,147	586,485	547,682
	516,012*	564,555*	528,972*
Total annualised cost, \$/y	1,296,563	1,358,846	1,423,665
	1,292,048*	1,341,989*	1,412,598*

*Results with flashing condensates from evaporation effects

Table 3: Results of optimisation for different number of evaporation effects for forward feed flow-pattern

Number of evaporation effects	Operating cost, \$/y	Investment cost, \$/y	Total annualised cost, \$/y
1	1,603,103	309,579	1,912,682
2	783,495	542,069	1,325,564
3	516,012	776,036	1,292,048
4	416,760	1,007,525	1,424,285

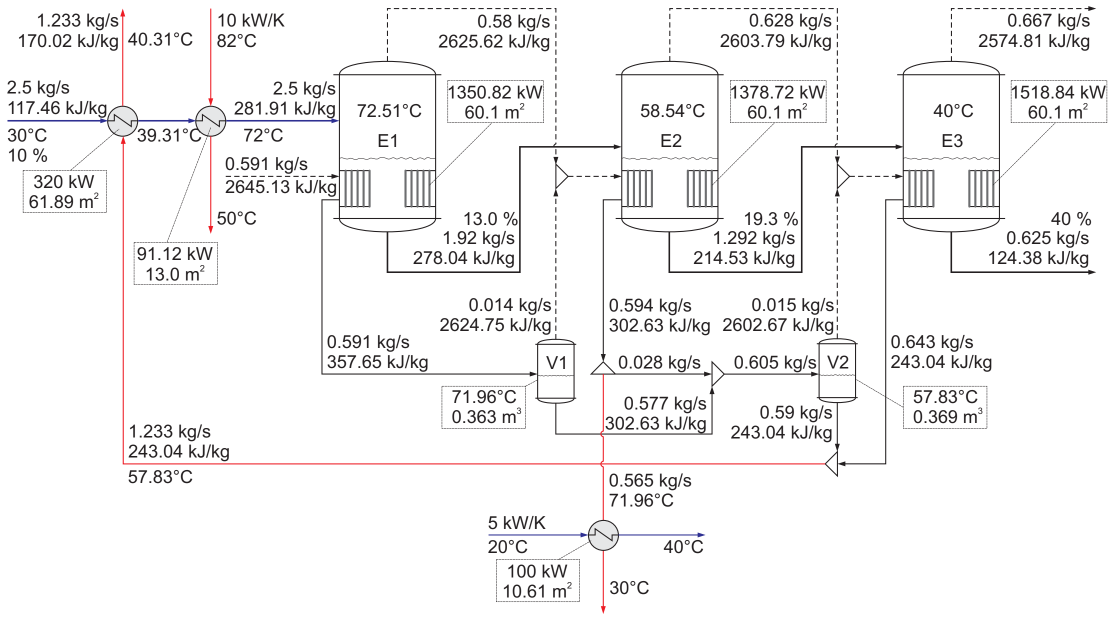

Figure 2: Optimal design of a heat-integrated multiple-effect evaporation system with background process hot and cold streams

5. Conclusions

A simultaneous optimisation and heat integration approach to MEES and HEN is presented in order to explore trade-offs between energy and capital costs within the overall network. The model of MEES from previous work (Ahmetović et al., 2016) was extended to incorporate multi-stage flash vessels for improving energy efficiency within the overall system. Hot and cold streams from the background process are included in the superstructure to improve heat recovery in the system. The proposed superstructure, its corresponding MINLP model, and solution strategies were applied to a case study with different flow-patterns of MEES. The results indicate that the forward feed flow-pattern has the lowest minimum TAC compared to the backward and the parallel feed flow-patterns. The optimum number of effects was found to be three for the forward feed flow-pattern. In the future work, the proposed model in this paper would be extended by incorporating mechanical and thermal vapour recompression systems in order to improve energy efficiency within the overall network.

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References

Ahmetović E., Suljkanović M., Kravanja Z., Maréchal F., Ibrić N., Mustafić N., Kermani M., Bogataj M., 2016. Analysis, Synthesis and Optimization of Multiple-Effect Evaporation Systems using Mathematical

Programming, AIChE 2016 Annual meeting, Computing and Systems Technology Division, Process Design II, 430h, San Francisco, CA, USA.
Bylund G., 2015, Dairy Processing Handbook, Tetra Pak International S.A., www.tetrapak.com/about/book-store, accessed 15.06.2017.
Chantasiriwan S., 2017, Distribution of juice heater surface for optimum performance of evaporation process in raw sugar manufacturing, Journal of Food Engineering, 195, 21-30.
Chawankul N., Chuaprasert S., Douglas P., Luewisutthichat W., 2001, Simulation of an agitated thin film evaporator for concentrating orange juice using AspenPlusTM, Journal of Food Engineering, 47, 247-253.
Hillenbrand J.B., Westerberg A.W., 1988, The synthesis of multiple-effect evaporator systems using minimum utility insights—I. A cascaded heat representation, Computers & Chemical Engineering, 12, 611-624.
Kumar D., Kumar V., Singh V.P., 2013, Modeling and dynamic simulation of mixed feed multi-effect evaporators in paper industry, Applied Mathematical Modelling, 37, 384-397.
McCabe W.L., Smith J.C., Harriott P., 2005. Unit operations of chemical engineering. Seventh edition. McGraw Hill, New York, USA.
Onishi V.C., Carrero-Parreño A., Reyes-Labarta J.A., Ruiz-Femenia R., Salcedo-Díaz R., Fraga E.S., Caballero J.A., 2017, Shale gas flowback water desalination: Single vs multiple-effect evaporation with vapor recompression cycle and thermal integration, Desalination, 404, 230-248.
Périn-Levasseur Z., Palese V., Maréchal F., 2008. Energy integration study of a multi-effect evaporator, 11th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, Prague (Czech Republic).
Rosenthal R.E., 2015, GAMS: A User's Guide: GAMS Development Corporation, Washington, DC, USA.
Ruan Q., Jiang H., Nian M., Yan Z., 2015, Mathematical modeling and simulation of countercurrent multiple effect evaporation for fruit juice concentration, Journal of Food Engineering, 146, 243-251.
Sharan P., Bandyopadhyay S., 2015, Integration of Multiple Effect Evaporators with Background Process, Chemical Engineering Transactions, 45, 1591-1596.
Sharan P., Bandyopadhyay S., 2016a, Energy Integration of Multiple Effect Evaporators with Background Process and Appropriate Temperature Selection, Industrial & Engineering Chemistry Research, 55, 1630-1641.
Sharan P., Bandyopadhyay S., 2016b, Integration of thermo-vapor compressor with multiple-effect evaporator, Applied Energy, 184, 560-573.
Sharan P., Bandyopadhyay S., 2017, Solar assisted multiple-effect evaporator, Journal of Cleaner Production, 142, Part 4, 2340-2351.
Sharma S., Rangaiah G.P., Cheah K.S., 2012, Multi-objective optimization using MS Excel with an application to design of a falling-film evaporator system, Food and Bioproducts Processing, 90, 123-134.
Smith R., Jones P.S., 1990, The optimal design of integrated evaporation systems, Heat Recovery Systems and CHP, 10, 341-368.
Turton R., Bailie R.C., Whiting W.B., Shaeiwitz J.A., 2009. Analysis, synthesis, and design of chemical processes. Prentice Hall, Upper Saddle River, New Jersey, USA.
Walmsley T.G., 2016, A Total Site Heat Integration design method for integrated evaporation systems including vapour recompression, Journal of Cleaner Production, 136, Part B, 111-118.
Westerberg A.W., Hillenbrand J.B., 1988, The synthesis of multiple-effect evaporator systems using minimum utility insights—II. liquid flowpattern selection, Computers & Chemical Engineering, 12, 625-636.
Xiao F., Smith R., 2001, Case Studies of Heat Integration of Evaporation Systems, Chinese Journal of Chemical Engineering, 9, 224-227.
Yee T.F., Grossmann I.E., 1990, Simultaneous optimization models for heat integration—II. Heat exchanger network synthesis, Computers & Chemical Engineering, 14, 1165-1184.