RESEARCH ON TRANSIENT RESPONSE CHARACTER ANALYSIS OF ORC WASTE HEAT RECOVERY SYSTEM FOR MARINE DIESEL ENGINE

Jiangnan Liu*, Zijian Zhang, Jingfen Li, Zhichao Gu, Jinyong Feng

Shanghai Marine Diesel Engine Research Institute,
Shanghai, China
jiangnanliu@163.com

ABSTRACT

Nowadays, maintaining the wholesomeness of the oceans, protecting the marine environment have become common norms for all the people in the world to abide by, and a collective mission for all mankind to undertake. The EEDI and EEOI index had already been stated by IMO and phased on due course so as to reduce the CO2 emission. Decreasing the emission from Marine diesel engine as the main power of the civil ships is the main key to achieve the purpose of reducing pollution.
Organic Rankine Cycle, which have been proved to be one of the most efficient low temperature waste heat recycle system for power generation by now, can utilize the exhaust from diesel engine to drive the power generator and thus lower the EEDI along with increasing the fuel efficiency. However, the steady output of the ORC waste heat recycle system have long been disturbed by the unstable working condition of diesel engine coursed by the mutable sailing environment.
This thesis had investigated the heat sources character of different type of diesel engine and their several working conditions, therefore, established the system model of ORC waste heat recovery system for marine diesel engine and researched the working condition of the cycle system which influenced by internal and external disturb. Then, the thesis worked on the transient response character effected by factors such as thermal inertia, evaporating pressure and evaporating temperature at multi time scale. Results show: the higher the load of the diesel engine, the more stable of the energy generated; the larger the thermal inertia, the dully system response. Eventually, with various system response character summarized, the thesis provides support data for the control system to improve the adaptability of the ORC waste heat recycle system applying to the vessel.

1. INTRODUCTION

The thermal efficiency of large marine diesel engines is generally between 45% and 55%, and about half of the energy is lost in various forms. 25% of the heat is taken away by exhaust (Long, 2012). High temperature exhaust heat belongs to medium and high grade energy, which can be used to generate electricity and generate power. Nowadays, the calls for energy saving and environmental protection are growing, and the international regulations on ship energy efficiency are increasingly stringent. The recovery and utilization of exhaust heat energy of diesel engine is beneficial to energy saving and emission reduction, to protecting the environment as well.
One of the characteristics of the organic Rankine cycle(ORC) is that the circulating working fluid differs widely. So, Liu *et al.*(2010), Wang *et al.*(2013) and Thurairaja *et al*.(2019) studied the optimal working fluid in the organic Rankine cycle under different conditions. Some scholars have applied organic Rankine cycle to low and medium temperature residual heat sources, such as geothermal energy(Liu and Gao, 2019), solar energy(Wang and Fu,2019), waste heat recovery of industrial waste gas(Liu *et al.*,2013).
By now, ORC is widely used in various fields as described above, but few in marine diesel engine. In view of the excellent application of ORC in the land, were it applied to ship waste heat recovery would greatly achieve the purpose of energy saving and emission reduction. Scholars had already carried out some research on off design conditions(Wei *et al.*,2006), but there is little research on the whole system

fluctuate in the dynamic process. In this paper, the off design condition and dynamic process of ORC waste heat recovery of marine diesel engine are studied and analyzed.

2. SYSTEM DESCRIPTION

Organic Rankine cycle which uses organic working fluid is different from traditional Rankine cycle that uses water. The boiling point of organic working fluid is low, and different kinds of organic working fluid can be used in different heat source conditions. So, ORC has a certain advantage in the recovery of residual heat energy.

2.1 System principle

Figure 1 is the diagram of ORC system for waste heat recovery of diesel engine. 1-2 is the process of evaporation under constant pressure in which organic working fluid absorbs the energy of exhaust from diesel engine in heater. 2-3 is the process that high-temperature and high-pressure steam is used to generate mechanical energy through the turbine, and the generator changes the mechanical energy into electric energy. 3-4 is the process that the exhaust steam from the turbine is cooled down into saturated liquid by cooling water when entering the condenser. 4-1 is the process that saturated liquid working fluid pressures up in the working fluid pump. These processes form a complete circulation. The dynamic model is shown in Figure 2. Some controllers have been added.

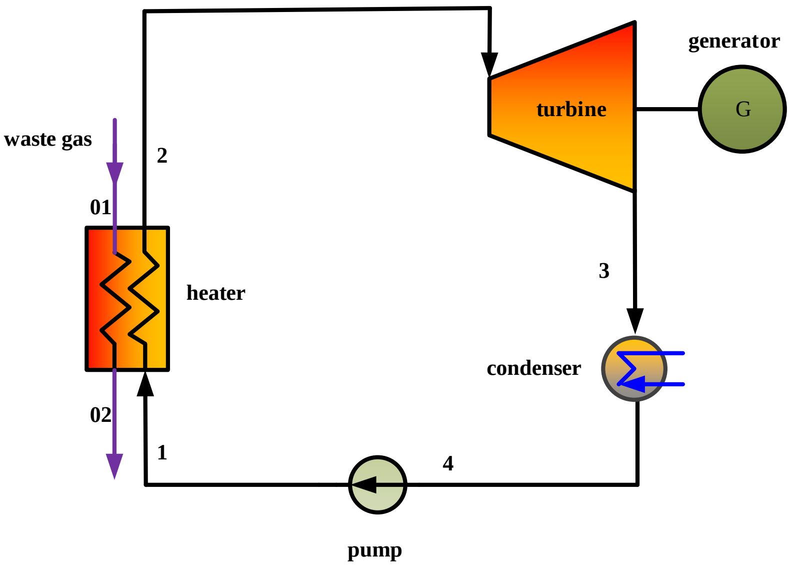


Figure 1: The diagram of ORC system

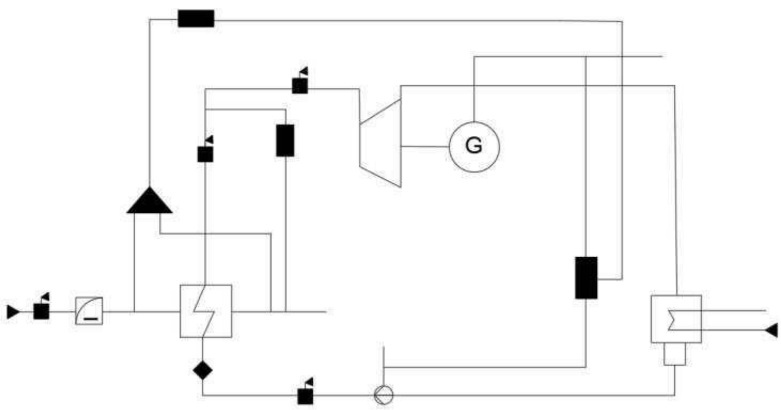


Figure 2: The dynamic model of ORC system

2.2 System design input

Table 1: Diesel engine operating parameters

Diesel engine working condition	25%	50%	75%	90%	100%	110%
Temperature(℃)	200	208	215	248	268	295
Mass flow(kg/s)	6.55	10.39	14.67	15.64	17.15	18.04

Table 2: System design condition input parameters

parameters	unit	number
Turbine Isentropic efficiency	-	0.75
Turbine mechanical efficiency	-	0.95
Generator efficiency	-	0.98
Cooling water temperature	℃	28
Pump Isentropic efficiency	-	0.6
Pump mechanical efficiency	-	0.95
Heat exchanger node temperature difference	℃	5
Heat exchanger pressure loss	-	3%

This paper takes exhaust gas from a low-speed marine diesel engine as the heat source. The exhaust gas characters of the diesel engine under different operating conditions is shown in Table 1. The design input parameters of the ORC system are listed in Table 2.

2.3 Working fluid characteristics

In this paper, R245fa is chosen as working fluid. R245fa is an isentropic fluid whose latent heat of vaporization is up to 196.09 kJ/kg. And it is non-corrosive and non-flammable which will not cause cavitation damage to the blade in the turbine. Moreover, R245fa is environment-friendly as its value of ozone depletion potential (ODP) is 0. The main characteristics of this substance are shown in Table 3.

Table 3: R245fa characteristics

Parameter name/unit	value
Chemical formula	$CHF_2CH_2CF_3$
Critical temperature/°C	154.01
Critical pressure/MPa	3.651
Molecular weight/kg·kmol^{-1}	134.05
Critical density/kg·m^{-3}	516.08
Normal boiling point/°C	15.14
Maximum temperature/°C	166.85
Maximum pressure /MPa	200
ODP	0
GWP/100years	950

3. RESULTS AND ANALYSIS

The operating conditions of the diesel engine are variable, so the exhaust temperature and flow rate changes continually. As the heat source of the ORC system changes, the operation of the ORC system is affected accordingly. Therefore, the influence between the working conditions of the diesel engine and the performance of the ORC system should be observed and studied so as to work out the corresponding reaction of the variation of the parameters in the system when various disturbances occur.

3.1 Energy recycle of diesel engine in variable load operation

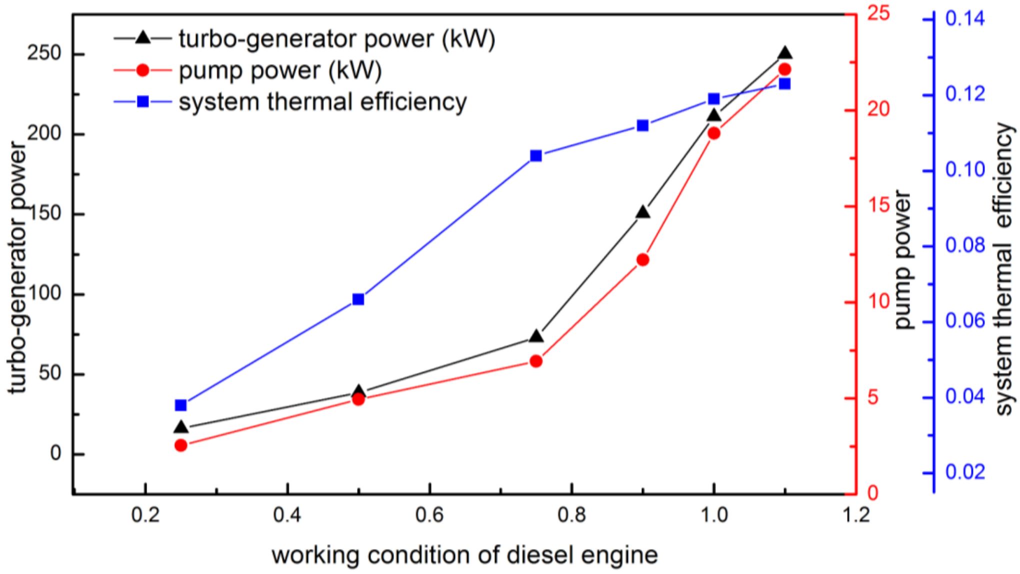


Figure 3: ORC performance under off-condition operating conditions

The heat recovery system's nominal working point is set at the 100% diesel engine load with following characters: 1) evaporation pressure of 2.5 MPA; 2) evaporation temperature of 150℃ ; 3) cooling water temperature of 28 ℃. Afterwards, the diesel engine loads are set as 25%、50%、75%、90%、100% and 110%, resulting the heat source and other circumstance differ causing different system status such as output、efficiency and turbo-generator power which are shown in Figure 3.

From figure 2, the output power and thermal efficiency of the waste heat recovery system increase along with the diesel engine load. Under the low load such as 25% and 50%, the large range of variation is due to the small residual heat energy that the fluid fails to evaporate completely in the evaporator, resulting in a decrease of the output power. By studying the performance of the system under the off-design condition, we can know that the performance of the waste heat recovery system is poor under the condition of low load. It is suggested that the waste heat recovery system be cut out and used under the condition of 75% or above that ORC can maintain high system thermal efficiency and output more power.

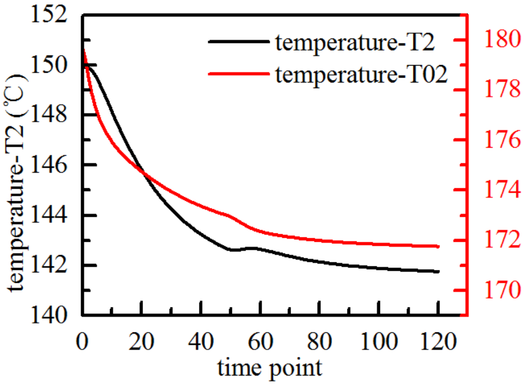
3.2 Effect of thermal inertia on system performance

When the inlet temperature or flow rate into the heat exchanger changes, the heat exchange process in it will not alter in a sudden. It occurs a slow course. That is so called the thermal inertia. By studying the influence of thermal inertia on the performance of the system, the variation of the performance parameters can be analyzed, which is helpful to ensure the safe and effective operation of the system. Considering that the heat source parameters have a complex influence on the system performance, this section will focus on the influence of heat source temperature and flow rate individually while keeping the other parameters unchanged.

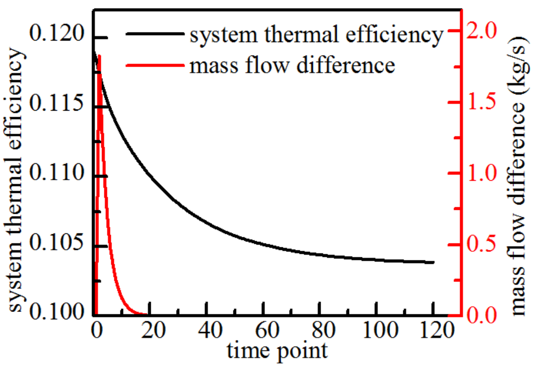
(1) Heat source flow

By adjusting the regulating valve on the flue gas side, the mass flow rate of the heat source is changed, while the responding of the working substance side lagged. The heat flux decreases from 17.15kg/s to 15kg/s, increases from 13kg/s to 16kg/s, as shown in Figure 4, Figure 5 (take one time point every 20 seconds, total 40min).

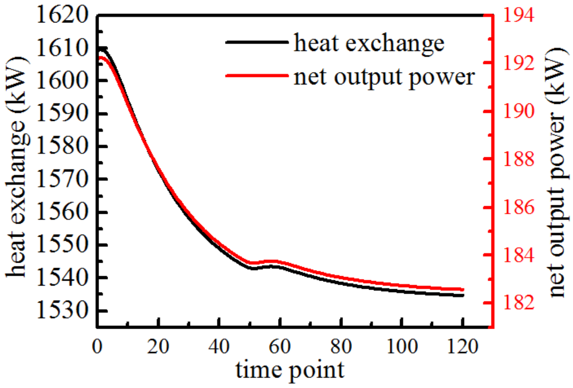
Figure 4 shows the change tendency of the system performance when the flow of the heat source is reduced. The outlet temperature of the evaporator、 the thermal efficiency of the system、 the heat exchange and the net output power are declined with the time, and the decrease of the amplitude is smaller and smaller as time passed. Because of the thermal inertia, the temperature of the flue gas side is changed directly, but fluid side has a certain delay that the temperature roughly remain immobilized in the first 2-3 min. The mass flow of the heat source has completely changed to 15 kg/s after 10 min, while under the affected of thermal inertia, the whole system adjusted much longer.



(a) Evaporator outlet temperature

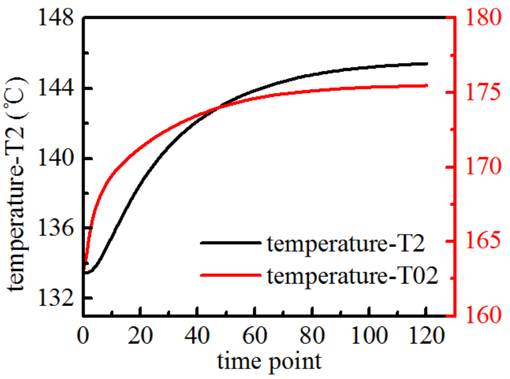


(b) Thermal efficiency and heat source flow difference

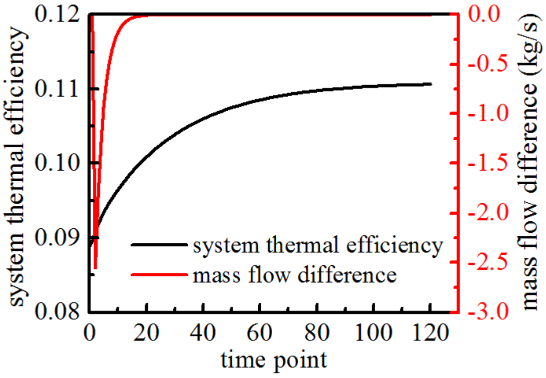


(c) Evaporator heat exchange and net output power

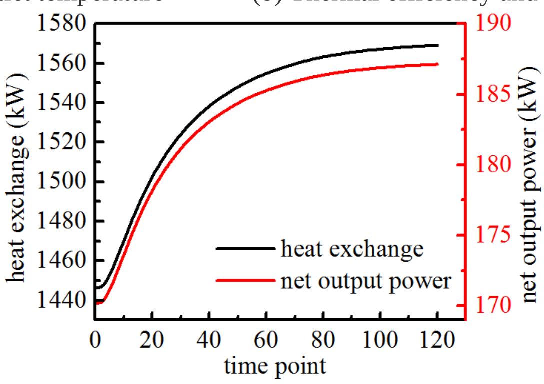
Figure 4: system performance when heat source flow is reduced



(a) Evaporator outlet temperature



(b) Thermal efficiency and heat source flow difference



(c) Evaporator heat exchange and net output power

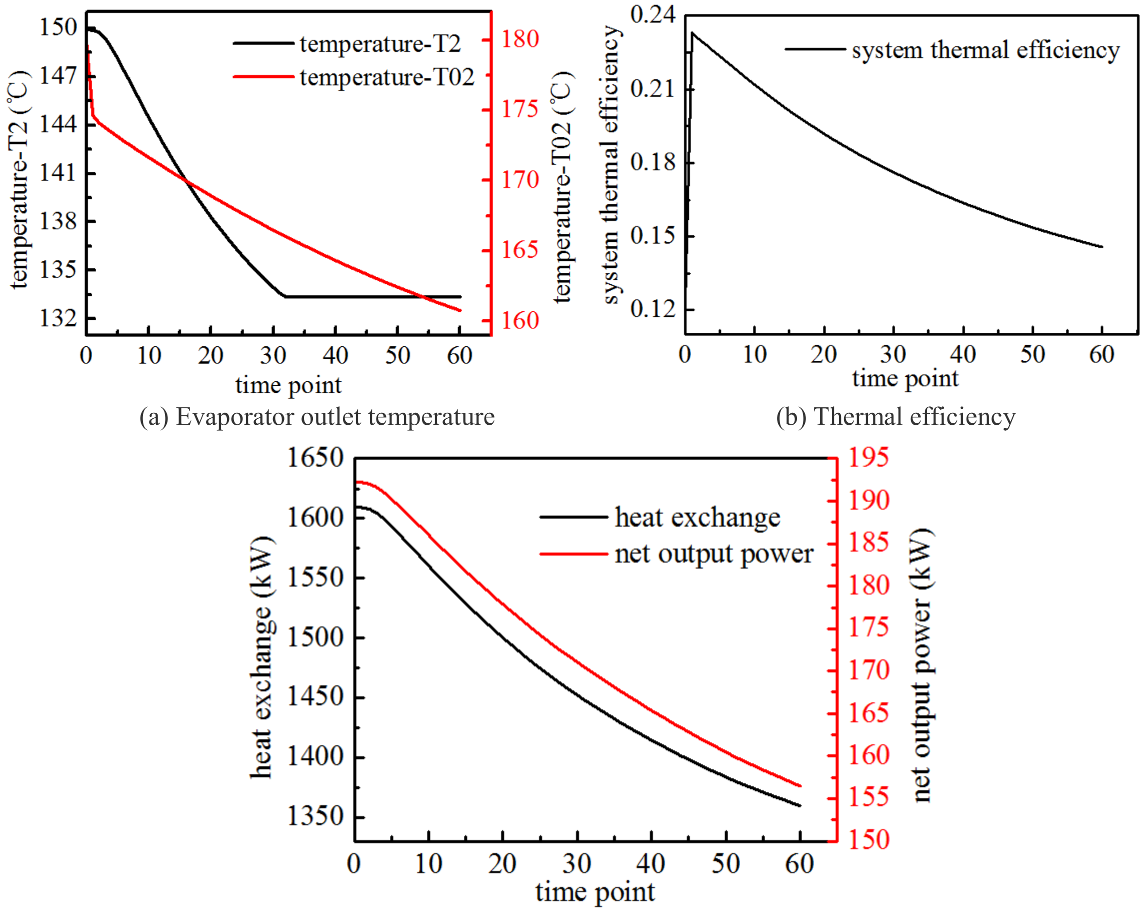
Figure 5: system performance when heat source flow is increased

Figure 5 shows the changing trend of system performance with the increase of heat source flow. The evaporator outlet temperature、 system thermal efficiency、 heat exchange and net output power all rise with time, and the range of increasement becomes smaller and smaller as time passed. Due to the existence of thermal inertia, the flue gas side changes directly, while the working fluid side has a certain delay that the working medium responds slowly at the first 2-3min. The mass flow rate of heat source has completely turned to 16 kg/s after 10min, yet the whole system is still changing due to the thermal inertia.

(2) Temperature change of heat source

When the temperature of heat source decreases from 268℃ to220 ℃, or increases from 268℃ to 290℃, the system behave is observed as shown in Fig.5 and 6 (the temperature change is taken at a time point every 10s).

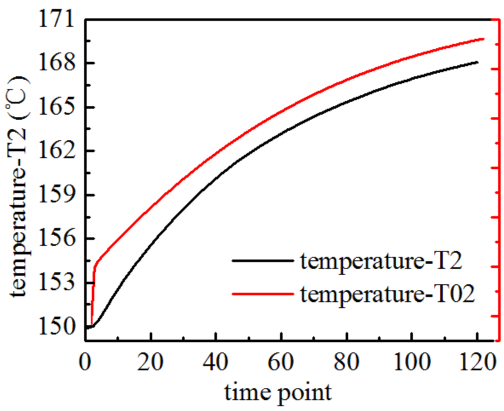
Figure 6 shows the changing trend of the system performance when the heat source temperature lowering down. The outlet temperature of the evaporator, the thermal efficiency of the system, the heat transfer and the net output power all decrease with time. Because of the existence of thermal inertia, the flue gas side changes directly, while the working fluid side has a certain delay, and the temperature change of the working fluid is not obvious when the decline occurs. The thermal efficiency of the system rising suddenly, which is due to the delay of heat transfer that the decrease of the output power is less than the decrease of heat source offering power, which means heat exchange dropped faster than the generator output. In Figure 6(a), the working fluid side has been reduced to boiling point, resulting in the existence of gas-liquid two-phase at the outlet of the evaporator, which is disadvantage to the turbine equipment. Therefore, when the heat source temperature decreases, the other parameters should be adjusted within the time the system still operated stably so as to prevent the existence of gas-liquid two-phase in the evaporator outlet, ensure not to damage the equipment.



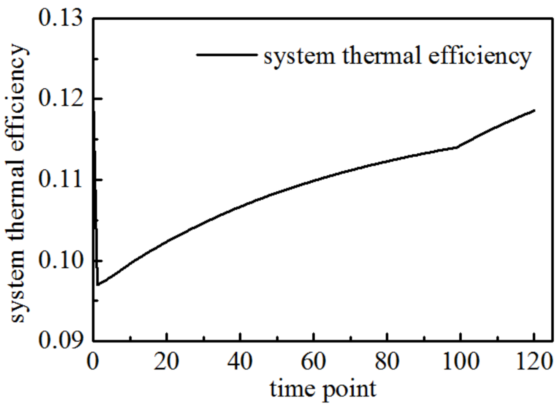
(a) Evaporator outlet temperature (b) Thermal efficiency

(c) Evaporator heat exchange and net output power

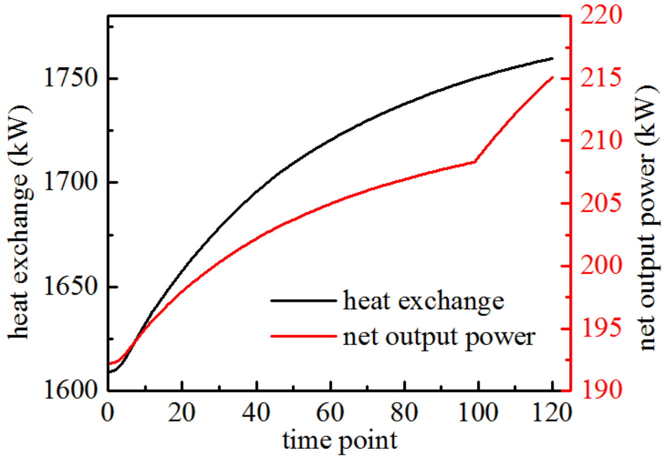
Figure 6: system performance when heat source temperature is reduced



(a) Evaporator outlet temperature



(b) Thermal efficiency



(c) Evaporator heat exchange and net output power

Figure 7: system performance when heat source temperature is increased

Figure 7 shows the changing tendency of the system performance when the heat source temperature rises. The outlet temperature of the evaporator, the thermal efficiency of the system, the heat transfer and the net output power all increase with time. Because of the existence of thermal inertia, the flue gas side changes directly, while the working fluid side has a certain delay, and the temperature change of the working fluid is not obvious when the change occurs. The thermal efficiency of the system decreases suddenly because the heat transfer delay causes the output power of the system to rise slower than that of the heat source. In Figure 7(a), the working fluid side of 166.85°C is higher than the stable temperature, which results in the change of working fluid characteristics, leading to the breaking point of output power and thermal efficiency. Therefore, when the heat source temperature rises, it is vital to adjust the other system parameters within the allowing time (partly contributed by the thermal inertia) to ensure that the working fluid does not deteriorate.

4. CONCLUSION

Under the condition of low load, the performance of the waste heat recovery system is poor. It is suggested that the waste heat recovery system be cut out. While when the load used under 75% or more the system can maintain a acceptable thermal efficiency and power output.
When the parameters of the exhausted gas are changed, for example the temperature of the flue gas side changes directly, due to the existence of thermal inertia, the working fluid side has a certain delay, and the variation trend of the system performance parameters tends to stably as time goes by.
When the heat source parameters are changed, we should pay attention to adjusting other relevant parameters such as working fluid flow in time during the system response, so as to prevent working fluid deterioration or equipment damage.

REFERENCES

Long, J., 2012, Heat-cascading technology based on one type of marine diesel engine, *Wuhan University of Technology*, Wuhan, China.

Liu J, Chen J, Qi Z, 2010, Thermodynamic analysis of low temperature ORC, *Chemical Engineering*, vol. 61 no. 2: p. 9-14.

Wang Z, Zhou N, Xia X, et al, 2013, Multi-objective optimization of ORC power generating system, *Chemical Engineering*, vol. 64 no. 5: p. 1710-1716.

Thurairaja K, Wijewardane A, Jayasekara S, et al, 2019, Working Fluid Selection and Performance Evaluation of ORC, *Energy Procedia*, Vol. 156: p. 244-248.

Liu C, Gao T, 2019, Off-design performance analysis of basic ORC, ORC using zeotropic mixtures and composition-adjustable ORC under optimal control strategy, *Energy*, Vol. 171: p. 95-108.

Wang S, Fu Z, 2019, Thermodynamic and economic analysis of solar assisted CCHP-ORC system with DME as fuel, *Energy Conversion and Management*, Vol. 186: p. 535-545.

Liu G, Liu Q, Zhang B, 2013, Election of ORC working medium based on exhaust heat resource , *Thermal power engineering*, vol. 28 no. 3: p. 241-245.

Wei D, Lu Z, Lu X, et al, 2006, Performances Analysis of the Organic Rankine Cycle Driven by Exhaust under Disturbance Conditions, *SJTU journal*, Vol. 32: p.59-62.