# Supplementary material

# SM. A: Background of the TMR system

The power loop converts the thermal energy provided using a heater to mechanical work to compress the refrigerant using the ECU unit shown in Fig. A.1(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 is100 mm, which is designed for a cooling capacity of 0.50 kW at expander pressure with a range of 200 kPa to 800 kPa [6]. 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 A.1(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. 2(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

Description automatically generated(a)

A picture containing text

Description automatically generated

(b)

**Fig. A.1.** Detailed design of (a) the expander-compressor unit (ECU), and (b) pneumatic solenoid valves.

# SM. B: Uncertainty analysis

To verify the reliability of the experimental results, the relative uncertainty of the performance indicators (PECU, , , Qev, and COP) are calculated using Eqns. (B1) and (B2) [9].

(B1)

(B2)

Therefore,

*=*  (B3)

(B4)

(B5)

(B6)

(B7)

(B8)

(B9)

Based on the accuracy of the measurement sensors shown in Table B.1, the results of the uncertainty analysis for the performance indicators are presented Table B.2.

**Table B.1**

Measuring instruments and their precision.

|  |  |  |  |
| --- | --- | --- | --- |
| Physical variable | Measuring device | Operating range | Accuracy |
| Pressure | Pressure gauges | 0 kPa to 2482 kPa | ± 1.6% |
| Temperature | Type K thermocouples | -50 oC to 1200 oC | ± 0.2 oC |
| Refrigerant volumetric flow meter | LZJ-10F Glass Tube Flowmeter | 3 L/min – 30 L/min | 2.5% |
| Water volumetric flow meter | Water rotameter | 100 L/h to1000 L/h | ± 4% |

**Table B.2**

Uncertainty results of the performance indicators.

|  |  |
| --- | --- |
| Performance indicator | Uncertainty |
|  | ± 1.60 % (± 39.712 kPa) |
|  | ± 3.4 % (± 0.0002 kPa) |
|  | ± 2.0% (± 0.004 kw) |
|  | ±3.4% (±0.02 kW) |
|  | ±3.4% (±0.03 kW) |
|  | ±4.8% (±0.47%) |
|  | ±4.0% (±0.1) |