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Study of the Flash Cycle Using Liquid Heat Recirculation (FC-LHR) for Energy Saving in Industry

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The flash cycle (FC) has been proposed as a power cycle for heat recovery at low temperature. The FC is not constrained by the pinch point of the heat exchanger in the heat source in contrast to the Rankine cycle (RC), because the temperature difference for heat exchange is reduced by sensible heat exchange. However, the energy efficiency of the conventional FC is insufficient because of the low efficiency of power generation. It is considered that the low efficiency is mainly due to the flash rate at low temperature being low theoretically. Moreover, the heat of the saturated liquid is not used sufficiently. Hence, an energy-saving FC was proposed as an improvement of the conventional FC in this research. The proposed FC includes not only an expander line from the flash evaporator to generate power, but also a liquid heat recirculation line from the flash evaporator to use the sensible heat of the saturated liquid. The liquid heat recirculation increases the efficiency of power generation.

1. Introduction

The Industry wastes a huge amount of sensible heat at low temperature, and wasted low-temperature (<200 °C) heat accounts for a large proportion of wasted heat. In Japan, the wasted low-temperature heat accounts for 70 % of the generation of the wasted heat in industry (Sato, 2006). In using energy efficiently, it is important to recover the wasted heat cascading. Moreover, renewable energy has attracted attention around the world. For example, geothermal energy and solar heat are utilized low temperature heat for thermal or electric energy (Keroneos et al., 2003). Low efficiency of power generation is an important problem in the conversion of thermal energy into electric energy, and results from a low-temperature heat and sensible heat source.

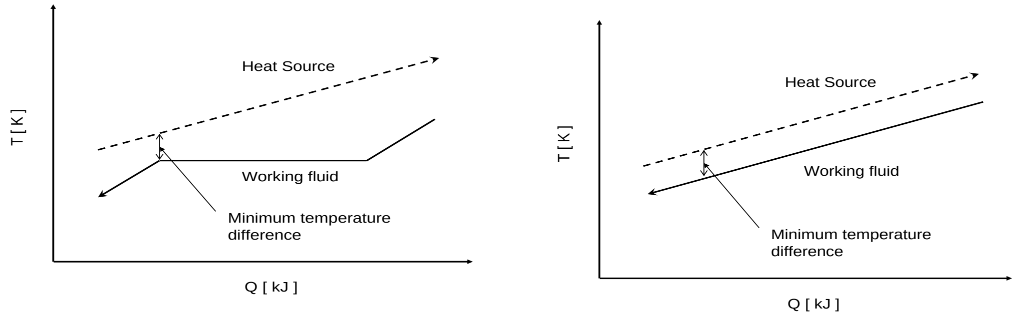

Figure 1: Temperature difference in the evaporator (left: ORC, right: OFC)

Nowadays, the organic Rankine cycle (ORC) is attracting attention in efforts to improve the efficiency of power generation using a low-temperature heat source. In the ORC, low-temperature heat is recovered through the vaporization of the working fluid – e.g. using parametric optimisation (Dai et al., 2009),

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trilateral cycles (Fischer, 2011), exergy evaluation (Heberle and Brüggemann, 2010), general analysis of renewables (Koroneos et al., 2003), zeotripic mixtures (Wang and Zhao, 2009). When employing the ORC, the maximum temperature difference in the evaporator is greater than the temperature at the pinch point of the heat exchanger (Figure 1, left), and heat energy provided by the heat source is thus not used efficiently.
To solve the problem of energy being wasted in a heat exchanger, the supercritical Rankine cycle (SRC) (Chen et al., 2011; Fischer, 2011) and flash cycle (FC) and organic flash cycle (OFC) (Ho et al., 2012a; Ho et al., 2012b) have been proposed for heat recovery at low temperature. For these cycles, there is no constraint by the pinch point in contrast to the case for the RC , because the temperature difference of the heat exchange can be reduced by sensible heat exchange (Ho et al., 2012b) (Figure 1, right).
However, when employing the SRC, the supercritical point of the working fluid is a condition of high pressure and high temperature. Thus, to use the waste heat of low temperature, pumping requires much electric energy for compensation. When employing the OFC, the efficiency of power generation by the conventional FC is insufficient. The main reason is considered to be that the flash rate at low temperature is theoretically low. Moreover, the heat of the saturated liquid is not used sufficiently. Hence, the energy-saving OFC was proposed as an improvement of the conventional OFC in this research. It is noted that the proposed FC includes not only an expander line from the flash evaporator to generate power but also a liquid heat circulation (LHC) line from the flash evaporator to use the sensible heat of the saturated liquid.

2. OFC system

2.1 Conventional OFC system

The conventional OFC system basically consists of an evaporator (HX1), flash evaporator (FE1), expander (EX1), condenser (HX2/HX4), cooler (HX3) and pump (P1), as shown in Figure 2. The stream S1 is fed into the evaporator (HX1), and heat from the heat source is then received. An effluent stream from HX1 (S2) is fed into the flash evaporator (FE1), and then divided into two streams (S2→FE1→S3, S6), namely the vapour phase stream (S3) and liquid phase stream (S6). S3 is fed into the expander (EX1) to generate power (S3→EX1→S4). The expanded stream (S4) is fed into the condenser (HX2), and S4 is condensed (S4→HX2→S5). The condensed stream S5 is fed into a mixer (M1). Liquid stream (S6) is fed into a valve (V1) and then depressed under adiabatic expansion. S7 is fed into the cooler (HX3), and S7 is cooled by S5 (S7→HX3→S8). The cooled stream S8 is mixed with S5 in M1 (S5, S8→M1→S9). Figure 2 shows a condenser (HX4), which can replace HX2 and HX3. The mixed stream S9 is fed into the pump (P1), and the stream is pumped by the feed pressure of S1 (S9→(S4)→S10→P1→S1).

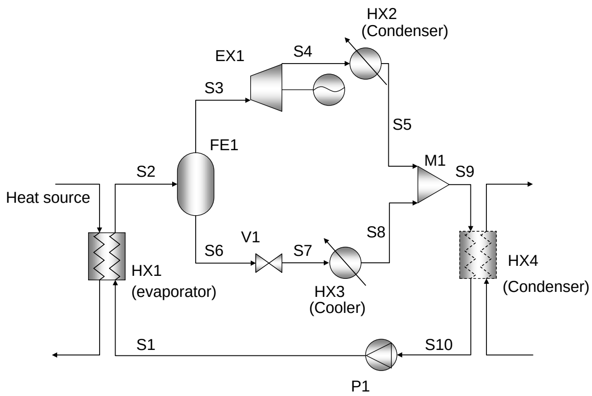

Figure 2: Conventional OFC system

The amount of vapour in FE1 is calculated from the enthalpy difference of the streams (S2, S3 and S6):

$$f_r = \frac{h_h' - h_l'}{h_l'' - h_l'} \tag{1}$$

where fr is the flash rate, h is enthalpy, prime and double-prime symbols respectively indicate the liquid phase and vapour phase, and subscripts h and l respectively indicate the high-pressure and low-pressure conditions.
In the case of a high temperature in the evaporator, the flash rate is low. For example, when using water as the working fluid, the S2 condition is set to 130 °C and 275 kPa, the S3 condition is set to 111.4 °C and

150 kPa, and the flash rate is 3.5 %. The efficiency of power generation is therefore low. Thus, a high flash rate is preferred for working fluids under the same temperature and pressure conditions (e.g., hydrocarbons). In this conventional process, the liquid internal energy of S6 is wasted in S7 by HX3. S6 has higher enthalpy than S8. The enthalpy difference needs to be used to increase the efficiency of power generation.

2.2 Proposed OFC system

A new system is proposed to improve the efficiency of power generation. The system is equipped with an LHR line from the flash evaporator to use the sensible heat of the saturated liquid.

Figure 3 illustrates the system. The stream S1 is fed into an evaporator (HX1), and heat from the heat source is then received. The effluent stream from HX1 (S2) is fed into the flash evaporator (FE1), and the stream is divided into two streams (S2→FE1→S3, S8), namely the vapour-phase stream (S3) and liquid-phase stream (S8). S3 is fed into the expander (EX1) to generate power (S3→EX1→S4). The expanded stream (S4) is fed into the condenser (HX2), and S4 is condensed (S4→HX2→S5). The condensed stream S5 is fed into a pump (P1), and the stream S5 is then pumped to the condition of S6 (S5→P1→S6). The S6 stream is heated by a heater (HX3), and the heated stream (S7) is fed into a mixer (M1) (S6→HX3→S7→M1→S1). The liquid stream (S8) is fed into a pump (P2), and the stream is pumped (S8→P1→S9). The stream S9 is fed into a heater (HX4), and S9 is heated (S9→HX4→S10). The heated stream is fed into M1, and S10 is mixed with S7. In the conventional process, liquid sensible heat is wasted. In contrast, liquid sensible heat is recirculated by this line (S8→P2→S9→HX4→S10). Moreover, there is no mixing exergy loss due to M1, because the stream condition of S10 is set the same as that of S7. In the proposed process, input energy is reduced by these improvements.

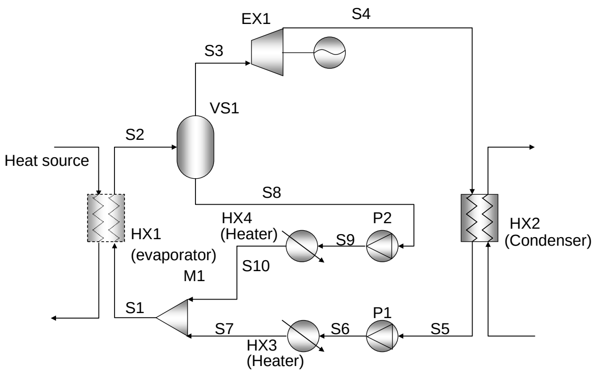

Figure 3: Proposed OFC system

3. System simulation

To evaluate the energy savings of the proposed FC, the energy balance was analyzed using the process simulator PRO/II (Invensys ver. 9.1). The Soave-Redlich-Kwong (SRK) was applied to this simulation as thermodynamics model. When using toluene as the working fluid, simulation conditions were a flow rate of 100 kmol h^{-1}, evaporator temperature of 150 °C, condenser temperature of 40 °C, temperature difference between the wasted sensible heat (heat source) and evaporator temperature of 10 °C, and adiabatic efficiency of the expander and pump of 70 %.

Simulation revealed that the proposed FC can generate output power whereas the conventional FC cannot. These results suggest that the proposed FC can achieve higher energy efficiency for heat recovery at low temperature compared with the conventional FC.

3.1 Conventional OFC system

Simulation results for the conventional OFC system are shown in Figure 4. The efficiency of power generation is defined as

$$\eta = \frac{\text{output energy}}{\text{input energy}} = \frac{W_{EX1}}{(H_{HX1}+W_{P1})} \tag{2}$$

where W is work and H is heating energy, and subscripts EX1, HX1 and Pl indicate the expander, heat exchanger, and pump respectively. In the simulation, the efficiency of power generation was 6.3 % (= EX1 / (HX1 + P1) = 34.4 / (543.4 + 1.2) × 100).

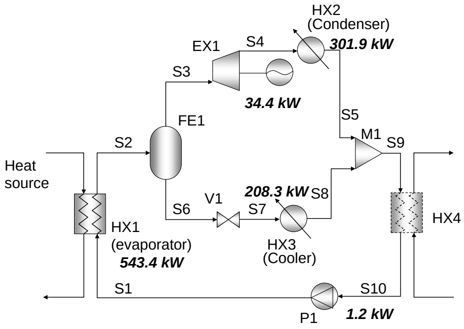

Figure 4: Conventional OFC system

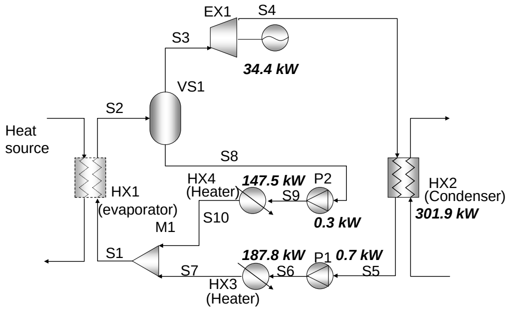

Figure 5: Proposed OFC system

3.2 Proposed system

Simulation results for the proposed OFC system are shown in Figure 5. The efficiency of power generation is defined as

$$\eta=\frac{\text{output energy}}{\text{input energy}}=\frac{W_{EX1}}{\left(H_{HX3}+H_{HX4}+W_{p1}+W_{p2}\right)} \tag{3}$$

where W is work and H is heating energy, and subscripts EX1, HX3, HX4, P1 and P2 indicate the expander, heat exchangers, and pumps.

Simulation revealed power generation efficiency of 10.2 % (= EX1 / (HX3 + HX4 + P1 + P2) = 34.4 / (187.8 + 147.5 + 0.7 + 0.3) × 100).

4. Results and discussion

The total input energy required for the proposed OFC system (Figure 5) was less than that required for the conventional system (Figure 4). In the case of the conventional OFC system, input energy of 94 % was wasted in the cooler. The proposed OFC system using the LHR required notably less total input energy. Numerically, the total input energy required was reduced by about 40% relative to the total input energy required for the conventional system, and the efficiency of power generation improved from 6.3% for the conventional system to 10.2% for the proposed system. The efficiency of power generation depends on the working fluid used. However, the efficiency of the power generation is better when using than proposed system than when using the conventional system in all cases of working fluid. To compare the energy efficiency, pentane and hexane were used for the conventional (Figure 4) and proposed (Figure 5) processes.

The results for the input temperature change are shown in Figure 6. The energy balance was analysed using the process simulator PRO/II. SRK was applied to this simulation as thermodynamics model. The simulation conditions were a flow rate of 100 kmol h^{-1}, temperature difference between the wasted sensible heat (heat source) and evaporator temperature of 10 °C, adiabatic efficiency of the expander and pump of 70 %, and flash rates (P1/P2) of the flash evaporator is set to 5. In all cases, the proposed system had better power generation efficiency than the conventional system throughout the temperature range.

To maximize the efficiency of power generation using the proposed system, it is important that the flash rate of the flash evaporator is optimized. Figure 7 compares the power generation efficiency for different flash rates (P1/P2) of the flash evaporator. Figure 8 presents the input power and heat versus flash rate. When using toluene as the working fluid, the optimization point of P1/P2 was less than 10. It is noted that a decrease in heat input affects the efficiency of power generation considerably.

To improve the efficiency of power generation, a multi-flash system is proposed to increase the generated power with increasing the vapour amount (Ho et al., 2012a). The double-flash system is shown in Figure 9. The power output improves from 34.4 kW for a single flash (Figure 4) to 41.2 kW for a double flash (Figure 9).

The efficiency of power generation is defined as

$$\eta=\frac{\text{output energy}}{\text{input energy}}=\frac{W_{EX1}+W_{EX2}}{\left(H_{HX1}+W_{p1}\right)} \tag{4}$$

where W is work and H is heating energy, and subscripts EX1, EX2, HX1 and P1 indicate the expander, heat exchangers, and pumps.

Simulation revealed power generation efficiency of 7.6 % (= (EX1 + EX2) / (HX1 + P1) = (34.4+6.8) / (543.4 + 1.2) × 100). The efficiency of power generation is lower than proposed OFC.

The double-flash system has a second flash evaporator (FE2) that increases amount of vapour. Therefore, the efficiency of power generation is greater than that for the single-flash system. Figure 10 presents T–s diagrams of the single-flash and double-flash systems. For the single-flash system, the energy input for vaporization of the working fluid is indicated by the area A_1, and the wasted heat is indicated by the area A_2. Potential energy for power generation is wasted in A_2 by adiabatic expansion. To reduce the potential energy loss, a double flash is applied in the OFC. The potential energy loss is reduced by the area A_3 in the figure. In the double-flash system, the area A_2 is used as vaporization heat of the working fluid. As a result, the efficiency of power generation achieved with the double flash is higher than that achieved with the single flash. Ho et al. also considered a two-phase OFC (2012b). Their system employs a two-phase turbine positioned between the heat exchanger of the heat source and the flash evaporator in Fig. 4, and can use the kinetic energy of the liquid.

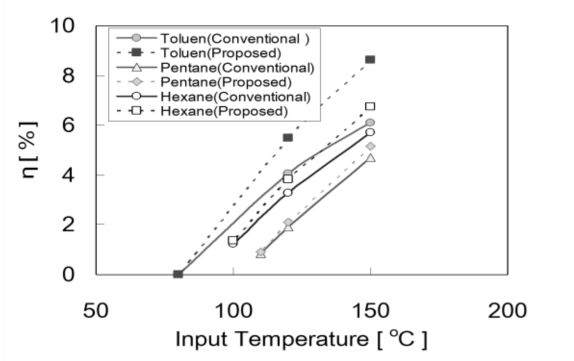

Figure 6: Comparison of power generation efficiency for different types of working fluid

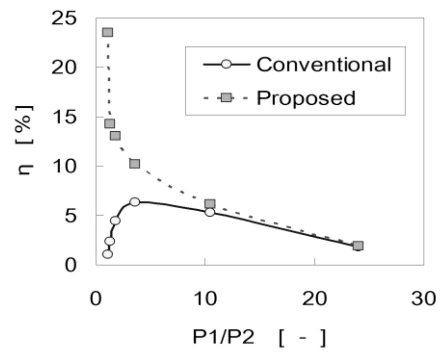

Figure 7: Comparison of the efficiency of power generation at different flash rates (P1/P2) of the flash evaporator (working fluid: toluene, temperature in evaporator: 150 °C, temperature in condenser: 40 °C)

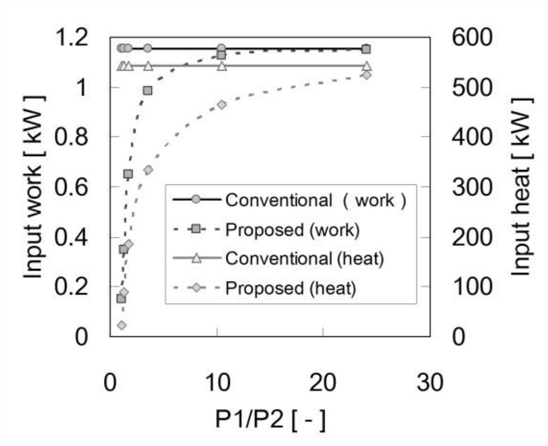

Figure 8: Input power and heat versus flash rate (working fluid: toluene, temperature in evaporator: 150 °C, temperature in condenser: 40 °C

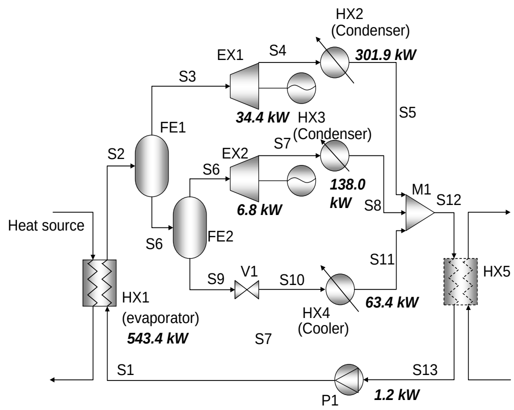

Figure 9: Double-flash system

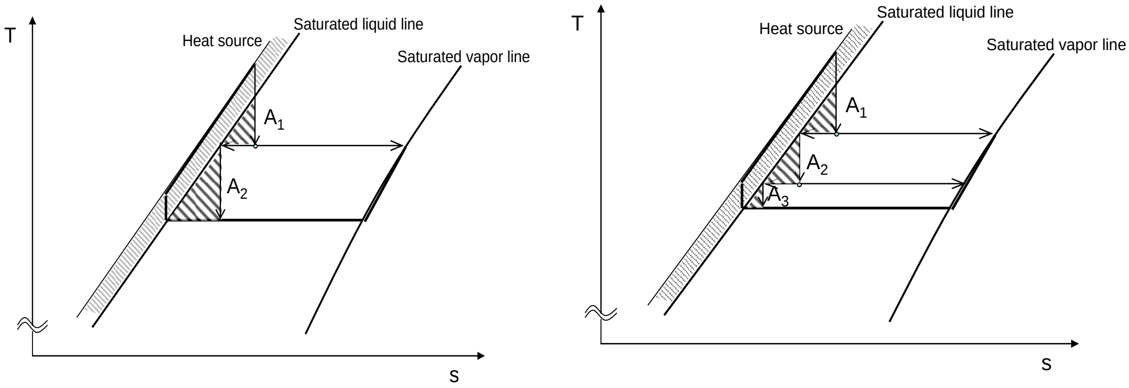

Figure 10: T–s diagrams for the OFC system (left: single flash, right: double flash)

5. Conclusions

An energy-saving FC was proposed as an improvement of the conventional FC. The proposed FC includes not only an expander line from the flash evaporator to generate power but also an LHR line from the flash evaporator to use the sensible heat of the saturated liquid. The efficiency of power generation is thus increased by the LHR. When using toluene as the working fluid, the efficiency of power generation was 6.3% for the conventional process and 10.2 % for the proposed system. Moreover, the efficiency of power generation is higher than conventional FC at lower flash rate (P1/P2). Therefore, there is every possibility of applying the proposed system to use much of the low-temperature heat wasted by industry. In addition, to maximize the efficiency of power generation, it is important that the flash rate of the flash evaporator be controlled since it strongly affects the efficiency.

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