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著者	Song Chunfeng, Liu Qingling, Ji Na, Deng Shuai, Zhao Jun, Kitamura Yutaka
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Intensification of microalgae drying and oil extraction process by vapor recompression and heat integration

Chunfeng Song [a, b], Qingling Liu [a, b] *, Na Ji [a, b], Shuai Deng [b], Jun Zhao [b], Yutaka Kitamura [c]

[a] *Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Technology, Tianjin University, 92 Weijin Road, Nankai District, Tianjin, P.R. China*

[b] *Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), Ministry of Education, Tianjin 300072, China*

[c] *Graduate School of Life and Environmental Sciences, University of Tsukuba, 1-1-1, Tennodai, Tsukuba, Ibaraki 305-8572, Japan*

* Corresponding author. Tel: +86-022-8740-1255.

E-mail: liuql@tju.edu.cn

Abstract

Reducing energy penalty caused by drying and oil extraction is the most critical challenge in microalgae biodiesel production. In this study, vapor recompression and heat integration are utilized to optimize the performance of wet microalgae drying and oil extraction. In the microalgae drying stage, the hot exhaust stream is recompressed and coupled with wet microalgae to recover the condensate heat. In the oil extraction stage, the exergy rate of recovered solvent is also elevated by compressor and then exchanged heat with feed and bottom stream in the distillation column. Energy and mass balance of the intensified process is investigated and compared with the conventional microalgae drying-extraction process. The simulation results indicated that the total energy consumption of the intensified process can be saved by 52.4% of the conventional route.

Keywords: Microalgae, drying, oil extraction, vapor recompression, heat integration

1. Introduction

Depletion of fossil fuel and its adverse environmental impact (*i.e.* greenhouse gases emission) contributed the rapid development of renewable energy (Khoo et al., 2013). Biofuel, recognized as biodiesel, bio-syngas, bio-oil, bioethanol, and bio-hydrogen, is one of the best alternatives to substitute fossil fuels (Guo et al., 2015). It has shown several significant advantages such as sustainability, environmental friendly and good adaptability (Yu et al., 2015). Moreover, biofuel (*e.g.* biodiesel) can reduce net carbon dioxide emissions by up to 78% on a life-cycle basis compared with conventional diesel fuel (Tyson, 2001; West et al., 2008; Piemonte et al., 2015).

Commonly, biofuel can be produced from wheat, palm, corn, soybean, sugarcane, rapeseed, oil crops, sugar beet and maize, which is defined as the first generation (Naiket al., 2010). Nevertheless, the first generation is claimed to be not very successful since it affects food security and global food markets (Noraini et al., 2014). Recently, the second generation has been exploited as an alternative of the first generation, such as waste and lignocellulose biomass. Compared to the existing feedstock, the second generation biofuel becomes more attractive and promising due to its economic and environmental benefit (Tran et al., 2013; Alaswad et al., 2015; Bhuiya et al., 2015). But, there are still a number of technical challenges (*i.e.* high production cost) that need to be overcome before their commercial application (Naik et al., 2010).

Microalgae, recognized as the third generation, are one of the most promising alternative sources for biofuel (Halim et al., 2012). Under suitable culture conditions, some microalgae species are able to accumulate up to 50%~70% of oil/lipid per dry weight, which can be converted to biodiesel (Pragya et al., 2013; Rashid et al., 2014). However, various technological and economic challenges need to be overcome before its industrial scale production, such as the difficulty of oil extraction and transesterification (Milledge and Heaven, 2013; Chen et al., 2015). The complex production route (usually including microalgae cultivation, harvesting, drying, lipid extraction and transesterification) leads to a high biodiesel production cost (Cooney et al., 2009; Torres et al., 2013).

Drying and lipid extraction are considered as the most energy-intensive sections (approximately 90% of the total cost) in microalgae biodiesel production process (Lardon et al., 2009). It is necessary and significant to develop cost-effective technologies for efficient microalgae drying and lipid extraction. In 2013, Aziz et al. applied heat circulation technology in microalgae drying process to reuse the waste sensible and latent heat. The simulation results indicated that the required drying energy of proposed process can be reduced by up to 90% of that required in conventional drying process. In 2015, Mubarak et al. evaluated different oil extraction methods, and concluded that organic solvents (such as hexane) are the most popular approach due to low capital investment. Although the development of wet microalgae drying and oil extraction process is remarkable, a comprehensive evaluation of is lacked. Further effort is still necessary to improve the microalgal biodiesel production efficiency and reduce the energy consumption.

The objective of this study is to optimize the existing microalgae drying and oil extraction process by vapor recompression and heat integration. In order to reduce energy consumption, the condensate heat in the drying stage is recovered to heat subsequent wet microalgae. In the oil extraction stage, the recovered solvent of distillation column is recompressed to heat the feed and bottom stream. As a result, the energy penalty caused by preheater and reboiler is avoided by using compression work.

Energy and material balance of the conventional and intensified process are simulated and validated by experiment. Then, the techno-economic feasibility is briefly discussed.

2. Processes description

2.1 Conventional microalgae drying and oil extraction process

The typical microalgae drying and oil extraction process is shown in Fig. 1. To obtain microalgae oil for the further biodiesel production, wet microalgae is dried by conventional dryer (*i.e.* rotary and spray dryer) (Show et al., 2015). In this work, the dryer is assumed to consist of heater and evaporator. Generally, the vapor phase after drying is exchanged heat with the fresh wet microalgae to reduce the energy requirement of pre-heating. However, the performance of heat exchange is usually poor due to the low grade of condensate heat. Therefore, additional heat (provided by heater) is necessary to remove most H_2O from solid biomass. The dried microalgae is then mixed with chemical solvent to extract lipid from microalgae cell in lysis reactor. The obtained mixture is further separated to collect a liquid stream composed of solvent and microalgae oil. Meanwhile, a solid stream of biomass rich in carbohydrates and proteins is also gathered. The waste solid biomass can be reused to produce biogas (*e.g.* pyrolysis) but not considered in this work. Microalgae oil mixture is further extracted through distillation to recover excess chemical solvent. The obtained microalgae oil is collected at the bottom of distillation column and sent to transesterification section. During oil extraction section, the heat requirement includes two parts, including pre-heater (Heater-2) and reboiler. To reduce energy consumption, the distillate stream is usually exchanged its waste heat with oil/solvent mixture before Heater-2.

2.2 Intensified microalgae drying and oil extraction process

Fig. 2 depicts the intensified microalgae drying and oil extraction process by vapor recompression and heat integration. To reduce the high energy consumption caused by drying and oil extraction, the waste heat associated with top streams in dryer and distillation column is tried to be recovered. Previous references indicated that when the effective heat coupling between the hot and cold streams is achieved, the waste sensible and latent heat could be potentially recycled in the chemical engineering process without additional heat utilization (Kansha et al., 2009; Waheed et al., 2014). By using vapor recompression, the gas phase after drying is further compressed to elevate the exergy rate and exchanged with the following wet microalgae. At the same time, the dried microalgae are also exchanged heat with wet microalgae to recover the waste sensible heat. In the oil extraction section, the exergy rate of distillate stream (recovered solvent) is firstly elevated by vapor recompression. Then, one part of compressed stream exchanges heat with oil/solvent mixture. The other part is used to heat the bottom stream (rich oil). By the effective waste heat recovery, the energy-intensive units (such as pre-heater and reboiler) can be avoided in the intensified process.

3. Material and methods

3.1 Material

Chlorella sp. is defined as the selected microalgae species in the process simulation. According to the report of Becker (2007), the composition (dry matter) of *Chlorella vulgaris* includes lipid (14%~22%), carbohydrates (12%~17%) and proteins (51%~58%). In addition, Kanda et al. (2011, 2012) indicated that the moisture content of natural blue-green microalgae (*Chlorella* sp. belongs to green microalgae) varied in the range of 78.2%~93.4%. Based on these data, the wet microalgae of this work is simulated as lipid (2%), carbohydrates (1.5%), proteins (5.5%) and water (91%). In detail, free fatty acids and triolein are taken into account corresponding to 5% and 95% of lipid content. Free fatty acids are represented by oleic acid (West et al., 2008; Song et al., 2015). Carbohydrate and protein are represented by sucrose and L-phenylalanine (Piemonte et al., 2015). Hexane is used as solvent for microalgae lipid extraction due to its high extraction efficiency compared with other organics (Peralta-Ruiz et al., 2013). Properties of the dominant components in microalgae are listed in Table 1.

3.2 Methods

3.2.1 Simulation

The main processing units of each route include dryer, distillation columns, heat exchangers, pumps, mixers, phase separators. Dryer was used to remove the moisture from wet microalgae. Mixers were used for blending solvents with biomass. Heaters and coolers were utilized for heating and cooling streams. Heat exchangers were used to recover the waste heat generated in the process. Pumps were used to transfer liquid streams. Separation of liquid/solid phases was carried out using separators. Solvent recovery was carried out by distillation column.

PRO/II simulator (Simulation Sciences Inc.) was used to simulate the conventional and intensified wet microalgae drying and oil extraction processes. The software package includes chemical component libraries, thermodynamic method libraries, unit operation modules, the thermodynamic data manager (Wang et al., 2014). In this study, the nonrandom two liquid (NRTL) thermodynamic method provided in PRO/II was used to calculate the mixture properties based on functional-groups that constitute the components. The built-in programmer, called ‘‘Calculator’’, was used to establish more accurate and system-specific algorithms for the specified parameter (Zhao et al., 2008). The programmer “Optimizer” was used to maximize the production rate of biodiesel and minimize the exergy loss of heat exchangers according to the defined parameters and operating conditions (Wang et al., 2014).

To simplify the complexity of simulation, the following assumptions are made: 1) all of the heat exchangers are counter-current type. 2) The minimum temperature approach is set at 10 °C. 3) The isentropic efficiency of the compressors and pumps is assumed to be 80%. 4) The heat and pressure loss during the biodiesel production process are assumed to be negligible. 5) In order to facilitate the understanding, heat exchanger (HX) is assumed that consisted of two parts, including heat donor (HD) and heat receptor (HR). 6) The dryer is simulated by the combination of heater and evaporator.

3.2.2 Experiment

The laboratory scale drying experiment was carried out to confirm the performance of heat integration. The spray dryer was utilized, and process flow diagram of drying process is shown in Fig. 3. *Chlorella* powder was provided by Xian Saiyang Biological Technology Co., Ltd. The powder was dried at 80°C for 24 h and stored at -20 °C. Distilled water was added into microalgae powder in order to reproduce harvested and concentrated wet microalgae (water content was assumed as 90%). The wet microalgae was sprayed through a metering pump with a downward flow and atomized into evaporator by nozzle. Compressed air was used to atomize the wet microalgae into droplets with small diameters. To simulate the compressed steam from the moisture in the microalgae, a steam generator (Lvding Energy Technology Co., Ltd.) was used to provide the desired evaporation heat. The generated hot steam was further heated by an electric heater forward the entrance of evaporator, and the flow rate of the steam was measured using a steam flow meter. Heat exchange occurred between the atomized droplets and superheated steam. The dry microalgae was collected at the bottom of evaporator, cyclone and filter.

4. Results and discussion

4.1 Energy and material balance

4.1.1 Conventional microalgae drying and oil extraction process

The energy and material balance of the conventional microalgae drying and oil extraction process is simulated and shown in Fig. 4. The properties of critical streams are listed in Table 2. As shown in the results, the wet microalgae are firstly heated to separate H_2O from biomass. To reduce the heat requirement (11.6 MW) of Heater-1, part of the condensate heat (3.4 MW) of gas phase (S8) after dryer is recovered by heat exchanger 1 (HX-1). The residual condensate heat (7.8 MW) is wasted by Cooler-1. In oil extraction stage, the dried microalgae (S12) is mixed with hexane (S13) to extract oil. By lysis reactor, carbohydrate and protein (S16) are separated from crude microalgae oil (S17). Then, the crude oil mixture is pre-heated (0.8 MW) by Heat-2 to phase transition temperature. By distillation purification, the excess hexane (S23) and pure microalgae oil (S22) are obtained as the top and bottom product, respectively. In distillation column, the input heat of reboiler is 2.15 MW, and the wasted heat by condenser is 1.1 MW. To reuse the condensate heat of recovered hexane (S24), heat exchanger 2 (HX-2) is integrated before Heater-2, and 2.8 MW can be recycled in the process. After heat recovery, the residual condensate heat (5.1 MW) is removed by Cooler-2. As a result, the total heat requirement of conventional microalgae drying and oil extraction process is 14.55 MW.

It can be observed that the waste heat of conventional route is substantial, including 7.8 MW by Cooler-1, 1.1 MW by condenser, and 5.1 MW by Cooler-2. That is because the performance of HX-1 and 2 is poor. For HX-1, although the temperature of hot stream (S8) is high, the latent heat of vapor phase is paired with the sensible heat of feedstock. Thus, the heat coupling is not optimal, and most of condensation heat is wasted by Cooler-1. For HX-2, the condensation heat of recovered hexane (S24) is low grade. Therefore, only part of waste heat can be recycled in the process. Although it seems that there is potential to improve the energy utilization of the conventional configuration by redesigning the heat exchangers (HX-1 and HX-2), the heat grade of hot stream in HX-1 and 2 is not high enough to achieve optimal heat coupling. The exergy rate elevation of hot stream before both heat exchange processes becomes particularly necessary. As a result, the utilization of additional work (by vapor recompression) would be an effective way to reuse both sensible and latent heat from waste hot stream.

4.1.2 Intensified microalgae drying and oil extraction process

Fig. 5 illustrates the energy and material balance of the intensified microalgae drying and oil extraction process. The properties of critical streams are listed in Table 3. As shown in the results, the waste heat generated in drying and oil extraction sections is reutilized by vapor recompression and heat integration. In drying section, the vapor phase (S7) is compressed (1.07 MW) and exchanged (by HX-2) with wet microalgae (S3) to recover the condensation heat (9.4 MW). Meanwhile, the waste sensible heat (3.6 MW) of liquid phase (S12) is recovered by heat exchanger 1 (HX-1). In oil extraction section, the distillate stream (recovered solvent, S24) at the top of column is compressed (1.7 MW) by compressor (Com. 2) to elevate the exergy rate. Then, part of compressed stream (S28) is used to heat (5.2 MW) the bottom stream (microalgae oil, S20) by heat exchanger 4 (HX-4). The other part of hot stream (S25) is used to heat (3.6 MW) the subsequent oil mixture (S17) before distillation treatment.

By the effective process integration, the energy-intensive units (*i.e.* pre-heater and reboiler) are avoided in the intensified microalgae drying and lipid extraction process. The energy requirement of the advanced process is mainly attribute to compressors (Com. 1 and 2), 2.7 and 1.07 MW. The recovered sensible and latent heat by each heat exchanger (HX-1 to 4) is 3.6, 9.4, 3.5 and 5.2 MW, respectively. It can be observed that 21.7 MW waste heat can be recovered in the intensified microalgae drying and oil extraction process by using 2.77 MW additional compression work. To assume the conversion efficiency as 0.4 between electricity and heat (Song et al., 2014), 2.77 MW compression work is equal to 6.93 MW thermal energy. Compared to the conventional microalgae drying and oil extraction approach, the energy requirement was reduced by 52.4%.

4.2 Experiment validation

To verify the heat integration performance of the proposed drying process, the temperature at different places of HX-1 and 2 are tested by K-type thermocouples. The temperature-enthalpy of both heat exchangers in the proposed process is shown in Fig. 6. Fig 6 (a) illustrates the sensible heat exchange occurred in the HX-1. The sensible heat of dry microalgae (hot stream) is coupled with the sensible heat of wet microalgae (cold stream). The temperature of dry microalgae decreases from 96 °C to 42 °C. By contrast, the temperature of wet microalgae increases from 25 °C to 50 °C. By using HX-1, the recovered sensible heat contributes to preheat the wet microalgae for evaporation treatment. Fig. 6 (b) depicts the heat exchange curve in HX-2. The involved heat includes the sensible and latent heat of moisture and the sensible heat of microalgae. With the temperature of hot steam varied from 200 °C to 80 °C, the wet microalgae is heated to 119 °C. This means that almost all of the evaporation heat required to evaporate water in the droplet is provided by the condensation heat of superheated steam. The experiment results indicate that an effective heat coupling is formed in the proposed drying process for latent and sensible heat exchange, which can minimize the total exergy destruction.

4.3 Techno-economic analysis

To evaluate the techno-economic feasibility, the capital and operational cost of conventional and intensified microalgae drying and oil extraction process is investigated. It is well known that the economic estimations could be conducted using the conceptual cost estimation methods (West et al., 2008). But these methods often have relatively poor accuracies of estimation, with a range of expected accuracy from +30% to -20% (Turton, 2003). As an alternative, commercial simulation softwares, which have the professional packages, can make accurate cost estimation (Seider et al., 2004). For example, Aspen Plus (including “Aspen Capital and In-Plant Cost Estimator” modules) has rich experience in commercial plants and engineering design. It provides specifications for detailed design, estimation and economic data, allowing quick modifications of the process equipment and sensitivity analysis (Lee et al., 2011). Thus, the economic estimation of this work is conducted by Aspen Capital and In-Plant Cost Estimator of Aspen Plus.

Table 4 summarizes the estimation results of the two routes. For the conventional process, the total capital and operational investment is 0.911 and 6.11M$ (million US dollar), respectively. For the intensified process, the total capital and operational investment is 1.117 and 1.16 M$. The high operational cost of conventional processes is mainly due to the utilization of excess heaters and reboilers (dryer and distillation). By contrast, although using compressors would increase the capital cost (approximately 22.6% that of conventional process), the operational cost of the intensified microalgae drying and oil extraction process can be significantly reduced by up to 81.0% that of conventional process. As a result, the total investment (sum of capital and operational cost) of intensified microalgae drying and oil extraction process can be reduced by 67.6% (4.744 M$). That can be explained by the fact that the effective heat coupling and process integration facilitates the waste heat recirculation in the advanced process. Techno-economic analysis results indicated that the intensification of microalgae drying and oil extraction process by vapor recompression and heat integration can significantly reduce the investment of biodiesel production.

5. Conclusion

In this study, the microalgae drying and oil extraction process has been intensified by vapor recompression and heat integration. In the intensified process, the waste condensate heat was recovered by vapor recompression, and then integrated with the cold streams. The simulation results indicated that the energy consumption of intensified process was reduced by 52.4% compared to the convention route. Although the capital cost of the intensified process increased 22.6% due to the utilization of compressors, the operational cost can be reduced by approximately 81.0%. The results of this work will be useful for reducing production cost of biodiesel industry.

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Figure captions

Fig. 1. Conventional microalgae drying and oil extraction process for biodiesel production (base case).

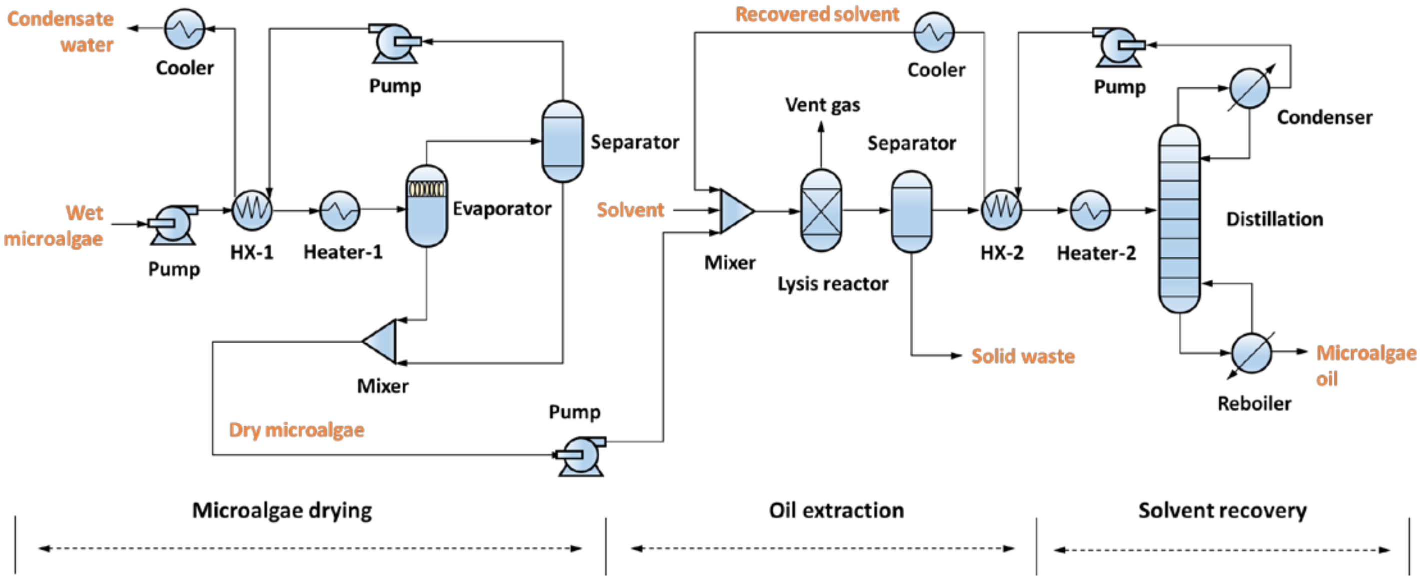
Fig. 2. Intensified microalgae drying and oil extraction process by vapor recompression and heat integration.

Fig. 3. Laboratory-scale spray dryer for wet microalgae drying.

Fig. 4. Energy balance of the conventional microalgae drying and oil extraction process (base case).

Fig. 5. Energy balance of the intensified microalgae drying and oil extraction process.

Fig. 6. Temperature-enthalpy of heat exchanger 1 and 2 (HX-1 and 2) in the proposed process.



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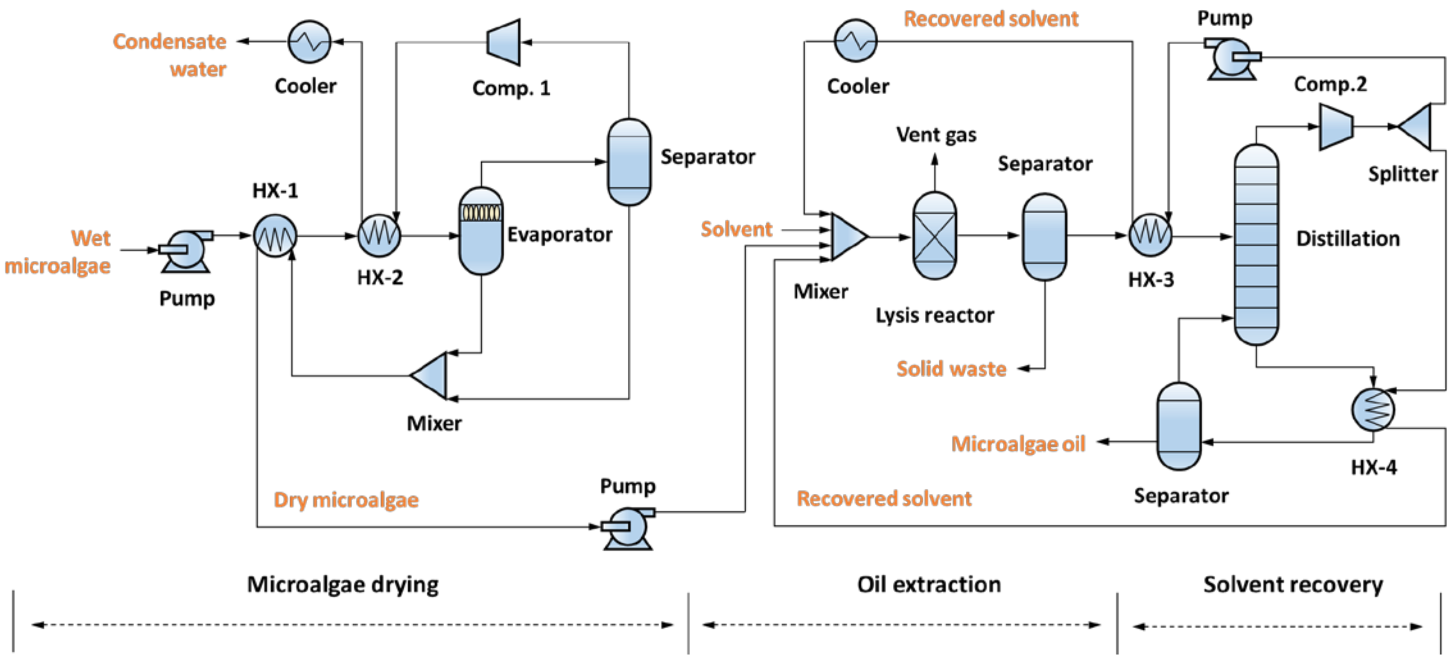

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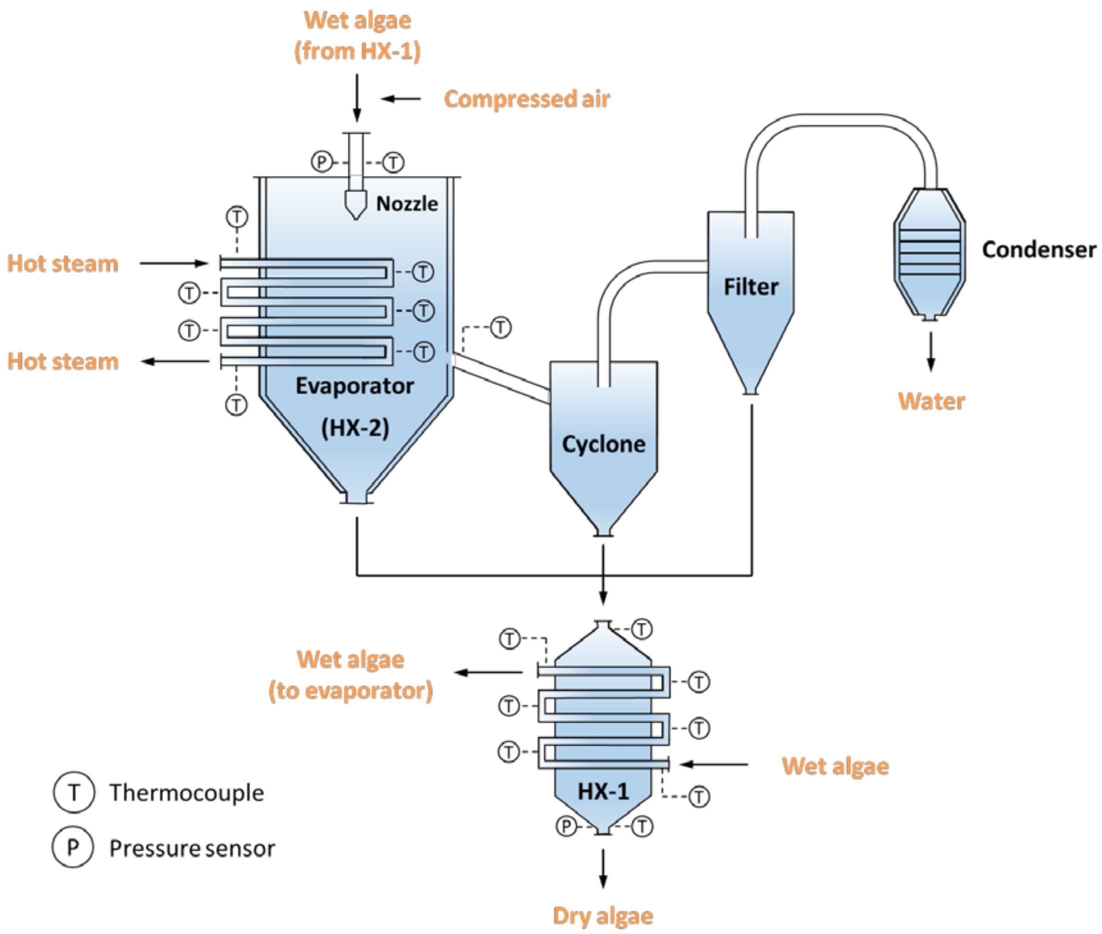

Fig. 3. Laboratory-scale spray dryer for wet microalgae drying.

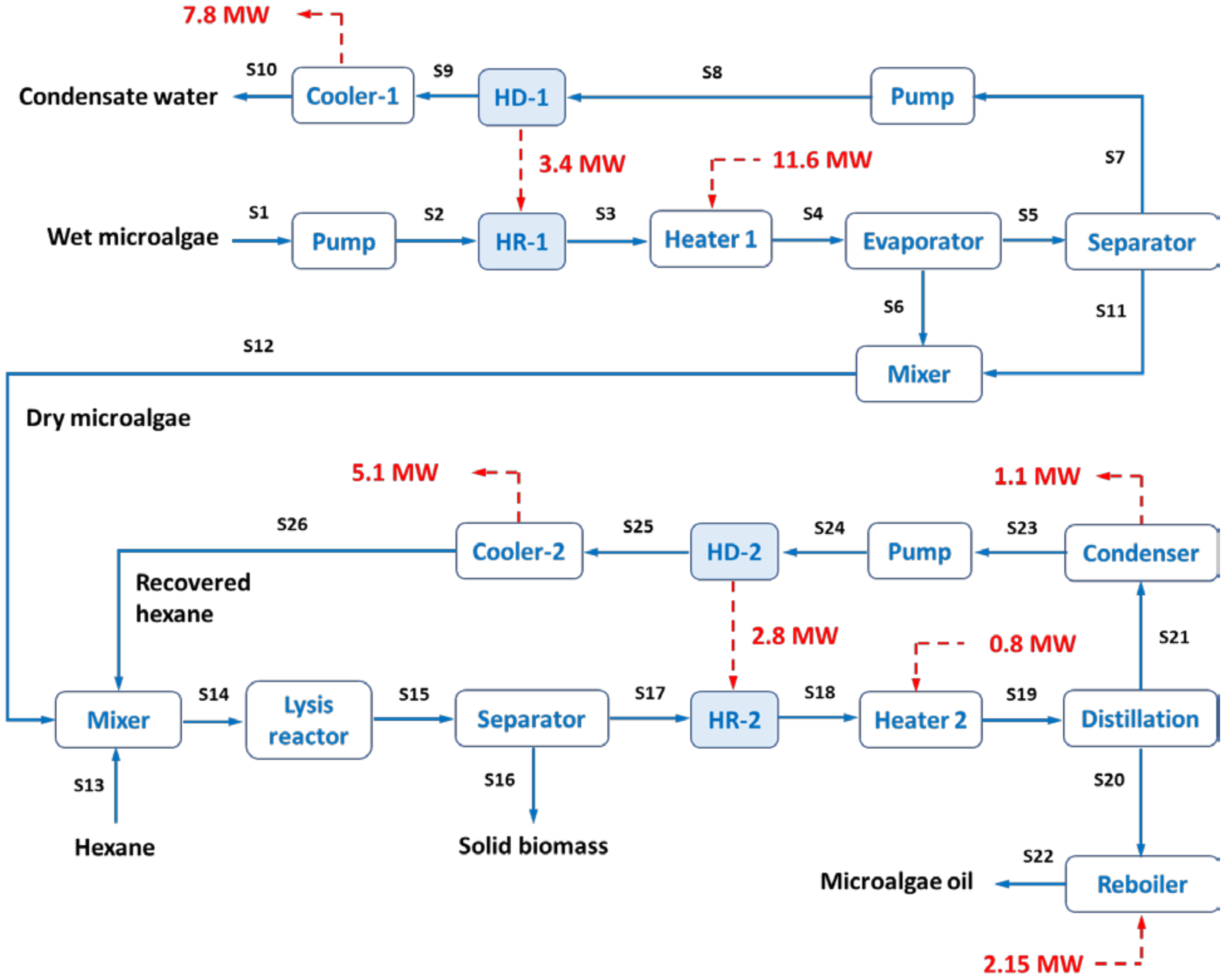

Fig. 4. Energy balance of the conventional microalgae drying and oil extraction process (base case).

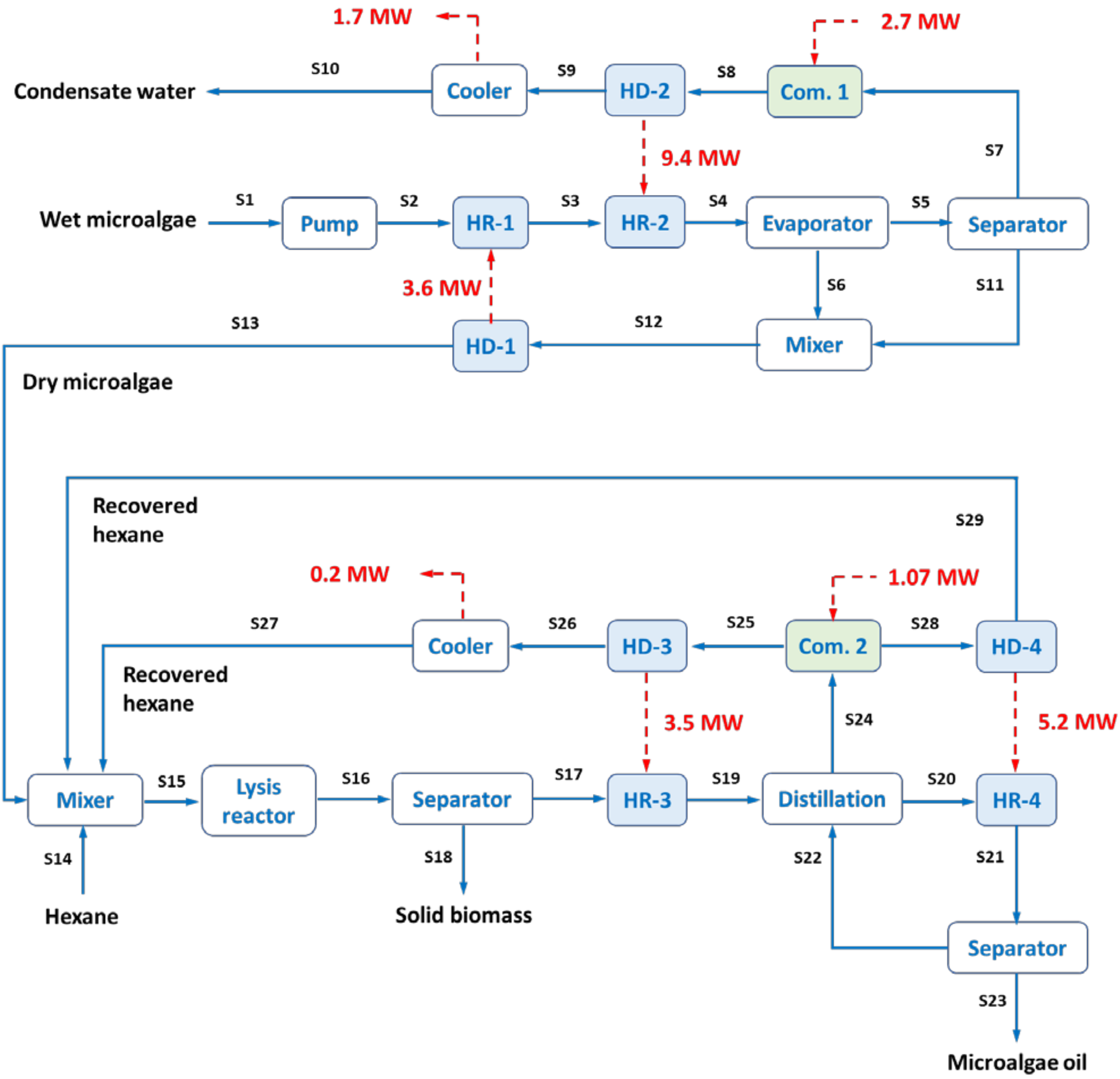

Fig. 5. Energy balance of the intensified microalgae drying and oil extraction process.

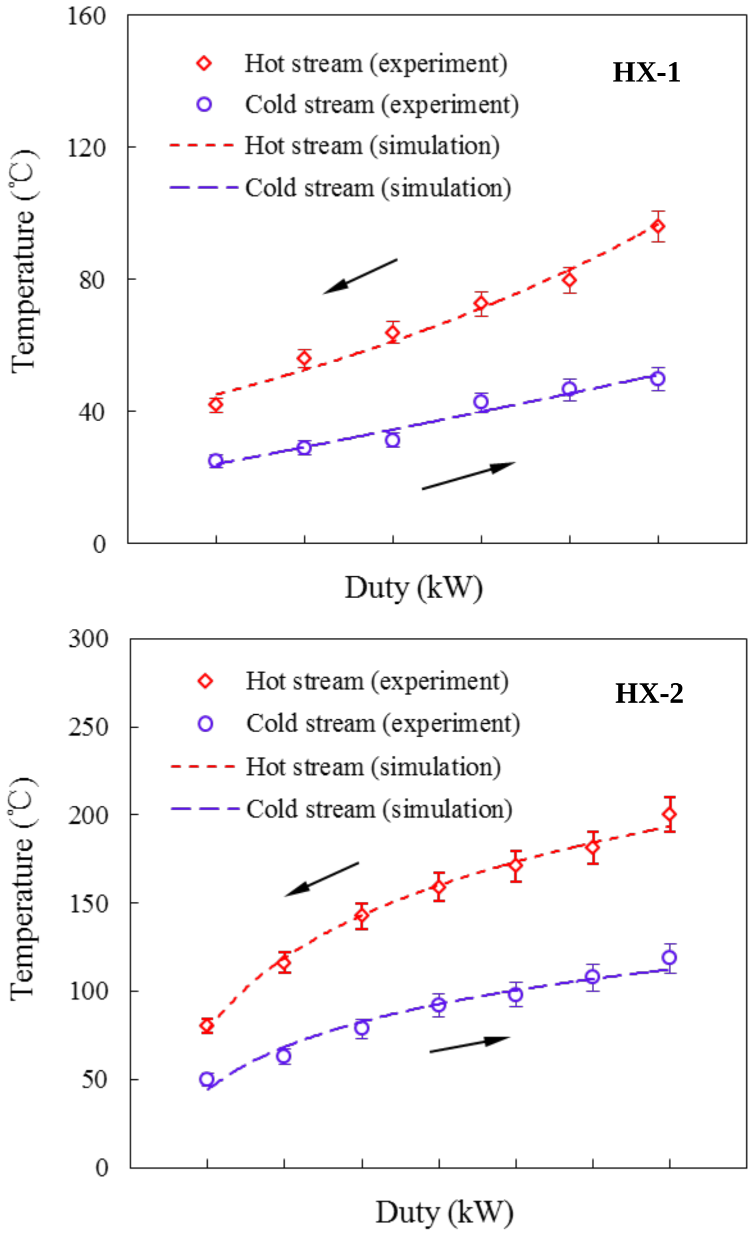

Fig. 6. Temperature-enthalpy of heat exchanger 1 and 2 (HX-1 and 2) in the proposed process.

Table 1

Thermodynamic properties of dominant components in microalgae.

Properties	Triolein	Oleic acid	Phenylalanine	Sucrose	Hexane
Chemical formula	$C_{57}H_{98}O_6$	$C_{18}H_{34}O_2$	$C_9H_{11}NO_2$	$C_{12}H_{22}O_{11}$	C_6H_{14}
Molar mass (kg/kmol)	885.43	282.46	165.2	342.3	86.18
Freezing point (°C)	—	13.0	—	—	—
Flash point (°C)	—	—	153.1	375.4	-26.0
Density (kg/m^3)	916.0	895.0	1290.0	1580.5	650.0
Boiling point (°C)	412.8	360.0	329.5	697.1	68.5
Critical temperature (°C)	588.8	507.9	580.9	789.9	234.2
Critical pressure (kPa)	1203.0	1390.0	3470.0	2690.0	2968.8

Table 2

Stream properties the conventional microalgae drying and oil extraction process.

	Drying								Oil extraction						
Stream No.	S1	S2	S3	S4	S7	S9	S10	S12	S17	S18	S19	S22	S23	S25	S26
Temperature (°C)	25	25	104	180	180	100	25	180	25	59	69	361	70	68	25
Pressure (kPa)	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101
Flow rate (kmol/h)	1000	1000	1000	1000	899.9	899.9	899.9	100.1	1265.5	1265.5	1265.5	19	1166.5	1166.5	1166.5
Composition															
Oleic acid	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.010	0.004	0.004	0.004	0.050	0.000	0.000	0.000
H_2O	0.910	0.910	0.910	0.910	0.999	0.999	0.999	0.101	0.013	0.013	0.013	0.000	0.014	0.014	0.014
Hexane	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.909	0.909	0.909	0.000	0.986	0.986	0.986
Sucrose	0.015	0.015	0.015	0.015	0.000	0.000	0.000	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Phenylalanine	0.055	0.055	0.055	0.055	0.000	0.000	0.000	0.549	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Triolein	0.019	0.019	0.019	0.019	0.001	0.001	0.001	0.190	0.074	0.074	0.074	0.950	0.000	0.000	0.000

Table 3

Stream properties the intensified microalgae drying and oil extraction process.

	Drying												Oil extraction								
Stream No.	S1	S2	S3	S4	S7	S8	S9	S10	S12	S13	S17	S19	S20	S21	S23	S24	S25	S26	S27	S28	S29
Temperature (°C)	25	25	104	135	135	308	308	308	135	25	25	68	140	361	360	71	427	35	25	427	113
Pressure (kPa)	101	101	101	101	101	245	245	245	101	101	101	101	101	101	101	101	490	490	490	490	490
Flow rate (kmol/h)	1000	1000	1000	1000	895	895	895	895	105	105	1265	1265	108	108	19	1169	300	300	300	869	869
Composition																					
Oleic acid	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.009	0.009	0.004	0.004	0.045	0.045	0.050	0.000	0.000	0.000	0.000	0.000	0.000
H_2O	0.910	0.910	0.910	0.910	0.999	0.999	0.999	0.999	0.142	0.142	0.013	0.013	0.093	0.093	0.000	0.038	0.038	0.038	0.038	0.038	0.038
Hexane	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.909	0.909	0.000	0.000	0.000	0.962	0.962	0.962	0.962	0.962	0.962
Sucrose	0.015	0.015	0.015	0.015	0.000	0.000	0.000	0.000	0.143	0.143	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Phenylalanine	0.055	0.055	0.055	0.055	0.000	0.000	0.000	0.000	0.525	0.525	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Triolein	0.019	0.019	0.019	0.019	0.001	0.001	0.001	0.001	0.181	0.181	0.074	0.074	0.862	0.862	0.950	0.000	0.000	0.000	0.000	0.000	0.000

Table 4

Techno-economical evaluation of different wet microalgae drying and oil extraction processes.

Performance indicator	Conventional process	Intensified process
Equipment cost (EC/M$)		
Reactors	0.177	0.177
Heaters	0.091	—
Evaporator	0.032	0.032
Distillation column	0.235	0.103
Separators	0.054	0.081
Heat exchangers	0.113	0.225
Pumps	0.012	0.004
Compressors	—	0.254
Contingencies (25% of EC/M$)	0.179	0.219
Fixed capital cost (FCC/M$)	0.893	1.095
Working capital cost (2% of FCC/M$)	0.018	0.022
Total capital costs (M$)	0.911	1.117
Operating costs (M$/yr)*	6.11	1.16

* The electricity price is defined as 0.06 $/kWh. The operation time of plants is assumed as 7000 h/yr.

The unit cost is estimated to be million US dollar (M$).