12th IEA Heat Pump Conference 2017

Advanced heat driven hybrid refrigeration and heat pump systems

Z. Tamainot-Telto*

School of Engineering – University of Warwick

Gibbet Hill Road, Coventry CV4 7AL, UK

Abstract

This paper describes two advanced heat driven hybrid refrigeration and heat pump systems. Each proposed conceptual hybrid system combines both thermal compressor and turbo-compressor. The turbine (coupled to a mechanical compressor) could be driven by direct expansion of high pressure and high temperature of desorbed gas coming out of the reactor beds (Adsorption Cycle - AdSC) or high pressure and high temperature steam coming out of a boiler (Rankine Cycle - RC). In both cases, the turbo-compressor is driving a separate Vapour Compression Cycle (VCC). For each system, a model is used to predict key performance indicators like COPs when the driving temperature is ranging from 100^{o}C to 250^{o}C. The Hybrid RC-VCC coefficient of performance (COP) is about 1.2 to 2 times better than Hybrid AdSC-VCC ones. With a condensing temperature of 40^{o}C, an evaporating temperature 15^{o}C and a driving temperature of 250^{o}C, Hybrid RC-VCC COP is 2.6 while Hybrid AdSC-VCC COP is 1.4.

Keywords: Adsorption; Rankine Cycle; Vapour Compression Cycle, Hybrid Heat pump; COP

1. Introduction

The condensing boiler is a gas or oil fired water heater mainly dedicated to space heating and domestic use: its efficiency is typically 0.90. There are about 1.6 million new units of condensing boilers sold for replacement or new houses in the UK every year leading to a stock of about 23 million units **[1].** Furthermore about 37% of the

* Corresponding author. Tel.: +44 24 76522108; fax: +44 24 76418922.
E-mail address: z.tamainot-telto@wawick.ac.uk.

primary fossil fuel consumption (mainly gas and oil) is dedicated to domestic heating which corresponds to about 25% of CO_2 emission **[2].** This means that any heat driven system with an efficiency which is above 0.90 will have an impact in respect of fuel saving therefore reduction of CO2 emission. Viessmann company has developed a hybrid heating appliance combining conventional condensing boiler associated to a single bed adsorption reactor using zeolite-water pair with a COP of about 1.3 **[3]**: this innovative boiler is currently on the market under the trade name of Vitosorp 200-F **[4]**. The development of an adsorption gas fired heat pump using activated carbon-ammonia pair with predicted COP of 1.6 is still ongoing at Warwick University UK **[5, 6].** In the prospect of saving the primary energy therefore reducing CO2 emission, this paper explore advanced heat driven hybrid refrigeration and heat pump systems. Two systems are described: combined adsorption cycle (AdSC) with mechanical vapour compression cycle, and combined Rankine Cycle (RC) with mechanical Vapour Compression Cycle (VCC). The mechanical vapour compression cycle is non-conventional as it is driven by a turbine. The main objective of this paper is to describe the systems and estimate some key performance indicators like the coefficient of performance (COP) or specific heating power (SHP) with the heat source temperature varying from 100ºC to 250ºC. The heat pump operating conditions are: the evaporating temperature is ranging between -5ºC and 15ºC while the condensing temperature varying between 40ºC and 60ºC. Both expander (Turbine) and compressor are assumed to have an isentropic efficiency of 80% each with transmission coupling efficiency of 80%. Furthermore, both sub-cooling and superheat are 4K and 7K respectively on the mechanical vapour compression loop.

2. Combined adsorption - mechanical vapour compression cycles (Configuration 1)

2.1. System description

If the conventional hybrid adsorption machine combines both thermal compressor and electrical mechanical compressor, the current conceptual hybrid combines both thermal compressor and turbo-compressor. The two beds (shaded green) are connected in parallel, and operate out of phase by the means of check valves. When one bed is desorbing at high pressure, the other is adsorbing the low pressure return gas. This arrangement allows for continuous cooling or heating to be produced as this sub-system the other conventional key components (condenser, expansion valve and evaporator) on the adsorption cycle loop. The turbine (coupled to a mechanical compressor) is driven by direct expansion of high pressure and high temperature of desorbed gas coming out of the reactor beds as illustrated in **Figure 1**. The ammonia gas will pass through the turbine which will then produce the mechanical work required by the compressor before the remaining heat is rejected in the condenser. The system then operates as in a conventional refrigeration cycle, before the low-pressure ammonia is re-adsorbed into the inactive bed (not in heating mode). The vapour compression cycle is driven by the turbine through its shaft power. This secondary circuit (mechanical compression loop) provides further cooling (via another evaporator to increase the cooling capacity of the adsorption cycle) or heating (via another condenser to increase the heating capacity of the adsorption cycle). For the purpose of simplicity, both heat source and heat sink (cooler) including system of valves managing various flow streams are not illustrated on the adsorption sub-system. Both thermal compression and mechanical compression loops are operating with ammonia refrigerant (R717) and offer the possibility designing and manufacturing the turbo-compressor as compact and hermetic component.

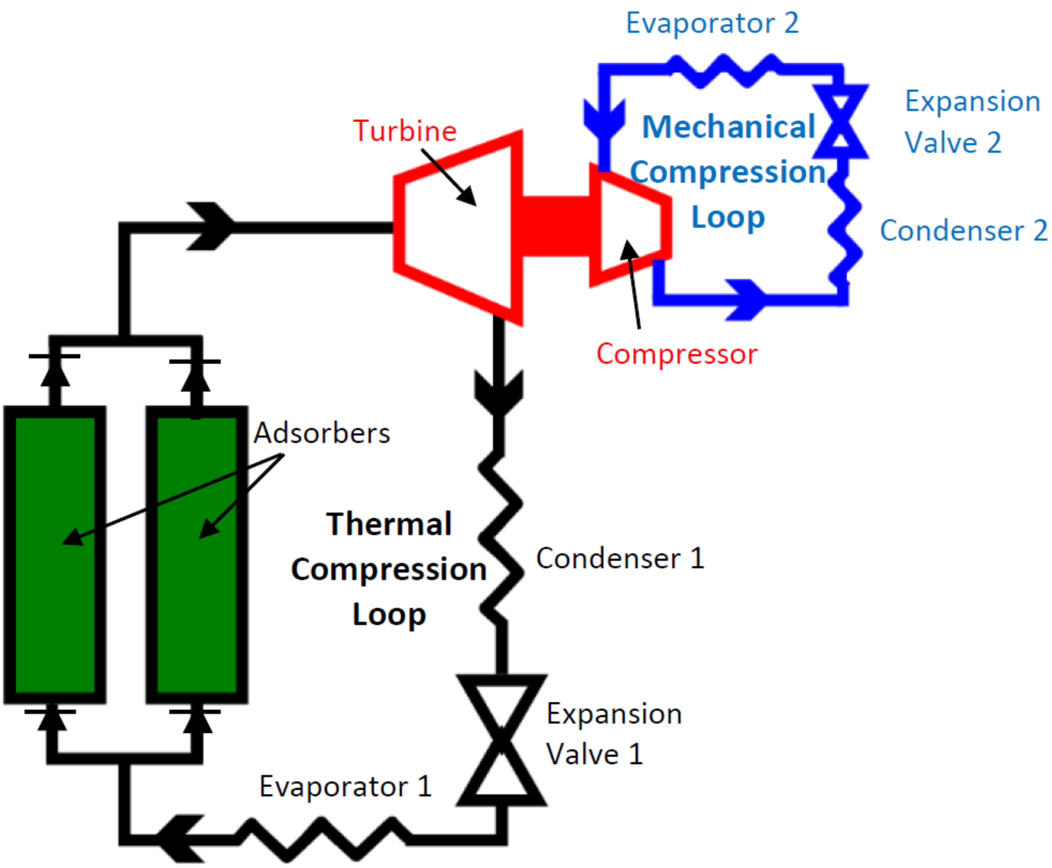

Figure 1: Illustration of an advanced heat driven hybrid system (Configuration 1) **[7]**

2.2. System performance

A pseudo thermodynamic model is used to predict some of the key performance indicators like COPs of such systems. For that purpose, a 2-beds configuration using compacted activated carbon 208C-Ammonia pair is selected for adsorption cycle (AdSC); the mechanical vapour compression loop also uses Ammonia as refrigerant. The two beds are assumed operating out of phase (adsorption, desorption) for pseudo-continuous heating or cooling production with a cycling time corresponding the laps time when the module average temperature approached the operating driving temperature within 5°C. Each adsorption bed is considered to be made of 40 tubular modules in shell-and-tube arrangement. The module is made of stainless steel tube (1/2" OD, 0.91 mm thickness and 1 m long) packed with granular activated carbon 208C (density of 750 kg/m^3, thermal conductivity of 0.44 W/m.K and contact tube wall-adsorbent heat transfer coefficient of 750 $W/m^2.K$). The convective heat transfer coefficient outside of each tube (in shell) is assumed infinite therefore the performance are estimated from the response to step change of external wall temperature of each tube (40°C to a set driving temperature). A numerical model of module (mainly based heat and mass balance equations) is associated to thermodynamic models of the remaining components. Simulations are carried out with a maximum gas pressure in the bed of 37 bar (corresponding to saturation temperature of 75°C). This maximum pressure and the bed average temperature at the end of heating cycle (desorption) are the turbine inlet conditions. The gas mass flow is estimated from ammonia mass uptake during the heating cycle while the work output of the turbine is an average value in the course of same time. **Figure 2** shows an example of intrinsic performance of a single module with a driving temperature of 250°C.

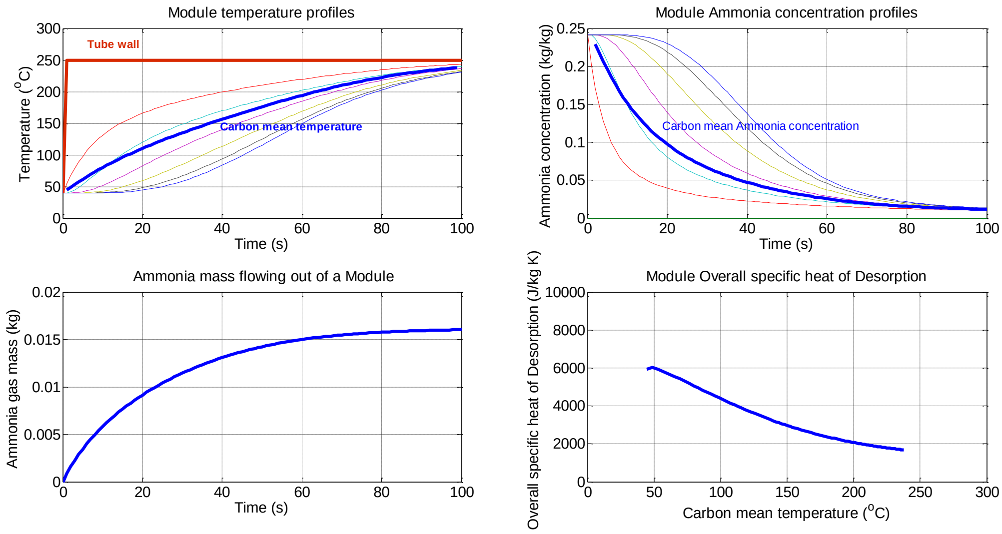

Figure 2: Single module thermal performance

Figure 3 shows the predicted performance of the system for a typical condensing temperature (T_C) of 40°C with evaporating temperature (T_E) ranging from -5°C to 15°C. For each evaporating temperature, the overall heating power output increases with the driving temperature while the COP decreases as expected. With the evaporating temperature T_E=15°C, the overall heating power output increases from 5 kW to 17.2 kW when the COP decreases from 1.5 to 1.4. These values of COPs are about 15% to 20% less than those of ordinary adsorption system with both heat and mass recovery **[5, 6]**. The performance of hybrid AdSC-VCC is highly dependent of AdSC through the turbine net work out driving the mechanical compressor. Furthermore the low pressure ratio across the turbine (about 0.40) limits the turbo-compressor power output (0.1 to 0.4 kW) therefore the contribution of the VCC in the overall heating power output: with a maximum heating power output of 35 kW, the VCC contribution is about 15% corresponding to about 5.2 kW.

The heat input mainly depends on both the bed pressure (fixed as 37 bar) and the driving temperature but less on the evaporating temperature: it increases from 3.5 kW (with driving temperature of 100°C) to 12.5 kW (with driving temperature of 250°C).

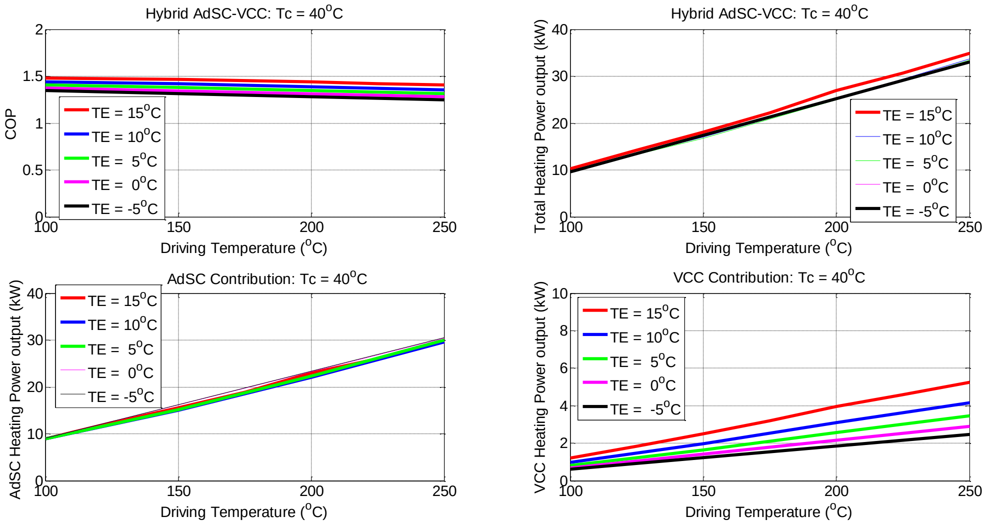

Figure 3: Performance of hybrid system (Configuration 1) combining Adsorption Cycle (AdSC) with Vapour Compression Cycle (VCC) – Condensing temperature Tc=40ºC

3. Combined Rankine - mechanical vapour compression cycles (Configuration 2)

3.1. System description

The hybrid configuration 2 consists of a conventional Rankine cycle combined to a vapour compression cycle as illustrated in **Figure 4**. The Rankine cycle uses water (R718) and comprises the boiler, the turbine, the condenser and the feed pump. As with the previous configuration, the turbine is coupled to a mechanical compressor which is driving a conventional refrigeration cycle operating with ammonia refrigerant (R717).

3.2. System performance

The thermodynamic model used to predict the key performance indicators is based on ordinary basic cycles for both Rankine and vapour compression. The feed pump work rate required is estimated from both the water pressure increase and average specific volume of water across the pump itself. Simulations are carried out with a fixed steam mass flow of 0.005 kg/s (18 kg/h). **Figure 5** shows the predicted performance of the system for a typical condensing temperature (T_C) of 40ºC with evaporating temperature (T_E) ranging from -5ºC to 15ºC. Both COP and overall heating power out increase with the driving temperature for each evaporating temperature as expected. The best performance are obtained with the highest evaporating temperature (T_E=15ºC) with the COP varying from 1.69 to 2.60 while the total heating power output ranges from 21 kW to 34.3 kW: a large proportion of heating power output is provided by the vapour compression loop corresponding to 42% (with 100ºC driving temperature) up to 73% (with 250ºC driving temperature). This is mainly due to the small decrease of the heating power output from the Rankine Cycle (RC) with a fixed condensing temperature (T_C=40ºC): from 11 kW (with 100ºC driving temperature) to 9.4 kW (with 250ºC driving temperature). In fact, the increase of heat input is mainly beneficial to the turbine net power which increases from 1.5 kW to 3.8 kW therefore boosting the heating power out from the Vapour Compression Cycle (VCC). The variation of heating power output from the Rankine Cycle (RC) with the driving temperature will remain unchanged as it depends only on the condensing temperature which is constant for this simulation (T_C=40ºC).

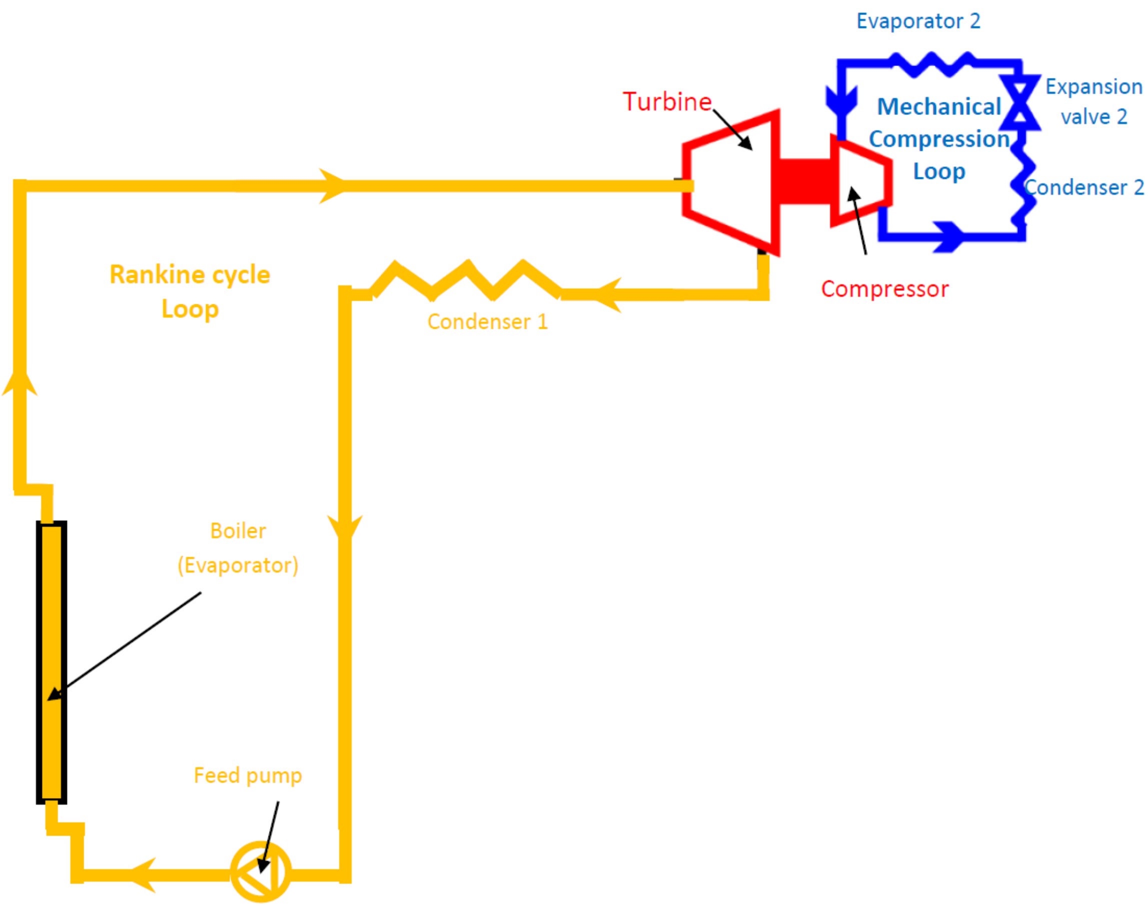

Figure 4: Illustration of an advanced heat driven hybrid system (Configuration 2)

With 5ºC evaporating temperature (T_E) which is fairly reflecting a mild winter average ambient temperature in the Midlands region (UK), the system performance are provided in **Figure 6** with the condensing temperature varying from 40ºC to 60ºC. As expected, higher the condensing temperature lower will be the overall heating power output therefore lower the COP: with the maximum condensing temperature of T_C=60ºC, the COP ranges from 1.16 to 1.51 while the overall heating power out varies from 14.1 kW to 19.2 kW. Due to small change in water latent with the current range of condensing temperature, estimated to about 2% drop, the variation of the heating power out coming from the Rankine Cycle (RC) is marginal and remains within the same range as previously. However its contribution in the overall heating power output is significant at the maximum condensing temperature: 50% to 79%.

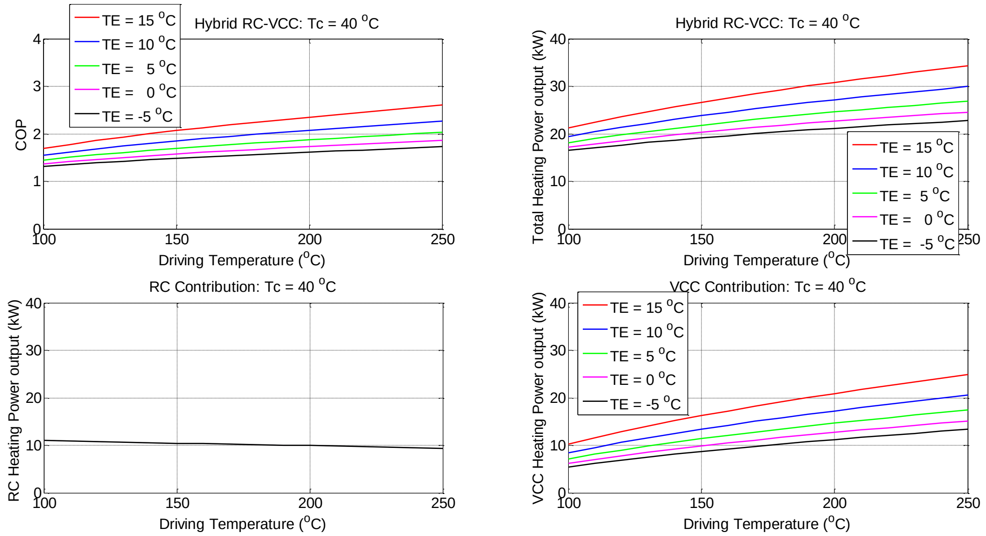

Figure 5: Performance of hybrid system (Configuration 2) combining Rankine Cycle (RC) with Vapour Compression Cycle (VCC) – Condensing temperature T_C=40°C

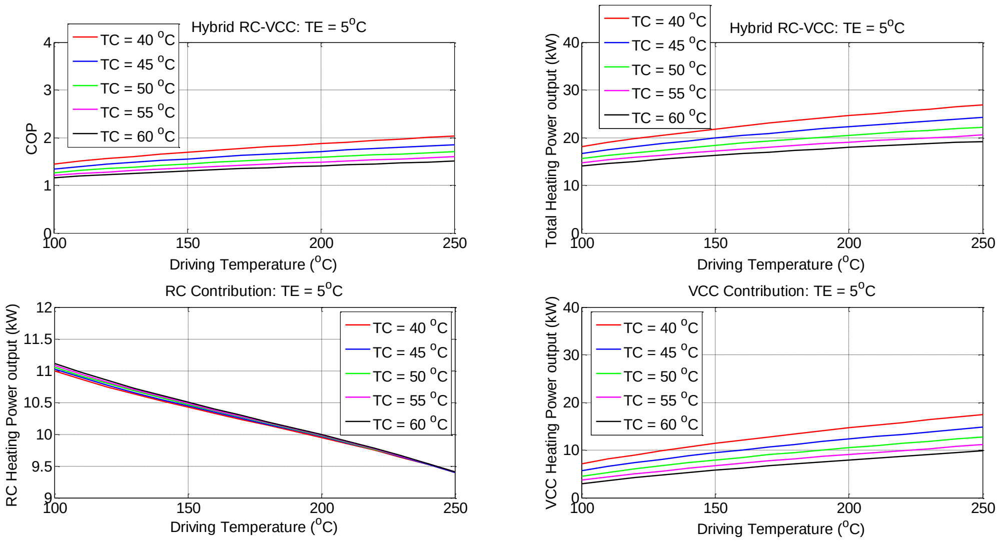

Figure 6: Performance of hybrid system (Configuration 2) combining Rankine Cycle (RC) with Vapour Compression Cycle (VCC) – Evaporating temperature T_E=5°C

4. Conclusions

Two advanced heat driven hybrid heat pump systems were described: an Adsorption Cycle (AdSC) with Vapour Compression Cycle (VCC) and a Rankine Cycle (RC) with Vapour Compression Cycle (VCC). A model was used to predict the performance of each hybrid system (Hybrid AdSC-VCC and Hybrid RC-VCC). The first indications are that for with driving temperatures ranging from 100ºC to 250ºC, the Hybrid RC-VCC coefficient of performance (COP) is about 1.2 to 2 times better than Hybrid AdSC-VCC ones. With a condensing temperature of 40ºC, an evaporating temperature 15ºC and a driving temperature of 250ºC, Hybrid RC-VCC COP is 2.6 while Hybrid AdSC-VCC COP is 1.4.

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