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DETERMINATION OF THE OPTIMAL RANKINE CYCLE FOR WASTE HEAT RECOVERY

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Abstract In this paper, the optimal Rankine cycle for waste heat recovery is considered after process integration. The exergetic efficiency is used to measure the thermodynamic performance of the recovery system. Comparing with recovering a single waste heat stream, heat recovery after process integration is much more complicated due to the changeable specific heat given by the process grand composite curves. Therefore, this paper attempts to focus attention on the influence of grand composite curves on the optimization.

Keywords waste heat recovery, Rankine cycle, process integration

1 INTRODUCTION

Much work has been done in regard to the recovery of waste heat using Rankine cycles[1-9]. But most were concerned with a single waste heat flow without taking process integration into consideration[1-7] and were not optimized[8,9]. In many cases, negligence of taking process integration into consideration may possibly result in certain misleading measures for the heat recovery. For example, in a factory there are four streams two streams to be heated and two streams to be cooled(see the data in Table 1)[10]. And there is only utility usage, as shown in Fig.1

Table 1 Stream data

Stream number	Condition	c_p, kW·℃$^{-1}$	T_{in}, ℃	T_{out}, ℃
1	hot	1	250	120
2	hot	4	200	100
3	cold	3	90	150
4	cold	6	130	190

There are two alternatives for recovering waste heat. The first is the direct employment of the heat rejected by the hot streams for power generation, without involving any heat integration of the process streams. If the heat-to-power efficiency is 15% then 79.5kW electrical power can be generated from the heat recovered.

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The second alternative is the implementation of heat exchange between the hot and cold streams for process integration, followed by the further recovery of the residual heat. As shown in Fig.2, during the heat exchange stage, heat consumed is only to 70kW, as indicated by be enthalpy of the top end of the grand composite curve. And 470kW heat will thus be recovered, whereas 60kW heat (the enthalpy of the bottom end of the grand composite curve) can be further recovered. If, at this time, the heat-to-power efficiency is 10%, 6kW power can be generated. If the heat-to-power efficiency at the hot utility is 30%, the second alternative would bring about a total generation of 147kW, much more than that without considering process integration. Therefore, any attempt to recover waste heat should take process integration into consideration. This paper will only consider waste heat recovery involving process integration.

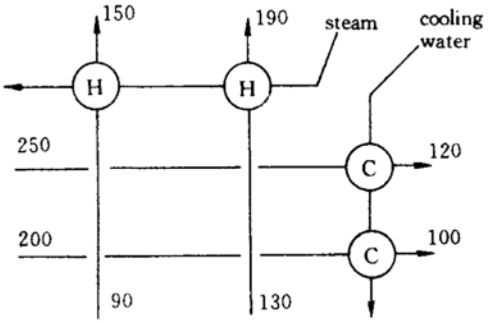

Figure 1 The original heat system

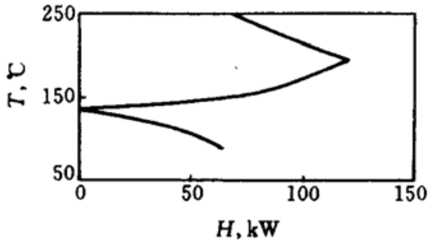

Figure 2 Grand composite curve

When a Rankine cycle for waste heat recovery is optimized after process integration, the situation is much more complicated than that with a single waste heat stream due to the changeable specific heat given by the process grand composite curves (GCC), as shown in Fig.3 Therefore this paper will focus attention on the influence of GCC contour on the optimization.

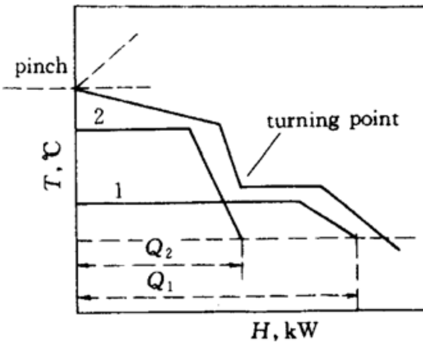

Figure 3 Changeable specific heat of GCC

2 OPTIMIZATION PROCESS

The thermodynamic performance of a waste heat power recovery system can be measured by the exergetic efficiency, which can be expressed as

$$\eta_e = \frac{W}{E_0} = \frac{Q_0}{E_0} \frac{Q}{Q_0} \frac{W}{Q} = \frac{1}{\Omega_0} \frac{Q}{Q_0} \eta_t \tag{1}$$

For any specific system, at a certain assigned GCC, E_0, Q_0 and Ω_0 are constant. So the objective function can be transformed as follows

$$Y_e = \eta_t Q / Q_0 \tag{2}$$

It is well known that when the boiling temperature of a Rankine cycle is high, the thermal efficiency of the cycle is greater, but generally, the waste heat recovery rate, Q/Q_0, is lower, as shown by curve 2 comparing with curve 1 in Fig. 3. Therefore, there is an optimal boiling temperature.

GCC below the pinch of a process shows the relationship between temperature and heat flow of the process source (which has the same shape with GCC but $\Delta T_{\min}/2$ above). Sometimes the heat flow is a monotonic function of interval temperature as shown in Fig.2, but sometimes there are pockets (the shaded areas in Fig.4), or turning points, as shown in Fig. 3. If the temperature difference or the heat load of the pocket is not large (the case in Fig.4), heat transfer from process to process would be possible. For a large pocket, as shown in Fig. 5, if heat is transferred between the processes, exergy loss will be high. And, a Rankine cycle can be placed inside the pocket, as shown in Fig.5. The heat rejected by the process is received by the working fluid of the cycle instead of process interchange, and the heat rejected by the cycle can be reintroduced into the process which needs heat supply. Then a power saving can thus be obtained. As to the GCC with turning points, we will discuss it later in this paper.

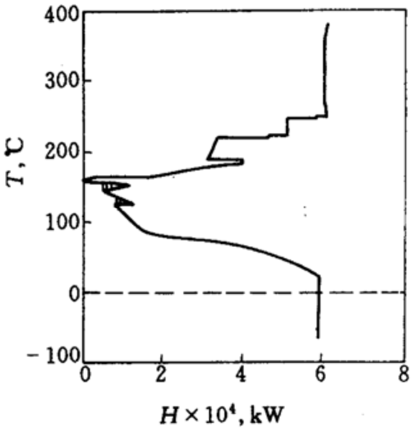

Figure 4 GCC of BTX unit-sulfolane process[11]

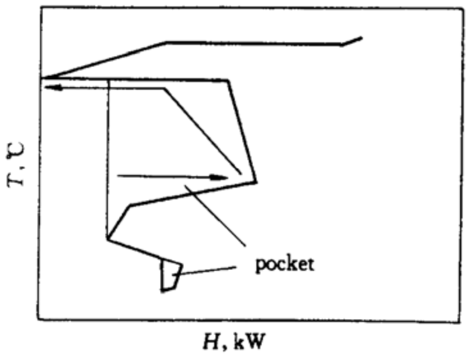

Figure 5 GCC of synthetic resin, dimer process[11]

For a given process, if we prescribe the condensing temperature, the efficiencies of the turbine and the pump, the heat accepted by unit mass working fluid and the thermal efficiency of the cycle are functions of the boiling temperature of the cycle. Then, after selecting a minimum approach temperature between the working fluid and the process fluids, ΔT_{min}, we can use the process in Fig.6 to get a Y_e-T_s curve and determine the optimal boiling temperature.

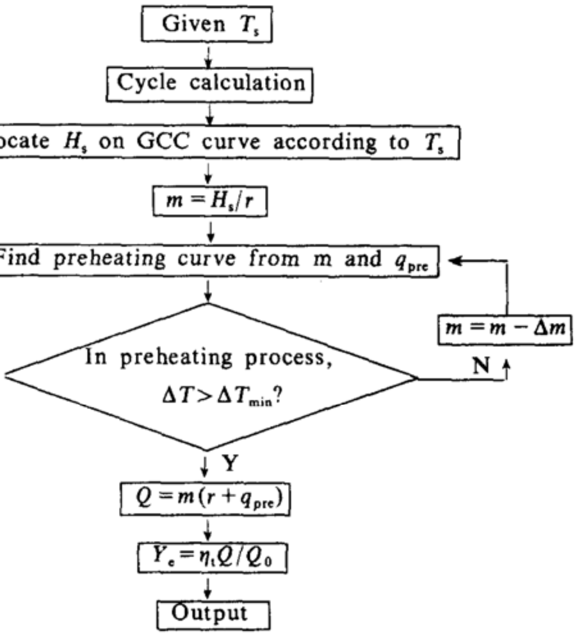

Figure 6 Calculating program

3 INFLUENCE OF GCC CONTOUR ON WORKING FLUID

Different working fluids have different thermodynamic performances, that is, different thermal efficiency η_t and different enthalpy curves, hence different work output.

When a working fluid is selected, not only η_t but also enthalpy curve should be considered. The property of the enthalpy curve of a working fluid can be measured with

$$a = 1 + q_{pre}/r \tag{3}$$

For a smooth GCC with which the heat load will increase greatly when temperature decreases, as shown in Fig.2, the greater the a, the higher will be the Q/Q_0, hence the greater the Y_e, because in general, the increment of Q/Q_0 is greater than that of η_t. So in most cases, the working fluid can be selected by the guidance of a. While for a steep GCC, such as Fig.7, a working fluid can always receive as much heat as it can, that is, Q/Q_0 trends to be maximized. In this case, the working fluid can be selected simply by taking η_t into consideration.

The GCC of the sulfolane process of a BTX (benzene, tolulene and xylene) unit is shown in Fig.4. Different working fluids are considered, and the condensing temperature is taken to be 30 ℃, ΔT_{min} as 10 ℃, turbine efficiency as 0.8 (It should be mentioned that the turbine efficiency can vary with stream and pressure ratio), and pump efficiency as 0.6. The $Y_e - T_s$ curves are shown in Fig.8. In this situation, R152a is the best.

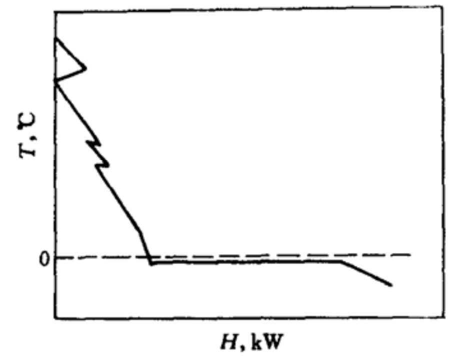

Figure 7 GCC of low density polyethene[11]

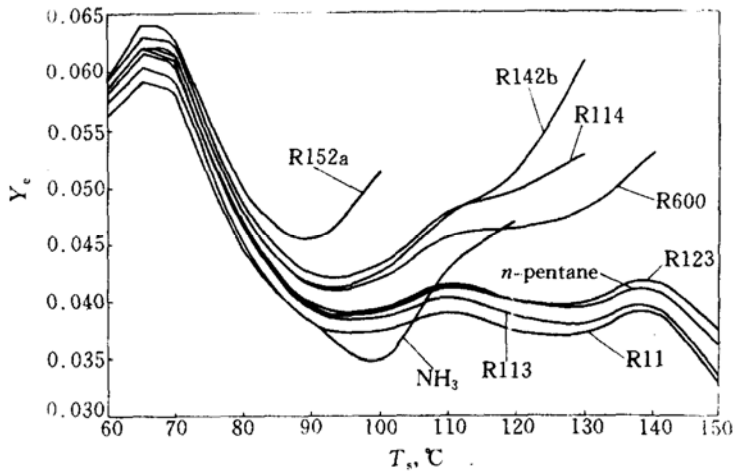

Figure 8 Y_e-T_s curves corresponding to the system in Fig.4

Table 2 The order of Y_e and a

Working fluid	$T_{s,opt}$,℃	a	Order of a	Y_e	Order of Y_e	Pressure ratio
R152a	66	1.3335	1	0.06398	1	2.55
R114	66	1.3321	2	0.06293	2	2.68
R600	67	1.3040	4	0.06219	3	2.67
R142b	68	1.3045	3	0.06193	4	2.75
n-pentane	65	1.2495	5	0.06179	5	3.00
R113	66	1.2432	6	0.06152	6	3.26
R123	65	1.2293	7	0.06144	7	2.99
R11	65	1.1840	8	0.06028	8	2.82
NH_3	65	1.1839	9	0.05907	9	2.53

Table 2 gives the calculation results for the system of Fig.4. Because the GCC around the optimal T_s is rather smooth, the order of Y_e is almost the same as the order of a.

4 OTHER INFLUENCES OF GCC CONTOUR

Besides the influence of smoothness or steepness mentioned above, there are other influences of the grand composite curve.

As shown in Fig.9, in the shaded region, heat transfer between processes is apparent, and the lowest temperature of the waste heat is much higher than the environment temperature. In this case, all waste heat can be consumed by the working fluid, that is, when the boiling temperature of a working fluid is lower than a certain temperature, $Q/Q_0=1$, Therefore, for a certain fluid, the optimal boiling temperature is the possible highest boiling temperature with $Q/Q_0=1$. The calculation results of some working fluids for this process are shown in Fig. 10. In this case, at the optimal boiling temperature, $Q/Q_0=1$, Y_e is equal to η_t for all working fluids.

Finally, consider the situation in Fig.3. On the curve there is a turning point.

Because of the restraint of the turning point, when the working fluid boils at a temperature above the turning temperature, total heat accepted by the working fluid id is determined by the heat load at this temperature (that is, the sum of the preheating heat from this temperature minus $\Delta T_{\min}$ to the boiling temperature and the latent heat is equal to the heat load). In this region, there is a local minimum Y_e and Y_e will increase with T_s until another turning point appears. In the process given in Fig.4, there are 3 turning points, so there are 3 local minimum Y_e resulting in S-shape in Fig. 8. If the turning temperature is relatively low, the optimal boiling temperature will be the highest possible boiling temperature determined by this turning point; whereas if the turning temperature is high, Y_e should be compared with that below the turning point. For example, in Figs.4 and 8, if R114 is used as the working fluid, it can be seen that though in the region above the turning point, Y_e increases with T_s, the optimal boiling temperature is below the turning point.

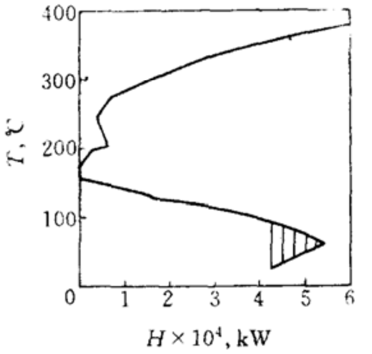

Figure 9 GCC of crude refinery unit

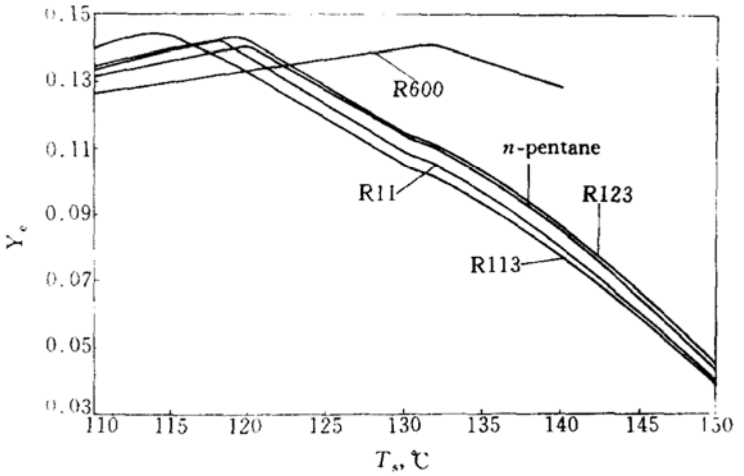

Figure 10 Y_e-T_s curves corresponding to the system in Fig.9

5 CONCLUSIONS

Waste heat recovery should be carried out with process integration. Y_e, the product of the waste heat recovery rate and the thermal efficiency of the Rankine cycle, can be used as an objective function for the selection of working fluids and the determination of the optimal boiling temperature.

GCC of the process has a great influence on the optimization. Generally, a working fluid with a higher product of η_t and Q/Q_0 will be most beneficial. When the GCC is smooth, the working fluid with a higher a (the ratio of heat accepted to the latent heat of the working fluid) is better. For a steep GCC, the working fluid with a higher η_t is better. If the waste heat has a final temperature much higher than the environment temperature, the optimal boiling temperature is the possible highest one with $Q/Q_0=1$. For the GCC with a turning point, there is a local minimum Y_e around the turning temperature. For the GCC with a large pocket, a Rankine cycle can be put into the pocket to recover exergy.

In this paper, economic factors are not considered. But for waste heat power recovery, the results of thermodynamic optimization are approaching economical benefits[12].

NOMENCLATURE

a	ratio between received heat and latent heat of unit mass working fluid ($a=q/r$)
c_p	heat capacity rate, kW · ℃$^{-1}$
E_0	maximum exergy available from waste heat, kW
H	enthalpy, kW
H_s	enthalpy on the GCC when $T=T_s$, kW
m	mass flow, kg · s^{-1}
Q	heat actually taken from waste heat, kW
Q_0	maximum heat available from waste heat, kW
q	heat consumed by unit mass working fluid, kJ · kg^{-1}
r	latent heat of unit mass working fluid, kJ · kg^{-1}
T	temperature, ℃
ΔT	approach temperature, ℃
W	total work generation from waste heat, kW
Y_e	product of thermal efficiency and waste heat recovery rate
η_e	exergetic efficiency
η_t	thermal efficiency
Ω_0	energy level of waste heat ($\Omega_0=E_0/Q_0$)

Subscripts

min	minimum
opt	optimal
pre	preheating
s	boiling temperature

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