THEORETICAL ANALYSIS OF AN ORC-VCR BASED AIR CONDITIONING SYSTEM BY HEAT RECOVERY OF JACKET COOLANT

Youcai Liang, Zhibin Yu*, Andrew Mckeown

School of Engineering, University of Glasgow,
Glasgow, United Kingdom
Youcai.liang@glasgow.ac.uk (Youcai Liang)
Zhibin.yu@glasgow.ac.uk (Zhibin Yu)
* Corresponding Author

ABSTRACT

The majority of the energy in the fuel burned by the combustion engines used in modern vehicles is lost in the form of waste heat. To address this issue, waste heat recovery has been proposed for increasing the overall efficiency of engine. The thermal energy contained in jacket water is usually ignored due to its low temperature. In this paper, a combined cycle based on an organic Rankine cycle (ORC) integrated with a vapour compression cycle (VCC) has been proposed to produce cooling for vehicle cabin by heat recovery of engine jacket water. In this system, the power generated in ORC is used to drive the VCC compressor. R134a is used as refrigerant in refrigeration cycle, different ORC working fluids are studied and compared. The results suggest that the concept is thermodynamically feasible and the heat contained in jacket water is sufficient for ORC-VCC system to provide enough cooling for a coach more than 40 seats, which could significantly enhance the performance depending on part-load of the engine. However, possible challenges during transient operations as well as issues related to scalability and reliability require further investigation.

1. INTRODUCTION

Air-conditioning is crucial for automobile industry, especially for the intercity buses. Most automobiles use vapour compression refrigeration systems for space cooling as well as transported goods since it is well understood, reliable, and compact. However, the compression is typically achieved by drawing power from the engine crankshaft and it increases 35% extra cost in fuel expenses for mid-size vehicles (Yilmaz, 2015). From the reviews of various literatures there is an indication that automobile engines utilizes only 35% of available energy for spark ignition engine and 40% for compression ignition engine, and the rest is released to the environment through exhaust gas and jacket water. Alternately, it is a matter of investigation that waste recovery of an engine for application in A/C can reduce the fuel economy of vehicles.

Thermally powered cooling technologies have been proposed by waste heat recovery of engine (Liang *et al.*, 2013, 2018). Absorption refrigeration system differs from vapour compression refrigeration system due to utilization of thermal energy source instead of electric energy. However, waste heat recovery from small sources such as automobile engines, application of the recovered heat to absorption chillers in particular, is scarce. From the literature review it was founded that the absorption chillers are generally used for large-scale industrial applications and the coefficient of performance (COP) is generally low for single-stage absorption cycle systems at a relatively small scale.

Vapour compression refrigeration system has been widely used in vehicle cabin cooling applications. However, it increases the fuel consumption of the engine since the compressor is driven by a part of the power generated in the engine. If the power needed can be met by waste heat recovery of engine, the fuel consumption would be reduced. An ideal case would be the incorporation of the waste heat recovery system with the existing automobile air conditioner. The advantage over the conventional air-conditioning system would be that it does not affect the design efficiency, life and fuel consumption of an engine, but it does add some weight. For this reason, the concept of combining ORC and VCC was proposed as an alternative refrigeration method by Prigmore and Barber (1975). Compared to the thermally powered absorption cooling technologies, the ORC-VCC has some potential advantages in terms of performance and simplicity. Furthermore, the VCC powered by an ORC can make use of the heat source throughout the year (Wang *et al.*, 2011a) to provide either cooling or electricity when cooling is not required (Wang *et al.*, 2011b), increasing the operational flexibility and improving the economic profitability. Great efforts have been devoted to the development of ORC-VCC systems since such a concept was proposed. Wali (1980a, 1980b) compared the performance of solar powered ORC-VCC systems for building cooling applications with five different working fluids. R113 and FC88 were considered as the best working fluids. To reduce the system complexity, Aphornratana and Sriveerakul (2010) proposed an ORC-VCC concept, in which the compressor and expander are integrated in the same unit, using the same working fluid and sharing the same condenser. Bu (2013a, 2013b and 2014) carried out a series of investigations on the working fluid of ORC-VCC ice makers and found that R600 is the most suitable working fluid. An experimental test of the ORC-VCC system was conducted by Wang (2011), and reported a COP of 0.48. Biancardi et al. (1982) introduced the design, fabrication and testing of a solar-powered organic Rankine cycle heat pump and chiller system, capable of delivering 63.3 kW of heating and cooling. When R11 was used as the working fluid, the heating COP of the system ranged from 1.6 to 2.25, while the cooling COP varied between 0.5-0.75.

In this paper, a vehicle air conditioner based on combination of ORC and VCC is proposed to make heat recovery of the engine jacket water, which is usually used pre-heat source or without recovery. This design aims to integrate the existing automobile air conditioner with an ORC that makes use of the low-temperature jacket water. Compared to waste heat recovery of the exhaust gas, waste heat recovery of jacket water avoids decomposition issue of the organic working fluids as well as the difficulty of searching compact and efficient heat exchanger as the ORC evaporator. Replacing the existing radiator with ORC also compensates the increased weight. Therefore, a thermodynamic analysis evaluation was carried out to demonstrate the potential and feasibility of the proposed A/C system.

2. CONCEPT OF THE PROPOSED ORC-VCC COMBINED SYSTEM

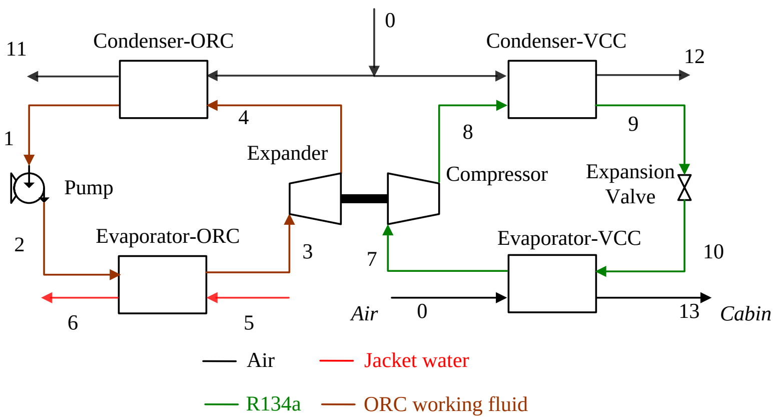

Figure 1: Schematic diagram of the ORC-VCC combined cycle

Figure 1 presents the schematic diagram of the proposed combined cycle. The system consists two basic thermodynamic cycles, an organic Rankine cycle and a vapour compression refrigeration cycle. The ORC is driven by the jacket water from engine and the power generated in Expander-ORC is used to power the compressor of vapour compression cycle. The refrigerant in Condenser-ORC and Condenser-VCC are both cooled down by the ambient air. In the refrigeration cycle, the cold air leaving Evaporator-VCC is supplied to the coach cabin. This design aims to replace the radiator and enhance the fuel energy efficiency.

In the present study, a commercial 6-cylinder, 4-stroke supercharged diesel engine is employed as topping system, which is normally used aboard coaches or buses. The mass flow rate of the jacket water is 1.5 kg/s and its temperature flowing into the heat exchanger is fixed to 90 ˚C and that outlet temperature is based on the heat absorbed by ORC cycle, but no lower than 75 ˚C.

3. ASSUMPTION AND MODELLING

The proposed system was modelled by using Matlab and Thermodynamic properties database REFPROP. Assumptions are listed as the following before modelling.

(1) The combined cycles are operated at steady state conditions.
(2) Both heat and pressure loss in all heat exchangers and pipes are assumed to be negligible.
(3) There is no energy loss from the common shaft between Expander and Compressor.
(4) The isentropic efficiency of pump and compressor are 0.8 and that of expander is 0.7.
(5) The PPTD in Evaporator-ORC is 5 ˚C and that in other heat exchanger is 3 ˚C.
(6) There is no superheat degree for working fluids at the expander inlet.

The modelling of each component is based on the conversation of mass and conversation of energy.

Table 1: Expressions for components and evaluation parameters

Components	**Energy balance**	**Parameter**	**Equation**
Pump	$W_P = m_{f-ORC}(h_2 - h_1)$	Net power output of ORC	$W_{net} = W_{\exp} - W_P$
Expander	$W_{\exp} = m_{f-ORC}(h_3 - h_4)$	Volumetric flow ratio	$VFR = \frac{V_4}{V_3}$
Evaporator-ORC	$Q_{eva-ORC} = m_{f-ORC}(h_3 - h_2)$	Thermal efficiency of ORC	$\eta_{ORC} = \frac{W_{net}}{Q_{eva-ORC}}$
Condenser-ORC	$Q_{cond-ORC} = m_{f-ORC}(h_4 - h_1)$	COP of cooling	$COP_c = \frac{Q_{eva-VCC}}{W_{net}}$
Expansion valve	$h_9 = h_{10}$		
Compressor	$W_{com} = m_{f-VCC}(h_8 - h_7)$		
Evaporator-VCC	$Q_{eva-VCC} = m_{f-VCC}(h_7 - h_{10})$		
Condenser-VCC	$Q_{cond-VCC} = m_{f-VCC}(h_8 - h_9)$		

4 RESULTS AND DISSCUSSION

The performance of the combined cycle affects by many factors. A detailed analysis for typical fluids has been carried out. Firstly, different working fluids are compared to figure out the most suitable fluid for the low temperature heat source, and find out the optimum evaporation temperature to match the operation temperature of jacket water. The effect of the ambient temperature and the required cold air temperature on the system performance is then studied.

4.1 Effect of working fluid

The jacket water of engine is used as the heat source of the ORC. The purpose of the thermostat in a diesel engine is to help keep the engine at its ideal operating temperature, normally ranging from 75-90 ˚C for high-duty diesel engine. The role of the thermostat is to regulate the flow of coolant around the engine to keep it at that ideal temperature. If the engine temperature increases to higher than 75 ˚C, the thermostat open and allows the coolant to flow into the radiator to be cooled down. Conversely, if the engine temperature is too low, the thermostat will cause the coolant to bypass the cooling system and prevent it from entering until the engine temperature is hot enough to warrant its introduction. In this study, the water temperature at the evaporator inlet is set to be 90, to figure out the potential of the waste heat recovery. The ORC cycle is proposed to replace the radiator, making use of heat contained in jacket water and providing power for the existing vapour compression air conditioner.

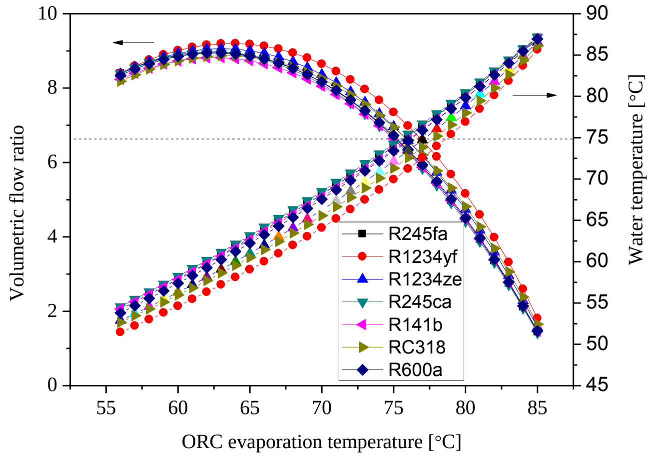

Figure 2: Effect of evaporation temperature on ORC net power output and temperature of jacket water leaving the Evaporator-ORC

Figure 2 shows the net power generated in ORC and the temperature of jacket water after heat recovery. It can be observed that as the ORC evaporation temperature increases, the net power generated in ORC first increases and then decreases. In the ORC, as the evaporation increases, the enthalpy of the working fluids at the expander inlet also increases. However, the mass flow rate of the working fluids decreases in order to achieve a higher evaporation temperature. That is why an optimm net power output can be obtained when the ORC evaporation temperature is around 65 ˚C. Among all the working fluid candidates, R1234yf and RC318 present better performance when the working fluids are operated at the same evaporation temperature. However, their maximum net powers exist when the evaporation temperature is 64 ˚C, which corresponds to the return jacket water temperature of 58 ˚C. As mentioned above, the ideal design for the waste heat recovery system should have as little influence as possible on the operating parameters of the engine. In order to ensure the engine is working at an efficient working condition, the jacket water temperature have to be maintained at about 75 to 80 ˚C. In other words, the jacket cooling water is limited to be cooled down no lower than 75 ˚C. Among all the working fluid candidates, R141b presents the highest power output when the return jacket water temperature is limited to be no lower than 75 ˚C.

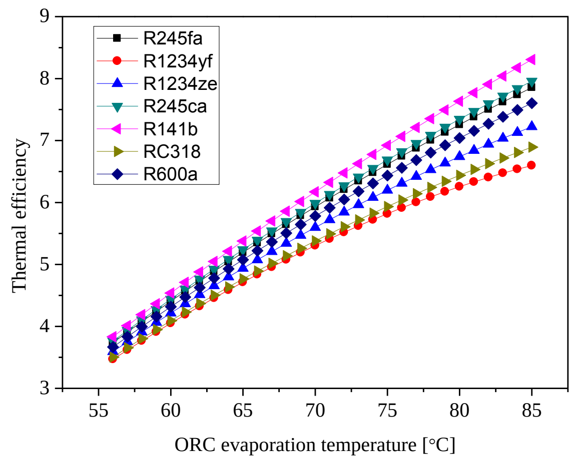

Figure 3: Effect of evaporation temperature on ORC thermal efficiency with different working fluids

Figure 3 shows the effect of evaporation temperature on the thermal efficiency. As mentioned above, the mass flow rate decreases, leading to less heat would be absorbed by the working fluid. Although the net power output increases firstly then decreases, the thermal efficiency keep increasing as evaporation temperature increases. The temperature of heat source and heat sink are two main factors that affect the ORC thermal efficiency. In this system, the jacket coolant water is used as the heat source, and the ambient air acts as heat sink. As the temperature of the heat source and heat sink are both fixed, the thermal efficiency indicates how efficient it is for different working fluids. It is clearly shown in Figure 3 that the thermal efficiency has close relationship with the thermodynamic properties of working fluids. Among all the working fluid candidates, R141b presents the highest thermal efficiency among all the working fluid candidates. This phenomenon agrees well with Figure 2, in which R141b generates the highest power if the jacket water is cooled down to the same temperature of 75 ˚C. Therefore, R141b is taken as the most suitable working fluid in the proposed system for heat recovery of low temperature jacket water.

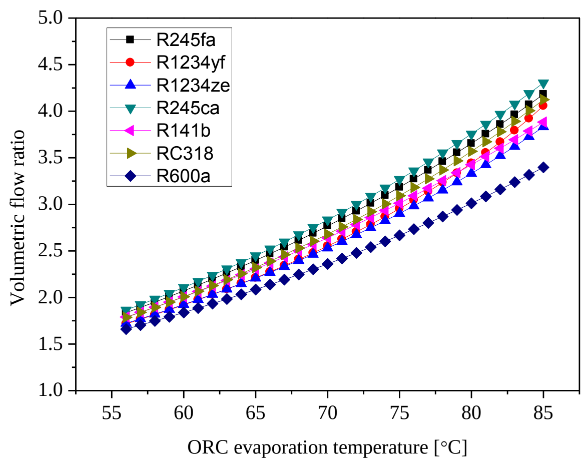

Figure 4: Effect of ORC evaporation temperature on pressure ratio during the expansion process

Volumetric flow ratio (VFR) is a parameter that shows how much the fluid volume increases during the process of expansion. Fluids with low volumetric VFR deliver a higher turbine efficiency. Figure 4 indicates that the VFR value increases with the increase of the ORC evaporation temperature. The main reason is that, in the present system, the ORC evaporation pressure becomes higher for a higher evaporation temperature. On the other hand, the condensation temperature remains the same for the same heat sink temperature with a fixed pinch point temperature difference. Subsequently, the pressure ratio as well as the volumetric flow ratio increases. It can be seen that the thermodynamic properties have great effect on VFR. Among all the working fluid candidates, R600a exhibits the minimum VFR for all the required temperature ranges.

4.2 Effect of ambient temperature

As mentioned above, ambient air is used as the heat sink in both ORC and VCC. As a result, the flow rate of ambient air is adjusted with respect to the changing ambient temperatures. According to results above, R141b is selected as the working fluid in ORC in the following study for its high ORC thermal efficiency. The ORC evaporation temperature is set to be constant 75 ˚C. In this way, the operation of the engine is not influenced by the application of WHR. The target temperature of cold air temperature is set to be 10 ˚C.

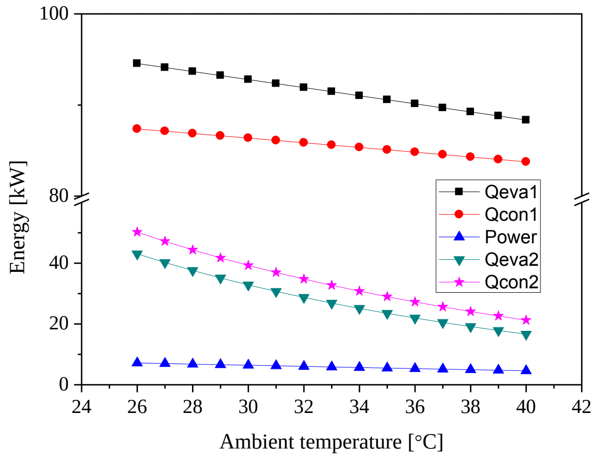

Figure 5: Effect of ambient temperature on energy capacity in main components

Figure 5 describes the variation of energy capacities in main components with respect to the ambient temperature. As shown in Figure 5, the energy capacity decreases with the increasing ambient temperature. Technically ambient temperature greatly affects the condenser in both ORC and VCC subsystems. As the ambient temperature increases, the condensation temperature increases, leading to a decrement of pressure difference between evaporator and condenser. In ORC power subsystem, the unit enthalpy difference in the expander also decreases, but the mass flow rate keeps unchanged. Therefore, the net power output in ORC becomes smaller along with the rise of ambient temperature. Furthermore, the energy capacity difference between evaporator and condenser becomes smaller (as shown in Figure 5), leading to a smaller power output. For the same reason, the system output performance deteriorates under the high ambient temperature since the energy capacity in both evaporator and condenser decreases.

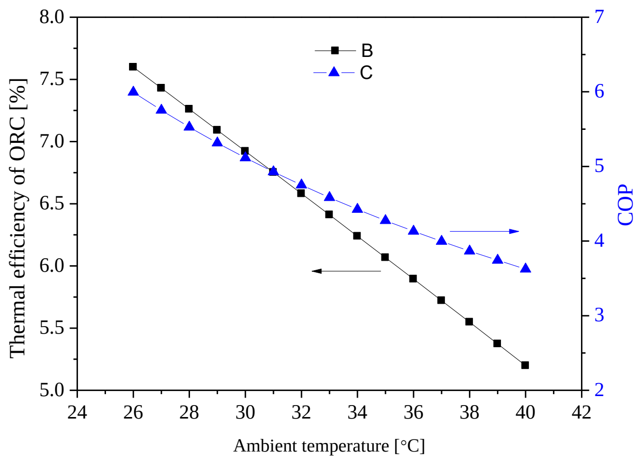

Figure 6: Effect of ambient temperature on the thermal efficiency of ORC and COP of VCC for a given cooling air temperature of 10 °C

The variation of the ORC thermal efficiency and coefficient of performance (COP) of refrigeration cycle is shown in Figure 6. Both thermal efficiency of ORC and COP of VCC strongly depend on the operating conditions, especially absolute temperature difference between heat sink and heat source. As mentioned above, when the ambient temperature becomes higher, the resulting smaller temperature difference between evaporation and condensation would lead to a decreasing thermal efficiency and heat injected. As a result, the net power output of ORC subsystem decreases.

From Figure 6, we can also see that the COP value also decreases along with the increasing ambient temperature.

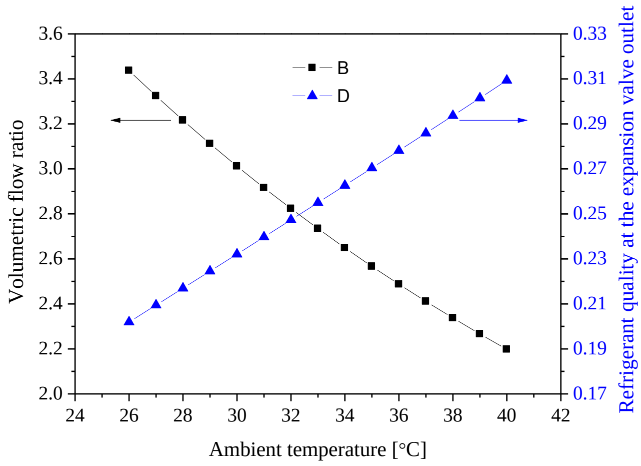

Figure 7: Effect of ambient temperature on the volumetric flow ratio

Figure 7 indicates that the VFR value decreases with the increase of the ambient temperature. Pinch point temperature difference method is adopted in the all the heat exchangers and the PPTD is fixed. As a result, the ORC condensation pressure becomes higher for a higher ambient temperature, which would lead to a lower VFR for a given evaporation temperature. That is why the VFR decreases as the ambient temperature becomes higher. Furthermore, it can be seen in Figure 7 that the refrigerant quality leaving the expansion valve increases with the ambient temperature. Subsequently, both the pressure ratio and the volumetric flow ratio increase.

4.3 Effect of the VCC evaporation temperature

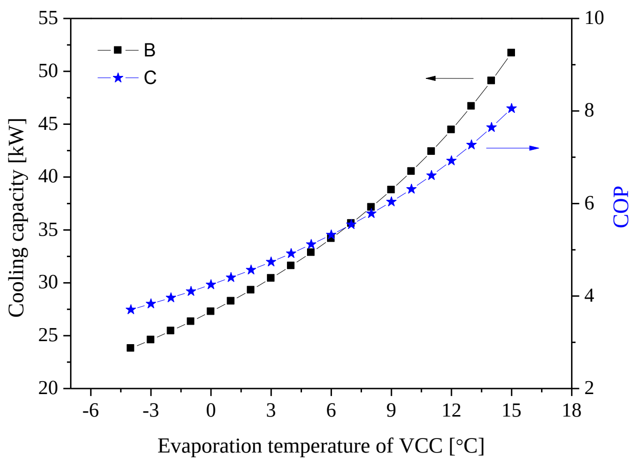

Figure 8: Effect of target refrigeration temperature on the cooling capacity and COP

Figure 8 shows the cooling capacity and the coefficient of performance against the evaporation temperature of refrigeration cycle. In this case, the ambient temperature is assumed to be 30 ˚C, which would be cooled down to the target temperature and then it is supplied into the cabin. As the evaporation temperature increases, the pressure ratio across the compressor decreases for a higher evaporation pressure. Subsequently, the power consumed by the compressor to decreases and cooling capacity increases. As a result, the COP increases with the combined effect of these two factors. The cooling capacity ranges from 23.8 kW to 51.7 kW. In this manner, the cooling capacity is sufficient to the actual cooling demand more than 40 seats if the cooling demand per person is roughly assumed to be 600 W. This result demonstrates that the proposed ORC-VCC combined cycle has great potential of providing cabin cooling by heat recovery from jacket coolant.

6. CONCLUSIONS

The vehicle air conditioning system integrated ORC and VCC has been designed and analyzed. The system aims to produce cabin cooling by recovering the low-temperature heat contained in the jacket water. The ORC absorbed heat from jacket water and produces mechanical power for compressor in refrigeration cycle. The conclusions are given as follows.

- R141b has the best performance to recover heat from low temperature jacket water while limiting minimum return water temperature to 75 ˚C.
- The ambient temperature affects the system performance and the fan speed of condenser can be adjusted in response to the changing ambient air temperatures.
- The produced cooling is sufficient for a coach more than 40 seats.

NOMENCLATURE

h	specific enthalpy	(kJ/kg)
m	Mass flow rate	(kg/s)
Q	heat	(kW)
W	mechanical power	(kW)
V	volumetric flow	(m^3/s)
Subscript		
P	pump	
exp	expander	
f	working fluid	
eva	evaporator	
cond	condenser	
com	compressor	
net	net power output	
c	cooling	

REFERENCES

Yılmaz, A., 2015, Transcritical organic Rankine vapor compression refrigeration system for intercity bus air-conditioning using engine exhaust heat. *Energy*, *82*, pp.1047-1056.

Shu, G., Liang, Y., Wei, H., Tian, H., Zhao, J. and Liu, L., 2013, A review of waste heat recovery on two-stroke IC engine aboard ships. *Renewable and Sustainable Energy Reviews*, *19*, pp.385-401.

Liang, Y., Shu, G., Tian, H., & Sun, Z. (2018). Investigation of a cascade waste heat recovery system based on coupling of steam Rankine cycle and NH 3-H 2 O absorption refrigeration cycle. *Energy Conversion and Management*, *166*, 697-703.

Prigmore, D. and Barber, R., 1975, Cooling with the sun's heat Design considerations and test data for a Rankine Cycle prototype. *Solar Energy*, *17*(3), pp.185-192.

Wang, H., Peterson, R., Harada, K., Miller, E., Ingram-Goble, R., Fisher, L., Yih, J. and Ward, C., 2011, Performance of a combined organic Rankine cycle and vapor compression cycle for heat activated cooling. *Energy*, *36*(1), pp.447-458.

Wang, H., Peterson, R. and Herron, T., 2011, Design study of configurations on system COP for a combined ORC (organic Rankine cycle) and VCC (vapor compression cycle). *Energy*, *36*(8), pp.4809-4820.

Wali, E., 1980, Working fluids for solar rankine-cycle cooling systems. *Energy*, *5*(7), pp.631-639.

Wali, E., 1980, Optimum working fluids for solar powered Rankine cycle cooling of buildings. *Solar Energy*, *25*(3), pp.235-241.

Aphornratana, S. and Sriveerakul, T., 2010, Analysis of a combined Rankine-vapour-compression refrigeration cycle. *Energy Conversion and management*, *51*(12), pp.2557-2564.

Bu, X., Wang, L. and Li, H., 2013, Performance analysis and working fluid selection for geothermal energy-powered organic Rankine-vapour compression air conditioning. *Geothermal Energy*, *1*(1), p.2.

Bu, X., Li, H.S. and Wang, L.B., 2013, Performance analysis and working fluids selection of solar powered organic Rankine-vapor compression ice maker. *Solar Energy*, *95*, pp.271-278.

Bu, X., Wang, L. and Li, H., 2014, Working fluids selection for fishing boats waste heat powered organic Rankine-vapor compression ice maker. *Heat and mass transfer*, *50*(10), pp.1479-1485.

Wang, H., Peterson, R. and Herron, T., 2011. Design study of configurations on system COP for a combined ORC (organic Rankine cycle) and VCC (vapor compression cycle). *Energy*, *36*(8), pp.4809-4820.

Biancardi, F.R., Sitler, J.W. and Melikian, G., 1982, Development and test of solar Rankine cycle heating and cooling systems. *International Journal of Refrigeration, 5*(6), pp.351-360.

ACKNOWLEDGEMENT

This research is funded by EPSRC (EP/N020472/1, EP/N005228/1, EP/R003122/1, and EP/P028829/1) in the United Kingdom.