# EXPERIMENTAL STUDY ON THE INFLUENCE OF HEAT EXCHANGERS ON THE ORGANIC RANKINE CYCLE PERFORMANCE

Xiaosheng Zheng[1], Xianglong Luo[1]*, Jianyong Chen[1], Zhi Yang[1], Yingzong Liang[1], Ying Chen[1]

[1]Guangdong Provincial Key Laboratory of Functional Soft Condensed Matter, School of Material and Energy, Guangdong University of Technology, No. 100 Waihuan Xi Road, Guangzhou Higher Education Mega Center, Panyu District, Guangzhou 510006, China
* Corresponding Author

## ABSTRACT

Organic Rankine cycle (ORC) is a common accepted low-grade heat-to-power technology. Although the ORC has been extensively investigated in the past decades, experimentally validated works occupy only a small fraction of published literature. The experimental test rig in most of the previous studies are mostly focus on the expander, cycle configuration, working fluid, and system performance. The experimental investigation on the heat exchanger is quite limited though the heat exchanger occupies important role in investment cost and irreversible loss. In the present study, an ORC experimental test rig with switchable heat exchangers and scroll expander is introduced. The system performance test and comparison are conducted for six ORCs with different heat exchanger area. Results show that ORC with 6.56m$^2$ evaporator and 10 m$^2$ condener features the maximum thermal efficiency at working fluid flow rate 0.12kg/s, heat source temperature 150$^o$C, and heat sink temperature 15$^o$C. The results show that the ORC performance is remarkably affected by the heat exchanger size and the present experimental study provide a valuable guidance for the reasonable heat exchanger design to improve the ORC performance.

## 1. INTRODUCTION

Recently, owing to the excessive consumption of traditional energy and deteriorating environmental pollution, development of renewable energy, energy saving, environmental protection and efficient energy conversion are getting recognized [1]. Organic Rankine cycle (ORC), as an efficient heat-to-power conversion technology, has a broad application prospect in the field of solar energy, geothermal energy, biomass energy, and waste heat [2]. The difference between ORC and steam Rankine cycle is that the former uses the organic working fluid with low boiling point while the latter uses water as heat-to-work conversion medium. In addition, the characteristics of the organic Rankine cycle system, such as simplicity, strong plasticity and adaptability, make it suitable for the distributed energy with a wide range of operating conditions. Therefore, the research on ORC system performance is of great significance. The previous ORC researches mainly focus on numerical simulation and optimization.

In recent years, many scholars carry out experiment research, in order to demonstrate design models or investigate the performance of real systems. The experimental studies mainly include research of system, performance test of expander and working fluid pump, comparison and selection of working fluid, and characteristic investigation of heat exchangers. Heat exchangers, key heat exchange equipment in the ORC system, not only determine the investment cos, but also affect the heat transfer characteristics and operation performance of ORC system. However, in the published literature, there are relatively few experimental researches on the relationship between heat exchangers and ORC system. Omid et al. [3] carried out an experimental investigation to study the influence of the Brazed Metal-foam Plate Heat Exchanger (BMPHE) on the performance of ORC system and compared with the basic ORC system with conventional Brazed Heat Exchanger. They analyzed the power density, pressure gradient and ORC performance and found that BMPHE will increase the pressure drop of 1.4-2.6 times, while the power density can be increased maximally by a factor of 2.5 utilizing BMPHE. Lee et al. [4] experimental studied the system responses employing different evaporator of plate and shell-and-tube evaporator connected to system. The results showed that the stability of ORC system with plate evaporator is significantly sensible to the degree of superheat. On the contrary, the system using shell-and-tube evaporator was relatively stable when the degree of superheat changed

from 0 to 17°C. Sun et al. [5] compared the influence of flow losses in two plate heat exchangers on the operation performance of ORC system between the practical cycle and ideal cycle. They concluded that the flow losses in heat exchangers of practical cycle lead to the increasing of irreversibility in evaporator and condenser (increases by 14.4% and 37.0%), as well as the decreasing of net power output, thermal efficiency and exergy efficiency (decreases by 16.1%, 17.0% and 16.9%, respectively). Alireza et al. [6] observed the characteristics of heat exchangers and operation performance of ORC system under different NTU. On one hand, increasing the NTU helped to improve the total heat transfer rate, net output work and thermal efficiency. On the other hand, the system installation cost increased with the rise in NTU of heat exchangers.

In conclusion, compared with other components of the ORC system, the researches about characteristics of the heat exchangers and their influence on the system are scarce. In this paper, the objectives of this research are not only to explore the heat transfer characteristics of heat exchangers with different areas in ORC system but also to investigate the relation between operation performance of ORC systems and heat exchangers with different heat transfer areas. In order to do so, a multiple heat exchangers test bench employing a series of heat exchangers with difference heat transfer areas was established. The calculation model of the ORC system was revealed. The experimental results were analyzed from the aspects of heat exchangers and system respectively under different operating conditions and heat exchange areas. Finally, the major conclusions were summarized.

## 2. EXPERIMENTAL FACILITY

The experimental facility, consists of six heat exchangers, is used to study the heat transfer characteristics of heat exchangers an operation performance of ORC system. Experimental apparatus is carried out by associating the heat source cycle and heat sink cycle with the basic ORC loop. As shown in the schematic diagram of Fig. 1, basic ORC loop consists of three evaporators (with area of 6.56 $m^2$, 3.71 $m^2$ and 3.30 $m^2$, respectively), three condensers (with area of 13.59 $m^2$, 10 $m^2$ and 5.42 $m^2$, respectively), scroll expander and diaphragm plunger pump. In addition, data acquisition and control system are set up to control the experimental components and collect the experimental data. Fig. 1 shows the photographs of the ORC laboratory bench, scroll expander, working fluid pump, brazing plate heat exchanger, plate, data acquisition and control system. More detailed information of the experimental test rig can be found in Ref. [7].

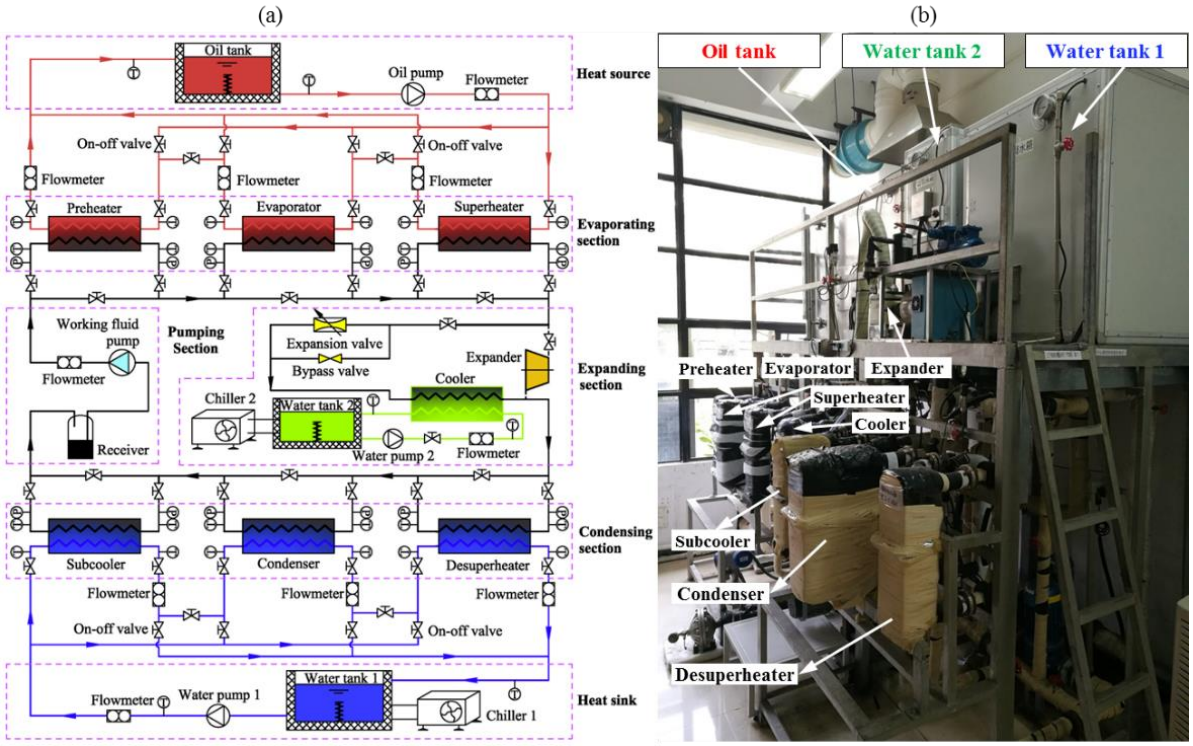



Fig. 1. (a) Schematic diagram and (b) photograph of the laboratory bench [7].

## 3. THERMODYNAMIC ANALYSES

Fig.2 indicates the *T-s* diagram of ORC system. The temperature and pressure of the inlet state point and outlet state point of expander, evaporator, condenser and fluid pump are measured by temperature sensor and pressure transmitter, respectively. The enthalpy, entropy of R245fa at each state points are calculated from REFPROP 10.0. The thermal efficiency ($\eta_{sys}$) is calculated by shaft power of expander, electricity consumption of fluid pump and heat load of evaporator. The detailed thermodynamic analysis model can be found in Ref. [7]. $\eta_{th}$ is obtained by the following equation.

$$\eta_{th} = \frac{W_{net}}{Q_{eva}} = \frac{W_{exp} - W_{pump}}{Q_{eva}} \quad (1)$$

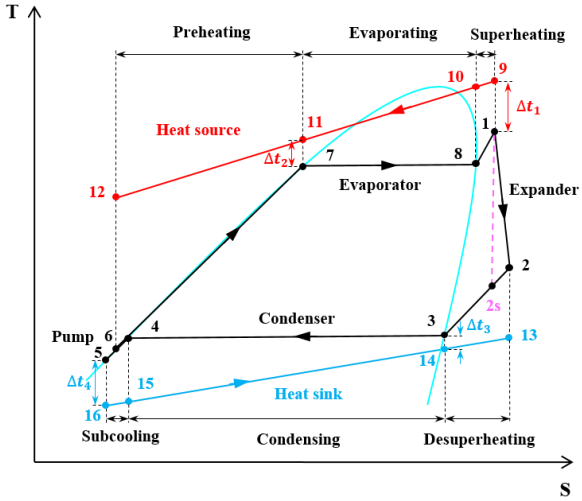



Fig. 2. Schematic *T-s* diagrams of ORC system.

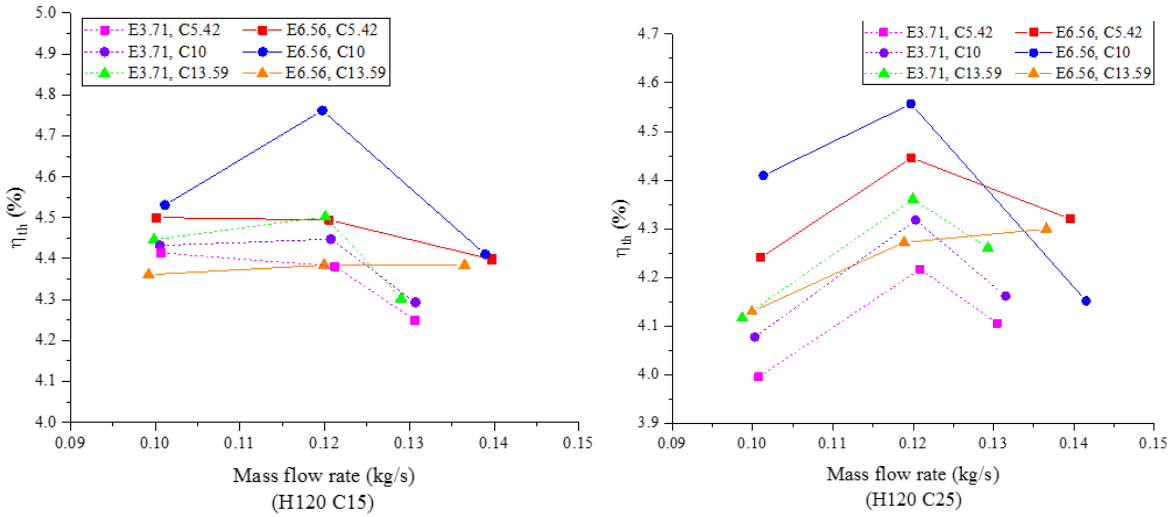
## 4. RESULT AND DISCUSSION

Two evaporators with heat transfer area of 3.71 $m^2$ and 6.56 $m^2$ and three condensers with heat transfer area of 5.42 $m^2$, 10 $m^2$ and 13.59 $m^2$ are combined in pairs to form six series of heat changers (E3.71C5.42, E3.71C10, E3.71C13.59, E6.56C5.42, E6.56C10 and E6.56C13.59). E3.71C5.42 means that the heat transfer area of evaporator and condenser are 3.71 $m^2$ and 5.42 $m^2$, respectively. Thus, six ORCs with different combination of evaporators and condensers are tested under five different conditions. The five operation conditions consist of one design condition (H130C20) and four off-design conditions (H120C15, H120C25, H140C15, H140C25). H130C20 indicates that the heat source temperature is 130 ºC and the heat sink temperature is 20 ºC. Table 1 lists the operation parameter of different heat changers under different conditions. The research is carried out by adjusting the ORC mass flow rate from 0.10 kg/s to 0.16 kg/s in four steps. Experimental data are obtained to compare and investigate the heat transfer characteristics of different heat changers and operation performance of ORC system adopting different heat changers under five conditions.

Table 1 Operation parameter of different heat changers under different conditions.

| Variable parameter | Initial value | Step size | Finishing value |
|---|---|---|---|
| Temperature of heat source ($T_h$) | 120 ºC | 10 ºC | 140 ºC |
| Temperature of heat sink ($T_c$) | 15 ºC | 5 ºC | 25 ºC |
| Mass flow rate of R245fa ($q_m$) | 0.10 kg/s | 0.02 kg/s | 0.16 kg/s |
| Heat transfer areas of evaporator ($A_{eva}$) | | 6.56, 3.71 $m^2$ | |
| Heat transfer areas of condenser ($A_{con}$) | | 13.59, 10, 5.42 $m^2$ | |
| Constant parameter | | value | |
| Volume flow rate of heat source ($q_{v,h}$) | | 1800 L/h | |
| Volume flow rate of heat sink ($q_{v,c}$) | | 1350 L/h | |
| Rotation speed of expander ($T_{exp}$) | | 1500 rpm | |

Fig. 3 shows the thermal efficiency of different ORC system under five conditions. As shown in Fig. 3, under a certain ORC system with an evaporator heat transfer area of 3.71 $m^2$, the increase of condenser heat transfer areas helps to increase the thermal efficiency of ORC system. This is because increasing the condenser heat transfer areas will rise the net power output of the system ($W_{net}$), while the heat exchange capacity of the system ($Q_{eva}$) remains almost constant. According to $\eta_{th} = W_{net}/Q_{eva}$, the thermal efficiency of ORC system increases with the rise in heat transfer areas of condenser under a certain ORC system. Under a certain ORC system with an evaporator heat transfer area of 6.56 $m^2$, the thermal efficiency of ORC tends to rise first and then decrease with the increase of condenser heat transfer areas from 5.42 $m^2$ to 13.59 $m^2$. The fundamental cause is that too large or too small heat exchange area of condenser reduce the net power output of ORC system. In addition, the change of condenser heat transfer areas slightly contributes to the change of heat exchange capacity of the system. As can be seen from Fig. 3, the maximum thermal efficiency of ORC system is 4.94% using E6.56C10 under H140C15. Overall, the ORC system with E6.56C10 has the highest thermal efficiency. Therefore, there is an optimal condenser area to maximize the ORC system efficiency under a certain ORC system with an evaporator heat transfer area of 6.56 $m^2$. When heat transfer areas of condenser are relatively smaller (5.42 $m^2$ and 10 $m^2$) and heat transfer areas of evaporator increases from 3.71 $m^2$ to 6.56 $m^2$, the thermal efficiency of ORC system always rises. This is because the working medium flow into the expander has a stronger ability to produce power with the increase of the evaporator heat transfer areas, thus increasing the net power output of ORC system. In addition, the rise range of net power output is larger than heat exchange capacity of the ORC system. As a result, increasing the heat transfer areas of evaporator helps to rise the thermal efficiency of ORC system under a relatively smaller heat transfer areas of condenser. However, when heat transfer areas of condenser are relatively larger (13.59 $m^2$) and heat transfer areas of evaporator increases from 3.71 $m^2$ to 6.56 $m^2$, the thermal efficiency of ORC system has no significant change. When the heat transfer areas of condenser area are too large, increasing the evaporator area will significantly increase the system resistance, thus increasing the power consumption of the working fluid pump ($W_{pump}$). Moreover, heat exchange capacity of the ORC system ($Q_{eva}$) will increase with the rise in heat transfer areas of evaporator. Although the net power output ($W_{exp}$) increases with the increase of evaporator area, generally, the thermal efficiency of the system ($\eta_{th}$) does not change significantly.



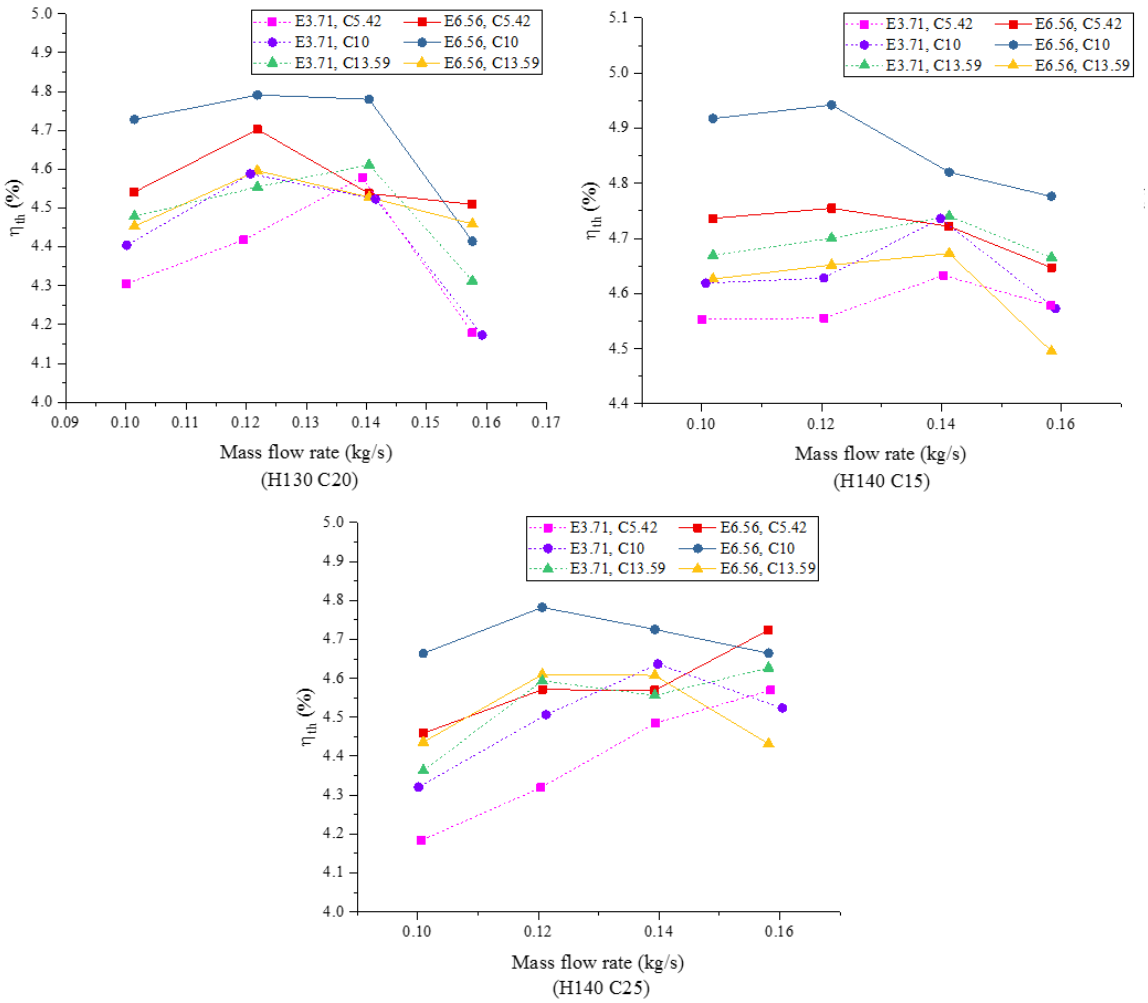



Fig. 3. Thermal efficiency of different ORC system under five conditions.

## 6. CONCLUSIONS

This research comprehensively investigated the influence of heat exchangers with different heat transfer areas on the operation performance of ORC system under variable conditions at the heat exchangers and system level respectively. The results showed that under a lower heat transfer area of evaporator, increasing the heat transfer areas of condenser helps to increase the net power output and thermal efficiency of ORC system. The maximum net power output of ORC system is 2.2 KW using E6.56C10 under H140C15. The maximum thermal efficiency of ORC system is 4.94% using E6.56C10 under H140C15.

## REFERENCES

[1] Landelle A, Tauveron N, Haberschill P, Revellin R, Colasson S. Organic Rankine cycle design and performance comparison based on experimental database. Appl Energ. 2017;204:1172-87.

[2] Park B, Usman M, Imran M, Pesyridis A. Review of Organic Rankine Cycle experimental data trends. Energ Convers Manage. 2018;173:679-91.

[3] Nematollahi O, Abadi GB, Kim DY, Kim KC. Experimental study of the effect of brazed compact metal-foam evaporator in an organic Rankine cycle performance: Toward a compact ORC. Energ Convers Manage. 2018;173:37-45.

[4] Lee Y, Kuo C, Liu C, Fu B, Hsieh J, Wang C. Dynamic Response of a 50 kW Organic Rankine Cycle System in Association with Evaporators. Energies. 2014;7:2436-48.

[5] Sun H, Qin J, Hung T, Huang H, Yan P, Lin C. Effect of flow losses in heat exchangers on the performance of organic Rankine cycle. Energy. 2019;172:391-400.

[6] Jafari A, Yang C, Chang C. Optimization of heat exchanger size of a 10 kW organic Rankine cycle system. Energy Procedia. 2017;129:851-8.

[7] Chen J, Zheng X, Guo G, Luo X, Chen Y, Yang Z. A flexible and multi-functional organic Rankine cycle system: Preliminary experimental study and advanced exergy analysis. Energ Convers Manage. 2019;187:339-55.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support from the State Key Program of National Natural Science Foundation of China (Grant No. 51736005) and National Natural Science Foundation of China (Grant No. 51876043).