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THERMO-ECONOMIC ANALYSIS OF BIOMASS-FIRED ORC COMBINED HEAT AND POWER SYSTEM VERSUS PINCH POINT LOCATION

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ABSTRACT

Organic Rankine cycle (ORC) coupled with biomass combustion boiler is an appealing and promising technology for small scale combined heat and power (CHP) plants. The aim of this paper is to investigate thermodynamic analysis and economic assessment of biomass-fired ORC CHP system, especially from the perspective of pinch point location. The thermo-economic model of bioenergy cogeneration system has been developed, in which the pressurized boiler hot water is worked as heat source for ORCs and the condensation heat can be fully utilized to supply domestic hot water. Results show that pinch point location from vaporization start point to preheating start point is observed with increasing boiler hot water temperature or decreasing evaporation temperature in evaporator. The pinch point location has slight influence on thermodynamic performance, while it has significant effect on economic assessment in this bioenergy system. The same optimal boiler hot water temperature with the specific evaporation temperature can be achieved in terms of total investment (INV_{tot}), dynamic payback period (*DPP*) and profit ratio of investment (*PRI*).

Keywords: biomass, organic Rankine cycle, combined heat and power, thermo-economic, pinch point

NONMENCLATURE

Abbreviations

ORC	Organic Rankine Cycle
CHP	Combined Heat and Power
DH	District Heating
BB	Biomass Boiler
SD	Superheat Degree
DPP	Dynamic Payback Period
PRI	Profit Ratio of Investment
NPV	Net Present Value
PHE	Plate Heat Exchanger
PPTD	Pinch Point Temperature Difference
PESR	Primary Energy Saving Ratio

Symbols

Q	Heat Transfer Rate
E	Exergy
W	Power
M	Mass Flow Rate
INV	Investment
EN	Earning
h	Specific Enthalpy
s	Specific Entropy
i	Discount Rate
n	Lifetime

1. INTRODUCTION

Worldwide energy demands are rising continuously with the shortage of fossil fuel resources and the risk of climate change due to global warming. Recently, the utilization of sustainable energy sources such as biomass attracts more interest with increasing global energy demands and environmental concerns [1]. The combined heat and power (CHP) system represents a crucial alternative to conventional system characterized by enabling simultaneous supply of electric power and hot water for district heating, as well as an increase in saving

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capability and energy efficiency, a reduction in greenhouse gas emissions and operating costs [2].

With respect to this promising cogeneration system, biomass-fired organic Rankine cycles (ORCs) represent an attractive solution for sustainable and reliable energy supply in distributed power generation applications [3], where traditional plants are technologically and economically unfeasible. Liu et al [4] presented a thermodynamic model of biomass-fired CHP system with ORC, and found that the electrical efficiency is predicted to be within the range of 7.5-13.5%, mainly depending on the hot water temperature from biomass boiler. Qiu et al. [5] tested the ORC-based CHP system utilizing a 50-kW biomass boiler to generate pressurized hot water, and the cooling water could be heated to a temperature (46 °C) suitable for domestic applications, corresponding to the CHP efficiency of 78.69% with HFE7000 as working fluid. Sartor et al. [6] concluded that the biomass combined heat and power plants connected to district heating (DH) networks are profitable only if a sufficient heat demand is available throughout the operation. Moreover, thermodynamic assessment of an integrated biomass-based multi-generation energy system was carried out by Ahmadi et al [7], and they concluded that system performance is notably affected by the pinch point temperature difference (PPTD) and evaporation temperature. Jakub et al. [8] described the design methodology of biomass-fired ORC CHP as a complex issue from not only thermodynamic and technical perspectives, but also economical and legal points of view.

Based on the literature research of biomass-fired CHP system coupled with ORC, there are few research studies focusing on heat source temperature for ORCs, evaporation temperature and PPTD, especially the interaction effects on system performance. In particular, the pinch point may locate at either the preheating start point or the vaporization start point in evaporator, which influences system performance significantly [9]. Besides, there is still a knowledge gap about pinch point location with varying hot source temperature and evaporation temperature in ORCs, specifically from the perspective of thermo-economic assessment. This article focuses on the combination of combustion of biomass as a primary energy conversion technology and ORC as a secondary energy conversion technology. In this bioenergy cogeneration system, the pressurized boiler hot water works as heat source for ORCs and the condensation heat can be fully utilized to supply domestic hot water for users. The PPTD analytic method is adopted to explore thermodynamic performance with boiler hot water temperature and evaporation temperature. The thermodynamic analysis and economic assessment of biomass-fired ORC CHP system versus pinch point location is explored.

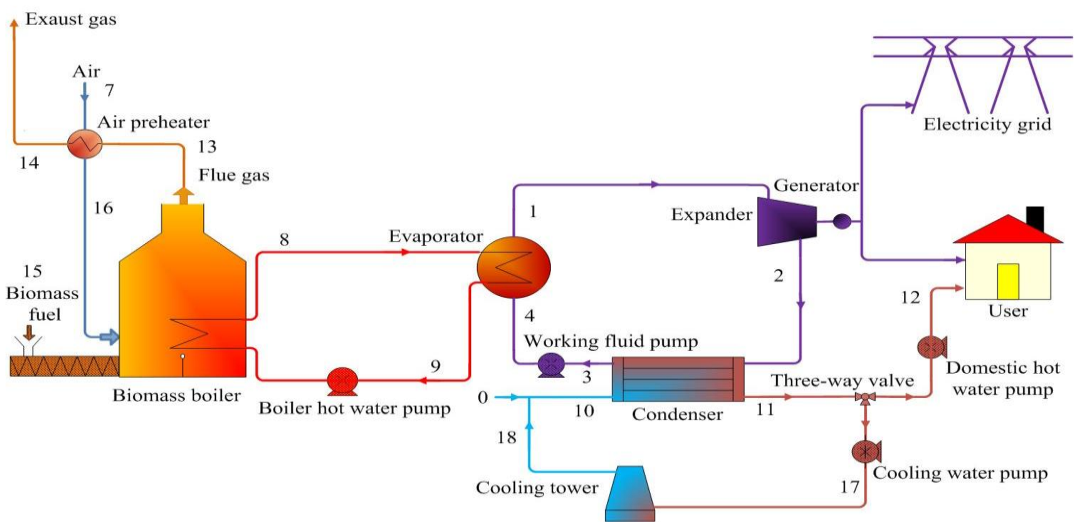

Fig 1 Schematic diagram of biomass-fired ORC CHP system

2. CYCLE DESCRIPTION

The schematic diagram of biomass-fired ORC CHP system is depicted in Fig.1, which mainly consists of biomass boiler, intermediate heat transfer loop, ORCs, cooling water loop, air preheater, electricity grid and user. In biomass boiler, the biomass fuel is combusted and transfers heat to the pressurized water in the intermediate heat transfer loop (process 9 to 8). Organic working fluid absorbs heat form the intermediate heat transfer loop (process 4 to 1) and then goes through the expander to generate power for users or electricity grid. Afterwards, organic working fluid (process 2 to 3) is condensed by cooling water (process 10 to 11) to produce domestic hot water for users (state 12) or releases heat through the cooling tower (process 17 to 18). The exhausted flue gas from biomass boiler transfers heat to the combustion air in the preheater (process 13

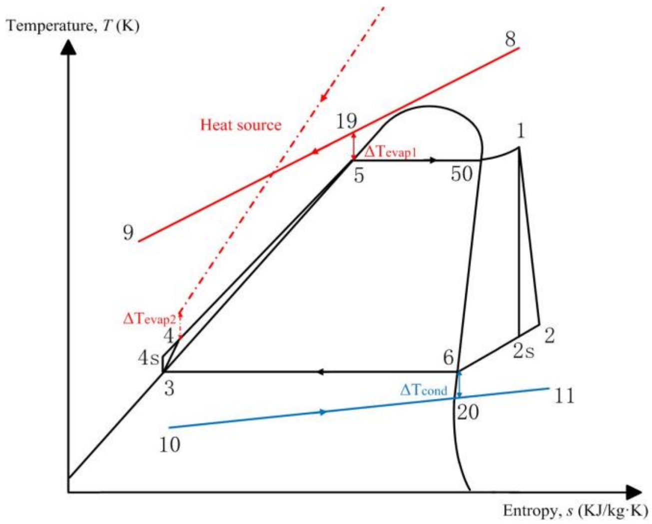

Fig 2 *T*-*s* diagram of biomass-fired ORC CHP system with slight superheat degree

to 14).

Fig. 2 illustrates the *T*-*s* diagram of biomass-fired ORC CHP system with slight superheat degree, in which the state points correspond to those in Fig. 1 respectively. It is noticeable that pinch point location may place at either the preheating start point (state 4) or the vaporization start point (state 5) in evaporator, which influences system performance considerably. Hence, the shift of pinch point location in evaporator is considered in this thermodynamic model. Although some research studies conclude that there should be no superheat degrees especially for dry working fluids in ORCs, no superheating is not realistic in practical engineering applications [10]. Besides, experiments conducted by Hu et al. [11] present that the superheat degree at evaporator outlet is the main factor correlated with ORC system's operation stability. Therefore, the slight superheat degree (T_{SD}=5 K) is taken into account herein. Concerning condensation conditions, the outlet temperature of cooling water reaches above 50 ℃ (state 12) to meet domestic hot water requirements [12], otherwise it would go through the cooling tower (process 17 to 18) to complete the cooling water loop.

3. METHODOLOGY

3.1 Thermodynamic model

The process of biomass fuel combustion plays an important role in the whole system performance. The nominal heat load of biomass boiler is 3 MW and the boiler efficiency is set to 90% [13]. The energy balance in biomass boiler can be expressed as:

$$\dot{Q}_{BN} = \dot{m}_{bf}\, LHV_{bf} \tag{1}$$

$$\dot{Q}_{in} = \dot{Q}_{BN}\, \eta_{BB} \tag{2}$$

$$\dot{Q}_{in} = c_{pw}\, \dot{m}_{bhw}(T_8 - T_9) \tag{3}$$

where $\dot{Q}_{BN}$ is the nominal heat load of biomass boiler, $\dot{m}_{bf}$ denotes the mass flow rate of biomass fuel and η_{BB} is the efficiency of biomass boiler; c_{pw} represents the average specific heat capacity and $\dot{m}_{bhw}$ is the mass flow rate of boiler hot water, while T_8 and T_9 represent temperature of state 8 and 9 in intermediate heat transfer loop respectively.

The input chemical exergy of biomass fuel can be defined as [14]:

$$\dot{E}_{bf} = \beta LHV_{bf} \tag{4}$$

$$\beta = \frac{1.044 + 0.016 \times \frac{H_{ad}}{C_{ad}} - 0.3493 \times \frac{O_{ad}}{C_{ad}} \times (1 + 0.0531 \times \frac{O_{ad}}{C_{ad}}) + 0.0493 \times \frac{N_{ad}}{C_{ad}}}{1 - 0.4124 \times \frac{O_{ad}}{C_{ad}}} \tag{5}$$

where β is the chemical-exergy coefficient, which is defined for solid hydrocarbons fuel (for O/C<2); H_{ad}, N_{ad}, O_{ad} and C_{ad} are ultimate element analysis based on dry basis.

The total transfer heat rate in the evaporator is given as:

$$\dot{Q}_{eva} = \dot{Q}_{in} \tag{6}$$

$$\dot{Q}_{eva} = \dot{m}_{wf}(h_1 - h_4) \tag{7}$$

where $\dot{m}_{wf}$ is the mass flow rate of working fluid, h_1 and h_4 are enthalpy of working fluid respectively.

When the cooling water exited from condenser meets domestic hot water requirements, namely T_{11} above 50 ℃, the useful heat rate acquired by domestic hot water as well as exergy value can be calculated as:

$$\dot{Q}_{dhw} = \dot{Q}_{cw} \tag{8}$$

$$\dot{E}_{dhw} = \dot{Q}_{dhw}(1 - T_{amb} / T_{dhw}) \tag{9}$$

where T_{amb} is the ambient temperature and T_{dhw} represents the average temperature of domestic hot water during heating process.

When the cogeneration system supplies domestic hot water, the net power output of Bio-ORC CHP system is given as:

$$\dot{W}_{net} = \dot{W}_{exp} - \dot{W}_{pwf} - \dot{W}_{pdhw} - \dot{W}_{pbhw} \quad (10)$$

The details regarding thermodynamic model of ORCs can be elsewhere [9]. The power efficiency and thermal efficiency of this cogeneration system can be calculated as:

$$\eta_e = \dot{W}_{net} / \dot{Q}_{BN} \quad (11)$$

$$\eta_{th} = (\dot{W}_{net} + \dot{Q}_{dhw}) / \dot{Q}_{BN} \quad (12)$$

Exergy analysis can help develop guidelines and strategies for more effective use of energy. The exergy efficiency of this CHP system is defined as:

$$\eta_{ex} = (\dot{W}_{net} + \dot{E}_{dhw}) / \dot{E}_{bf} \quad (13)$$

The Primary Energy Saving Ratio (*PESR*) is also adopted to compare both generation alternatives and to determine if the regulatory support for efficient energy systems agrees well with environmental results. Besides, the assessment with *PESR* complements the first and second efficiency results. This parameter can be calculated as:

$$PESR = 1 - \frac{\dot{F}}{\dfrac{\dot{W}_e}{\eta_{ref,e}} + \dfrac{\dot{Q}_{heat}}{\eta_{ref,th}}} \quad (14)$$

where $\dot{F}$ is the input fuel rate, while $\dot{W}_e$ and $\dot{Q}_{heat}$ are output power and heat rate of researched energy system; the net electricity efficiency of reference subsystem ($\eta_{ref,e}$) is assumed as 33% [15] and the reference thermal efficiency $\eta_{ref,th}$ is equal to the biomass boiler efficiency of 90%.

3.2 Economic assessment model

The plate heat exchangers (PHEs) exhibit excellent heat transfer characteristics, which allows more compact configuration design than conventional shell and tube heat exchangers. Thus, PHEs are used as evaporator and condenser in this study.

Specifically, PHE is subdivided into 3 zones herein, that is, liquid zone, two-phase zone and vapor zone, each of them being characterized by a heat transfer area A_i and a heat transfer coefficient K_i, which is defined as:

$$\frac{1}{K} = \frac{1}{K_{cf}} + \frac{1}{K_{hf}} \quad (15)$$

Then, total heat transfer area of heat exchanger for ORC is obtained according to the following equation:

$$A_{total} = A_{liquid} + A_{two-phase} + A_{vapor} \quad (16)$$

The details regarding the PHE model can be found in our previous research work [9].

The module costing technique (MCT) is widely applied in system's economic analysis and adopted to evaluate the investment of component at a specific size or capacity.

$$\lg C_{p,X} = K_{1,X} + K_{2,X} \lg Y + K_{3,X} (\lg Y)^2 \quad (17)$$

where Y represents the capacity of turbine and pump or the area of evaporator and condenser respectively. Furthermore, K_1, K_2 and K_3 are the coefficients of component costs.

Subsequently, the purchased cost of each component in the year of 2018 can be calculated by

$$C_X = C_{BM,X} CEPCI_{2018} / CEPCI_{2001} \quad (18)$$

where *CEPCI* is the chemical engineering plant cost index with considering the effect of time on purchased equipment costs [16].

When the CHP system supplies domestic hot water, the investment of cooling water loop would not be included, while the domestic hot water pump would be considered, for which the total investment can be computed as:

$$INV_{tot} = C_{eva} + C_{exp} + C_{con} + C_{pwf} + C_{pdhw} + C_{BB} + C_{pbhw} + C_{aph} \quad (19)$$

The annual operation time can be assumed to be 8000 h per year [2], and the annual expenditure of biomass fuel can be calculated as:

$$C_{bf} = \dot{m}_{bf} T_{op} P_{bf} \quad (20)$$

where $\dot{m}_{bf}$ is the mass flow rate of biomass fuel, T_{op} is the annual operation time and P_{bf} is the price of biomass fuel.

As the cogeneration system supplies electricity and domestic hot water, the earnings of power and heat can be given as:

$$EN_E = \dot{W}_{net} T_{op} P_e \quad (21)$$

$$EN_H = \dot{m}_{dhw} T_{op} P_{dhw} \quad (22)$$

where P_e is the sale price of electricity, and P_{dhw} is the price of domestic hot water, in which the purchase price of industrial water has been subtracted.

The maintenance cost of this system can be calculated as:

$$C_M = r_M INV_{tot} \tag{23}$$

where r_M is the ratio of operating maintenance costs for total system investment, which is assumed equal to 1.65% [17].

The capital recovery factor (CRF) can be presented as:

$$CRF = i\frac{(1+i)^n}{(1+i)^n - 1} \tag{24}$$

where n is the lifetime of 20 years and i is the discount rate of 5% [13,17].

Therefore, the net annual income of this Bio-ORC CHP system is given as:

$$NAI = EN_E + EN_H - C_{OM} - C_{bf} \tag{25}$$

The dynamic payback period (year) for total system investment is defined as:

$$DPP = \frac{\ln\dfrac{NAI}{NAI - iINV_{tot}}}{\ln(1+i)} \tag{26}$$

The profit ratio of investment (*PRI*) can be given as:

$$PRI = \frac{NAI}{INV_{tot}} \tag{27}$$

The net power index (*NPI*) representing the ratio of the net power output to the total investment is indicated as:

$$NPI = \frac{INV_{tot}}{\dot{W}_{net}} \tag{28}$$

The levelized energy cost (*LEC*) can be presented as:

$$LEC = \frac{CRF \cdot INV_{tot} + C_M + C_{bf}}{\dot{W}_{net} T_{op}} \tag{29}$$

The net present value (*NPV*) for the whole Bio-ORC CHP system can be expressed as:

$$NPV = \sum_{1}^{n=20} \frac{NAI}{(1+i)^n} - INV_{tot} \tag{30}$$

4. RESULTS AND DISCUSSION

4.1 Variation of T_9 with transfer of pinch point

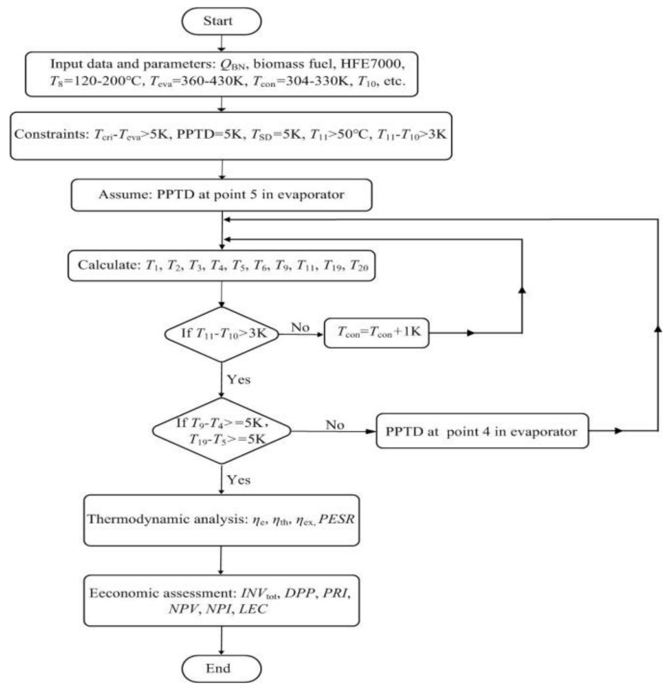

Fig 3 Flow chart of thermo-economic analysis of biomass-fired ORC CHP system

The flow chart of thermo-economic analysis of biomass-fired ORC CHP system versus pinch point location is clearly shown in Fig.3, which includes input parameters and constraints. Based on Liu and Qiu's simulation and experimental results [4-5], HFE7000 is recommended for biomass-fired CHP system with boiler hot water as heat source for ORC. Thereby, the organic fluid of HFE7000 is selected as working fluid in this paper.

To meet domestic hot water requirements, the condensation temperature is given as 326 K, with which the cogeneration system can supply electricity and heat simultaneously. The comparison of TD_4 and TD_5 with boiler hot water temperature and evaporation temperature is presented in Table 1. Note that TD_4 represents the temperature difference of points 4 and 9, while TD_5 equals to the temperature difference of points 5 and 19 (see Fig.2). The data indicate that the shift of PPTD from point 5 to 4 initially occurs at T_{bhw}=180 ℃ and T_{eva}=360 K, and then the PPTD is still at point 5 with increasing evaporation temperature. As for T_{bhw}=185 ℃, the corresponding evaporation temperature for pinch point shift is 370 K, while T_{eva}=380 K for T_{bhw}=190 ℃ and T_{eva}=395 K for T_{bhw}=195 ℃. When the boiler hot water temperature reaches 200 ℃, the PPTD totally locates at point 4 with evaporation temperature ranging from 360 K to 430 K. In summary, the PPTD begins to shift from T_5, namely the vaporization start point, to T_4, that is, the preheating start point, with increasing heat source temperature or decreasing evaporation temperature. Additionally, the evaporation temperature corresponding to the just starting shift of pinch point increases with improving boiler hot water temperature.

Table 1 Comparison of TD_4 and TD_5 with boiler hot water temperature and evaporation temperature (HFE7000)

T_{bhw}	175℃		180℃		185℃		190℃		195℃		200℃	
T_{eva} (K)	TD_5	TD_4	TD_5	TD_4	TD_5	TD_4	TD_5	TD_4	TD_5	TD_4	TD_5	TD_4
360	5	6.5	5.3	5	6.7	5	8.1	5	9.5	5	10.9	5
365	5	7.9	5	5.6	6.1	5	7.7	5	9.3	5	10.9	5
370	5	9.7	5	7.0	5.4	5	7.2	5	8.9	5	10.6	5
375	5	11.8	5	8.7	5	5.7	6.5	5	8.4	5	10.3	5
380	5	14.3	5	10.8	5	7.3	5.7	5	7.8	5	9.8	5
385	5	17.3	5	13.3	5	9.3	5	5.3	7.0	5	9.3	5
390	5	20.6	5	16.1	5	11.6	5	7.1	6.3	5	8.6	5
395	5	24.5	5	19.4	5	14.3	5	9.2	5.4	5	7.9	5
400	5	28.9	5	23.1	5	17.4	5	11.7	5	5.9	7.2	5
405	5	33.8	5	27.4	5	20.9	5	14.4	5	7.9	6.5	5
410	5	39.5	5	32.1	5	24.8	5	17.5	5	10.1	5.9	5
415	5	45.9	5	37.5	5	29.1	5	20.7	5	12.4	5.4	5
420	5	53.2	5	43.5	5	33.9	5	24.2	5	14.5	5.0	5
425	5	61.7	5	50.3	5	39.0	5	27.6	5	16.3	5.0	5
430	5	71.6	5	57.9	5	44.1	5	30.4	5	16.6	5.6	5

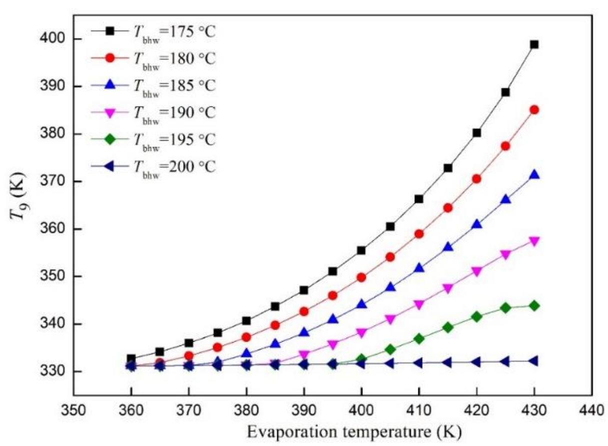

Fig 4 Variation of T_9 with boiler hot water temperature and evaporation temperature

As the shift of PPTD has critical influence on the outlet temperature of boiler hot water leaving evaporator, the variation of T_9 is presented in Fig.4. It is noteworthy that T_9 increases rapidly with improving evaporation temperature when the PPTD locates at point 5, and the varying trend declines with a increase of boiler hot water temperature. However, T_9 has the same value as the PPTD transfers to point 4, and that is to say the boiler hot water temperature and evaporation temperature have no effects on T_9. The main reason for this is that the constraints of PPTD=5 K and T_{con}=326 K lead to the constant value of T_9.

4.2 Thermodynamic analysis of biomass-fired ORC CHP system

The thermodynamic analysis of biomass-fired CHP system with boiler hot water temperature and evaporation temperature is illustrated in Fig. 5. It depicts that the power efficiency rises rapidly with increasing evaporation temperature, while the boiler hot water temperature has little effect. With respect to exergy efficiency and *PESR*, they have the same varying trend and both reach the highest value at T_{bhw}=200 ℃ and T_{eva}=430 K.

As for thermal efficiency, the values vary with the range of 89.78%-89.85%, which can be attributed to the consumed power of boiler hot water pump. Ultimately, it can be deduced that the shift of pinch point has slight influence on thermodynamic performance in this bioenergy system. As the condensation heat can be fully utilized to supply domestic hot water, the thermal efficiency nearly approaches the figure of 89.85% and the *PESR* is within the range of 8.6%-15.7%, which can save the primary energy resources substantially.

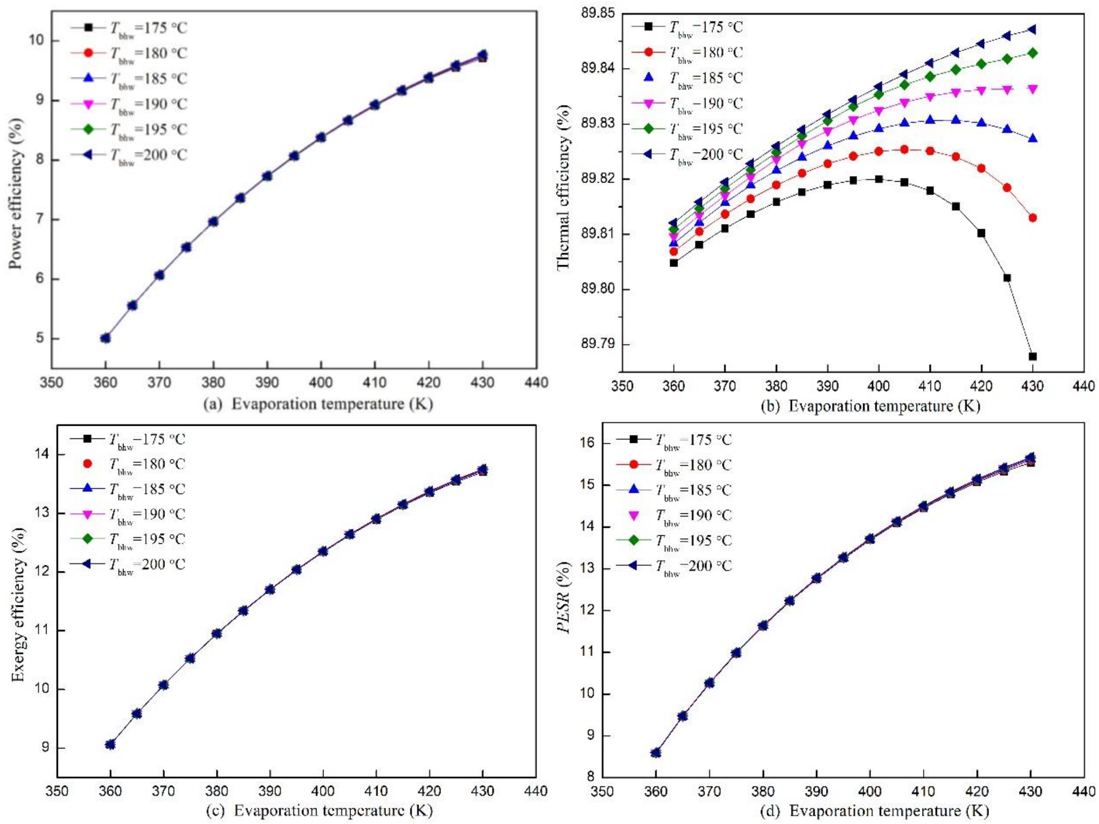

Fig 5 Thermodynamic analysis of biomass-fired CHP system with transfer of pinch point

4.3 Economic assessment of biomass-fired ORC CHP system

The economic assessment of biomass-fired ORC CHP system with boiler hot water temperature and evaporation temperature is illustrated in Fig. 6. Fig.6 (a) presents that the total investment rises with increasing evaporation temperature, for which the expenses of ORCs increase with improving output electricity. It highlights that the pinch point location has significant effects on total investment of biomass-fired ORC CHP system. The main reason is that the ratio of preheating heat capacity to vaporization heat capacity and temperature difference change substantially with pinch point location in evaporator. Furthermore, the heat exchangers contribute a large proportion to the total investment of ORCs, for which the costs mainly depend on the heat transfer area and materials. Besides, the optimal boiler hot water temperature corresponding to the specific evaporation temperature can be achieved with the objective function of INV_{tot}. In contrast, the investment rises rapidly with increasing evaporation temperature when the PPTD locates at point 4, while the evaporation temperature has slight effect on INV_{tot} as pinch point shifts to vaporization start point, namely point 5.

Figs. 6 (b) and (c) indicate the similar economic evaluation results, in which the same optimal boiler hot water temperature with specific evaporation temperature can be achieved in terms of *DPP* and *PRI*. Besides, the economic assessment further presents that the biomass-fired ORC CHP system is economically attractive. From the perspective of long-term economic evaluation, the *NPV* reduces with increasing evaporation temperature, while the boiler hot water temperature has little influence on its value. This is because the revenue of domestic hot water has dominant effect on the benefits of this bioenergy cogeneration system.

The comparison of *NPI* and *LEC* with pinch point location is illustrated in Fig.7. Fig.7 (a) shows that the *NPI* declines with increasing evaporation temperature and the boiler hot water has significant influence on its values. This is caused by interaction influences of total investment and power efficiency with evaporation temperature. As for the *LEC*, it reduces rapidly with increasing evaporation temperature, while the boiler hot water temperature has little influence on its value. The main reason is that the expenditure of biomass fuel contributes to a large proportion of annual maintenance and operation costs.

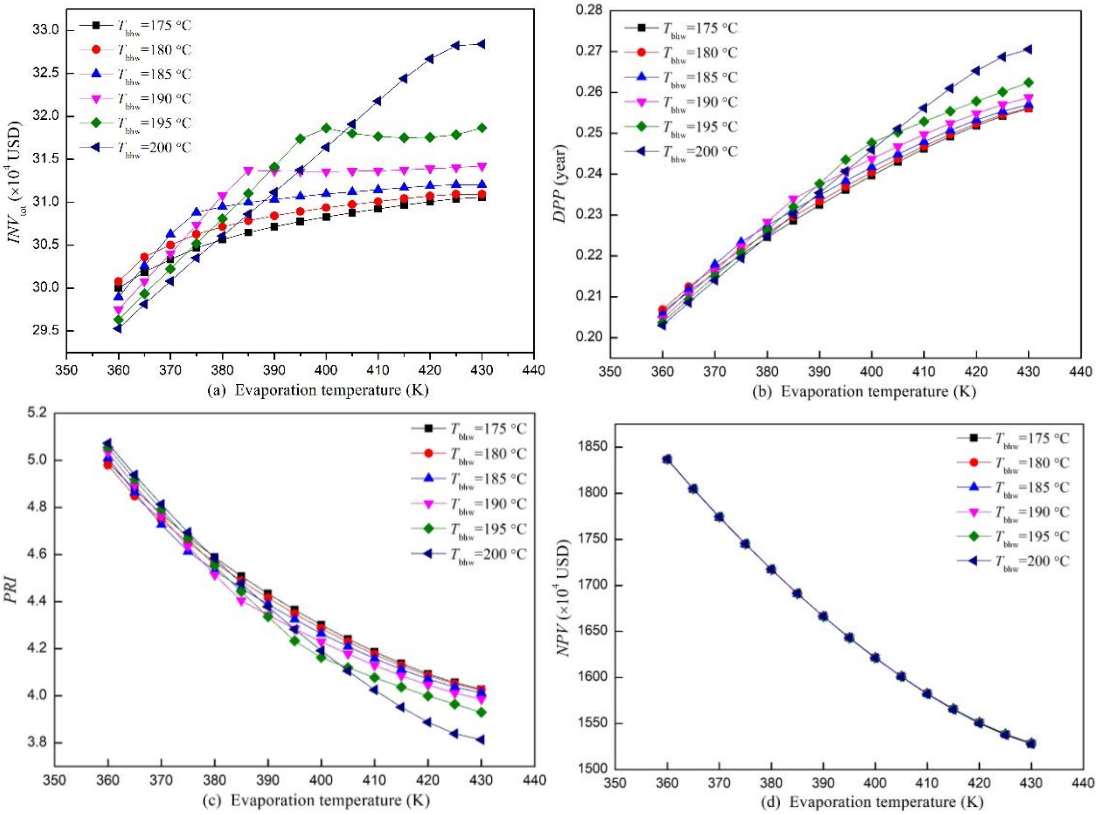

Fig 6 Economic assessment of biomass-fired CHP system with transfer of pinch point

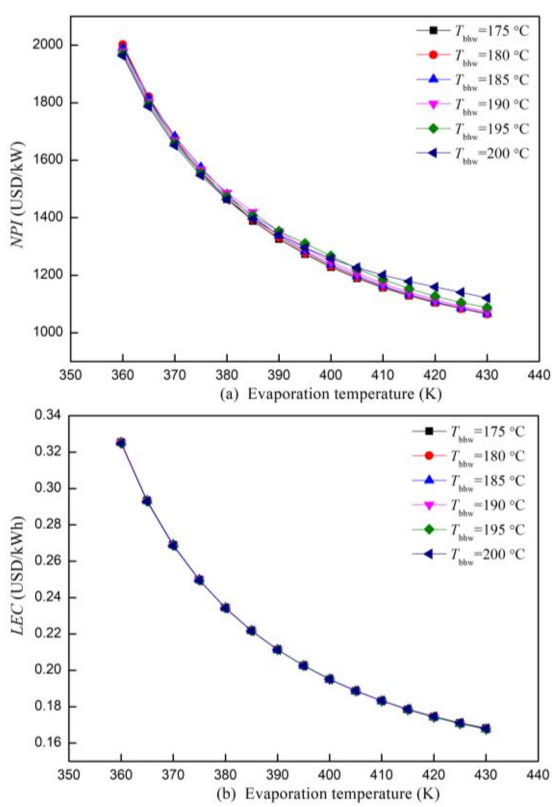

Fig 7 Comparison of *NPI* and *LEC*

Compared with Mazzola's technological economic analysis, the *LEC* of conventional diesel internal combustion generator was estimated about 0.29 USD/kWh [18]. The majority values of *LEC* for biomass-fired ORC CHP system are obviously less than 0.25 USD/kWh (see Fig.7 (b)), especially with high evaporation temperature. Moreover, the *NPI* of this bioenergy cogeneration system is less than 2000 USD/kW corresponding to the *DPP* of 0.20-0.30 year, which is in line with Algieri's research results [19] that the payback period of biomass-fired ORC system for CHP generation is less than 1 year with the net present value of 2800 USD/kW. This further verifies that the developed biomass-fired ORC CHP system is economically attractive.

5. CONCLUSIONS

The thermo-economic model of biomass-fired ORC CHP system has been developed in this paper. The PPTD analytic method is adopted to explore thermodynamic performance with boiler hot water temperature and evaporation temperature. The thermo-economic assessment versus pinch point location is carried out.

The shift of PPTD from vaporization start point to preheating start point is observed with increasing boiler hot water temperature or decreasing evaporation temperature in evaporator. The transfer of pinch point has slight influence on thermodynamic performance, while it has significant effect on economic assessment in this bioenergy system. The system investment rises rapidly with increasing evaporation temperature with PPTD locating at vaporization start point, but the evaporation temperature has slight effect on INV_{tot} as PPTD places at preheating start point. The evaporation temperature corresponding to the just starting shift of pinch point increases with improving boiler hot water temperature. Besides, the same optimal boiler hot water temperature with specific evaporation temperature can be achieved in terms of INV_{tot}, *DPP* and *PRI*.

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REFERENCE

[1] Fabian Schipfer, Lukas Kranzl. Techno-economic evaluation of biomass-to-end-use chains based on densified bioenergy carriers (dBECs). Appl Energy 2019; 239:715-24.

[2] Jakub Mascuch, Vaclav Novotny, Vaclav Vodicka, Jan Spale, Zbynek Zeleny. Experimental development of a kilowatt-scale biomass fired micro e CHP unit based on ORC with rotary vane expander. Renew. Energy 2018; https://doi.org/10.1016/j.renene.2018.08.113.

[3] Jang Y, Lee J. Optimizations of the organic Rankine cycle-based domestic CHP using biomass fuel. Energy Convers Manage 2018; 160:31-47.

[4] Liu H, Shao Y, Li JX. A biomass-fired micro-scale CHP system with organic Rankine cycle (ORC)-Thermodynamic modelling studies. Biomass Bioenergy 2011; 35:3985-94.

[5] Qiu GQ, Shao YJ, Li JX, Liu H, Riffat SB. Experimental investigation of a biomass-fired ORC-based micro-CHP for domestic applications. Fuel 2012; 96:374-82.

[6] Sartor K, Quoilin S, Dewallef P. Simulation and optimization of a CHP biomass plant and district heating network. Appl Energy 2014; 130:474-83.

[7] Ahmadi P, Dincer I, Rosen MA. Development and assessment of an integrated biomass-based multi-generation energy system. Energy 2013; 56:155-66.

[8] Pietropaolo Morrone, Angelo Algieri, Teresa Castiglione. Hybridisation of biomass and concentrated solar power systems in transcritical organic Rankine cycles: A micro combined heat and power application. Energy Convers Manage 2019; 180:757-68.

[9] Zhu YL, Li WY, Sun GZ, Li HJ. Thermo-economic analysis based on objective functions of an organic Rankine cycle for waste heat recovery from marine diesel engine. Energy 2018; 158:343-56.

[10] Su W, Hwangb Y, Deng S, Zhao L, Zhao D. Thermodynamic performance comparison of organic Rankine cycle between zeotropic mixtures and pure fluids under heat source. Energy Convers Manage 2018; 157:169-75.

[11] Hu K, Zhu J, Zhang W, Liu K. Effects of evaporator superheat on system operation stability of an organic Rankine cycle. Appl Therm Eng 2017; 111:793-801.

[12] Navarro-Esbrí J, Molés F, Peris B, Mota-Babiloni A, Martí JP, Collado R, González M. Combined cold, heat and power system, based on an organic Rankine cycle, using biomass as renewable heat source for energy saving and emissions reduction in a supermarket. Energy Procedia 2017; 129:652-9.

[13] Patel B, Desai NB, Kachhwaha SS. Thermo-economic analysis of solar-biomass organic Rankine cycle powered cascaded vapor compression-absorption system. Sol. Energy 2017; 157:920-33.

[14] Al-Sulaiman FA, Hamdullahpur F, Dincer I. Greenhouse gas emission and exergy assessments of an integrated organic Rankine cycle with a biomass combustor for combined cooling, heating and power production. Appl Therm Eng 2011; 31(4):39-446.

[15] Maraver D, Sin A, Royo J, Sebastián F. Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters. Appl Energy 2013; 102(0):1303-13.

[16] Mignard D. Correlating the chemical engineering plant cost index with macro-economic indicators. Chemical Engineering Research and Design 2014; 92(2): 285-94.

[17] Yang MH, Yeh RH, Huang TC. Thermo-economic analysis of the transcritical organic Rankine cycle using R1234yf/R32 mixtures as the working fluids for lower-grade waste heat recovery. Energy 2017; 140: 818-36.

[18] Mazzola S, Astolfi M, Macchi E. The potential role of solid biomass for rural electrification: A techno economic analysis for a hybrid microgrid in India. Appl Energy 2016; 169:370-83.

[19] Algieri A, Morrone P. Energetic analysis of biomass-fired ORC systems for micro-scale combined heat and power (CHP) generation. A possible application to the Italian residential sector. Appl Therm Eng 2014; 71(2):751-9.