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Pinch Position Between Heat Carrier and Working Fluid in Organic Rankine Cycle for Waste Heat Recovery

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A huge amount of low temperature waste heat is wasted in refineries. Organic Rankine cycle (ORC) is an effective way to generate power from recovered heat. The Pinch point between the heat carrier and the working fluid limits the amount of heat transferred from the waste heat carrier to the working fluid, which affects the power output directly. For ORC without superheating, the Pinch point would appear at two possible positions, the start point of preheating, namely Preheating Pinch Point (PPP), or the start point of vaporization, namely Vaporization Pinch Point (VPP). In this paper, factors are analyzed, which may influence the Pinch position, including the heat capacity flow rate of waste heat carrier; waste heat inlet temperature, evaporation temperature, the ratio of latent heat to sensible heat of working fluid. A mathematical model including above parameters is deduced, which can not only predict the Pinch position accurately and calculate the heat recovered easily, but also find out the proper way to increase the amount of heat recovered.

1. Introduction

A huge amount of low temperature waste heat is wasted in refineries. Organic Rankine cycle (ORC) is one of effective ways to recover such heat to generate power. The thermodynamic properties of the working fluids and operating conditions directly affect the performance of the system. Many studies have been done mainly focused on the stand-alone ORC. Cycle modifications such as regeneration, turbine bleeding, reheat (Desai et al., 2009) are effective ways to improve the thermal efficiency. However the overall system performance not only depends on the thermal efficiency (Varga Z. et al., 2012). Liu et al. (2004) proposed total heat recovery efficiency and heat availability to evaluate the performance of ORC systems. Heat availability indicates the amount of heat recovered which is restricted by the Pinch position between the waste heat carrier and the working fluid. So it is necessary to investigate the Pinch position in order to increase the amount of heat recovered. Exgery destruction in evaporator due to irreversibility is caused by Pinch point limitations, fluid friction, etc(D. Meinel et al. 2014). Guo et al. (2011) proposed a computer model based on the Pinch analysis to analyze the transcritical Rankine power cycles driven by low temperature geothermal sources. Guo et al. (2014) established a physical mathematical model to seek the Pinch position. Based on the mathematical model, they compared the matching potentials between heat source and working fluid for subcritical and supercritical cycles. In the open literatures, few researches focused on the PPP which may be desirable in waste heat recovery. In this paper, we will study the factors that determine the Pinch point position, and then the way to improve the amount of heat recovered can be found easily. A mathematical model is proposed to predict Pinch position and calculate the heat recovered.

2. Effect of Pinch position on the heat recovered and the influence factors on the Pinch position

In an organic Rankine cycle for waste heat recovery, the power output equals the product of thermal efficiency and the heat recovered. At a specific evaporation temperature, the thermal efficiency is close to a constant for most of the working fluids, although it slightly increases with the increase of the critical temperature. Therefore, at a given evaporation temperature, the power output mainly depends on the

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amount of heat recovered. For a given waste heat source, the mass flow rate of working fluid is gradually increased until the Pinch appears. The Pinch may appear at two possible positions, namely the PPP and VPP, as shown in Figure 1. If the PPP appears first, the amount of heat recovered reaches the maximum, and the outlet temperature of the waste heat reaches the minimum (see Figure1 (a)). If the VPP appears first, the waste heat is not totally recovered, and the outlet temperature of waste heat is much greater than the inlet temperature of working fluid - see Figure1 (b). It is obvious that the amount of heat recovered and the outlet temperature of the waste heat carrier are largely different for the two situations. The Pinch position is determined by the relative position of the waste heat carrier line and the working fluid line in the T-H diagram. So all the factors that can affect the shape of the two lines may have influence on the Pinch position. If the condensation temperature is fixed, the heat capacity flow rate and inlet temperature of waste heat carrier determine the shape of the waste heat line; evaporation temperature and the ratio of sensible heat to latent heat determine the shape of the working fluid line. Therefore this work will investigate which and how all the above factors affect the Pinch position.

In this paper, the condensation temperature is assumed to be 40 °C which is restricted by the ambient temperature, and the Pinch temperature difference is set as 10 °C. We investigated the subcritical ORC without superheating using two common used working fluids as they have big difference in the ratio of latent heat to sensible heat. The critical properties of the two fluids are listed in Table 1.

2.1 Effect of waste heat capacity flow rate on the Pinch position

In this section, the inlet temperature of the waste heat carrier is fixed at 155 °C. The heat capacity flow rate of the waste heat carrier are taken as 0.1 kW/°C,1 kW/°C, and 10 kW/°C. With R245fa as the working fluid, the mass flow rate of working fluid is gradually increased until the Pinch appears. The results at specified evaporation temperatures are given in Table 2. The temperature difference between evaporation temperature and the temperature of waste heat at the start point of vaporization is 10°C (Pinch temperature difference), which means that the Pinch points appear at the start point of vaporization (VPP) for all the listed conditions in Table 2. It is evident that the heat capacity flow rate has no effect on the Pinch position, and the outlet temperature of the waste heat carrier keeps the same with the variation of the heat capacity flow rate. The variation of the heat capacity flow rate can only change the total amount of waste heat, but the temperature profile remains the same. The ratio of heat rejected in each temperature interval to the total available heat is a constant. In the T-H diagram, variation of the heat capacity flow rate only change the horizontal coordinate of the waste heat line, but the vertical coordinate remains unchanged. The maximum flow rate of the working fluid varies with the variation of the heat capacity flow rate proportionally, and the horizontal coordinate of the working fluid line enlarges or shrinks accordingly. Although the variation of the heat capacity flow rate changes the shape of the waste heat line, the working fluid line changes accordingly, and the Pinch position will not change.

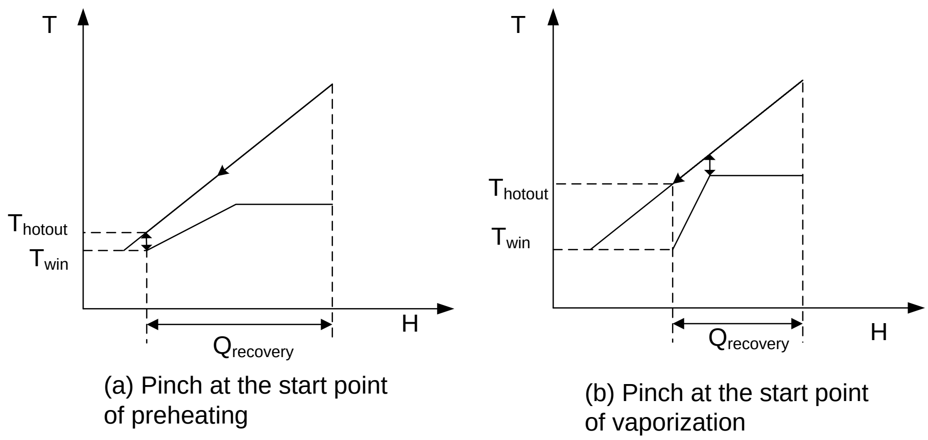

Figure 1: T-H diagram for the heat transfer in ORC with different Pinch positions

Table 1: Critical properties of working fluids used in this paper

Working fluids	Critical temperature(°C)	Critical pressure (bar)
R236fa	124.92	32.19
R245fa	154.05	36.40

Table 2: Results under different waste heat capacity flow rate with R245fa as the working fluid

Waste heat carrier capacity flow rate (kW/°C)	Evaporation temperature (°C)	Working fluid mass flow rate (kg/s)	Waste heat temperature at vaporizing start point (°C)	Waste heat outlet temperature (°C)	Pinch point position	$\frac{\left[T_{hotin}-(T_{eva}+\Delta T)\right]R_S}{R_L}-(T_{eva}-T_{win})$
0.1	80	0.0417	90	66.3	VPP	<0
	90	0.0374	100	73.0	VPP	<0
	100	0.0328	110	81.0	VPP	<0
	110	0.0278	120	90.7	VPP	<0
1	80	0.417	90	66.3	VPP	<0
	90	0.374	100	73.0	VPP	<0
	100	0.328	110	81.0	VPP	<0
	110	0.278	120	90.7	VPP	<0
10	80	4.17	90	66.3	VPP	<0
	90	3.74	100	73.0	VPP	<0
	100	3.28	110	81.0	VPP	<0
	110	2.78	120	90.7	VPP	<0

2.2 Effect of waste heat inlet temperature on the Pinch position

As the heat capacity flow rate of waste heat carrier has no effect on the Pinch position, the heat capacity flow rate is taken as 1 kW/°C in the following calculations. With R236fa as the working fluid, the inlet temperatures of waste heat carrier are assumed as 155 °C, 165 °C, and 175 °C. As shown in Table 3, with the inlet temperature of waste heat carrier 155 °C, as the difference between evaporation temperature and the temperature of waste heat at the start piont of vaporization is 10 °C except the evaporation temperature 120 °C, and so the Pinch position is the VPP at all the listed evaporation temperatures except 120 °C. When the inlet temperature of waste heat carrier is 165 °C, at the evaporation temperature 110 °C, the Pinch position is PPP, which is VPP when the inlet temperature is 155 °C. When the inlet temperature of waste heat is 175 °C, as the temperature difference between the working fluid inlet temperature(40°C) and the outlet temperature of waste heat (50 °C listed in Table 3) is 10 °C (Pinch temperature difference), and so the Pinch position is the PPP at all the listed evaporation temperatures. Meanwhile the amount of heat recovered reaches the maximum and the outlet temperature reaches the minimum 50 °C. It is evident that the inlet temperature has effect on the Pinch position. When the other parameters are fixed, the higher the inlet temperature of a waste heat, the Pinch position more likely appears at the start point of evaporation, and vice versa.

2.3 Effect of evaporation temperature on the Pinch position

From the results given in Table 3, the Pinch positions at different evaporation temperatures are not at the same position when the inlet temperature of waste heat is fixed at 165 °C. The Pinch appears at the start point of vaporization at the evaporation temperature of 80 °C, 90 °C, 100 °C, and at the start point of preheating at the evaporation temperature of 110 °C, 120 °C. When the inlet temperature of waste heat is 175 °C, the Pinch appears at the start point of preheating for all the evaporation temperatures. So the evaporation temperature and inlet temperature of waste heat both have influence on the Pinch position. For a given waste heat source, Pinch may appear at different positions at different evaporation temperatures, and so it is necessary to optimize the evaporation temperature in organic Rankine cycle for waste heat recovery (Lakew et al., 2010).

Table 3: Results under different waste heat inlet temperatures with R236fa as working fluid

Waste heat inlet temperature (°C)	Evaporation temperature (°C)	Working fluid mass flow rate (kg/s)	Waste heat temperature at vaporizing start point (°C)	Waste heat outlet temperature (°C)	Pinch point position	$\frac{\left[T_{\mathrm{hotin}}-(T_{\mathrm{eva}}+\Delta T)\right]R_{\mathrm{S}}}{R_{\mathrm{L}}}-(T_{\mathrm{eva}}-T_{\mathrm{win}})$
155	80	0.59	90	56.6	VPP	<0
	90	0.56	100	59.5	VPP	<0
	100	0.53	110	62.3	VPP	<0
	110	0.53	120	62.7	VPP	<0
	120	0.61	131.2	50	PPP	>0
165	80	0.690	90	51.48	VPP	<0
	90	0.667	100	52.23	VPP	<0
	100	0.657	110	51.74	VPP	<0
	110	0.662	121.4	50	PPP	>0
	120	0.675	138.9	50	PPP	>0
175	80	0.760	92.4	50	PPP	>0
	90	0.739	102.9	50	PPP	>0
	100	0.725	114.2	50	PPP	>0
	110	0.719	127.5	50	PPP	>0
	120	0.734	146.7	50	PPP	>0

Table 4: Comparison of R236fa and R245fa under the same operating condition

Working fluid	Evaporation temperature (°C)	Sensible heat (kJ/kg)	Latent heat (kJ/kg)	Ratio of latent to sensible heat	Waste heat temperature at vaporizing start point (°C)	Waste heat outlet temperature (°C)
R236fa	120	131.8	38.51	0.29	131.2	50
R245fa	120	122.6	112	0.91	130	80.7

2.4 Effect of the ratio of latent heat to sensible heat of working fluid on the Pinch position

In this section, we compared the results for R245fa and R236fa under the same operating condition as shown in Table 4. The inlet temperature of the waste heat is assumed as 175 °C. For R236fa, the Pinch position is at the start point of preheating, the amount of heat recovered reaches the maximum, and the outlet temperature of waste heat reaches the minimum, 50 °C. For R245fa, the Pinch position is at the start point of vaporization. The outlet temperature of waste heat carrier is 80.7 °C and the waste heat is not recovered effectively. The amount of heat recovered and the outlet temperature of the waste heat are largely different for the two working fluids. The operation conditions are identical for the two working fluids, but the Pinch position is different. The reason is that the shape of working fluid lines for the two working fluids are different, namely the ratio of latent heat to sensible heat are largely different for the two working fluids. The values of that ratio are 0.29 and 0.91 for the two working fluids as listed in Table 4.

3. Mathematical model

The results discussed above indicate that, when the condensation temperature is fixed, the heat capacity flow rate of waste heat has no effect on the Pinch position; the inlet temperature of waste heat, the evaporation temperature and the ratio of latent heat to sensible heat have influence on the Pinch position, which determine the Pinch position comprehensively. According to the T-H diagram and energy balance equation, a mathematical model is established as followings.

When the Pinch position is at the start of vaporization, the outlet temperature of the waste heat is greater than the sum of the inlet temperature of the working fluid and the Pinch temperature difference, namely, $T_{\mathrm{hotout}} > T_{\mathrm{win}}+\Delta T$. The heat rejected by the waste heat carrier from the inlet temperature to the Pinch point determines the maximum mass flow rate of the working fluid, which is expressed as Eq. (1). The heat Q_1 needed to preheat the working fluid to the evaporation temperature is denoted as Eq. (2). The heat Q_2 rejected by the waste heat from the Pinch temperature to $T_{\mathrm{win}}+\Delta T$ is expressed as Eq. (3). As $T_{\mathrm{hotout}} > T_{\mathrm{win}}+\Delta T$, then we can obtain Inequality (4). Substituting Eqs. (2) and (3) into Inequality (4), Inequality (5) yields, and then the amount of heat recovered is calculated by Eq. (6).

$$M=\frac{C_{\mathrm{P}}\left[T_{\mathrm{hotin}}-(T_{\mathrm{eva}}+\Delta T)\right]}{R_{\mathrm{L}}} \tag{1}$$

$$Q_1=\frac{R_{\mathrm{S}}C_{\mathrm{P}}\left[T_{\mathrm{hotin}}-(T_{\mathrm{eva}}+\Delta T)\right]}{R_{\mathrm{L}}} \tag{2}$$

$$Q_2=\left[(T_{\mathrm{eva}}+\Delta T)-(T_{\mathrm{win}}+\Delta T)\right]C_{\mathrm{P}} \tag{3}$$

$$Q_1<Q_2 \tag{4}$$

$$\frac{\left[T_{\mathrm{hotin}}-(T_{\mathrm{eva}}+\Delta T)\right]R_{\mathrm{S}}}{R_{\mathrm{L}}}-(T_{\mathrm{eva}}-T_{\mathrm{win}})<0 \tag{5}$$

$$Q=\frac{C_{\mathrm{P}}\left[T_{\mathrm{hotin}}-(T_{\mathrm{eva}}+\Delta T)\right](R_{\mathrm{S}}+R_{\mathrm{L}})}{R_{\mathrm{L}}} \tag{6}$$

where M is the maximum mass flow rate of the working fluid; C_{P} is the heat capacity flow rate of the waste heat; T_{hotin} is the inlet temperature of the waste heat; T_{hotout} is the outlet temperature of the waste heat; T_{eva} is the evaporation temperature; ΔT is the Pinch temperature difference; R_{S} is the sensible heat of the working fluid from the inlet temperature to evaporation temperature, and R_{L} is the latent heat of evaporation at the corresponding evaporation temperature.

Similarly, when the Pinch position is at the start point of preheating, the outlet temperature of the waste heat is $T_{\mathrm{win}}+\Delta T$, which is the minimum of the waste heat outlet temperature. Parameters should meet the Inequality (7), and the amount of heat recovered reaches the maximum as expressed in Eq. (8).

$$\frac{\left[T_{\mathrm{hotin}}-(T_{\mathrm{eva}}+\Delta T)\right]R_{\mathrm{S}}}{R_{\mathrm{L}}}-(T_{\mathrm{eva}}-T_{\mathrm{win}})>0 \tag{7}$$

$$Q=C_{\mathrm{P}}\left[T_{\mathrm{hotin}}-(T_{\mathrm{win}}+\Delta T)\right] \tag{8}$$

$$\frac{\left[T_{\mathrm{hotin}}-(T_{\mathrm{eva}}+\Delta T)\right]R_{\mathrm{S}}}{R_{\mathrm{L}}}-(T_{\mathrm{eva}}-T_{\mathrm{win}})=0 \tag{9}$$

When the parameters satisfy Eq. (9), the preheating Pinch point and vaporization Pinch point appear simultaneously. The outlet temperature of the waste heat is still $T_{win}+\Delta T$, and the heat recovered can be calculated by Eq. (8). The slope of the waste heat line and that of the preheating stage of the working fluid line are equal.

To demonstrate the effectiveness of the mathematical model, the value of the left hand side of Inequality (5) is calculated as listed in the last column of Tables 2 and 3. It is apparent that the value of the mathematical expression is consistent with the Pinch point position. Once the value of the mathematical expression is obtained, the Pinch point position can be determined and the amount of heat recovered can be calculated from Eq. (6) or Eq. (8), depending on the sign of the mathematical expression. For example, as shown in Table 3, with the inlet temperature of waste heat 155 °C, when the evaporation temperatures are 80 °C, 90 °C and 100 °C, the values of the mathematical expression are negative, So the Pinch point is the VPP and the amount of heat recovered can be calculated by Eq. (6).When the evaporation temperature is 120 °C, the value of the mathematical expression is positive. So the Pinch point is PPP and the heat recovered can be calculated by Eq. (8). The mathematical model can predict the Pinch position accurately and then the heat recovered can be calculated easily.

4. Conclusion

In this paper, we investigated the Pinch position between the working fluid and waste heat carrier in ORC for waste heat recovery. The Pinch may appear at the start point of preheating (i.e. the exit of waste heat) or the start point of vaporization. With the Pinch point at the start point of preheating (PPP), the amount of heat recovered reaches the maximum. With the Pinch point at the start point of vaporization (VPP), the Pinch point limits the heat transferred from the waste heat carrier to working fluid, and the waste heat is not recovered effectively. The results show that, with a fixed condensation temperature, the heat capacity flow rate of the waste heat carrier has no effect on the Pinch position; the inlet temperature of the waste heat carrier, evaporation temperature, the ratio of latent heat to sensible heat of the working fluid, have effect on the Pinch position. Pinch is determined by all these factors comprehensively. A mathematical model is established incorporating all these factors. As the power output mainly depends on the heat recovered at specified evaporation temperature, PPP is more desirable in waste heat recovery. The mathematical model can not only predict the Pinch position accurately, but also calculate the heat recovered easily. The mathematical model can be used as a criterion in the selection of working fluid and operating conditions in the future work.

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