Applied Thermal Engineering 134 (2018) 95–106

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Prototype of hybrid refrigeration system using refrigerant R723

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HIGHLIGHTS

- A prototype of 10 kW cooling hybrid refrigeration machine is described.
- The machine combines both adsorption and conventional systems.
- The ammonia blend R723 is the refrigerant for both sub-systems.
- The preliminary test results show a total cooling production of 6 kW.

ARTICLE INFO

Article history:
Received 9 June 2016
Revised 21 December 2017
Accepted 26 December 2017
Available online 31 January 2018

Keywords:
Adsorption
Vapour compression
Ammonia mixture R723
Hybrid refrigeration

ABSTRACT

A proof of concept 10 kW cooling capacity hybrid refrigeration machine, designed and built at University of Warwick, is described in this paper. The hybrid system uses ammonia mixture R723 (40% Dimethyl ether, 60% Ammonia) which is compatible with conventional refrigeration copper alloy (Cu90Ni10) and environmentally friendly. It combines sorption (thermal) and conventional vapour compression (electrical) technology in two separate refrigerant loops. Shell and tubes adsorption generators with activated carbon – R723 pair are used as thermal compressor while a semi hermetic reciprocating compressor is used in the conventional vapour compression loop. The hybrid machine is designed as water chiller with an evaporation temperature of 5 °C and condensing temperature of 40 °C. The preliminary experimental tests are mainly designed to check the system operational functionality. Those preliminary results show a maximum cooling production of 6 kW with 2/3 from mechanical compression and 1/3 from thermal compression (adsorption cycle). Further additional work is yet to be carried in order to establish full and detailed performance of prototype under development.

1. Background and introduction

Air-conditioning and refrigeration systems used in human dwellings consume mainly electricity. Conventional refrigerating and heat pump systems, i.e. mechanical vapour compression technology, are electrically driven and thus indirectly emit carbon dioxide. They also utilise refrigerants that are not environmentally friendly. Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) used as refrigerants for many years have depleted the ozone layer while fluorocarbons (FCs) and hydrofluorocarbons (HFCs) have high global warming potential (GWP) causing global warming phenomena. These reasons lead to the use of alternative technologies such as sorption which is heat driven. Sorption systems use waste heat or solar energy and utilise natural refrigerants (water, ammonia, alcohols) that do not harm the ozone layer (zero ozone depletion potential) and have small or no impact in global warming (low or zero global warming potential). Sorption systems have been under research for the last forty years. Research has focused on improving their performance mainly COP and specific cooling or heating power and the machine compactness. Although advancements have been made in adsorption technology producing more compact and lighter systems with higher efficiency [1,2], their COPs are still perceived as lower than the conventional refrigerating and heat pump systems. In fact, the COPs of both adsorption and conventional systems should not directly be compared since each one represents a different entity by definition: for example in refrigeration application, with adsorption system the COP is defined as the ratio of the cooling production by the net heat rate input needed to operate the thermal compressor while with the conventional machine it is a ratio of the cooling production by the net electrical power consumption required to drive the mechanical compressor. Looking on the market, a conventional air conditioning system with a COP of 3.61 and 15 kW cooling capacity [3] could be as good as an adsorption air conditioning system with a COP of 0.65 with 16 kW cooling capacity [4]. By assuming an electrical power plant (burning coal) with a typical efficiency of 35% [5] and a minimum

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https://doi.org/10.1016/j.applthermaleng.2017.12.103
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Nomenclature

COP	coefficient of performance
Cu90Ni10	copper alloy (90% Copper and 10% Nickel)
EDC	Electrically Driven Compressor
HDC	Heat Driven Compressor
HRS	Hybrid Refrigeration Systems
ID	Inner Diameter (m or mm)
k	Dubinin coefficient
n	Dubinin coefficient
OD	Outer Diameter (m or mm)
P	pressure (Pas or bar)
R134a	tetrafluoroethane refrigerant
R717	ammonia refrigerant
R718	water refrigerant
R723	ammonia blend refrigerant (40% Dimethyl ether, 60% Ammonia)
R744	carbon dioxide refrigerant
T	temperature (K or °C)
x	concentration (kg Refrigerant kg^{-1} Carbon)

Subscripts

amb	*ambient*
C	condensing, condensation
E	evaporating, evaporation
in	inlet
out	outlet
o	under saturation
sat	under saturation conditions
w	water

electrical energy transmission and distribution efficiency of 88% [6], it means in fact that the conventional air conditioning system has an intrinsic COP of about 1.11 versus 0.65. This means at this point in time that the performance gap between the two systems is narrow enough for the two products to compete on the market with different selling points than the COP. Overall, the selling arguments of sorption technology in cooling and refrigeration market are its low running cost and sustainability: those machines are mainly waste heat or solar thermal driven and often use natural and environmentally friendly refrigerant like water as refrigerant (R718). The market share of sorption cooling machines is growing and there are predictions of about 6% worldwide with of about 32% in Pacific Asia from 2017 to 2025 [7].

The proposed Hybrid systems combines these two technologies (adsorption and conventional electrical driven mechanical compression) into a system with more desirable characteristics such as more flexible operation, tolerance under extreme temperature conditions and reduced running cost. Various hybrid adsorption cooling systems that combine adsorption with different technologies i.e. vapour compression, liquid or solid desiccant cooling, ejector, suction pump, thermoelectric cooling can be found in the literature. These theoretical and experimental hybrid systems are reviewed thoroughly in literature [8]. Cyklis [9] proposes a cascade system of Lithium Bromide-Water absorption with vapour compression heat pump using CO_2 refrigerant (R744) for freezing application (−10 °C to −20 °C) Ma et al. [10] proposed hybrid consists of three sub-systems for air conditioning application (21 °C indoor air temperature versus 34 °C outdoor air temperature): a liquid desiccant (Lithium Bromide solution) is associated in cascade with a vapour compression heat pump which is then operating in parallel with a solar driven Silica gel-Water adsorption chiller. There are some publications on adsorption hybrid systems but it appears that the research is limited to modelling of thermodynamic cycles of activated carbon thermal compressor combined in series with mechanical compressor operating as a booster and vice versa and often using R134a as refrigerant [11,12]. As part of this research project (EP/J000876/1), four hybrid configurations as illustrated in Fig. 1 [13] were proposed and fully assessed in the prospect of manufacturing and testing one demonstration prototype within both time and cost as well as potential technical constraints.

Hybrid Refrigeration Systems 1 (HRS1): The system consists of three heat exchangers (cooler, condenser and evaporator), two compressors (one conventional and one thermal), two water circulation pumps, a float valve/receiver and a 3-way valve as shown in Fig. 1a. For this configuration, only one compressor operates at one time on common refrigerant loop. It could either be the Heat Driven Compressor (HDC) or the Electrically Driven Compressor (EDC) that is operating. A 3-way valve diverts the refrigerant to the relevant operating compressor. This could be used for waste/solar heat driven refrigeration machine backed up by electrical power as the waste/solar heat sources are usually intermittent. This flexibility offers the advantage of cost effective running cost of machine.

Hybrid Refrigeration Systems 2 (HRS2): With this configuration, two compressors (HDC and EDC) could operate at the same time on two separate refrigerant loops as shown in Fig. 1b but clear distinctive and independent cycles A and B. This avoids the challenge of oil contaminating the adsorbent. Although each loop has its basic components (compressor, condenser, expansion device and evaporator), the condensers and evaporators could be integrated within the same air stream and the same chilled water stream respectively. In order to minimize the cost, condensers (condenser 1 and condenser 2) could also be built as a single integrated heat exchanger with two separated refrigerant loops and common air stream. It will be the same for the evaporators (evaporator 1 and evaporator 2): two separated refrigerant loops and common water stream.

Hybrid Refrigeration Systems 3 (HRS3): Two compressors (HDC and EDC) must operate at the same time on two separate refrigerant loops. However, the two distinctive cycles have in common one heat exchanger (Inter-cooler) that acts as evaporator for cycle A (HDC) and condenser for cycle B (EDC) (see Fig. 1c). This is similar to conventional cascade with the main advantages of operating where a very wide range of temperature between the condenser and the evaporator is required and having better COP. This layout is highly appropriate for ice production (−5°C) or freezing application (−10 °C to 20 °C] in a very hot environment (35–45 °C).

Hybrid Refrigeration Systems 4 (HRS4): Two compressors (HDC and EDC) could operate at the same time on a common refrigerant loop. This system configuration is similar to the HRS1 with the exception that there is not a 3-way diverting valve but a check valve placed at the outlet of the EDC to prevent any flow back of refrigerant gas to the evaporator through the EDC while not operating (see Fig. 1d).

All four Hybrid Refrigeration Systems layouts described could also be transformed into a heating-only heat pump (domestic hot water and/or space heating) or combined cooling and heating by replacing the air steam with the associated fan by a water stream linked to a pump. This would require a highly regenerative HDC to justify not using directly the heat source for heating demands. For these purposes, the HDC must have at least two generators with both mass and heat recovery or a more complex HDC with four generators with both mass and heat recovery [14].

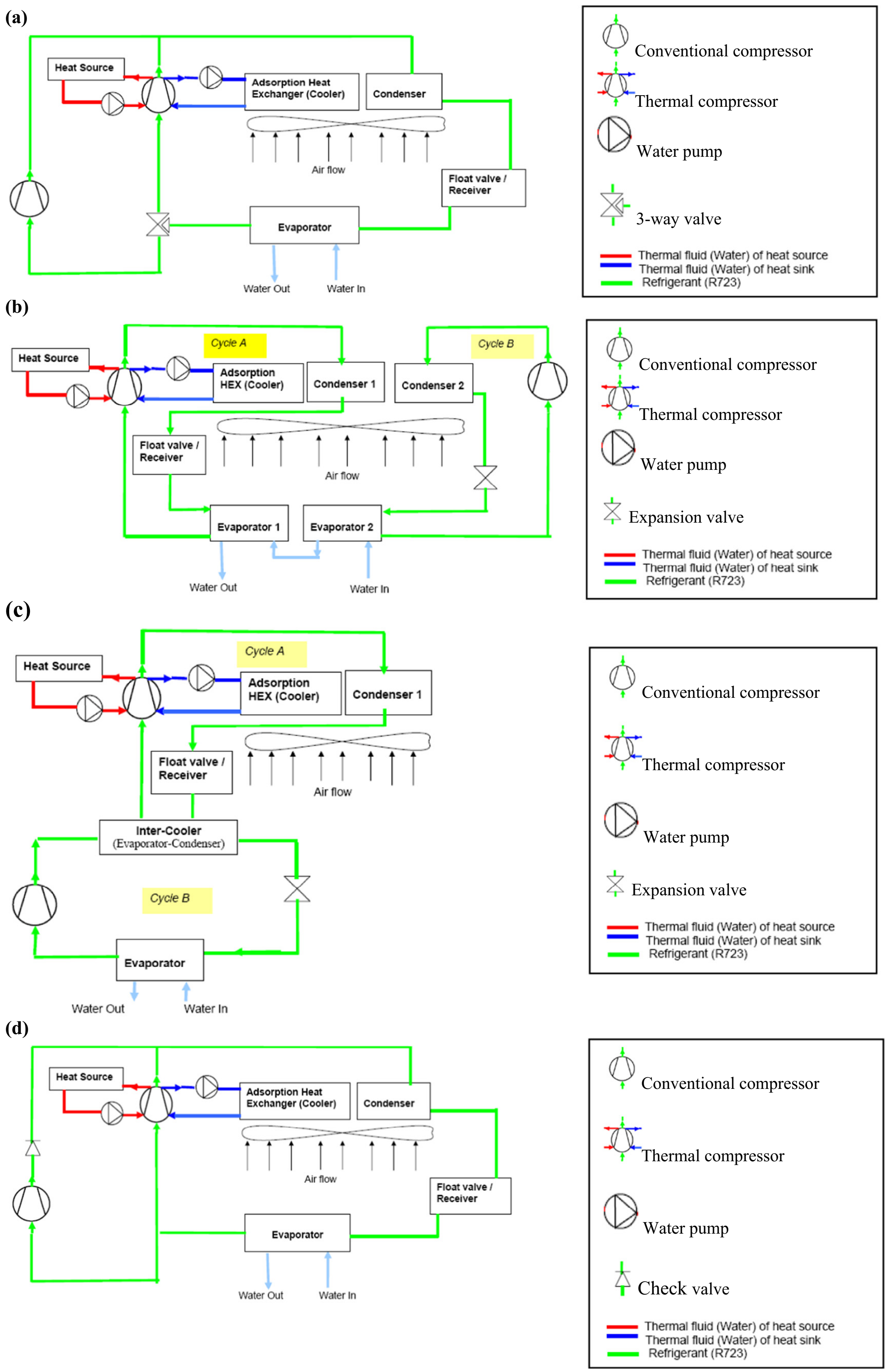

Fig. 1. Layout of the hybrid refrigeration system (HRS) configurations [13]. (a) HRS 1 - Only one compressor operates at one time on common refrigerant loop via a 3-way valve (3-WV). (b) HRS 2 - Two compressors could operate at the same time on two separate refrigerant loops. (c) HRS 3 - Two compressors must operate at the same time on two separate refrigerant loops (Cascade cycle). (d) HRS 4 - Two compressors could operate at the same time with common refrigerant loop.

Although R723 has good miscibility with mineral and synthetic oils, the oil effect on the sorption reactor performance will need to be investigated in depth including looking at the compressor sensibility to carbon dust built up within a system closed loop before considering a hybrid system with common refrigerant loop such as Hybrid 1 and Hybrid 4. Even if the presence of oil could have a negative effect on sorption generator performance, the use of oil free type of Electrically Driven Compressor (EDC) such as reciprocating compressor from Aximaref could not be a viable option since the products on the market are only for high flow capacity (300–8000 m^3/h) when we are looking for 5–10 m^3/h type of range. With the lack of hermetic compressors for Ammonia (R717) and Ammonia blend refrigerants such as R723, the semi-hermetic from Frigopol was identified as alternative choice for this key component. For the purpose of demonstrating the concept of small cooling capacity hybrid refrigeration machine with minimum manufacturing risk, the Hybrid Refrigeration Systems 2 (HRS2) configuration was selected. This layout selection also offers the advantage, after construction and full testing, to modify the prototype by rerouting the pipes connections for different layout configurations without major new components requirement.

In this work a hybrid refrigeration machine prototype of about 10 kW cooling capacity that combines a conventional mechanical compressor with a thermal one (adsorption generator) utilising ammonia mixture R723 is described. The machine is designed as water chiller and both mechanical and thermal compressors can be operated in parallel giving flexible operation to the system. The main objective of this paper is to describe the hybrid water chiller and presents preliminary test results aimed to check the system operational functionality.

2. Methodology - Description of the hybrid refrigeration system

The hybrid refrigeration machine was modelled and then designed and built according to British Standard (mainly BS EN 378-2:2000 [15], BS 7005:1988 [16]) and EU pressure vessel safety regulations (BS PD CEN/TR 14549:2004 [17]). All the components

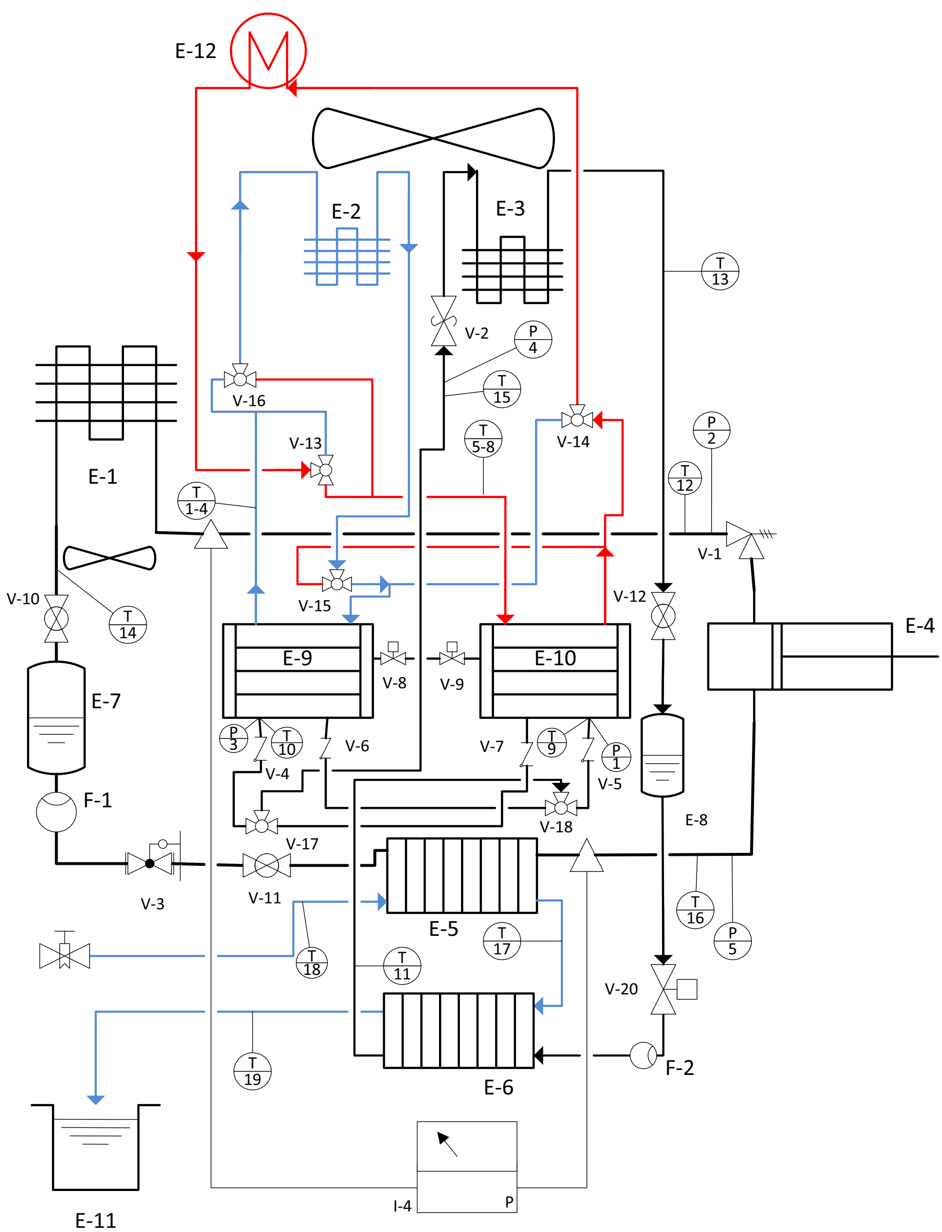

Fig. 2. Flow diagram of the hybrid refrigeration system with the main and auxiliary components.

of the system chosen are compatible with refrigerant R723. The design and modelling of the system as a water chiller were carried out based on the following specified operating conditions:

(a) A chiller for cooling water with air cooled condensers combining adsorption and conventional vapour compression refrigeration utilising refrigerant R723.
(b) Condensing temperature: 40 °C.
(c) Evaporating temperature: 5 °C.
(d) Overall maximum cooling capacity: 10 kW.

A simple model (mainly based on compressors) of this the hybrid refrigeration system when operating with Ammonia refrigerant (R717) has are already being published [18] and further details including simulation with R723 are not provided in this paper. The novel hybrid refrigeration system consists of two separate loops as shown in Fig. 1. Each loop has its basic components (compressor, condenser, expansion device and evaporator), the condenser (Condenser 1) and cooler of the adsorption cycle are integrated within the same air stream. The evaporators (Evaporator 1 and Evaporator 2) are integrated within the same chilled water stream. There are five heat exchangers (cooler, Condenser 1, Condenser 2, Evaporator 1 and Evaporator 2), two compressors (conventional/mechanical and thermal).

With this configuration, we were able to operate the two compressors (HDC and EDC) at the same time on two separate refrigerant loops as shown in Fig. 1 (clear distinctive cycles A and B). Cycle B is the adsorption cycle and Cycle A is the mechanical vapour compression cycle. This avoided the challenge of oil contaminating the adsorbent. A detailed flow diagram of the actual system can be seen in Fig. 2 with Table 1 detailing all of the main and auxiliary components shown in it.

The heat source driving the adsorption is supplied by the hot water loop (80–90 °C, 24 L/min): both hot and cold water are managed by two pairs of 2 integrated 3-way valves with a single actuator. The two refrigeration systems were packed in a steel frame box of 178 cm height, 100 cm length and 79 cm width. The various parts of the refrigerant cycle coming in contact with R723 were connected mainly via 1/2 in. stainless steel tubing and partially via 1/4 and 1/8 in. ones. Fig. 3 shows pictures of the hybrid refrigeration system in both angled (a) and sided (b) views.

2.1. Mechanical vapour compression cycle (Cycle A)

2.1.1. Mechanical compressor

The mechanical vapour compression cycle consists of: a mechanical compressor, a condenser, a receiver, a thermostatic expansion valve, an evaporator and system protection. There are few companies in the market that manufacture compressors of small and medium capacities compatible with ammonia or ammonia blends. A compressor that does not let the refrigerant come in contact with its motor's cooper winding is suitable for our system. Therefore a Frigopol separating hood refrigerant compressor type 7-ELEC-1.5 with motor nominal power of 1.1 kW was chosen. The separating hood between rotor and stator makes impossible any chemical reaction between R723 refrigerant (40% Dimethyl ether, 60% Ammonia) and the motor's cooper winding. The motor of the compressor is air cooled and runs on single face alternating current (230 V, 50 Hz). With a condensing temperature of 40 °C and evaporating temperature of 7 °C, it can deliver up to 7 kW of cooling power.

2.1.2. Condenser

The condenser was manufactured by Beehive Coils Ltd. according to our design specifications (8.5 kW, T_C = 40 °C, T_{amb} = 30 °C, mass flow of 0.01386 kg/s). It is an air cooled coil and fin type condenser made of copper alloy (90Cu-10Ni) which is compatible with refrigerant R723. The brazing material used for the joints was Sifbronze™ No2 (Bronze alloy with 9% Nickel). Its condensing capacity is 8.5 kW for a volumetric flow of 0.972 m^3/s and air entering at 30 °C and leaving at 37.3 °C while the refrigerant R723 is condensing at 40 °C. Detailed information of the condenser can be seen in Table 2.

2.1.3. Receiver and expansion valve

The receiver was designed and manufactured at the University of Warwick. It is about 2 l cylinder with dome ends made of stainless steel that can withstand pressure up to 40 bar (height: 330 mm, inner diameter: 110 mm, wall thickness: 2.2 mm). It was pressure tested with pressurised water up 40 bar at 20 °C temperature. The basic criteria for choosing the expansion valve were the compatibility with ammonia (R717) and its capacity. From the Danfoss catalogue, the thermostatic expansion valve TEA 20-1 with

Table 1
Detailed list of the hybrid refrigeration system components (in Fig. 2).

ITEM	QTY.	MANUF.COMP/PART NO.	DESCRIPTION
E-1	1	Beehive coils/690 mm H × 175 mm D × 750 mm O/H	Air-cooled condenser (8.5 kW)
E-2	1	Beehive Coils/614 mm H × 50 mm D × 680 mm O/H	Cooler (4 kW)
E-3	1	Beehive Coils/614 mm H × 220 mm D × 680 mm O/H	Air-cooled condenser (4.5 kW)
E-4	1	Frigopol 7-ELEC-1.5	Mech. Compressor (1.5 kW)
E-5	1	Alfa Nova 14-28H	Evaporator (7 kW)
E-6	1	Alfa Nova 14-20H (82L × 77W × 207H)	Evaporator (2 kW)
E-7	1	Univ. of Warwick	Receiver (2 l)
E-8	1	Univ. of Warwick	Receiver (3 l)
E-9	1	Univ. of Warwick/2 × 300 mm L × 150 mm D	Generator (bed 1)
E-10	1	Univ. of Warwick/2 × 300 mm L × 150 mm D	Generator (bed 2)
E-11	1	Univ. of Warwick	Water tank
E-12	1	Univ. of Warwick	Water heater
V-1, V-2	1	Henry Technologies	Safety Relief valve (26 bar)
V-3	1	Danfoss TEA 20-1	Thermostatic Expansion valve
V-4–V-7	4	Swagelok	Stop check valve
V-8–V-9	2	Danfoss EVRA 3	Solenoid valve for mass recovery
V-19	1	Danfoss AKVA 10-1	Solenoid expansion valve
I-4	1	Danfoss KP15A	Pressure regulator/pressostat
F-1, F-2	1	Henry SG-1006	Sight glass
V-10–V-12	3	RS Stainless steel 1/2 in.	Ball valves
V-13–V-18	6	RS Stainless steel 1/2 in.	3-way valves

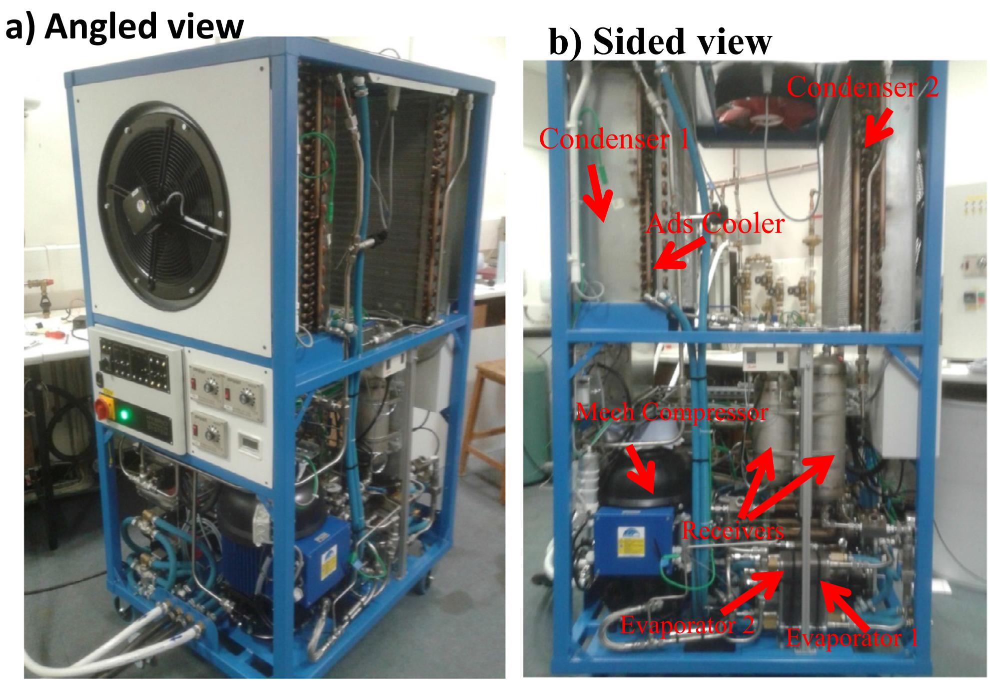

Fig. 3. University of Warwick hybrid refrigeration system.

Table 2
Technical specifications of the Condenser 2 (mechanical vapour compression loop).

Q20041	Condenser
Air flowrate	0.972 m^3/s
Air inlet temperature	30 °C
Air outlet temperature	37.3 °C
Thermal power	8.5 kW
Refrigerant	R723
Fins	Aluminium (230 Fins)
Tubing	3/8″, CuNi10 in circuits with CuNi10 return bends and headers
Fin face	686 mm H × 650 mm W (approximately)
Overall	690 mm H × 175 mm D × 750 mm O/H (approximately)
Test	Unit tested under pressurised water up to 33 bar

rated capacity of 3.5 kW at −15 °C evaporating temperature and 32 °C condensing temperature, was therefore chosen. The evaporating temperature ranges from −20 °C to 30 °C while the maximum working pressure is 19 bar.

2.1.4. Evaporator

The evaporator was a compact plate heat exchanger made of stainless steel by Alfa Laval brazed plate type of heat exchangers from AlfaNova series that matched our requirements. It is AlfaNova 14–28H heat exchanger with 7 kW refrigerating capacity ($T_{w,in}$ = 20 °C, $T_{w,out}$ = 7 °C, T_E = 5 °C).

2.1.5. Auxiliaries

In order to protect the system from low suction or high discharge pressures, a pressostat (KP 15A) from Danfoss was used. In addition, a pressure relief valve manufactured by Henry (Type PRV 5340 set at 26 bar) was used as safety valve to protect the system from high undesirable pressure.

2.2. Adsorption cycle (Cycle B)

The adsorption cycle consists mainly of: a thermal compressor, a condenser, a receiver, an electronic expansion valve, an evaporator, a cooler, 3 actuators each linked to two 3-way valves and 4 stop check valves.

2.2.1. Thermal compressor

The thermal compressor consists of four tubular generators designed and manufactured at Warwick University [19,20]. For reasons of simplicity it was operated as a two bed generator (each bed has two sets of generator in parallel operating simultaneously). It is entirely made of stainless steel. Fig. 4. shows CAD drawings of the generators. Each cylinder (320 mm Length × 150 mm Diameter) is filled with 0.90 kg of packed granular activated carbon 208C and could withstand up to 40 bar pressure. Table 3 shows in details the key specifications of the generator. There are two distinct loops: the water loop (for heating and cooling) and the refrigerant loop (R723). The refrigerant (gas) is adsorbed by the packed activated carbon that fills the space between stainless steel micro tubes (769 tubes, 1.2 mm OD, 0.8 mm ID and 315 mm Length). The micro tubes cool/heat up the activated carbon during adsorption/desorption.

2.2.2. Condenser

The condenser was manufactured by Beehive Coils Ltd according to our design specifications (4.5 kW, T_C = 40 °C, T_{amb} = 30 °C, mass flow of 0.006 kg/s). It is an air cooled coil and fin type condenser made of metal alloy Cu90Ni10 (90% Copper and 10% Nickel) which is compatible with refrigerant R723. The brazing material used for the joints was Sifbronze™ No2. Its condensing capacity is 4.5 kW for a volumetric air flow of 0.889 m^3/s and air entering at 30 °C and leaving at 34.2 °C while the refrigerant R723 is condensing at 40 °C. Detailed information of this condenser is provided in Table 4.

2.2.3. Receiver and electronic expansion valve

Like the previous receiver, the receiver of adsorption loop was designed and manufactured at the University of Warwick. It is a 3 l cylinder made of stainless steel with dome ends that can withstand pressure up to 40 bar (height: 430 mm, inner diameter: 110 mm, wall thickness: 2.2 mm). An expansion valve compatible with R723 was chosen from Danfoss. It is an ON/OFF electrically oper-

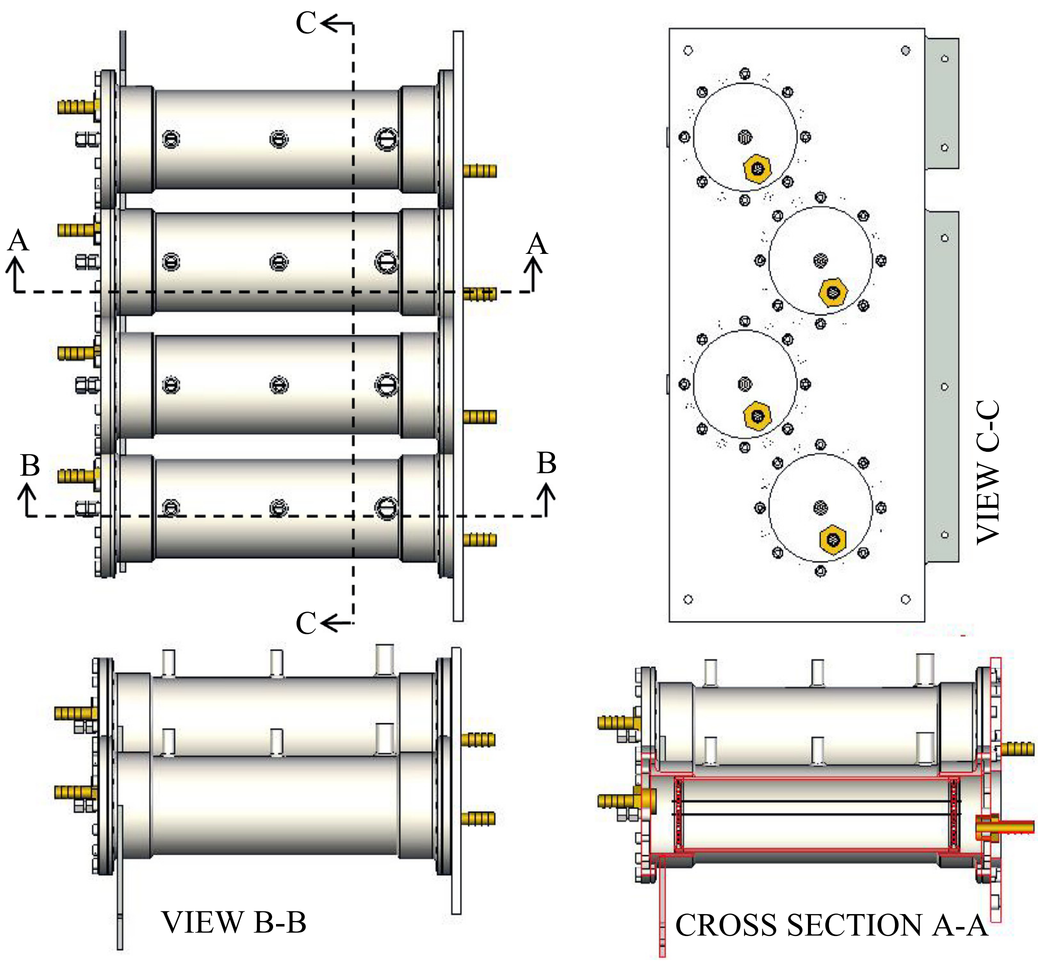

Fig. 4. Snapshot of CAD drawings of the generators layout (thermal compressor).

Table 3
Generator specifications.

Type of carbon	Chemviron 208C (compacted)
Micro-pore specific volume	0.500 g cm^{3}
Thermal enhancement additives	None
Packed density	670 kg m^{-3}
Mass of carbon	0.985 kg
Dubinin-Astakhov equation for R723	n = 1.187
uptake *x* [21]	k = 3.7342
$x = x_o exp\left[-k\left(\frac{T}{T_{sat}} - 1\right)^n\right]$	x_o = 0.354 kg kg^{-1} carbon
Operating temperature	200 °C (maximum)
Operating pressure	20 bar (maximum)
Operating cycle time	Less than 100 s

Table 4
Technical specifications of the condenser used in the adsorption cycle.

Q20040 A	Condenser
Air quantity	0.889 m^3/s
Air entering	30 °C
Air leaving	34.2 °C
Duty	4.5 kW
Refrigerant	R723
Fins	Aluminium (220 fins)
Tubing	3/8″, 90/10 Cupro nickel in circuits with cupro nickel return bends and headers
Fin face	610 mm H × 600 mm W (approx)
Overall	614 mm H × 220 mm D × 680 mm O/H (approx)
Test	Unit tested under pressurised water up to 33 bar

ated valve with a rated cooling capacity of 4 kW AKVA 10-1). The electrical power of the associated coil is about 10 W under 220 Vac.

2.2.4. Evaporator

The evaporator was a compact plate heat exchanger made of stainless steel purchased from Alfa Laval. It is AlfaNova 14–20H heat exchanger with 2 kW refrigerating capacity ($T_{w,in}$ = 20C, $T_{w,out}$ = 7 °C, T_E = 5 °C).

2.2.5. Cooler

The cooler is aimed for cooling the generators during the adsorption phase (heat rejection). It is a coil and fin type heat exchanger known also as Low Pressure Hot Water (LPHW) coil. The coil is made of cooper and the fins are made of aluminium. The cooler (Q20040 A) was integrated in the same air stream of condenser 1. Its cooling capacity is 4 kW for a volumetric flow of 0.889 m^3/s with air entering at 34.2 °C and leaving at 37.9 °C while the water is entering at 90 °C and leaving at 40 °C with a volumetric flow of 0.019 l/s. The detailed information of the condenser are provided in Table 5.

2.2.6. Auxiliaries

Six 3-way valves made of stainless steel were used to divert the flow of water and refrigerant accordingly. Specifically two 3-way valves were used for the refrigerant loop and four 3-way valves for the water loop. The operation of the 3-way valves was done by three actuators. Each actuator was modified to operate two valves simultaneously. The actuator is ¼ turn with spring return

Table 5
Technical specifications of the cooler (LPHW) used in the adsorption cycle.

Q20045 A	LPHW Coil
Air quantity	0.889 m^3/s
Air entering	34.2 °C
Air leaving	37.9 °C
Duty	4.0 kW
Medium	Water 90–40.0 °C for 0.019 L/s
Fins	Aluminium (220 fins)
Tubing	3/8″ Copper
Inlet/outlet	3/8″ OD
Fin face	610 mm H × 600 mm W (approx)
Overall	614 mm H × 50 mm D × 680 mm O/A (approx)
Test	Unit tested under pressurised water up to 20 bar

from Zoedale (Reference ER10.573MF). The electrical power of each actuator is about 26 W under 24 V_{dc}.

Four check valves (from Parker: C Series – 23TR 8Z(A)-C8L-1/3-T-SS) were placed on the generator: two on each bed. They are essential to independently managing refrigerant gas flow in adsorption cycle as they maintain the beds pressurised (cracking pressure of 0.02 bar). As with the mechanical vapour compression loop, a pressure relief valve manufactured by Henry (Type PRV 5340 sets at 26 bar) was used as safety valve to protect the system from high pressure.

2.3. Instrumentation and control

To measure the temperatures and pressures of the system 20 thermocouples (marked as **T** in Fig. 2) and 5 pressure transducers (marked as **P** in Fig. 2) were placed on specified positions. The thermocouple used are K-type mineral insulated (1 mm diameter stainless steel shield × 200 mm long) supplied by TC Direct. The pressure transducers used were UNIK 5000 GE with a pressure range of 0–17 bar (output signal 4–20 mA, supply voltage 7–28 V_{dc}). Three water flow meters were used to measure the flow of the hot, cold and chilled water respectively.

The system control was designed for both manual and automatic operation mode. The automatic mode is essential for the operation of the adsorption cycle; a program written in DASYLab 13.0 was used for the operation of the 3-way valves (timing and duration of opening/closing the ports) and recording the temperature and pressure readings every second (1 s). The manual mode was used mainly for system initial functionality testing and safety testing by the means of manual electrical switches.

3. Preliminary experimental results

Before charging the adsorption and the mechanical vapour compression systems were tested for leakage. After satisfactory of leak and vacuum tests carried out on both system loops, the systems were charged with R723. The vapour compression system and the adsorption system were filled with 0.79 kg and 1.5 kg of R723 respectively. During the preliminary testing both systems were tested initially independently.

The first preliminary test of the mechanical vapour compression was carried out under ambient temperature of 24 °C, evaporating temperature of 8 °C and chilled water flow rate of 9 l/min. The cooling power was estimated from water mass flow that circulates inside the evaporator, the specific heat of water and the water temperature difference across the evaporator. The maximum cooling power observed was approximately 4.2 kW as illustrated in Fig. 5. During about the 5 min operation, the electrical driven part

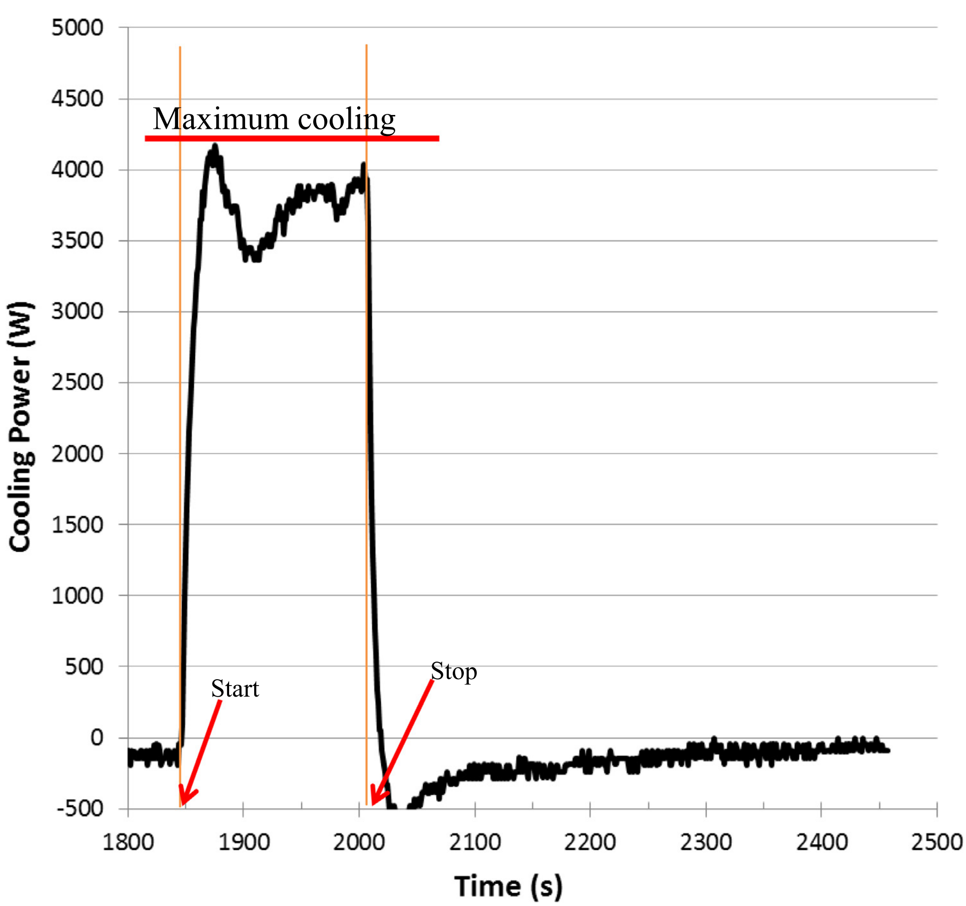

Fig. 5. Cooling production (With electrical driven compressor).

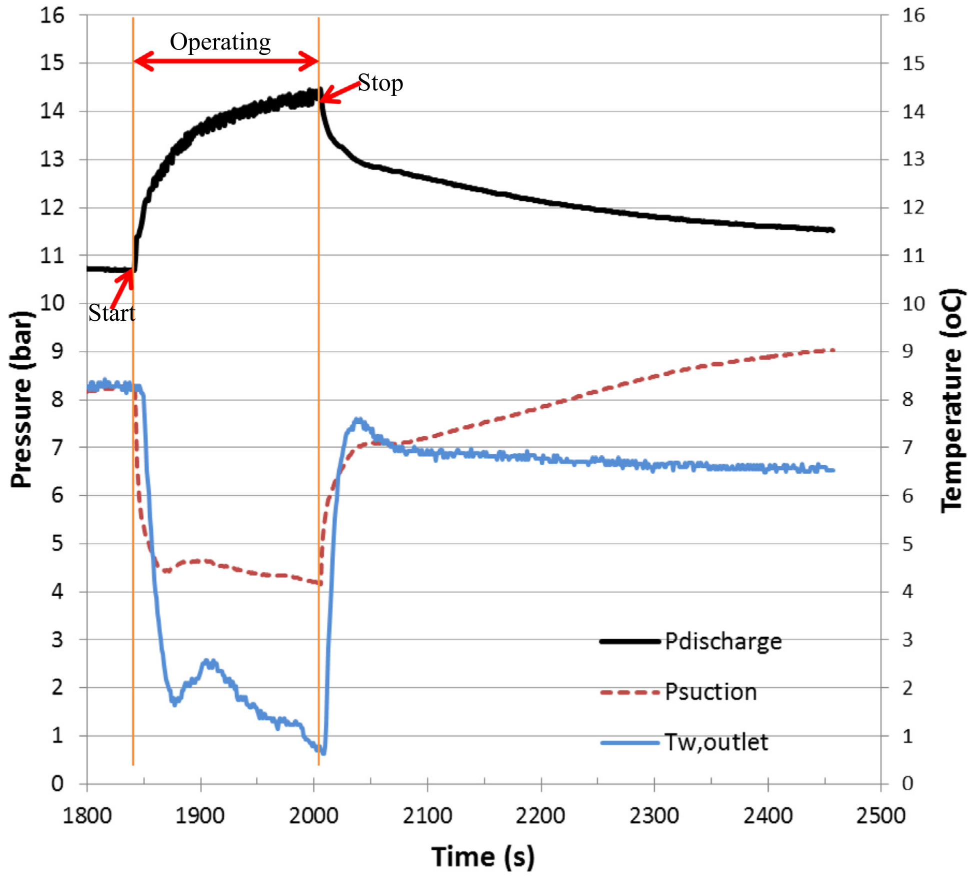

Fig. 6. Refrigerant pressure profiles and chilled water temperature outlet of the evaporator (T_{outlet}) (With electrical driven compressor).

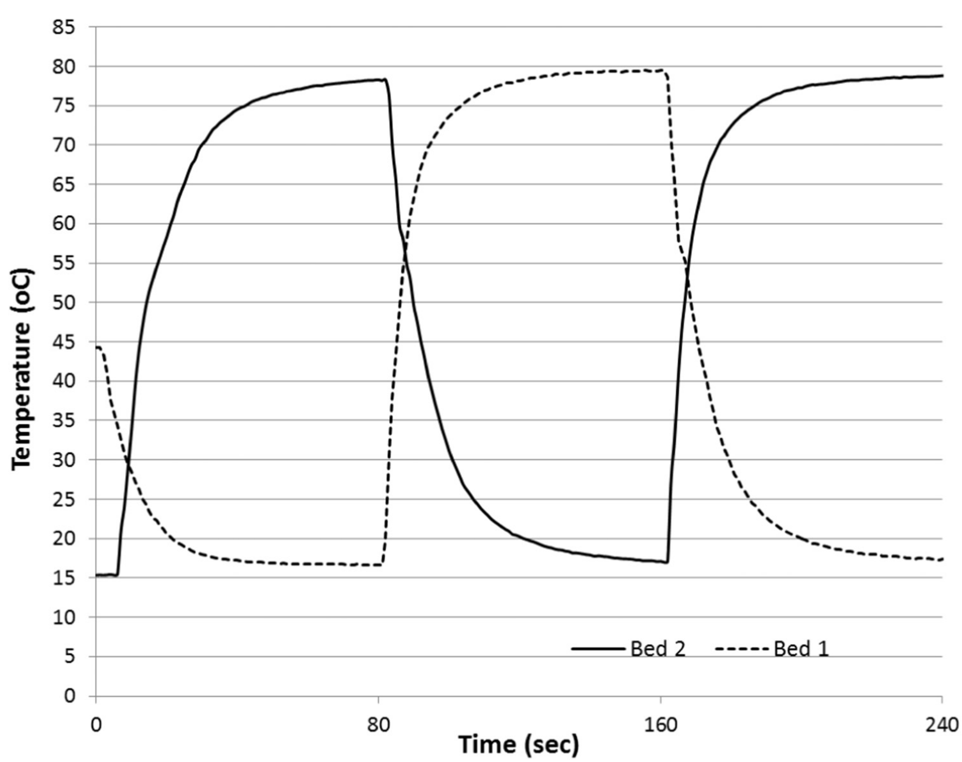

Fig. 7. The average temperature of Bed 1 and Bed 2 during heating/cooling (desorption/adsorption) with 80 s cycling time at 80 °C driving temperature and opening/closing time of the electronic expansion valve set at 2s–5s (With thermal compressor).

of the system has produced cooling with an average COP of 4.8. Fig. 6 shows the pressure profiles discharge pressure and suction pressure along with the temperature of the chilled water at the outlet of the evaporator.

Regarding the adsorption system, preliminary experiments were carried out under different opening/closing times of the electronic expansion valve in order to find the optimum operating conditions based on higher and more continuous cooling production. Therefore, while keeping the driving temperature constant at 80 °C and cycling time 80 s the opening/closing time was varied 2s–6s, 2s–5s, 2s–4s, 2s–3s and 2s–2s. It was observed that from the second cycle out of five cycles, the generator will follow a steady trend of both temperature and pressures profiles. It was concluded at this early stage that an opening/closing time of 2s–5s could be considered for initial experimental tests with 80 s cycling time and a minimum number of cycles of 3.

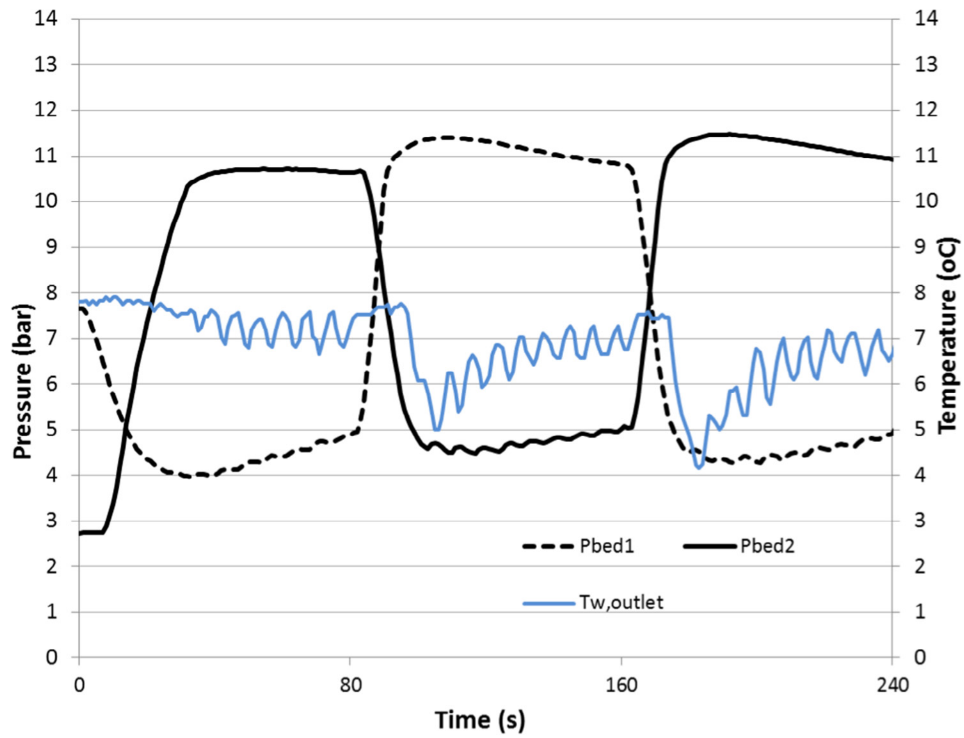

Fig. 8. Bed Pressure profiles and chilled water temperature outlet of the evaporator ($T_{w,outlet}$) with 80 s cycling time, 80 °C driving temperature and opening/closing time of the electronic expansion valve set at 2s–5s (With thermal driven compressor).

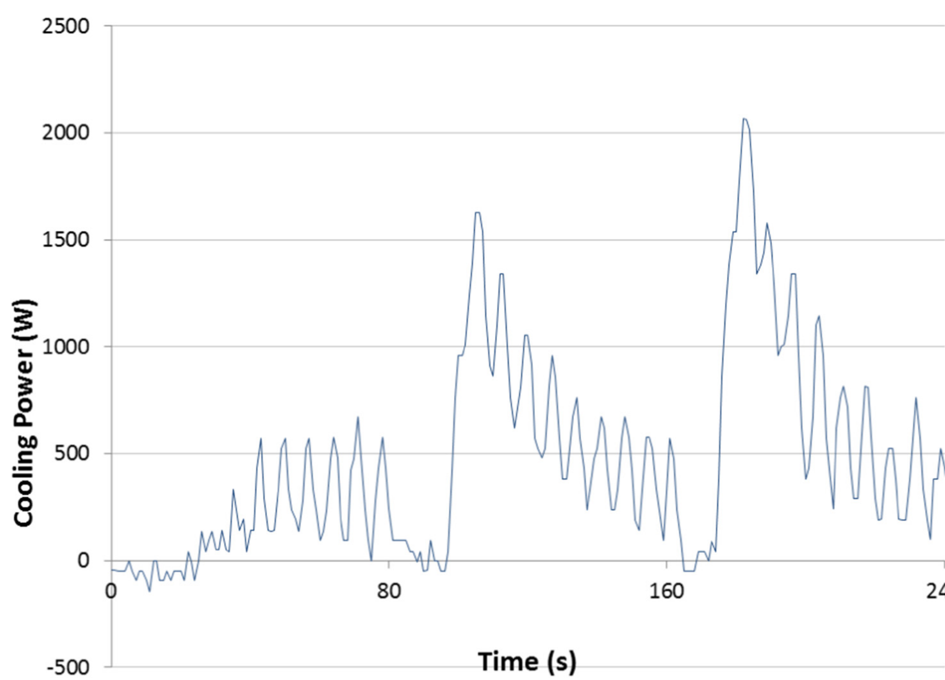

Fig. 9. The cooling power of the adsorption system with 80 s cycling time, 80 °C driving temperature and opening/closing time of the electronic expansion valve set at 2s–5s (With thermal compressor).

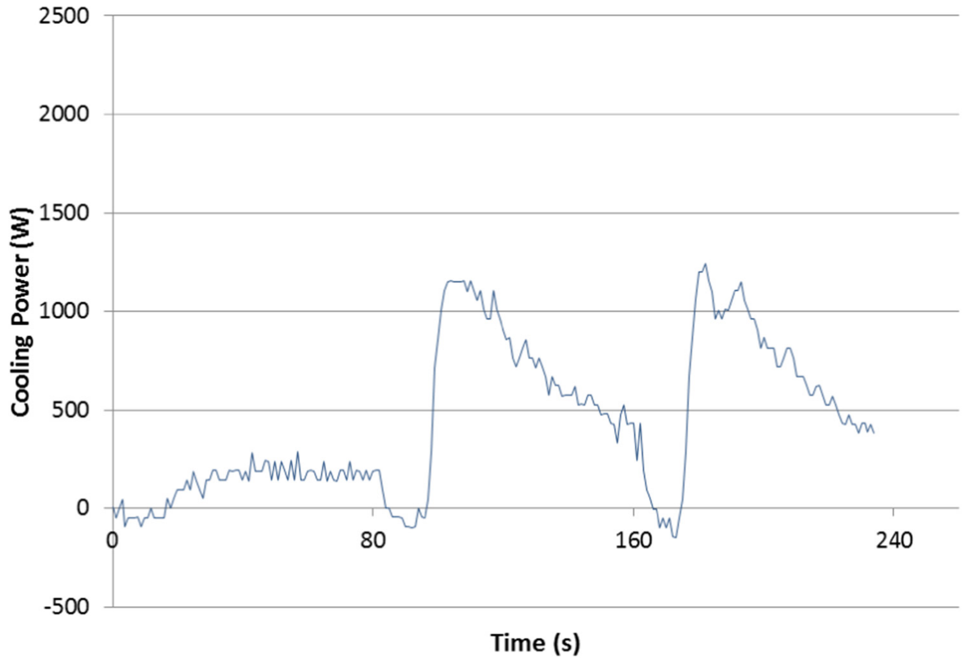

Fig. 10. The cooling power of the adsorption system with 80 s cycling time, 80 °C driving temperature and opening/closing time of the electronic expansion valve set at 2s–3s (With thermal compressor).

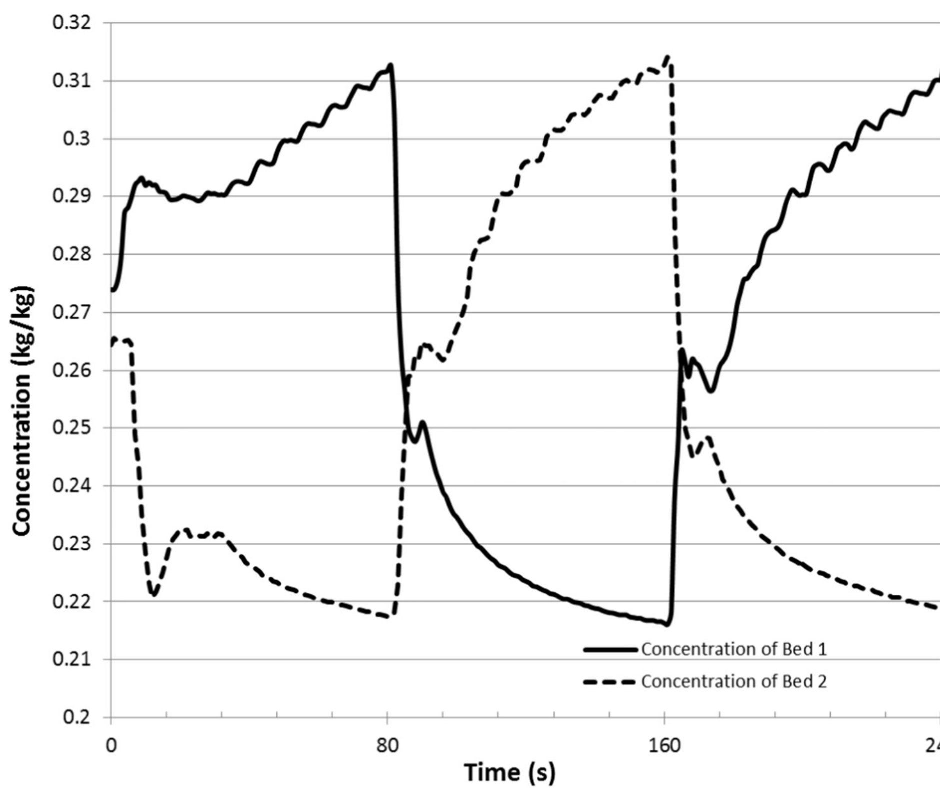

Fig. 11. The concentration × (kg R723/kg carbon) of Bed 1 and Bed 2 during heating/cooling (desorption/adsorption) with 80 s cycling time at 80 °C driving temperature and opening/closing time of the expansion valve set at 2s–5s (With thermal compressor).

Fig. 7 shows reactor bed temperature profiles. Since there is no thermocouple embedded within each bed, this temperature an average value calculated from both inlet and outlet temperatures of water flowing through the reactor. This temperature profile is typical for two beds operating out phase with fixed cycling time (adsorption/desorption). For this test, the temperature and pressure swings are about 63 °C and 7 bar respectively. The pressure profiles of the beds along with the temperature of the chilled water at the outlet of the evaporator are shown is Fig. 8. The cooling power of the system (estimated from water mass flow that circulates inside the evaporator, the specific heat of water and the water temperature difference across the relevant evaporator) is illustrated in Fig. 9: the maximum cooling power was approximately 2 kW after three cycles. However the cooling production more unstable compared to test with an opening/closing time of 2s–5s which has more stable cooling production but low peak value (1.2 kW) as illustrated in Fig. 10.

From both temperatures and pressures variation within the beds, the refrigerant concentration is calculated using Dubinin-Astakhov equation (see Table 3) and its profiles are illustrated in Fig. 11. The estimated concentration swing is about 0.095 kg of refrigerant R723/kg carbon corresponding to an estimated average refrigerant mass flow rate of about 2 g/s which is typical value for the current cooling power output range (up to 2 kW).

4. Conclusion

A novel hybrid refrigeration system that combines conventional refrigeration technology with adsorption technology was described in detail and the preliminary results were presented. The preliminary tests showed that it can produce maximum 6 kW of cooling power with both systems operating in parallel (mechanical vapour compression: 4 kW and adsorption system with driving temperature of 80 °C: 2 kW).

Further work

Additional investigation will include the improvement of control system [22], the optimization of cycling time of solenoid expansion valve on adsorption cycle or its replacement with a stepper motor electronic expansion valve in order to control further evaporator feeding with refrigerant therefore achieving better stability of cooling power. Furthermore, the control of adsorption cycle based on cooling power output or a set bed temperature will be explored and the overall coefficient of performance will also be estimated.

Acknowledgments

The project is supported by EPSRC-UK (Grant EP/J000876/1) and Chemviron Carbons Ltd (Lockett Road, Lancashire WN4 8DE, UK).

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