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4 **Design and dynamic investigation of low-grade power generation systems with CO₂**
5
6 **transcritical power cycles and R245fa organic Rankine cycles**

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24
25 **ABSTRACT**

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29 This paper deals with the dynamic experimental investigation on low-grade power generation
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31 systems with CO₂ transcritical power cycles (T-CO₂) and R245fa organic Rankine cycles
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33 (ORC). These two systems were heated indirectly by exhaust gases of an 80 kWe micro-
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35 turbine CHP unit through a hot thermal oil system. The main components of each test system
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37 included a plate-type gas generator/ evaporator, a turboexpander with high speed generator, a
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39 finned-tube air cooled condenser and a liquid pump. Both test rigs were fully commissioned
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41 and instrumented from which comprehensive dynamic experimental investigations were
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43 conducted to examine the effects of some important dynamic operational processes on system
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45 performance. These included the system start-up, variation of working fluid pump speed,
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47 change of thermal oil pump speed and system shutdown. These can lead to fully understand
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49 the dynamic and inertia behaviours of the system operations and thus to obtain robust
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51 controls. The experimental results reveal that working fluid mass flow rates are affected
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53 significantly by the start-up and shutdown processes, followed by the temperatures and
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62 pressures at turbine inlets and outlets. The research outcomes can contribute significantly to
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64 understand the system dynamic operating processes and thus instruct the system controls and
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66 safety operations.
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71 *Keywords:* CO₂ transcritical power cycle, R245fa organic Rankine cycle, dynamic
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73 investigation, experimental transient performance.
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81 Nomenclature 82

83 h enthalpy (J/kg)
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85 \dot{m} mass flow rate (kg/s)
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88 W power generation (W)
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92 *Greek symbols* 93

94 η efficiency
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96
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98 *Subscripts* 99

100 all overall
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102 f working fluid
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104 is isentropic
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107 m measured
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109 t turbine
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111 1 turbine inlet
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113 2 turbine outlet
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123 **1. Introduction**
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128 The consumption of fossil fuels in power generation is continuously increasing which has
129 been leading to more serious environmental issues such as excessive CO₂ emissions, severe
130 atmospheric pollution and high energy cost etc. Subsequently, there is an urgent obligation to
131 generate power using industrial waste heat [1] and renewable energy [2] with low
132 temperatures typically ranging from 100 °C to 350 °C and applicable thermodynamic power
133 cycles such as Organic Rankine Cycle (ORC) [3] , transcritical power cycle (TPC) [4],
134 trilateral flash cycle [5] and Brayton cycle [6] etc. Among these technologies, ORC and TPC
135 promise high potential and therefore are widely applied in industrial applications and small-
136 scale energy productions.
137

138 Compared to a century-old steam Rankine power plant, the ORC system has the similar
139 working mechanism for power generation but uses an organic working fluid instead such as
140 R245fa, which has a lower boiling point at higher pressure and is condensable at lower
141 pressure. Thus, the ORC system is expected to achieve a higher efficiency with greater power
142 generation when applied to a low-grade heat source [7]. However, a common challenge for
143 any ORC system is the optimal selection of appropriate working fluid and particular design of
144 thermodynamic power cycle. By the theoretical study on nine applicable working fluids for
145 ORC, R245fa was found to be the most suitable one for an engine waste heat-recovery
146 application when safety levels were inclusively consisted [8]. In another research, a zeotropic
147 fluid of R152a/R245fa with different compositions were applied and compared in low-grade
148 ORC systems [9]. It was demonstrated that pure R245fa of the mixture could present the
149 highest thermal efficiency but required larger expander size and consequent higher system
150 cost. Further balance and compromise need to be considered when selecting an ORC working
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180 fluid. On the other hand, from the environmental impact point of view, the conventional ORC
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182 working fluid HFCs have zero Ozone Depletion Potential (ODP) but mostly have higher
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184 Global Warming Potentials (GWP). Such evidences will definitely affect long-term
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186 utilisation of HFC working fluids in ORCs. Subsequently, some natural working fluids such
187
188 as CO₂ and NH₃ tend to be more attractive in the applications of low-grade power generation
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190 systems [10].
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193 As listed in Table 1, CO₂ is an environmental friendly natural working fluid with no safety
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195 matter. In addition, CO₂ has superb thermophysical properties, despite its high critical
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197 pressure and low critical temperature, and lower manufacturing cost than the organic fluids
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199 since it can be obtained from waste products of many industry processes. Nevertheless, the
200
201 feasibility of CO₂ working fluid in low-grade power generation needs to be investigated.
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203 Correspondingly, a thermodynamic analysis and comparison between CO₂ transcritical power
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205 cycle (T-CO₂) and R245fa organic Rankine cycle have been researched [11]. The research
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207 results revealed that the thermal and exergy efficiencies of the T-CO₂ system were slightly
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209 lower than those of R245fa ORC system. In addition, the energetic and exergetic analyses
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211 and comparisons of transcritical power cycles with both CO₂ and R32 working fluids were
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213 investigated [12]. The results showed that R32 system could achieve higher thermal
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215 efficiency but operated at much lower pressures. For a T-CO₂ system, CO₂ is most likely
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217 operating at higher pressure of about 120 bar or above such that the system components and
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219 controls need to be specially designed. One feasible way to utilise CO₂ as a working fluid and
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221 maintain relatively low operating pressure is to mix CO₂ with one of ORC fluids such as
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223 R161 and R152a [13] or isopentane and propane [14].
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228 Although a large body of theoretical research has been conducted on the ORC and T-CO₂
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230 systems, experimental investigations on these systems are even more important to valid the
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232 theoretical analyses and verify system design and operation. Moreover, during the theoretical
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239 investigations, the efficiencies and power generations of the system turbine or expansion
240 machine are usually kept constants when different working fluids are employed which
241 however are difficult to be controlled and maintained in experimental operations unless the
242 systems are in steady states. A domestic-scale R245fa ORC system with a hermetic scroll
243 expander has been researched experimentally [15] in which a global electric efficiency was
244 around 8% at steady state when the expander inlet temperatures were in a range of 120-150°C.
245 In another research, a single-stage axial flow turbine was utilised in a regenerative R245fa
246 ORC system in which the maximum steady power outlet and system efficiency could reach 6
247 kW and 7.98% respectively at heat source temperature about 130°C[16]. For the T-CO₂
248 systems, a number of relevant researches can be found from literatures. Typically, CO₂
249 transcritical power cycles driven by solar energy were constructed and investigated
250 experimentally at steady states with the system power generation efficiency between 8.78 %
251 and 9.45% [17, 18].

252 Although a number of experimental investigations on both ORC and T-CO₂ systems have
253 been carried out, most of the research outcomes were based on steady states . Practically,
254 either ORC or T-CO₂ systems operate under transient or quasi- transient conditions such as
255 the waste heat recoveries from automotive and biomass boilers. The dynamic process
256 analyses of heat source and working fluid pump could lead to optimal system controls so that
257 the system can utilise efficiently the applicable heat source thus achieve better and safety
258 performances [19]. From the literature reviews, a zeotropic mixture of R245fa and R365mfc
259 was studied by focusing on its dynamic behaviours in the ORC system and the performance
260 in each system component [20]. In addition, a kW-scale R123 ORC system with a turbine to
261 examine the heat transfer and dynamic power conversion processes was constructed and
262 tested [21]. The experimental results indicated that the mass flow rate through the turbine was
263 different from that through the pump during the dynamic test. Therefore, the comprehensive
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298 dynamic experimental analysis for ORC and T-CO₂ systems during different operating
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300 processes need to be further investigated and developed. Move over , in order to further
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302 optimise the T-CO₂ and R245fa ORC control systems, the start-up and shutdown processes of
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304 both systems need to be conducted, which have not been investigated so far.
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307 Subsequently, in this study, an experimental investigation was conducted on small-scale T-
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309 CO₂ and R245fa ORC system test rigs coupled to an 80 kWe CHP unit with hot thermal oil
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311 system. The CO₂ and R245fa turbines were employed to convert thermal energy into
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313 electricity in each system. Dynamic behaviours of both systems are demonstrated with time
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315 during various important operational processes. These include both system start-up processes,
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317 response of R245fa ORC system against variation of working fluid pump conditions,
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319 responses of T-CO₂ system against variation of thermal oil pump condition and both system
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321 shutdown processes. The investigated results have significant contributions to the component
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323 and control designs for both systems.
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328 **2. Experimental facility and methodology**

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332 Fig. 1 shows the schematic diagram of the CHP, T-CO₂ and ORC systems, which have
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334 been set up in the laboratory at Brunel University London. Each of the T-CO₂ and ORC
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336 systems was classified into two group levels with different colours in which red indicates the
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338 high temperature level while blue the low temperature level. In addition, each system
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340 consisted of four separate fluid loops, i.e., the exhaust gas, thermal oil, CO₂/ R245fa, and
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342 ambient air. The heat source for both the T-CO₂ and ORC systems was the exhaust flue gases
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344 from an 80 kWe CHP unit. The high temperature exhaust flue gases passed through an
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346 integrated thermal oil boiler of the CHP and heated the thermal oil through the intermediate
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348 thermal oil loop . The high temperature thermal oil was then circulated by a variable speed oil
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357 pump through a plate-type heat exchanger which was acted as either CO₂ gas generator or
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359 ORC evaporator. The CO₂ or R245fa ORC fluid was then heated up or evaporated and
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361 superheated before being expanded in each expander.
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364 Accordingly, the T-CO₂ or R245fa ORC system was mainly comprised of a thermal oil-
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366 heated gas generator or a evaporator, a turbo expander with high speed generator, a finned-
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368 tube air-cooled condenser and a working fluid liquid pump, as shown in Fig1 and Fig.2
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370 (photos). The high pressure CO₂ or R245fa flow was heated through the gas generator or
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372 evaporator and left as a high temperature or superheated vapour. The vapour working fluid
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374 (CO₂ or R245fa) with high pressure and higher temperature was then expanded through the
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376 CO₂ or R245fa turbine, as shown in Fig.3. The expansion process in the CO₂ or R245fa
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378 turbine turned a shaft and its magnetic coupling connection to drive a permanent magnet
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380 synchronous generator at a rated rotation speed of up to 18,000 rpm. Each generator delivered
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382 electric power to the campus electric grid by means of a smart inverter and transformer. The
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384 ABB smart inverter in each turbine system allowed the generator speed to be matched and
385
386 monitored with the electric power generated so that each turbine and generator could operate
387
388 smoothly. In order to create bypass for the CO₂ and R245fa flow whenever necessary, two
389
390 throttle valves were installed separately in parallel to the CO₂ and R245fa turbines, as shown
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392 in Fig. 1.
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395 After expansion (Point 2), the low pressure CO₂ or R245fa vapour was extracted from each
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397 individual turbine and flew to one assigned finned-tube air cooled condenser, which used
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399 ambient air to condense the CO₂ or R245fa fluid from a superheated into liquid state at Point
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401 4. The ambient air flow rate through each condenser was controlled using a variable speed
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403 fan installed above the condenser. In addition, the ambient air temperature was adjusted by
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405 mixing warm exhaust air from the condenser and cold inlet ambient air through four
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407 recircular fans installed on each corner side of the condenser outlet, as shown in Fig. 2. Each
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416 condenser outlet was connected by a liquid receiver to ensure no vapour cavitation at each
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418 working fluid pump inlet. The liquid level in each liquid receiver was also monitored by a
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420 fitted sight glass to indicate if there was sufficient liquid stored. A triplex plunger CO₂ pump
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422 fed the low pressure liquid CO₂ from Point 5 into the high pressure gas generator at Point 6
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424 while a seal-less diaphragm type R245fa pump circulated the low pressure R245fa liquid
425
426 from Point 5 into high pressure evaporator at Point 6. Thereafter, the T-CO₂ or ORC cycle
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428 repeated in each closed loops. The running speed of the liquid CO₂ or R245fa pump was also
429
430 adjusted by a frequency drive inverter, as shown in Fig. 2, which could control the CO₂ or
431
432 R245fa working fluid mass flow rate and operating pressure in each system.
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436 Temperature sensors and pressure transducers were placed at the inlet and outlet of each
437
438 main system component and a number of fluid mass flow meters were also installed in each
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440 system, as shown in Fig.1. Table 2 shows the measurement principle, measuring range and
441
442 accuracy of these measurement devices. The hot thermal oil temperatures were measured
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444 with inflow K-type thermocouples with accuracy of $\pm 0.5^{\circ}\text{C}$ at prior and after the gas
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446 generator or evaporator. For the T-CO₂ system, the temperatures were measured by inline K-
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448 type thermocouples with $\pm 0.5^{\circ}\text{C}$ accuracy while the pressures were measured with MBS 33
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450 pressure transducers of $\pm 0.3\%$ accuracy and 0.5s response time. A twin V-shaped tube type
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452 mass flow meter with 0-1800 kg/h range and $\pm 0.1\%$ accuracy was used to measure the liquid
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454 CO₂ mass flow rate. For the R245fa ORC system, the temperatures were measured with
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456 inflow K-type thermocouples of $\pm 0.5^{\circ}\text{C}$ accuracy to get the most precise temperature reading
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458 while the pressures were measured using AKS 32 pressure transducers with $\pm 0.3\%$ accuracy
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460 and 0.5s response time. The liquid R245fa mass flow rate was measured by a twin tube type
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462 mass flowmeter with 0-6500kg/h range and $\pm 0.15\%$ accuracy. In addition, a power meter
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464 with accuracy of $\pm 0.8\%$ was used to determine the output current, voltage and power of CO₂
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466 turbine or R245fa turbine of each system. Each system condenser had a hot wire anemometer
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475 with an accuracy class of ± 0.15 m/s at full range of 1.27-78.7 m/s to measure the ambient air
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477 velocity and two K-type thermocouples at the inlet and outlet of each condenser. The data
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479 acquisition unit for the T-CO₂ or ORC system was from CompaqDAQ (National Instruments
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481 data logger system) connected with LabVIEW software to record and present the
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483 measurements from thermocouples, pressure sensors and mass flow meters.
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488 **3. Results and analysis**

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492 The method to evaluate transient performances of the T-CO₂ and ORC systems at different
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494 operating conditions is proposed in this paper. It consists of four parts: analysis of each
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496 system start-up process and preliminary test, response of the R245fa ORC system
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498 performance against different working fluid pump speeds, response of the T-CO₂ system
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500 performance against different thermal oil pump speeds and analysis of each system shutdown process.
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502 During the tests, the CO₂ and R245fa pump frequencies were controlled to be changed from
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504 0Hz to 35 Hz and 0 Hz to 40 Hz respectively, while the thermal oil pump frequencies were
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506 controlled to be varied from 0 Hz to 25 Hz and 0 Hz to 50 Hz for the T-CO₂ and R245fa
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508 ORC systems individually. These setting were designed to ensure that the inlet working fluid
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510 temperature was below maximum value at 110 °C (120 °C for a short operational period) for
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512 each turbine and the working fluid inlet pressure was below 110 bar for the CO₂ turbine and
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514 less than 14 bar for the R245fa turbine as required by the turbine manufacturers. In addition,
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516 all the thermophysical properties of CO₂ and R245fa such as entropy and enthalpy etc. were
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518 calculated using REFPROP 8.0 software [22] based on the temperature and pressure
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520 measured at each point.
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526 *3.1 Analysis of the system start-up processes and preliminary tests*

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536 Purposely, transient processes of the T-CO₂ and R245fa ORC test systems operated and
537 were recorded separately from the system start up to steady state and then working fluid mass
538 flow rate increased abruptly to steady condition again. For the T-CO₂ system, the dynamic
539 process took about 52 min while the R245fa ORC continued roughly 120 min to complete ,in
540 which, for the system start-up processes, the T-CO₂ and ORC systems took around 19 min
541 and 40 min respectively. It is noticed that the start-up process of T-CO₂ system was much
542 faster than that of the R245fa ORC system.
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551 The dynamic variations of cycle point temperatures at the inlet and outlet of each turbine
552 and working fluid mass flow rate of each system are plotted and demonstrated in Fig.4. For
553 each cycle, when the system started up, the working fluid mass flow rate increased
554 immediately to a peak value and then dropped abruptly to reach steady state. After that, the
555 motor frequency of each system liquid pump was controlled to step up such that the working
556 fluid mass flow rate amplified instantly and thereafter reached another steady state.
557 Correspondingly, for each system, with the system start up, the turbine inlet and outlet
558 temperatures both increased and decreased a bit once the working fluid mass flow rate
559 dropped from its peak value. These two working fluid temperatures then approached
560 gradually to their steady states and thereafter dropped abruptly with the sudden went up of
561 working fluid mass flow rate and then quickly reached to their steady states.
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575 At the same time period shown in Fig. 4, the dynamic variations of working fluid
576 pressures at the inlet and outlet of each turbine were recorded and depicted in Fig.5. In the
577 start-up process, for each system the turbine inlet and outlet pressures both increased
578 immediately when the working fluid pump started up. The high pressure working fluid
579 flowed rapidly into the turbine, passed through the turbine blades and reduced the working
580 fluid pressure at the turbine outlet. Thereafter two working fluid pressures reached
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593 moderately to their steady state. As expected, when further increased working fluid mass
594 flow rate of each system, the working fluid pressures at turbine inlet and outlet both increased
595 immediately with higher working fluid mass flow rate and then came to their steady states
596 again.
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602 At the same time periods, the dynamic variations of turbine power generation and pressure
603 ratio of each turbine are plotted in Fig. 6. The pressure ratio of turbine was calculated by the
604 pressures at the turbine inlet and outlet while the actual turbine power output was measured
605 directly by a power meter installed at outlet wire of each turbine. In the start-up process, for
606 each system, the turbine output and pressures ratio both increased immediately to the peak
607 values and then dropped to troughs. After that, the turbine power output and pressure ratio
608 increased gradually to their steady states. The troughs for turbine power output and pressure
609 ratio were caused by the sudden changes of the temperature and pressure differences and
610 working fluid mass flow rates. As the working fluid mass flow rate suddenly increased, the
611 turbine power output and pressure ratio both augmented significantly and reached steady
612 states again for the T-CO₂ system. However, for the R245fa ORC system, the variation trends
613 of the turbine power outlet and pressure ratio were relatively small due to the lower turbine
614 inlet and outlet pressure increases. Consequently, the turbine power outlet could reach around
615 494 W and 655 W in the dynamic processes for the T-CO₂ and R245fa ORC systems
616 respectively.
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633 Meanwhile, the dynamic variations of working fluid temperatures at the inlet and outlet of
634 each condenser were recorded and are plotted in Fig. 7. For each system, the start-up process
635 and preliminary test affected significantly on each condenser inlet temperature rather than on
636 the condenser outlet. The variation tendency of condenser inlet temperature was more or less
637 the same as the corresponding turbine outlet temperature considering only the connection
638 pipe and fitting temperature losses involved. Meanwhile, the condenser outlet temperature of
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652 each system varied a little during the start-up process and preliminary test period considering
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654 of constant heat sink parameters and higher condenser performance.
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658 659 *3.2 Response of R245fa ORC system against variation of working fluid pump condition* 660

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663 As shown in Fig. 1, a R245fa liquid pump was installed after the liquid receiver in the
664 R245fa ORC system. In addition, a frequency drive inverter was attached to the R245fa
665 liquid pump. Therefore, the R245fa liquid pump speed could be controlled by the modulation
666 of ORC pump frequency. To investigate the dynamic processes of R245fa ORC system
667 against variable working fluid pump speeds, a test matrix of working fluid pump speed swing
668 was designed and is listed in Table 3. For each stage of the test, only the condition of working
669 fluid pump speed was adjusted, while the parameters of heat source (thermal oil) and sink
670 (ambient air) remained unvaried. In the first stage of the test, a lower ORC pump converter
671 frequency of 37.5 Hz was maintained until the ORC system approached to steady state. After
672 30 min, ORC pump condition was quickly switched to higher frequency of 40 Hz unit and the
673 ORC system turned to steady state again. After 35 min, the ORC pump condition was quickly
674 switched back to a further lower ORC pump converter frequency of 35 Hz and maintained for
675 30 min to steady condition again.
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690 Correspondingly, the dynamic variations of ORC pump speed and R245fa mass flow rate
691 were therefore recorded and are plotted in Fig. 8. The ORC pump speed increased with a
692 higher converter frequency and decreased with a lower frequency but not in a monotonically
693 adjusting manner. The peak and lowest values were formed on the ORC pump speed curve.
694 In addition, it can be seen that the mass flow rate could sensitively follow the change of the
695 ORC pump speed, which was changed by the pumping frequency, without apparent time
696 delay. From stage I to stage II, R245fa mass flow rate increased by 3.26%, which naturally
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711 brought a significant increase of ORC pump speed from 730 RPM to 779 RPM. Furthermore,
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713 from stage II to stage III, R245fa mass flow rate decreased by 9.8%, which in turn led to a
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715 larger decrease of ORC pump speed from 779 RPM to 680 RPM.
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718 At the same time period , the dynamic variations of working fluid temperatures and
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720 pressures at the inlet and outlet of the R245fa turbine were measured and are shown in Fig. 9.
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722 The R245fa turbine inlet and outlet temperatures were dropped down as soon as the R245fa
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724 ORC pump was switched to a higher speed except that the turbine outlet temperature
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726 decreased in a larger extent than the turbine inlet temperature, which indicates that the
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728 temperature at low pressure side (turbine outlet) is more sensitive than that of high pressure
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730 side (turbine inlet)to the pump speed. However, when the R245fa ORC pump was switched
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732 back to a lower speed, the temperature at the turbine inlet and outlet fluctuated slightly and
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734 increased in a manner similar to the system start-up process. In percentage, when the ORC
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736 pump speed increased from 730 RPM to 779 RPM, the R245fa turbine inlet and outlet
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738 temperatures decreased by 0.97% and 7.3% respectively. On the other hand, when the
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740 R245fa ORC pump speed decreased from 779 RPM to 680 RPM, the cycle point
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742 temperatures of turbine inlet and outlet amplified 11.54% and 23.88% respectively. However,
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744 the pressures of turbine inlet and outlet had the similar variation tendency with ORC pump
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746 speed and R245fa mass flow rate during this period. Unlike other parameters, the pressures of
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748 turbine inlet and outlet went through little variation with 1.54% and 2.15% when the ORC
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750 pump speed increased from 730 RPM to 779 RPM, 4.79% and 7% when the ORC pump
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752 speed decreased from 779 RPM to 680 RPM respectively.
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756 Meanwhile, the dynamic variations of the ORC working fluid temperatures and pressures
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758 at condenser inlet and outlet were recorded and are shown in Fig. 10. The condenser inlet
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760 temperature and pressure fluctuated slightly during each stage and changed in a manner
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762 similar to the turbine outlet temperature and pressure when the ORC pump speed changed.
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770 However, the condenser inlet temperature and pressure was lower than those at the turbine
771 outlet by about 1.98°C and 0.84 bar respectively at each stage. In addition, this result also
772 shows that the condenser outlet temperature and pressure could be almost immune to the
773 variation of ORC pump conditions, which ensured the continuous operation of ORC system.
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779 Table 3 shows the summarised working condition in this transient test. For each steady
780 state condition, the turbine overall efficiency is calculated with equation 1.
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$$783 \eta_{t,all} = \frac{W_{t,m}}{\dot{m}_f(h_1 - h_{2,is})} \quad (1)$$

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786 Thus, during this transient test (from stage I to stage III), the measured turbine power
787 generations were 694.44 W, 697.12 W and 686.52 W respectively. Correspondingly, the
788 calculated turbine overall efficiency were 15.7%, 16.0% and 15.3% each .
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793 794 3.3 Response of T-CO₂ system against variation of thermal oil pump condition 795 796 797

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799 To examine the effect of the heat source mass flow rate on the T-CO₂ system performance,
800 the thermal oil flow rate was controlled to vary from 0.46 kg/s to 0.36 kg/s by modulating the
801 oil pump frequency from 25 Hz to 20 Hz. The inertia behaviour when thermal oil brought the
802 thermal energy from the exhaust gas to the T-CO₂ system could be helpful against the
803 variation of exhaust gas temperature. Thus, when the oil pump frequency changed from 25
804 Hz to 20 Hz, the thermal oil temperature was varied automatically from 139.6°C to 144.1°C
805 without modulating the CHP power outlets. In the meantime, as listed in Table 4, all
806 parameters of T-CO₂ system such as CO₂ pump frequency, condenser air velocity and
807 ambient air temperature were remain unvaried due to its larger inertia.
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818 Subsequently, the dynamic variations of the thermal oil inlet and outlet temperatures were
819 measured and are shown in Fig. 11. In the first stage of the test, higher thermal oil mass flow
820 rate of 0.46 kg/s and 139.6°C thermal oil temperature were maintained until T-CO₂ system
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829 was at steady state. Then thermal oil mass flow rate was quickly switched by hand to 0.36
830 kg/s and maintained to steady state again. During this process, the thermal oil temperature
831 approached gradually to their steady state at 144.1°C. However, the thermal oil outlet
832 temperature wend down as soon as the thermal oil pump was switched to lower frequency
833 and thereafter increased moderately to steady state again. In percentage, the thermal oil inlet
834 temperature increased by 3.25% and thermal oil outlet temperature decreased by 8.9% when
835 the thermal oil mas flow rate reduced from 0.46 kg/s to 0.36 kg/s.
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838 Correspondingly, the dynamic variations of working fluid temperatures and pressures at
839 CO₂ turbine inlet and outlet are shown in Fig. 12. The CO₂ turbine inlet and outlet
840 temperatures were decreased at larger extents than the changes of thermal oil outlet
841 temperatures when the thermal oil mass flow rate was changed to a lower value, as shown in
842 Fig. 10, which means that the inertia and thermal capacity of thermal oil cycle are much
843 bigger than that of T-CO₂ system. In addition, when the thermal oil mass flow rate reduced,
844 the variations of CO₂ turbine inlet pressures had the similar tendency with those of CO₂
845 turbine temperatures. However, the turbine outlet pressure was almost kept steady state when
846 the thermal oil mass flow rate decreased. Not many random pressure values were observed in
847 the results due to high accuracy of pressure transducers and smooth flow through the CO₂
848 turbine. Quantitatively, when the thermal oil mass flow rate decreased from 0.46 kg/s to 0.36
849 kg/s, the percentage decrease rates of turbine inlet temperature, turbine outlet temperature,
850 turbine inlet pressure and turbine outlet pressure were 11.03%, 12.72% , 2% and 0.6%
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874 Meanwhile, the dynamic variations of temperatures and pressures at the CO₂ condenser
875 inlet and outlet are depicted in Fig. 13. As expected, the condenser inlet temperature and
876 pressure had the similar variation tendency with the turbine outlet temperature and pressure
877 when the thermal oil mass flow rate reduced. However, condenser outlet temperature pattern
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888 matched the ambient air trend and the CO₂ was cooled down to approximately 26°C during
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890 the steady state and dynamic processes. As predicted, the condenser outlet pressure had the
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892 same pattern as the condenser inlet pressure and the steady state pressure was around 66 bar,
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894 implying that the CO₂ pressure loss is negligible during the condensation process, which is
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896 different from the larger condenser pressure loss in R245fa ORC system. Quantitatively,
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898 when the thermal oil mass flow rate decreased from 0.46 kg/s to 0.36 kg/s, the condenser
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900 inlet temperature, condenser outlet temperature, condenser inlet pressure and condenser outlet
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902 pressure decreased 12.69%, 1.11%, 0.56% and 0.58% respectively.
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905 For the transient test of thermal oil pump, the decreased thermal oil mass flow rate had
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907 decreased the measured turbine power generation and calculated turbine overall efficiency.
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909 The measured turbine power generations were in the range of 494.3 W to 430.5 W, and the
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911 calculated turbine overall efficiency had the range of 11.2% to 10.7% when the thermal oil
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913 flow rate reduced from 0.46 kg/s to 0.36 kg/s.
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918 *3.4 Analysis of the system shutdown processes*

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922 For the last test, the transient processes of the T-CO₂ and R245fa ORC test systems were
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924 investigated when the systems operated from the steady states to shutdown processes. The
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926 dynamic process took around 25 min to complete for each system. However, the shutdown
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928 processes of T-CO₂ and R245fa ORC systems occupied only 5 min. The whole test also
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930 clearly indicates that the start-up process was much slower than the shutdown process for
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932 each system which may require more awareness on thermal lagging. Lower thermal oil pump
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934 frequency at 15 Hz for the T-CO₂ system and lower cycle liquid pump frequency at 32.5 Hz
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936 for the R245fa ORC system were chosen instead of previous steady state conditions because
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947 there could be serious damage to both turbines when each system was shutdown at a higher
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949 pressure level.
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951 Correspondingly, the dynamic variations of working fluid temperatures at the inlet and
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953 outlet of each turbine and working fluid mass flow rates at the system shutdown processes are
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955 shown in Fig. 14. For each cycle, when the CHP system was shutdown at 20min from steady
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957 state condition and the motor frequency of the cycle liquid pump was reduced gradually, the
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959 working fluid mass flow rate decreased moderately from steady state to a lower value. After
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961 that, the working fluid mass flow rate dropped suddenly to zero when the motor frequency of
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963 cycle liquid pump was shut down completely. However, in order to avoid too many two
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965 phases or liquid working fluid passing through the blade of turbine during the shutdown
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967 period, the time required for the shutdown had to be reduced. During the time from 20min to
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969 25min of each system, the turbine inlet and outlet temperatures both quickly went down once
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971 the working fluid mass flow rate reduced from its steady state condition until to zero. In
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973 addition, after the working fluid mass flow rate became zero, these two working fluid
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975 temperatures increased gradually from their lowest values. This signified that the thermal oil
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977 had been transferring heat to CO₂ or R245fa through the gas generator or evaporator even
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979 though all the systems were shut down.
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983 Meanwhile, the dynamic variations of working fluid pressures at the inlet and outlet of
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985 each turbine at shutdown period were recorded and are shown in Fig. 15. It can be seen that
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987 the both turbine inlet pressures could quickly follow the change of working fluid pump
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989 shutdown processes without apparent time delay. Depending on the pumping frequency, the
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991 turbine outlet pressures reduced gradually to their minimum values, which were 53 bar and
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993 1.48 bar for T-CO₂ and R245fa ORC systems respectively. In addition, during the shutdown
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995 processes, both turbine inlet pressures need about 3 min to reach the same values as the
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997 turbine outlet pressures.
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1006 At the same time period, the dynamic variations of the turbine power generation and
1007 pressure ratio of each turbine are plotted in Fig. 16. In the shutdown process, for each system,
1008 the general trend was the slight decrease of the pressure ratio between the turbine inlet and
1009 outlet with reduced pumping frequency. When the working fluid pump was shutdown, the
1010 pressure ratio sharply decreased to 1. Meanwhile, the pressure ratio through the turbine
1011 dropped as the turbine inlet and outlet pressures decreased during the shutdown process.
1012 Consequently, as show in Fig. 15, the turbine inlet pressure reduced to the same values as the
1013 turbine outlet pressure when the pressure ratio reduced to 1. With the decrease of pressure
1014 ratio and mass flow rate in the turbine, the turbine power generation reduced sharply from
1015 334 W to 0 W and from 661 W to 0 W in T-CO₂ and R245fa ORC systems respectively.
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1028 Meanwhile, the dynamic variations of working fluid temperatures at the inlets and outlets
1029 of each condenser were measured and are shown in Fig. 17. During the shutdown process of
1030 both systems, the condenser inlet temperature data had the same pattern as the temperature at
1031 the outlet of the turbine. In addition, the condenser inlet temperature decreased to about 20°C
1032 from 52 °C and 93°C at the CO₂ condenser and R245fa condenser respectively. As expected,
1033 the condenser outlet temperature pattern matched the ambient temperature trend in both
1034 systems. However, unlike the results in Fig.14, the condenser inlet and outlet temperatures
1035 did not have increase after the both the values meet. In order to avoid additional heat transfer
1036 from heat source to both the systems and quasi-stationary operating conditions of each
1037 component, the condensers and the cooling system of CHP system were kept running until all
1038 the temperatures reached same value as the ambient.
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1053 **4. Conclusions**

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1065 In this study, design and experimental procedures were carried out with the aim of
1066 dynamic investigating the performances of T-CO₂ and ORC systems with different turbines.
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1068 The design procedures for both systems and their integrations with an 80kW CHP unit as
1069 well as the transient experimental results are presented. The performance and operational
1070 characteristics of each system were examined by different transient tests, which included
1071 analysis of the system start-up process and preliminary test, response of the R245fa ORC
1072 system against variation of working fluid pump speed condition, response of the T-CO₂
1073 system against variation of thermal oil pump condition and analysis of each system shutdown
1074 processes. Several useful research outcomes have been obtained. Due to the start-up process
1075 of each system, the mass flow rate, turbine inlet and outlet temperatures, turbine power
1076 output and pressure ratio of each turbine and condenser inlet temperature increased
1077 immediately and then dropped abruptly to reach steady state while the turbine inlet and outlet
1078 pressures both increased immediately and reached moderately to their steady state in the
1079 process. In addition, the turbine power outputs can reach around 494 W and 655 W in the
1080 preliminary processes for T-CO₂ system and R245fa ORC system respectively.

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1082 By analysing the individual effects, response of R245fa ORC system against variation of
1083 working fluid pump condition, the ORC pump speed, R245fa mass flow rate, and the
1084 pressures at turbine inlet, turbine outlet and condenser inlet increased with a higher converter
1085 frequency and decreased with a lower frequency but not in a monotonically adjusting manner.
1086 However, the working fluid temperatures at turbine inlet and outlet and condenser inlet all
1087 decreased with a higher converter frequency and increased with a lower frequency. The
1088 maximum R245fa turbine electric power outlet and R245fa turbine overall efficiency are
1089 found to be 697.12 W and 16% respectively, which are located at the highest working fluid
1090 pump frequency zone.
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1124 For the response of T-CO₂ system against variation of thermal oil pump condition, the
1125 temperatures of thermal oil outlet, CO₂ turbine inlet and outlet and CO₂ condenser inlet and
1126 the pressure of turbine inlet went down as soon as the thermal oil pump was switched to a
1127 lower frequency and thereafter increased moderately to their state again. Meanwhile, the
1128 pressures of turbine outlet, condenser inlet and outlet and temperature of CO₂ condenser
1129 outlet were almost kept steady state when the thermal oil mass flow rate decreased. The
1130 maximum T-CO₂ turbine electric power outlet and CO₂ turbine overall efficiency were
1131 achieved to be 494.3 W and 11.2% respectively, which were located at the highest thermal oil
1132 pump frequency zone. For the system shutdown processes, for each system, the temperatures
1133 at turbine inlet and outlet and condenser inlet and the pressures at turbine inlet and outlet all
1134 quickly went down once the working fluid mass flow rate reduced from its steady state
1135 condition. In addition, the pressures of turbine inlet and outlet would approach the same value
1136 when the working fluid pump was closed.
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1165 **References**

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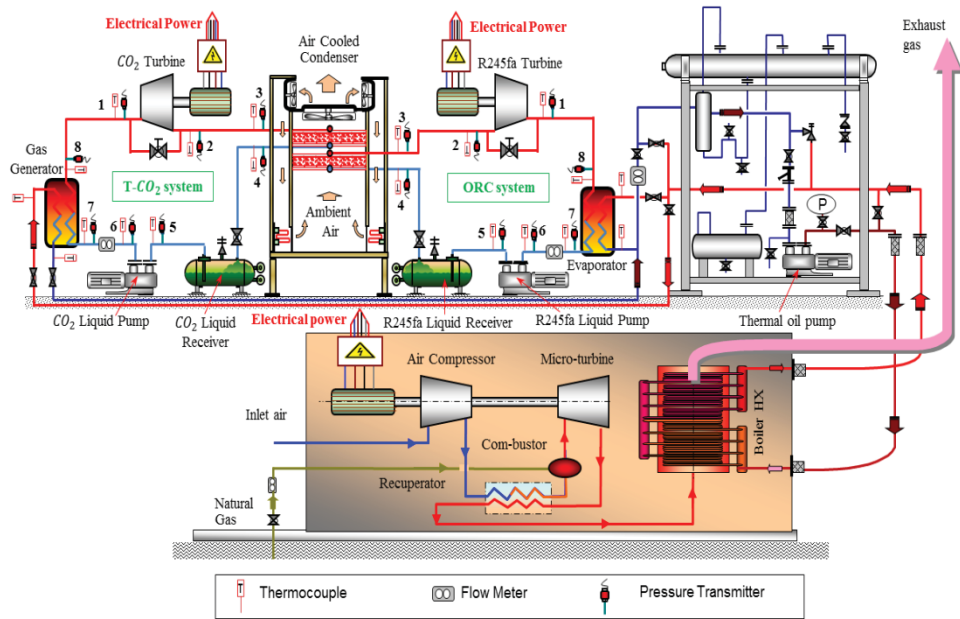
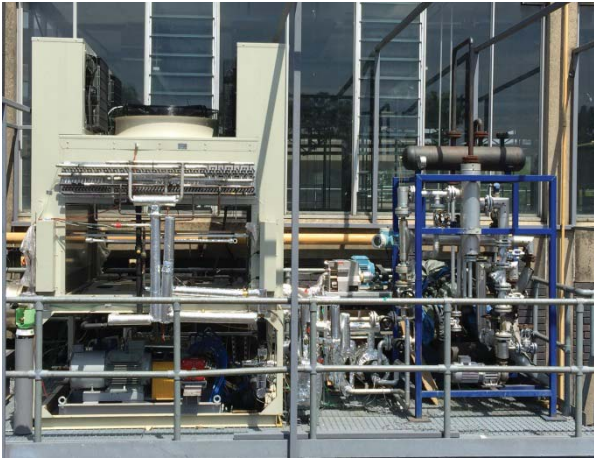


Fig.1. Test facilities of integrated CHP, T-CO₂ and ORC systems.



T-CO₂ and ORC Test Rigs

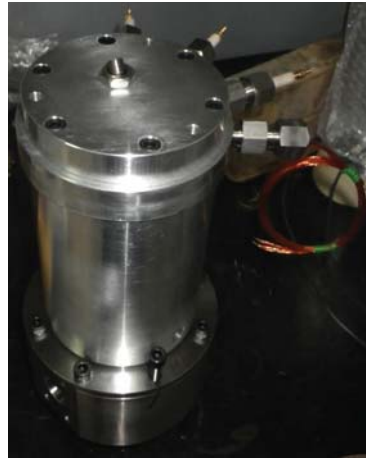


System Control Panel

Fig.2. Photographs of the test rigs and control panel.



R245fa turbine



CO₂ turbine

Fig.3. Photographs of R245fa turbine and CO₂ turbine.

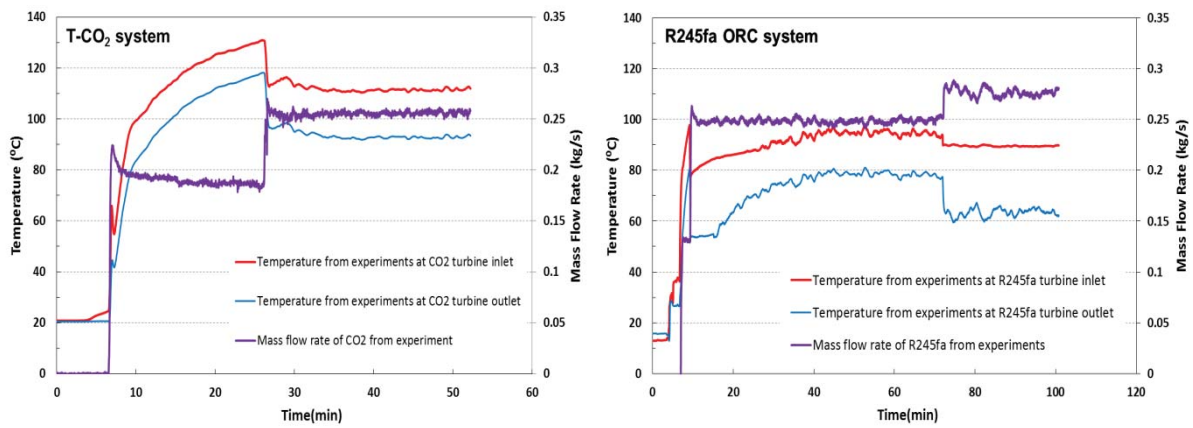


Fig.4. Variations of measured turbine inlet and outlet temperatures and working fluid mass flow rates with time

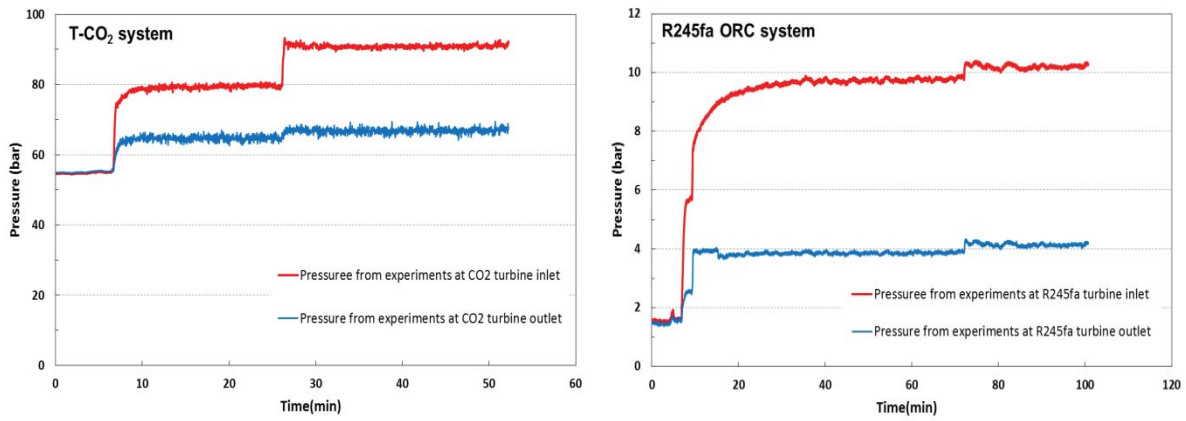


Fig.5. Variations of measured turbine inlet and outlet pressures with time

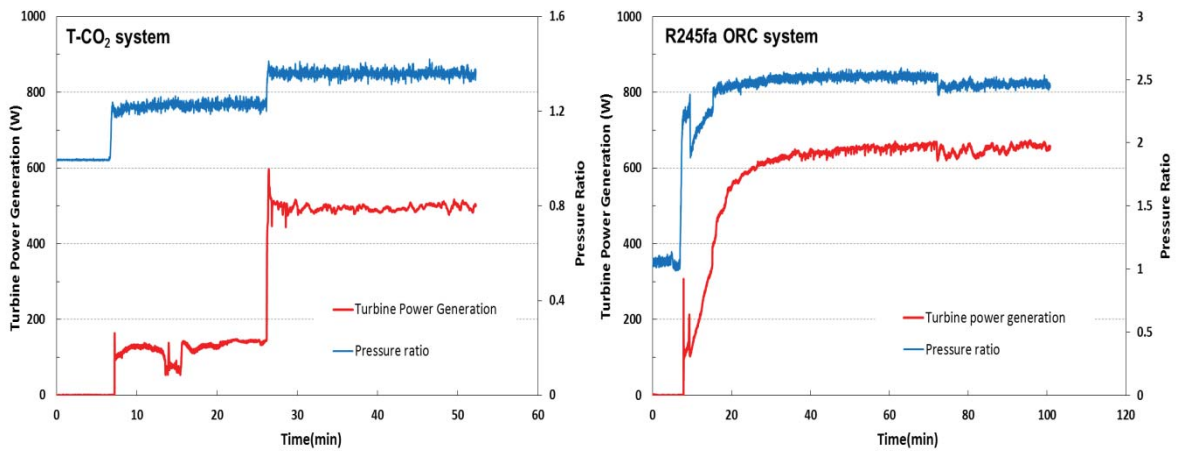


Fig.6. Variations of measured turbine power generations and calculated pressure ratios with time

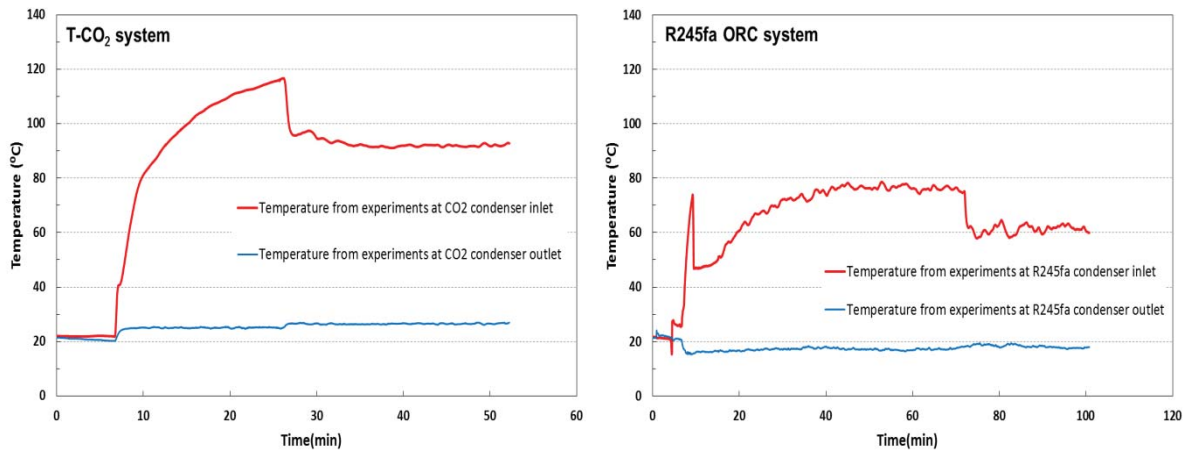


Fig.5. Variations of measured condenser inlet and outlet temperatures with time

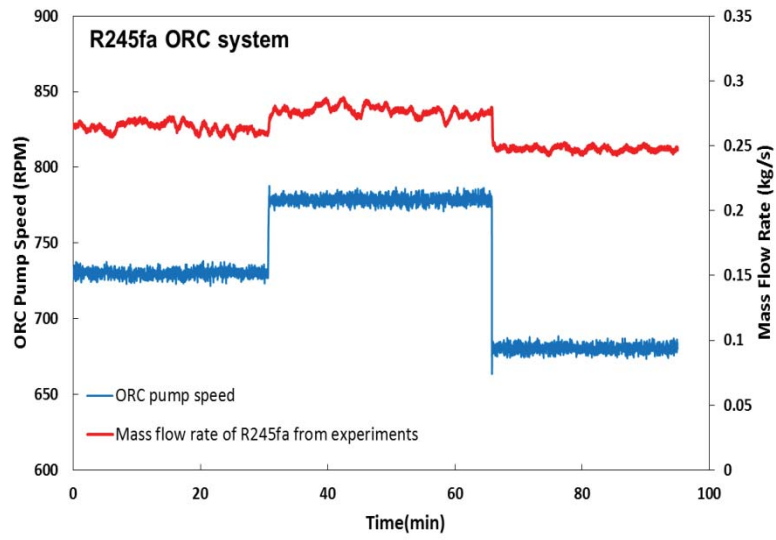


Fig.8. Variations of measured ORC pump speed and R245fa mass flow rate with time

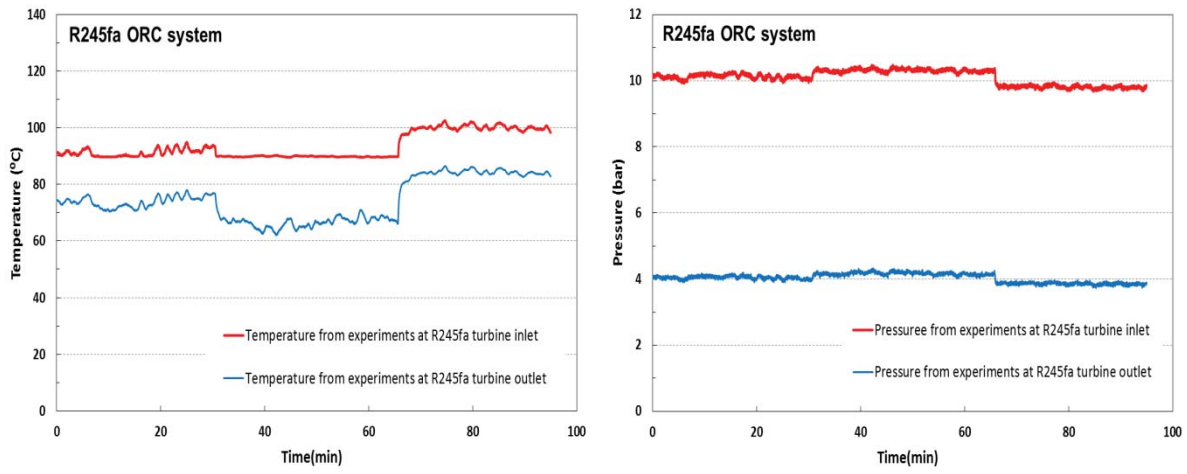


Fig.9. Variations of measured temperatures and pressures at turbine inlet and outlet with time

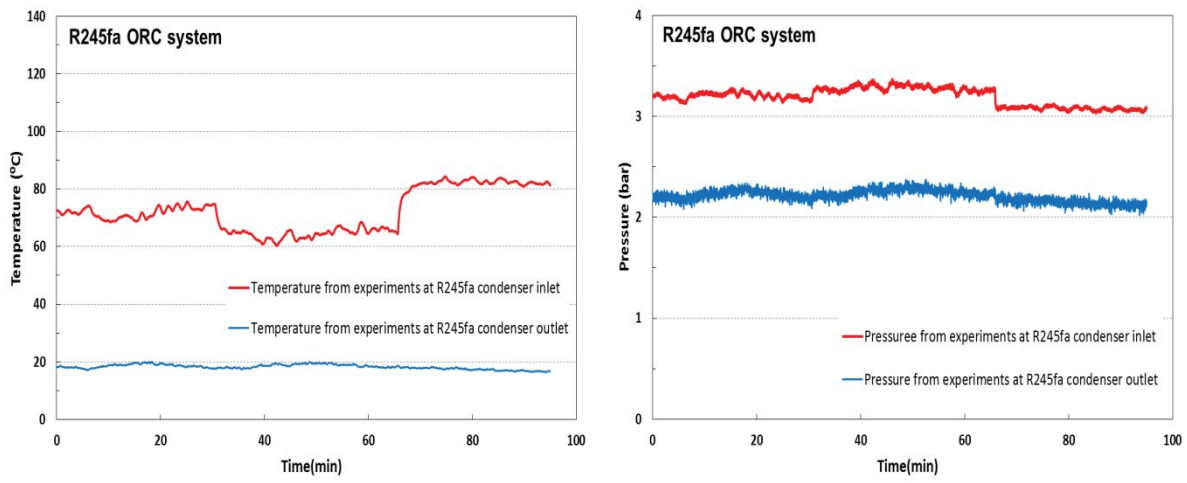


Fig.10. Variations of measured temperatures and pressures at condenser inlet and outlet with time

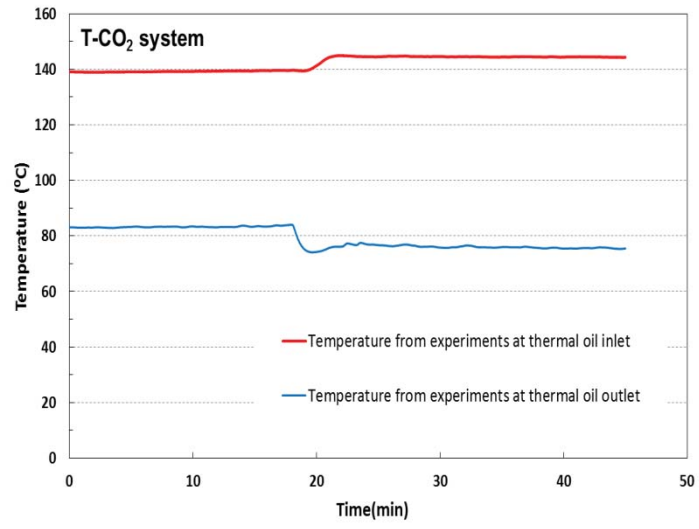


Fig.11. Variations of measured thermal oil inlet and outlet temperatures with time

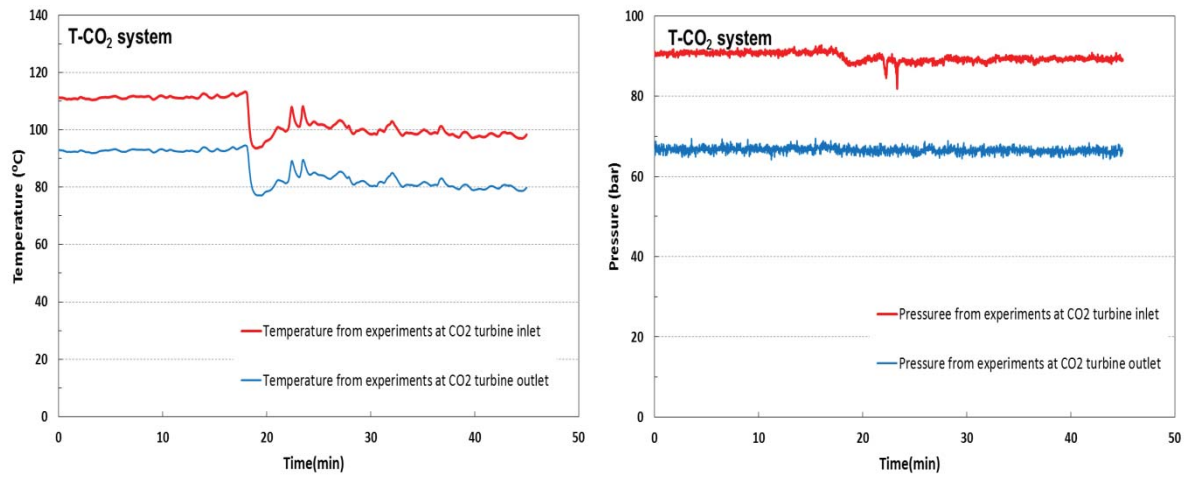


Fig.12. Variations of measured temperatures and pressures at turbine inlet and outlet with time

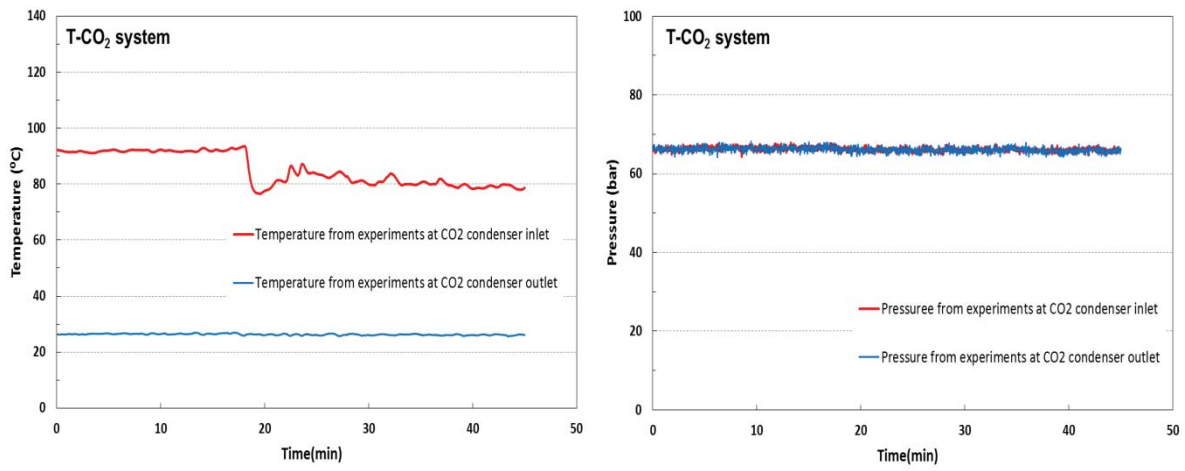


Fig.13. Variations of measured temperatures and pressures at condenser inlet and outlet with time

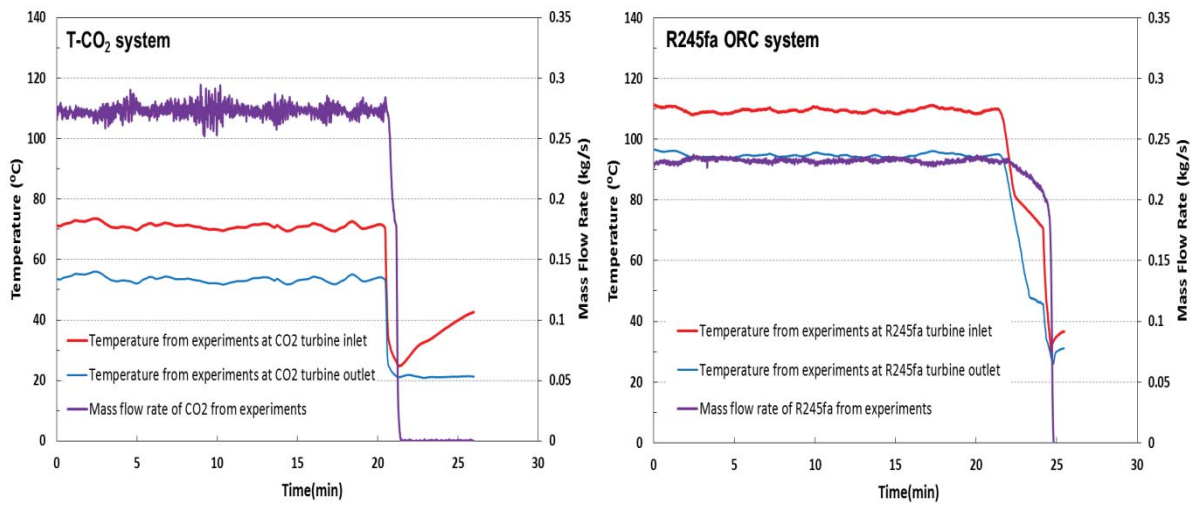


Fig.14. Variations of measured turbine inlet and outlet temperatures and working fluid mass flow rates with time

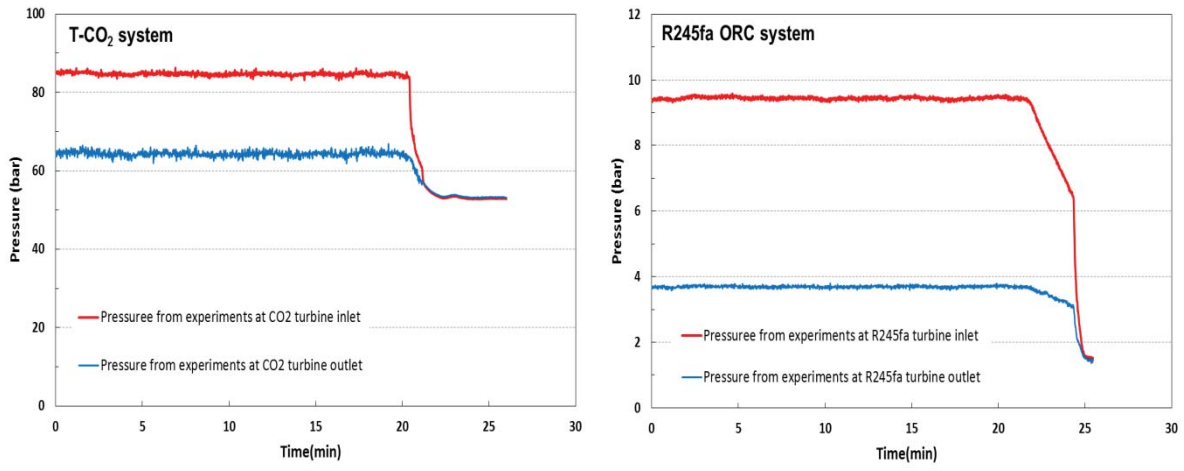


Fig.15. Variations of measured turbine inlet and outlet pressures with time

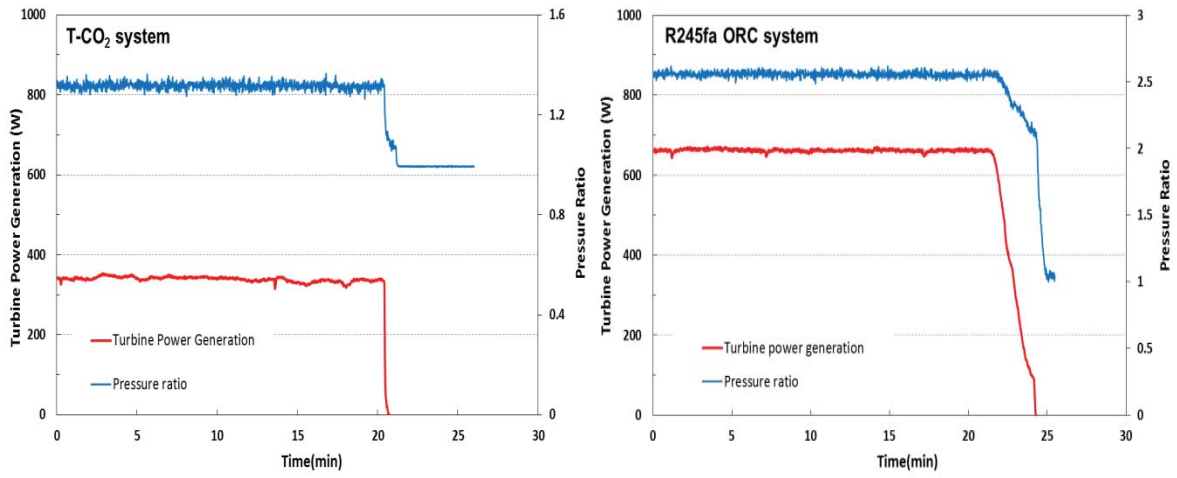


Fig.16. Variations of measured turbine power generations and calculated pressure ratios with time

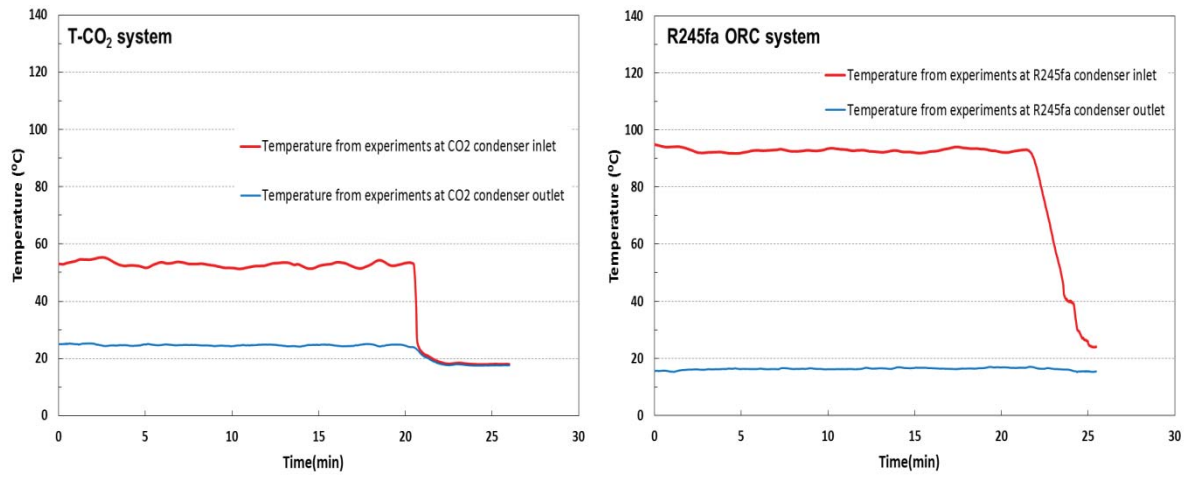


Fig.15. Variations of measured condenser inlet and outlet temperatures with time

Table 1 The properties for R245fa and CO₂ (R744).

Substance	Thermophysical data				Environmental data			Safety data
	Molecular mass	T _c (°C)	P _c (Mpa)	T _b (°C)	ODP	GWP	Atmospheric (yr)	ASHRAE Safety group
CO ₂ (R744)	44.01	31.1	7.38	-78.4	0	1	>50	A1
R245fa	134.05	154	3.65	15.1	0	1030	7.6	B1

Table 2 The parameter measurements and uncertainties

Parameters	Sensors	Measuring range	Accuracy
Temperatures	K-type thermocouple	(-10) to 1100°C	±0.5°C
Pressures (T-CO ₂)	MBS 33	0~160 bar	±0.3%
Pressures (ORC)	AKS 32	0~25 bar	±0.3%
Mass flow rate (T-CO ₂)	Twin V-shaped tube type flow meter	0~1800 kg/h	±0.1%
Mass flow rate (ORC)	Twin tube type flow meter	0~6500 kg/h	±0.15%
Air flow rate	TA465 air flow meter	1.27~78.7 m/s	±0.15 m/s
Electric power outputs	Digital multimeter	1 mW~8 kW	±0.8%

Table 3 The operating conditions for the working fluid pump operating speed in R245fa ORC system.

Stage	ORC pump frequency (Hz)	ORC pump speed (RPM)	Oil temperature (°C)	Oil pump frequency (Hz)	Oil flow rate (kg/s)	Condenser air velocity (m/s)	Ambient air temperature (°C)
I	37.5	730	131.1	50	1.08	3.67	17.0
II	40	779	131.1	50	1.08	3.67	17.0
III	35	680	131.1	50	1.08	3.67	17.0

Table 4 The operating conditions for the thermal oil pump operating speed in T-CO₂ system.

Stage	CO ₂ pump frequency (Hz)	CO ₂ mass flow rate (kg/s)	Oil temperature (°C)	Oil pump frequency (Hz)	Oil flow rate (kg/s)	Condenser air velocity (m/s)	Ambient air temperature (°C)
I	35	0.257	139.6	25	0.46	3.67	26
II	35	0.257	144.1	20	0.36	3.67	26

Conflict of Interest

I would like to confirm that there is no conflict of interest for this paper.

Best regards

Prof. Yunting Ge