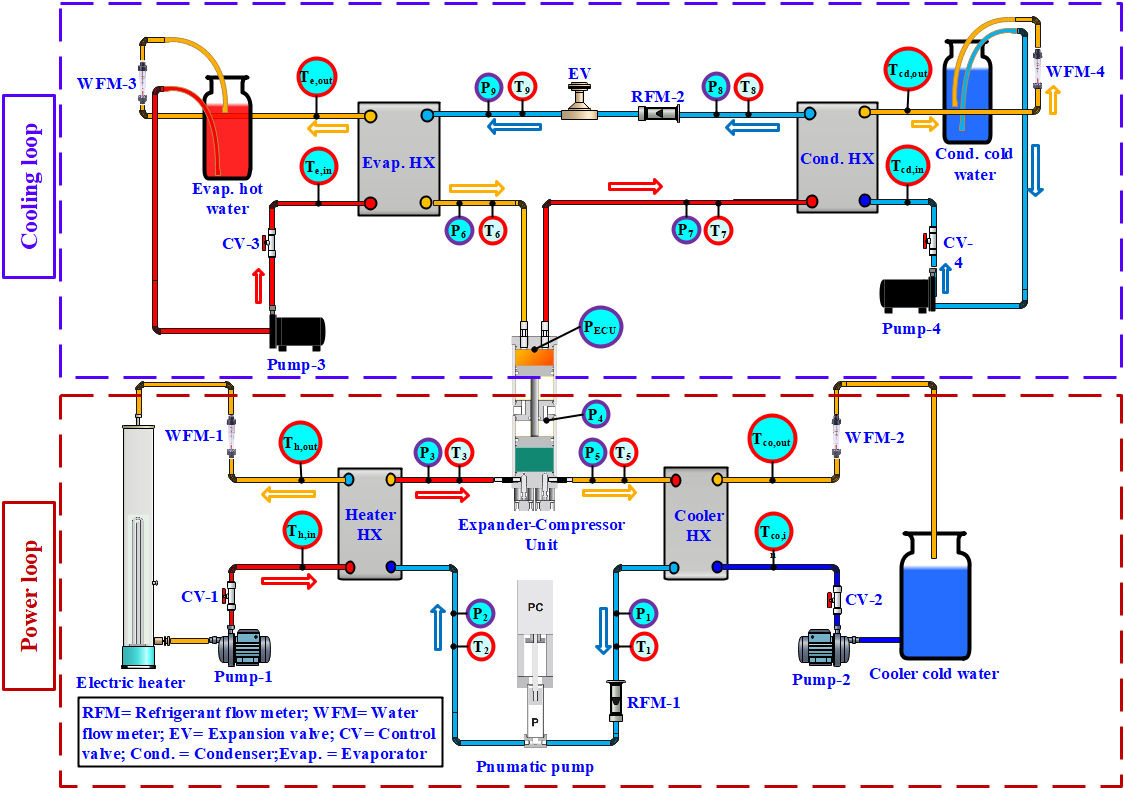
# Supplementary Material

SM. A. Experimental setup of the ECU-based ORC-VCC

Fig. S1. shows the arrangement of the experimental setup. It is made up of a cooling loop (vapor compression cycle, VCC) and a power loop (organic Rankine cycle, ORC) that are integrated via an expander-compressor unit (ECU). A pneumatic pump, heater, expander cylinder, and cooler make up the bulk of the power loop. Additionally, an evaporator, compressor cylinder, condenser, and expansion valve make up the majority of the cooling loop.

In the power loop, the pneumatic pump is equipped with a stroke length adjuster to control the pressure ratio through the compression of the working fluid (power loop refrigerant, PLR) from the low-pressure side (state 1) to the high-pressure side (state 2). The heater is a heat exchanger that is used to absorb heat from external hot water to evaporate the PLR to reach saturated vapor or superheated vapor phase at state 3. The external hot water is heated using an electric heater that is equipped with a temperature controller and control valve to heat a specified water flow to the desired temperature. After the heating process, the heated PLR is expanded to the low-pressure side (state 5) by pushing the expander piston to compress the cooling loop refrigerant. The expander of the power loop is part of the expander-compressor unit (ECU), which is described in detail in the Supplementary material (SM. B). Then, the PLR is cooled to the saturated liquid phase (state 1) through the cooler by rejecting heat to the cold water of the cooler, which is circulated using pump 2. The cooler cold water temperature is controlled using ice cubes to maintain it at the desired value.

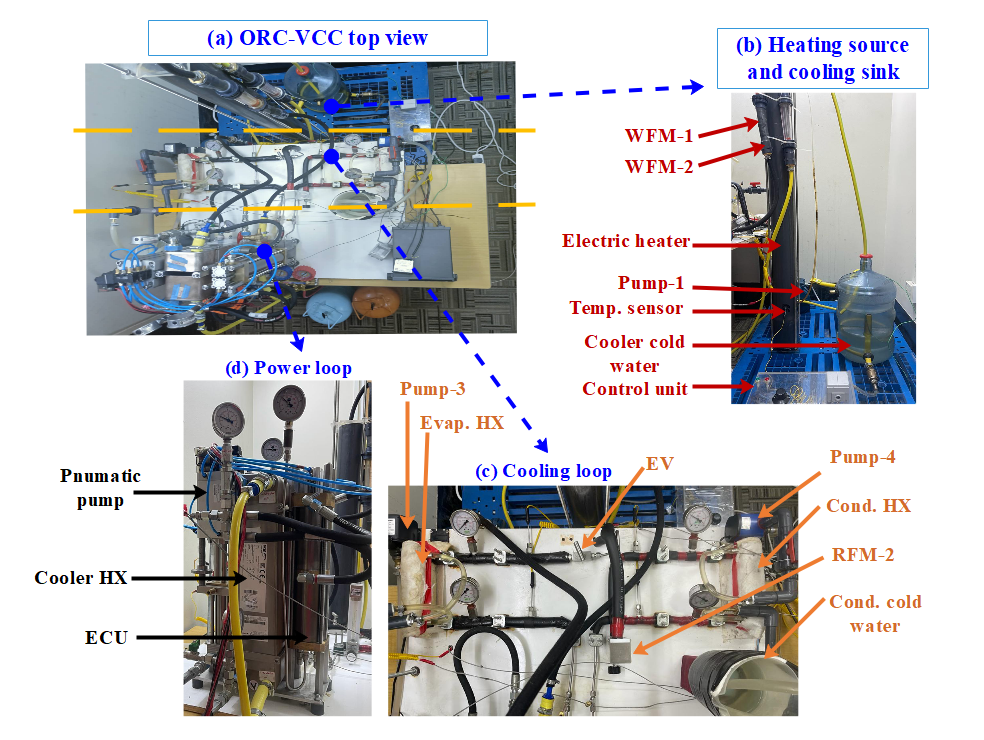


**Fig. S1.** Schematic diagram of the experimental layout of the TMR system.

In the cooling loop, the cooling loop refrigerant (CLR) enters the compressor cylinder at low pressure (state 6) to be compressed to high pressure at state 7 using the expansion process of the PLR. Then, the pressurized CLR is cooled down to the saturated liquid phase (state 8) by rejecting the heat into the circulated cold water (using pump 4) through the condenser. After that, the CLR is expanded through an expansion valve to the low pressure at state 9 to perform the evaporation process by absorbing heat from the circulated hot water (using pump 3). A mini-dry block heater is used to control the temperature of the evaporator hot water.

In addition, the flow of the circulated cold and hot water in both loops is controlled using a control valve for each circulation and a water flow meter (WFM) is used to measure its volumetric flow rate. Furthermore, as shown in Fig. S1, both power and cooling loops are fully instrumented by installing pressure and temperature sensors at the inlet and outlet of each component. Also, the flow rates of the PLR and CLR are measured using refrigerant flow meters RFM-1 and RFM-2, respectively.

A top view of the experimental setup is presented in Fig. S2(a). The circulating pumps of the power loop have a flow capacity of 600 – 1800 L/h and are connected with water flow meters (300-3000 L/h Plastic Tube Water rotameter, model: LZS-25). Similar pumps and flow meters are used for the circulated water in the cooling loop with a capacity of 100 – 270 L/h for each pump and 100 – 1000 L/h for each rotameter (model: LZS-15). For the refrigerant flow, calibrated LZJ-10F Glass tube flowmeter refrigerant flow meters are used. The hot water of the heater is heated by a 12 kW 3-phase electric heater, which is installed inside a PVC pipe with an inner diameter of 101.6 mm and length of 1.60 m (Fig. S2(b)). The PVC pipe is partially filled with water to be heated to the desired temperature using a thermostat controller and the hot water is circulated using Pump-1. A plate heat exchanger (Model: B25THx30/1P-SC-M 2x22U + 2 x1”& 22U) is used for the heater and another heat exchanger (Model: B25THx40/1P-SC-M 2x22U + 2 x1”& 22U) is used for the cooler. These heat exchangers are arranged together with the pneumatic pump and the ECU as shown in Fig. S2(d). Also, as shown in Fig. S2(c), two identical plate heat exchangers are used for the evaporator and condenser of the cooling loop (Model: B3-014-12D-3.0). These heat exchangers are selected due to their compactness, high performance, and compatibility with several refrigerants including R134a, R407C, and R410 that are used in this study. Finally, for the expansion process of the CLR, a needle-based expansion valve is used (Model: WINFLOW ¼” NPT [F], stainless steel). The technical details of the measuring instruments are provided in the Supplementary material (SM. B, Table B.1).



**Fig. S2.** Experimental setup.

SM. B. Expander Compressor Unit (ECU)

The power loop converts the provided thermal energy using a heater to mechanical work to compress the refrigerant using the ECU unit shown in Fig. S3(a). It consists of two cylinders (expander and compressor cylinders, items # 2) with a piston in each cylinder. The expander and compressor pistons are connected (item # 3) with a rigid rod (item # 5). The diameters of each piston is 80 mm and the length of the stroke is 100 mm, which is designed for a cooling capacity of 0.50 kW at expander pressure with a range of 200 kPa to 800 kPa [1]. To perform the power stroke and back-stroke in continuous alternation, the valves of the expander chambers (A and D) must be controlled (forced control) to adjust their opening and closing times. This is possible using electric, hydraulic, or pneumatic actuators. In the present experimental work, pneumatic solenoid valves are used as shown in Fig. S3(b). In contrast, the valves of the compressor cylinder are self-actuating non-return valves. To prevent the leakage of the working fluids in each cylinder, each piston was sealed using ethylene-propylene O-rings (EPDM 72x80x4). These O-rings have excellent ozone and chemical resistance properties and are compatible with many polar fluids that adversely affect other elastomers. The ports of the auxiliary cover of the ECU (item 4 in Fig. S3(a).) are used for the lubrication process of the ECU pistons using a refrigeration oil. The lubricant oil (Suniso SL32) creates a seal between the piston rings and cylinder wall, which reduces wear, provides better compression. Also, the lubricant oil provides stability and corrosion protection which extends service life and minimizes maintenance costs.

Diagram

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(b)

**Fig. S3.** Detailed design of (a) the expander-compressor unit (ECU), and (b) pneumatic solenoid valves.

**References**

[1] Sleiti AK, Al-Khawaja M, Al-Ammaria WA. A combined thermo-mechanical refrigeration system with isobaric expander-compressor unit powered by low grade heat – Design and analysis. Int J Refrig 2020;120:39–49. https://doi.org/10.1016/j.ijrefrig.2020.08.017.