EVALUATING HEAT INTEGRATION SCHEME FOR BATCH PRODUCTION OF OLEIC ACID

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ABSTRACT

Research works on Process System Engineering are well established for conventional sectors of bulk chemical manufacturing, such as that in the oil and gas and petrochemical industries. However, relatively less attention has been given to the area of bio-related and fine chemical production. This paper demonstrates the use of process synthesis and analysis tools in evaluating heat integration schemes for a batch production of oleic acid from palm olein using immobilised lipase.

Oleic acid is a fatty acid found in animal and vegetables oils. It is mainly used in the food industry to make synthetic butters and cheeses, as well as to flavour baked goods, candy, ice-cream and sodas. In the first section of this paper, a case study involving the production of oleic acid from palm olein using immobilised lipase is modelled in a commercial batch process simulation software SuperPro Designer v5.0. Apart from performing the mass and energy balances on the overall process, detailed scheduling of the batch manufacturing has also been carried out. This provides the necessary information to carry out the batch heat integration scheme, i.e. the exact start and end time, as well as the duration when the process hot and cold streams exist.

In the second section of this paper, technique is presented for integrating hot and cold process streams in the oleic acid production case study. Unlike continuous processes, apart from the heat transfer driving force, time dimension is another important decision variable to be considered in a batch heat integration work. In this case study, the maximum energy recovery (MER) objective is achieved without the use of heat storage system.

Keywords: Batch processes, modelling and optimisation, heat integration, pinch analysis, fine chemical processing.

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1.0 INTRODUCTION

The systematic approach in addressing the energy integration in a process plant began during the global energy crisis in the late 1970s. Since then, pinch technology has been accepted globally as an effective tool in designing a cost optimal heat exchanger network (HEN). Towards the late 1980s, the work on HEN design has become rather well established. A few good reviews of the well established HEN techniques can be found in the literature.[1-4] However, most of the researches on HEN synthesis have focused on continuous process. Much less work has been carried out for the synthesis of batch HEN problem.

The very early work addressing energy integration for batch processes were reported by Vaselenak *et al.*[5] They worked on the heat recovery between vessels whose temperatures vary during operations. They presented a heuristic rule for the concurrent heat exchange and a mixed-integer linear programming solution for the restricted target temperature. Yet, these authors did not consider the time dependence of streams in which some streams may only exist in the plant for a certain period of time. They also investigated the opportunity for rescheduling and the generation of rescheduling superstructures in their later work.[6]

Besides the heuristics and numerical solutions, heat integration scheme for batch processes have also been studied by other researchers who used the technique of pinch analysis. One of the earliest work to divert pinch analysis from continuous to batch heat integration was reported by Kemp and Macdonald.[7, 8] They developed the targeting tool called *time-dependent heat cascade analysis* that allows the minimum utility and heat storage targets to be obtained for a maximum energy recovery (MER) network. These authors also reported batch HEN design and identified rescheduling opportunities in their later publications.[9-12]

Concurrent with the seminal work of Kemp and Macdonald,[6, 7] Linnhoff and his co-workers[13, 14] also presented their own batch HEN synthesis work based on the conventional approach of HEN synthesis in continuous mode.[1] They developed a *time slice model* to obtain the utility targets for the batch HEN. However, their work is confined to the use of a simple scheduling diagram. No representation of which streams were thermodynamically capable of exchanging heat was obtained. In a later publication Obeng and Ashton[15] made use of the cascade analysis to calculate the energy targets for the time slice model. Yet, the utility target identified by the time slice model is not as accurate as that by the time-dependent heat cascade analysis by Kemp & co-workers.[7-9]

Since then, later work on batch heat integration schemes are mainly focusing on the mathematical optimisation approaches.[16-25] While mathematical optimisation approaches offer the flexibility of incorporating other considerations (e.g. scheduling, multi-product plant, etc.), its main disadvantage lies in the limitation of allowing designer to incorporate their decision making view during the network synthesis stage.

In this paper, heat integration is conducted on a case study involving the production of oleic acid from palm olein using immobilised lipase. Due to the batch operation nature of the manufacturing process, the case study is firstly modelled in the batch process simulation software of SuperPro Designer v5.0. The simulation model provides the overall mass and energy balances and detailed scheduling of the batch manufacturing process. Next, pinch analysis technique is used to locate the minimum hot and cold utility targets for the case study. This involves the use of the time-dependant heat cascade analysis technique.[7-9] In this case study, it is found that the MER objective is achieved without the use of heat storage system.

2.0 CASE STUDY DESCRIPTION

FIGURE 1 shows the simulation flowsheet for the production of oleic acid from palm olein using immobilised lipase, modelled in the batch simulation software of SuperPro Designer v5.0. Palm olein, a mixture that contains oleic, linoleic, stearic, palmitic and glycerine, is firstly fed with water into a Batch Stir Tank Reactor (BSTR). Immobilised lipase is next added into the BSTR for the selective conversion of olein compound of the palm olein mixture into oleic acid. The effluent from the BSTR which consist of the converted oleic acid and other unreacted compounds is filtered using a plate-and-frame (P&F) filter press to separate the immobilised lipase for reuse in the BSTR.

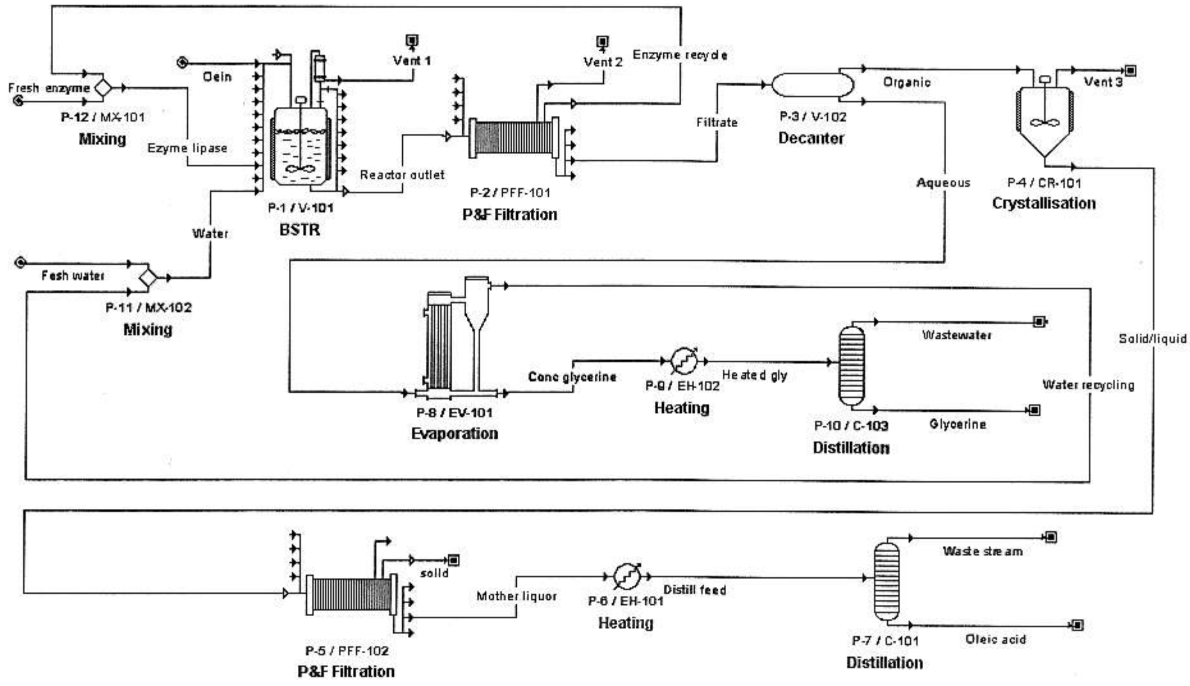

FIGURE 1. Process Flowsheet for Oleic Acid Production

Due to the insolubility of palm olein and fatty acids in water, the filtrate from the press filter will form a liquid mixture of aqueous and the organic phases. This two phases filtrate is then sent to a decanter where it will be settled into the different aqueous and organic phases. The aqueous phase mainly consists of water and glycerine while the organic phase is made up of the unreacted palm olein, fatty acids and trace amount of water and glycerine. The aqueous phase is sent to a triple-effect evaporator in which the water-glycerine solution (sweet-water) is concentrated to a glycerine purity of 80%. Water recovered from the evaporator is recycled to the BSTR. Purification is next proceed in a distillation column where glycerine is purified to 99% and is sold as a by-product of the process.

On the other hand, the organic phase from the decanter is sent to a crystalliser where the stearic and palmitic acids are crystallised. The crystallised stearic and palmitic acids is then separated from the mother liquor using another P&F filter press. The mother liquor is next sent to a vacuum distillation column where oleic acid of 80% purity is recovered as the bottom product while other components emitted as waste in the column top product stream.

3.0 BATCH HEAT INTEGRATION

Unlike in the case of continuous processes, time is another important variable to consider for heat integration work on batch processes. A process stream may only exist during a certain period of time in a process. Thus, heat transfer from the hot process streams to the cold process streams is constrained not only by temperature, but also by time. TABLE 1 shows the stream data of the case study that is extracted from the simulation results. Process streams which need to undergo heating operation is termed as cold streams while hot streams are designated to streams that require cooling. As shown in TABLE 1, there are four process cold streams (C1-C4) and nine process hot streams (H1-H9) in this case study. Before heat integration is carried out, this process requires a total amount of 1329.20 kWh for hot utility and 1517.46 kWh for cold utility.

TABLE 1: Steam Data for Oleic Acid Case Study

ID	Process stream	T_s (°C)	T_t (°C)	Time (h)	Heat flow (kW)	Heat load (kWh)	FC_p (kW/K)
C1	Heater P-6	-10.00	310.00	9.80-11.30	626.20	939.30	1.957
C2	Reboiler of P-7	321.38	321.74	9.80- 11.30	115.10	172.65	319.722
C3	Reboiler of P-10	261.80	262.80	6.60-11.60	12.09	60.45	12.090
C4	Heater P-9	98.70	230.00	6.60-11.60	31.36	156.80	0.239
H1	Effect 1 of P-8	163.00	50.00	6.10-11.10	15.47	77.35	0.137
H2	Effect 2 of P-8	133.00	50.00	6.30-11.30	12.81	64.07	0.154
H3	Effect 3 of P-8	98.70	50.00	6.30-11.30	96.76	483.81	1.987
H4	Condenser of P-7	262.50	76.60	9.80-11.30	150.80	226.20	0.811
H5	Condenser of P-10	172.00	78.80	6.60-11.60	35.23	176.15	0.378
H6	P-7 top stream	76.60	50.00	9.80-11.30	2.09	3.14	0.079
H7	P-7 bottom stream	321.74	50.00	9.80-11.30	279.30	418.95	1.028
H8	P-10 top stream	78.80	50.00	6.60-11.60	0.69	3.44	0.024
H9	P-10 bottom stream	262.80	50.00	6.60-11.60	12.87	64.35	0.060

Kemp and co-workers[8,9] showed that utility targets for repeated batch processes are exactly the same as in the case of continuous process, providing heat storage system is installed to transfer heat across different time intervals. Hence, utility targets for continuous process provide the upper bound on the MER objective to be achieved for given repeated batch processes. However, heat storage system is often not preferable due to its technical constraints which include heat losses and inefficiency. One should firstly determine the necessity of heat storage installation by identifying the upper bound of MER objective, i.e. by assuming the process is operated in continuous mode.

TABLE 2 shows the heat cascade analysis that is carried out for the case study that would be operated in continuous mode, with the minimum approach temperature $\Delta T_{\min}$ of 10°C. As shown, ΔH is the net heat exchange between the hot and cold streams in each temperature interval. Cumulative heat load (denoted by Cum. ΔH) is the cumulative heat exchange from one temperature interval to another, vertically from the highest to the lowest temperature interval. A negative Cum. ΔH value signifies negative heat transfer gradient, implying that heat is transferred from lower temperature to higher temperature interval. Clearly, such arrangement is physically infeasible. To ensure feasible heat cascade, the largest (absolute) negative Cum. ΔH value, i.e. 380.30 kWh is added at the top temperature interval. This value represents the external hot utility that will be cascaded down to the temperature interval to give positive heat cascade throughout the temperature intervals, and finally yields an external cooling load of 568.52 kWh at the lowest temperature interval. The point where the Cum. ΔH achieves zero represents the pinch point of the network.

TABLE 2: Infeasible and Feasible Heat Cascades for Continuous Mode Operation

T	ΔT	Infeasible heat cascade		Feasible heat cascade	
		ΔH	Cum. ΔH	ΔH	Cum. ΔH
326.74			0		380.30
	0.36	-172.65		-172.65	
326.38			-172.65		207.65
	9.64	0		0	
316.74			-172.65		207.65
	1.74	2.68		2.68	
315			-169.97		210.33
	47.2	-65.78		-65.78	
267.8			-235.74		144.55
	1	-61.84		-61.84	
266.8			-297.59		82.71
	9	-12.54		-12.54	
257.8			-310.13		70.17
	0.3	-0.33		-0.33	
257.5			-310.46		69.84
	22.5	2.83		2.83	
235			-307.63		72.67
	68	-72.67		-72.67	
167			-380.30		**0** **(PINCH)**
	9	7.39		7.39	
158			-372.91		7.39
	30	45.18		45.18	
128			-327.73		52.57
	24.3	55.35		55.35	
103.7			-272.38		107.92
	10	34.72		34.72	
93.7			-237.66		142.64
	19.9	266.78		266.78	
73.8			29.12		409.42
	2.2	25.60		25.60	
71.6			54.72		435.02
	26.6	280.27		280.27	
45			334.99		715.29
	50	-146.77		-146.77	
-5			188.23		568.52

Next, time-dependant heat cascade analysis technique[7-9] is used to locate the minimum utility targets for the case study operated in a single batch operation mode, without the installation of batch storage system. Process hot or cold streams are located at their individual time interval before the utility targeting procedure is carried out. TABLE 3 shows the infeasible heat cascade for each time interval. Resembling the situation in TABLE 2, negative Cum. ΔH values are observed in temperature intervals 6.60-11.60.

To achieve feasible heat cascade for all time intervals, the largest (absolute) negative Cum. ΔH value found in each time interval is added at the top temperature interval. This yields positive heat cascade throughout all the time intervals, as shown in TABLE 4. Note that in TABLE 4, the pinch temperature form a locus of zero Cum. ΔH (numbers in bold), consistent with the finding of Kemp and co-workers.[7-9] Adding the targets over the whole period of the batch give the minimum hot utility as 380.30 kWh and cold utility as 568.52 kWh, identical to the utility targets of the case study that would be operated in continuous mode (TABLE 2).

TABLE 3: Infeasible Heat Cascade According for Each Time Interval

T	ΔT	Time (h)											
		6.10-6.30		6.30- 6.60		6.60- 9.80		9.80- 11.10		11.10- 11.30		11.30- 11.60	
		ΔH	Cum. ΔH	ΔH	Cum. ΔH	ΔH	Cum. ΔH	ΔH	Cum. ΔH	ΔH	Cum. ΔH	ΔH	Cum. ΔH
326.74			0.00		0.00		0.00		0.00		0.00		0.00
	0.36	0.00		0.00		0.00		-143.87		-28.77		0.00	
326.38			0.00		0.00		0.00		-143.87		-28.77		0.00
	9.64	0.00		0.00		0.00		0.00		0.00		0.00	
316.74			0.00		0.00		0.00		-143.87		-28.77		0.00
	1.74	0.00		0.00		0.00		2.24		0.45		0.00	
315.00			0.00		0.00		0.00		-141.64		-28.33		0.00
	47.20	0.00		0.00		0.00		-54.81		-10.96		0.00	
267.80			0.00		0.00		0.00		-196.45		-39.29		0.00
	1.00	0.00		0.00		-39.29		-16.27		-3.25		-3.02	
266.80			0.00		0.00		-39.29		-212.72		-42.54		-3.02
	9.00	0.00		0.00		0.00		-10.45		-2.09		0.00	
257.80			0.00		0.00		-39.29		-223.18		-44.64		-3.02
	0.30	0.00		0.00		0.06		-0.33		-0.07		0.00	
257.50			0.00		0.00		-39.23		-223.50		-44.70		-3.02
	22.50	0.00		0.00		4.39		-1.63		-0.33		0.34	
235.00			0.00		0.00		-34.85		-225.13		-45.03		-2.68
	68.00	0.00		0.00		-39.51		-25.23		-5.05		-3.04	
167.00			0.00		0.00		-74.36		-250.36		-50.07		-5.72
	9.00	0.00		0.00		5.83		0.91		0.18		0.45	
158.00			0.00		0.00		-68.53		-249.45		-49.89		-5.27
	30.00	1.03		1.03		32.78		8.18		0.61		1.49	
128.00			1.03		1.03		-35.76		-241.26		-49.28		-3.78
	24.30	0.83		1.77		38.71		11.31		1.43		1.21	
103.70			1.86		2.80		2.96		-229.96		-47.85		-2.57
	10.00	0.34		0.73		23.69		7.64		1.19		1.10	
93.70			2.20		3.52		26.65		-222.32		-46.67		-1.47
	19.90	0.68		11.33		175.66		64.63		12.24		2.18	
73.80			2.88		14.86		202.31		-157.70		-34.42		0.71
	2.20	0.08		1.25		16.89		6.17		1.16		0.05	
71.60			2.96		16.11		219.20		-151.53		-33.26		0.75
	26.60	0.91		15.15		204.19		50.26		9.14		0.56	
45.00			3.87		31.26		423.38		-101.27		-24.12		1.31
	50.00	0.00		0.00		0.00		-122.31		-24.46		0.00	
-5.00			3.87		31.26		423.38		-223.58		-48.59		1.31

4.0 CONCLUSION

In this work, heat integration study is conducted for a case study involving the production of oleic acid from palm olein using immobilised lipase. The process is firstly modelled in a batch process simulation software to obtain the overall mass and energy balances and the detailed scheduling of the batch manufacturing. Next, pinch analysis technique is employed to target the minimum hot and cold utility consumptions of the process. An amount of 948.90 kWh of energy has been recovered for the case study. This represents the savings of 71.4% and 62.5% for hot and cold utilities respectively. It is also found that the maximum energy recovery (MER) objective is achieved without the use of heat storage system. This turns out to be an advantage for the process as many technical problems associated with heat storage system can be avoided.

TABLE 4: Infeasible Heat Cascade According for Each Time Interval

T	ΔT	Time (h)											
		6.10-6.30		6.30- 6.60		6.60- 9.80		9.80- 11.10		11.10- 11.30		11.30- 11.60	
		ΔH	Cum. ΔH	ΔH	Cum. ΔH	ΔH	Cum. ΔH	ΔH	Cum. ΔH	ΔH	Cum. ΔH	ΔH	Cum. ΔH
326.74			0.00		0.00		74.36		250.36		50.07		5.72
	0.36	0.00		0.00		0.00		-143.87		-28.77		0.00	
326.38			0.00		0.00		74.36		106.49		21.30		5.72
	9.64	0.00		0.00		0.00		0.00		0.00		0.00	
316.74			0.00		0.00		74.36		106.49		21.30		5.72
	1.74	0.00		0.00		0.00		2.24		0.45		0.00	
315.00			0.00		0.00		74.36		108.72		21.74		5.72
	47.20	0.00		0.00		0.00		-54.81		-10.96		0.00	
267.80			0.00		0.00		74.36		53.91		10.78		5.72
	1.00	0.00		0.00		-39.29		-16.27		-3.25		-3.02	
266.80			0.00		0.00		35.07		37.64		7.53		2.70
	9.00	0.00		0.00		0.00		-10.45		-2.09		0.00	
257.80			0.00		0.00		35.07		27.19		5.44		2.70
	0.30	0.00		0.00		0.06		-0.33		-0.07		0.00	
257.50			0.00		0.00		35.13		26.86		5.37		2.70
	22.50	0.00		0.00		4.39		-1.63		-0.33		0.34	
235.00			0.00		0.00		39.51		25.23		5.05		3.04
	68.00	0.00		0.00		-39.51		-25.23		-5.05		-3.04	
167.00			0.00		0.00		**0.00**		**0.00**		**0.00**		**0.00**
	9.00	0.00		0.00		5.83		0.91		0.18		0.45	
158.00			**0.00**		**0.00**		5.83		0.91		0.18		0.45
	30.00	1.03		1.03		32.78		8.18		0.61		1.49	
128.00			1.03		1.03		38.61		9.10		0.79		1.94
	24.30	0.83		1.77		38.71		11.31		1.43		1.21	
103.70			1.86		2.80		77.32		20.40		2.22		3.15
	10.00	0.34		0.73		23.69		7.64		1.19		1.10	
93.70			2.20		3.52		101.01		28.04		3.41		4.25
	19.90	0.68		11.33		175.66		64.63		12.24		2.18	
73.80			2.88		14.86		276.67		92.66		15.65		6.43
	2.20	0.08		1.25		16.89		6.17		1.16		0.05	
71.60			2.96		16.11		293.56		98.84		16.81		6.47
	26.60	0.91		15.15		204.19		50.26		9.14		0.56	
45.00			3.87		31.26		497.74		149.09		25.95		7.03
	50.00	0.00		0.00		0.00		-122.31		-24.46		0.00	
-5.00			3.87		31.26		497.74		26.78		1.49		7.03

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