2022

Carnot -Equivalent Air Cycle Heat Pump Leveraging Isentropic and Isothermal Compression and Expansion Principles – A Theoretical Analysis

Daniel Bacellar

Selorm Tsikata

Reinhard Radermacher

Carnot -Equivalent Air Cycle Heat Pump Leveraging Isentropic and Isothermal Compression and Expansion Principles – A Theoretical Analysis

Daniel Bacellar[1*], Selorm Tsitaka[1], and Reinhard Radermacher[1]

[1]University of Maryland, College Park, MD
(dfbace@umd.edu)

* Corresponding Author

ABSTRACT

Air cycle heat pumps (ACHP) have great potential for tackling HVAC&R contributions to climate change, social-economic gaps worldwide and ventilation concerns enhanced by the COVID-19 Pandemic. Air has no global warming potential (GWP), it is available everywhere, and could result in less complex - and possibly lower cost - systems. Conventional air cycles near ambient temperatures, however, have lower COP compared to conventional vapor compression cycles (VCC) using higher GWP refrigerants, since they operate too far from the saturation region (large "superheat horns"). Despite the progress shown in the literature, all of the proposed ACHP configurations are still limited by the compression and expansion processes which are at best done isentropically. A better alternative is the isothermal compression/expansion which can be achieved by coupling the work and heat exchange processes together. Isothermal compression/expansion of air is often used for energy storage and power generation. An overlooked opportunity is using such concepts in heat pumps. In this paper, we present a theoretical analysis on a proposed Carnot-Equivalent Air Cycle (CAC) as a heat pump leveraging both isentropic and isothermal compression/expansion principles. The key lessons are: isothermal compression/expansion eliminate the temperature "horns"; and it is a function of its ability to transfer heat, i.e., the component's UA; CAC temperature lift is decoupled from the pressure lift; CAC COP is very sensitive to the isothermal efficiency and in the ideal case is approximately 5 times greater than the reversed Brayton Cycle; the isothermal compression/expansion need to be at least 90% in order for the system to become truly competitive against conventional VCC; the volumetric flow rates for the same capacity are an order of magnitude larger for CAC compared to VCC, which will result in larger compressors/expanders.

1. INTRODUCTION

Electricity consumption from commercial and residential buildings in the U.S. - dedicated to powering HVAC&R equipment - are, respectively, more than 40% and 70% of the total consumption (Goetzler *et al.* 2019). The current state-of-the-art are vapor compression cycles (VCC) using self-contained working fluids to transport heat between reservoirs. Such refrigerants whether they are HFC's (e.g., R410A, R454B), HFO's (e.g., R1234yf), or natural refrigerants (e.g., Propane) have at least some degree of global warming potential (GWP) and/or are flammable/toxic. Leakage is a major issue since it results in direct greenhouse gas (GHG) emissions from refrigerants, but it also degrades VCC performance (Kim and Braun 2010), resulting in increased power consumption, thus its indirect GHG emissions. Furthermore, the current needs of higher ventilation rates due to airborne transmissible diseases such as COVID-19, requires VCC's to operate at lower efficiencies since it increases the cycle's temperature lift.

One solution to address refrigerant concerns, is the air cycle heat pump (ACHP), an idea that dates back from 19th century proposed by Said Carnot and Lord Kelvin (Thomas 1948). The ACHP could be the ideal cycle since it is free, and it is the most abundantly available working fluid on the planet; it does not have Ozone Depletion Potential (ODP) nor Global Warming Potential (GWP)[1]. Heat pump costs can be greatly reduced once the leakage concerns from refrigerants are eliminated.

Conventional air cycles (single phase working fluids) near ambient temperatures, even with regeneration (Spence *et al.* 2004, Hou and Zhang 2009, Yang *et al.* 2016), aftercoolers (Spence *et al.* 2004) or dehumidification (Nobrega and Sphaier 2013), will always have lower COP compared to conventional VCC (two-phase working fluids) typically below 3 (e.g., Fleming *et al.* 1998, Hou and Zhang 2009, Nobrega and Sphaier 2013, Li *et al.* 2017) since they operate

[1] Moisture and CO_2 present in the air are themselves GHG's, however using the air from the environment in the ACHP would not constitute of added GHG to the atmosphere.

too far from the saturation region. The greater the superheat, the larger the specific volume, thus the higher the compressor work for the same pressure ratio ("superheat horn"). For the reversed Brayton cycles, the latter is responsible for nearly 90% of all the irreversibility (Qian *et al.* 2016). If air could be compressed near the saturation it would require almost 4 times less work for the same pressure ratio, and it would be equivalent to a conventional R410A compression (Figure 1). This explains why air cycles become more attractive at lower/cryogenic temperatures (Spence *et al.* 2005, Hou *et al.* 2006, Hou and Zhang 2009, Nobrega and Sphaier 2013). A more comprehensive review of the literature on ACHP's applications and performances is summarized in Table 1.

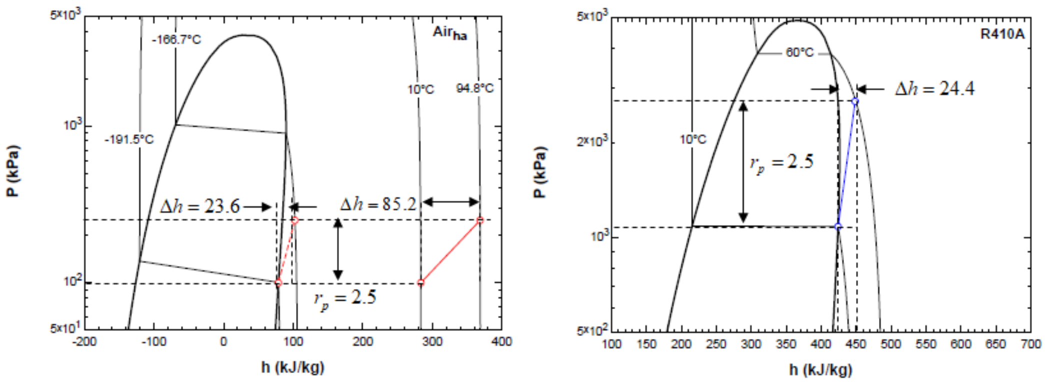

Figure 1: Compression process in the P-h diagram for air and R410A.

Table 1: Literature Survey on Air Cycle Heat Pumps.

Author	Type	Application	Description	Findings
Fleming *et al.* (1998)	Numerical	Refrigeration	Blast freezing system, transport food refrigeration, transport air conditioning	• $-55 \le T \le 0°C$ • $0.2 \le Q \le 2kW$ • $0.05 \le COP \le 0.25$ • $0.45 \le \eta_s \le 0.75$
Spence *et al.* (2004)	Numerical/ Experimental	Refrigeration	Optimized and tested an air cycle unit for trailer refrigeration using **aftercooler** and **regenerator**	Prototype consumed 25% more power than design, and 100% compared to the baseline VCC
Hou *et al.* (2006)	Numerical	Refrigeration/cryocoolers	Investigated cryocooler technology using reversed Brayton cycle with **regeneration** with air and helium as working fluids	• $-80 \le T \le -30°C$ • $0.3 \le \eta_s \le 0.8$
Hou *et al.* (2009)	Numerical	Refrigeration	Analyzed the suitability of humid air for deep freeze application in an open reversed Brayton cycle with **regeneration**	• $-55 \le T \le 0°C$ • $0.7 \le COP \le 1.3$ • $0.84 \le \eta_s \le 0.90$ • Humidity may lead to frost formation in component
Zhang *et al.* (2011)	Numerical	Heat Pump / Air Conditioning	Investigated open air cycle system used for space cooling in Chinese trains	• $r_p = 2.0\text{-}2.5$ • $COP = 1.0\text{-}1.3$ • $\eta_s > 0.85$
Nobrega, Sphaier (2013)	Numerical	Refrigeration	Investigated using **desiccant wheel** in an air cycle using **regeneration**	• $-40 \le T \le 10°C$ • $1.4 \le r_p \le 2.5$ • $2 \le COP \le 9$ • $0 \le \varphi \le 0.75$ • 75% relative humidity reduces in 25% compared to dry air for $r_p>2$ • Desiccant allows higher COPs at high pressure ratios with temperatures above dew point
Zhang *et al.* (2015)	Numerical	Heat Pump	Analyzed potential improvements in air cycles using **regeneration for space heating**	• $2.0 \le Q \le 3.4kW$ • $0.1 \le COP \le 0.25$ • $0.65 \le \eta_s \le 0.95$ • $1.0 \le T_r \le 1.5$ • COP can increase by 20% when temperature ratios are below 1.5.

Yang *et al.* (2016)	Numerical with validation	Water heating	Investigated air cycles with **regeneration** for water heating in cold climates	• $1.0 \leq Q \leq 2.4$kW • $1.2 \leq COP \leq 1.7$ • $0.9 \leq \eta_s \leq 0.95$
Li *et al.* (2017)	Numerical	Heat Pump /Air conditioning	Investigated using turbochargers in air cycle heat pumps for electric vehicles	• $-20 \leq T_{amb} \leq 20$°C • $1.4 \leq COP \leq 2.3$ • 12-15% more power consumption than VCC

Despite the progress shown in the literature, all of the proposed ACHP configurations are still limited by the compression and expansion processes which are at best done isentropically. Even though lower temperature applications are more suitable for isentropic air compression, they also operate at large temperature lifts thus penalizing COP. A better alternative is the isothermal compression/expansion. The technology aiming to achieving the latter has come a long way, and the current state-of-the-art is very promising (e.g. Cherry *et al.* (2015-21), however most of the effort dedicated to isothermal air compression/expansion is heavily focused on Compressed Air Energy Storage (CAES) (Table 2).

Table 2: Literature Survey on Air Isothermal Compression/Expansion.

Author	**Type**	**Application**	**Description**	**Findings**
Coney *et al.* (2002)	Experimental	CAES / Power Generation	Investigated quasi-isothermal air compression with large amounts of water sprayed into the chamber using nozzles	• Potential cost reduction in (less steps and components). • 20-25% reduction in input power • No need for oil lubrication at low speeds • Very reliable with pressure ratio 1:25
Kim *et al.* (2004)	Numerical	Power generation (Ericsson cycle) / Heat Pump	Investigated isothermal scroll compressor/expander using heat pipe with external fins	• $W_t/W_s = 1.6$ • $\eta_{cycle,t}/\ \eta_{cycle,s} = 1.2$ • 126% greater COP • $n = 1.043$
Bell *et al.* (2012)	Numerical	Power generation (Ericsson cycle)	Investigated water flooded scroll compressors	Newly developed mathematical model liquid flooded systems
Park *et al.* (2012)	Numerical	CAES / Power Generation	Investigated isothermal compression/expansion using coolant (water) as piston with direct contact between fluids	Non-uniform pressure and temperature distribution; brief peaks of temperature increase
Igobo & Davis (2014)	Review	Power generation	Reviewed of quasi-isothermal methods of expansion for low-temperature power engines: shell heating and liquid flooding	• Liquid flooding result in greater overall performance deterioration, partly attributed to increased suction pressure drop and viscous losses. • Shell heating: 40% and 20% increase in work and efficiency, respectively
Qin & Loth (2014)	Numerical with validation	CAES	Investigated liquid piston compression efficiency with droplet heat transfer	• $0.71 \leq \eta_t \leq 0.98$ • Temperature increase: 50°C-70°C (vs. 180°C for adiabatic) • 20% less work input
Zhang *et al.* (2017)	Numerical	CAES / Power Generation	Conducted numerical analysis of quasi-isothermal expansion with spraying tiny water droplets	• 12% increase in power yield. • 18°C temperature drop (vs. 178°C for adiabatic expansion)
He & Wang (2018)	Review	CAES / Power Generation	Reviewed best expander for CAES (diabatic, adiabatic, and isothermal): reciprocating, scroll, screw, centrifugal	• Best expanders for • Diabatic CAES: centrifugal • Adiabatic CAES: centrifugal (large-scale), reciprocating and scroll (micro-scale), screw (small-scale)

				• Isothermal: reciprocating and scroll (micro-scale), screw (small-scale)
Guanwei *et al.* (2018)	Experimental	CAES	Investigated isothermal compression using micron-sized (10–100 μm) water spray into the piston chamber	• $0.895 \leq \eta_t \leq 0.933$ • Temperature increase: 36.7°C-67.5°C (vs. 92.1°C for adiabatic)
Weiqing *et al.* (2018)	Numerical	CAES	Investigated isothermal piston with porous medium for compression	• $0.7 \leq \eta_t \leq 0.95$ • Compression efficiency increases by 11% (1200RPM) and 28% (120RPM) at the compression ratio of 7
Ren *et al.* (2019)	Experimental	CAES	Investigated isothermal piston with porous medium for compression	• 12-17% reduced work • Heat transfer accounts for 92% of the work
Patil *et al.* (2020)	Experimental	CAES	Investigated spray injection to achieve near-isothermal compression in liquid piston	• $0.75 \leq \eta_t \leq 0.95$ • 25% work input reduction • r_p = 1-3.5
Dib *et al.* (2021)	Experimental	CAES / Power Generation	Investigated water injection and pistons with integrated heat exchangers in compression and expansion	• $0.6 \leq \eta_t \leq 0.7$ • n = 1-1.06 • r_p = 4

CAES is used across almost every industry, is reliable, and low-cost (He and Wang 2018), which justifies the research, however the vast majority of the literature on isothermal compression/expansion is dedicated to power generation, leaving a gap where such technologies may have great impact: heat pumps.

Kim *et al.* (2014) presented a comprehensive study on isothermal technology for power generation, but is one of the very few in the literature to mention heat pumps. Their brief analysis on heat pumps with isothermal compression/expansion was dedicated to the reversed Ericsson cycle. The Ericsson cycle has two isothermal processes and two isobaric processes, and while it theoretically yields higher efficiencies is still not the best possible cycle.

In this paper we present a theoretical analysis on a proposed Carnot-Equivalent Air Cycle (CAC) as a heat pump leveraging both isentropic and isothermal compression/expansion principles. We present a theoretical description of the system, a discussion on fundamentals and definitions, and finally a few analyses comparing the CAC against conventional reversed Brayton cycle (RBC) and VCC's with different refrigerants typically suitable for space cooling and heating. To the best of authors' knowledge, such cycle configuration has not yet been discussed in the literature.

2. MATERIALS AND METHODS

2.1 Reversed Brayton Cycle (RBC) vs. Carnot-Equivalent Air Cycle (CAC)

The ideal reversed Brayton cycle (RBC) (Figure 2a) consists of two isobaric processes and two isentropic processes (Figure 3) where the consumption and generation of work, although reversible, consist of changing both temperature and pressure simultaneously. This requires a following heat exchange process to reduce and increase the temperature after the compression and expansion processes, respectively. The isentropic (adiabatic) work is progressively limiting as the temperature changes; in the case of compression, the increase in temperature requires from the compressor greater work input, and the decrease in temperature limits the expander's potential to generate work. The higher the pressure and temperature lift/drop, the less efficient these systems will be.

Work and heat are thermodynamic path functions unlike enthalpy and entropy which are state functions; which means that the process between fixed points A and B will be more or less efficient depending on the route taken. In the RBC, the work and heat processes are decoupled, i.e., work first goes through an adiabatic process and then the heat is removed/added therefore the path is broken into two sub-paths (A'-B-C / D'-D-A in Figure 3a). A more efficient way would be having a single path connecting A and B, and to do that the heat and work processes must occur simultaneously. An ideal process for this configuration is the isothermal compression/expansion (A'-C/ D'-A in in Figure 3a).

A cycle composed of two strictly isothermal processes cannot work since there is no temperature change and therefore it has no use. The proposed cycle herein then consists in splitting the compression and expansion into isentropic followed by isothermal processes. As the working fluid is compressed adiabatically, the temperature will increase according to the pressure increase up until a certain point, then it is maintained while the pressure will continue to increase characterizing the isothermal compression. Analogously, the isentropic expansion will reduce the temperature down until an intermediate pressure, then maintained while the pressure decreases in the isothermal expansion. If the isentropic expansion brings the temperature back to the initial temperature then the cycle constitutes of a Carnot equivalent air cycle (CAC) (Figure 2b) since it has two isentropic processes, two isothermal processes and two temperature levels closing the cycle in only four processes (Figure 3).

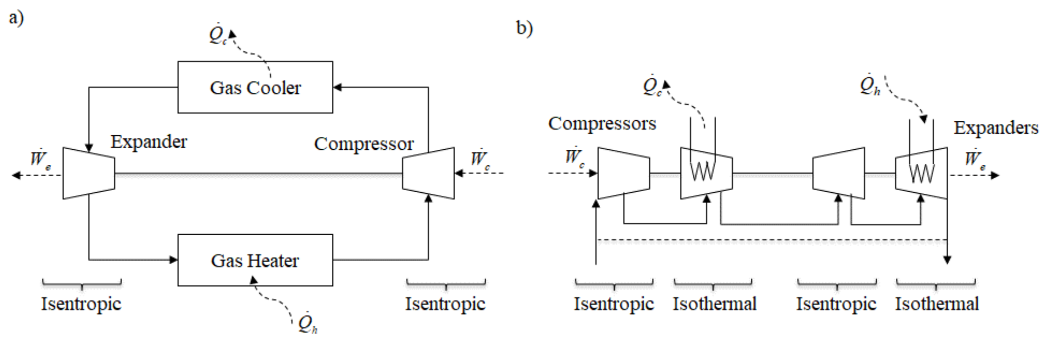

Figure 2: Air cycles: a) conventional reversed Brayton cycle; b) Carnot-equivalent air cycle.

The area between processes A'-B-C and A'-C in Figure 3, is the reduced compressor work between the RBC and CAC, and the area between D'-A and D'-D-A is the added generated work in the expander.
In practice, it will often be desirable to control the temperature levels according to the cooling and heating needs. Because the heat source will likely be at room temperature, whether you're using water or air as secondary fluid, the expander must bring the temperature sufficiently below that. On the compressor/heating side, the heat rejection will occur either to ambient air or water (water heating); the compressor must then elevate the temperature accordingly. In an open loop configuration, the intake air will be at a higher temperature than the exhaust air which will reduce the benefits from the ideal CAC, but would allow using the abundantly available ambient or room air, and the exhaust can be discharged indoors or outdoors depending on the mode of operation.

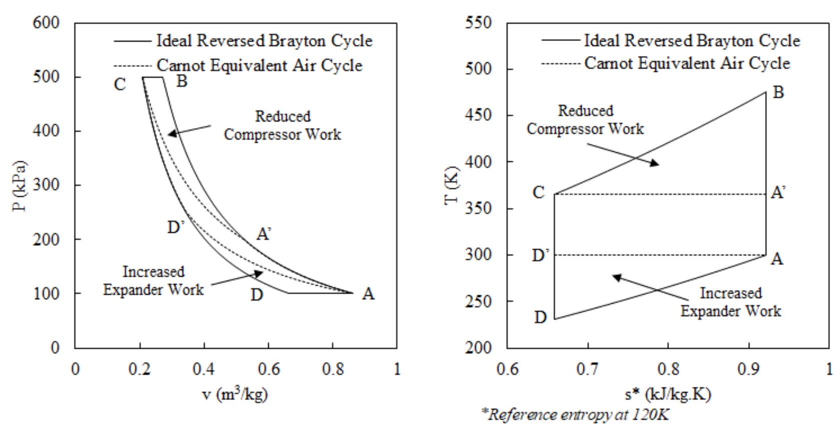

Figure 3: P-v and T-s diagrams for the ideal closed cycles.

2.2 Fundamentals and Definitions

2.2.1 Work

In closed systems, the compression/expansion work is defined as the product of pressure by the change in volume (eq. (1)) from A to B, which is analogous to a constant force applied to a body displaced by a length L. In open systems, when there are fluxes of mass crossing the boundaries of the control volume, one needs to consider the work caused by the displacement of the fluid in addition to the work consumed/generated by the system. In which case, it is convenient to use enthalpy instead of internal energy to express the fluid's change in thermal energy. The first law for open systems differs from closed systems in such way that the net-work consumed/generated is defined as the product of volume by the change in pressure.

For compression and expansion of the gases that are operating far in the superheated region and below critical pressure or temperature, we may use the polytropic process and Ideal Gas equation of state to determine the work of a fluid. A generic polytropic process is described in eq. (2), while the typical isentropic (adiabatic) work has an equivalent formulation, except the polytropic coefficient is equal to $k=c_p/c_v$. Finally, the isothermal work is a particular case when n=1, and its formulation differs from all other polytropic processes, as shown in eq. (3). The work is the area of the plots with respect to the y-axis in a pv-diagram; the isothermal has the smallest and the largest areas for compression and expansion, respectively (Figure 4). Another perspective is that for the same volume change, the isothermal requires smaller pressure ratio (r_p), therefore, less compressing power, and for same pressure ratio, it generates more power.

$$\delta q = du + \delta w_{cs} = du + pdv = dh - d(pv) + pdv = dh - vdp; \delta w_{os} = -vdp \tag{1}$$

$$w_{c,p} = -\int_A^B v \cdot dp = -\int_A^B \left(\frac{C}{p}\right)^{1/n} \cdot dp = p_A v_A \frac{n}{n-1}\left(\left(r_p\right)^{\frac{n-1}{n}} - 1\right); pv^n = C; n > 1 \tag{2}$$

$$w_t = -\int_A^B v \cdot dp = -\int_A^B \frac{C}{p} \cdot dp = RT \ln\left(r_p\right); pv = C; n = 1 \tag{3}$$

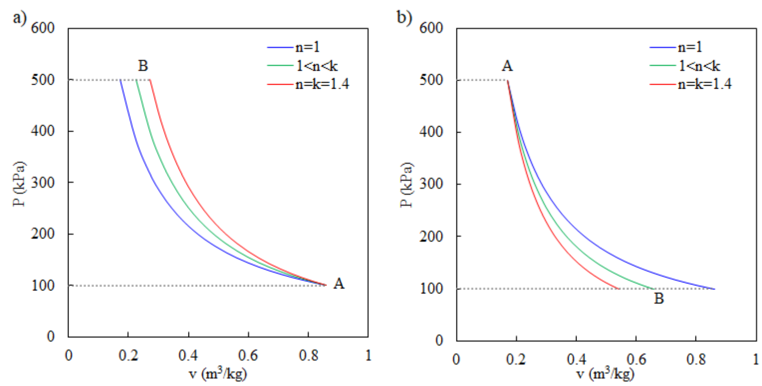

Figure 4: P-v diagrams: a) Compression; b) Expansion.

2.2.2 Efficiencies

The isentropic work is adiabatic, i.e., there is no heat transfer, and while the actual process may involve some heat loss/gain, it is much smaller in magnitude. The work may be directly extracted by the enthalpy difference between inlet and outlet, which for ideal gases may be simplified as the product of the specific heat and the temperature difference (eq. (4)).

In the case of the isothermal process, one has work and heat in the same order of magnitude occurring simultaneously. In the ideal isothermal process for ideal gases, there is no enthalpy difference between inlet and outlet, while the heat gain/rejected is the exact amount of work consumed/generated (eq. (4)). For non-ideal gases the working fluid discharge enthalpy will differ from the inlet, as such both the enthalpy and the heat transfer are accounted for. The heat transfer effectiveness will define how much work is consumed/generated, as well as the working fluid outlet state. The inefficiencies will be reflected in the enthalpy difference. The isothermal efficiency (eq. (5)) is then directly correlated to the isothermal compressor/expander overall heat conductance (UA), i.e., how effectively it can exchange heat.

$$q = \Delta h - w \rightarrow \begin{array}{l} q \approx 0; w \approx \Delta h \approx c_p \Delta T \\ \Delta h \approx 0; w \approx q = UA \cdot \Delta T \end{array} \tag{4}$$

$$\eta_{t,c} = \frac{w_{ideal}}{w_{actual}} = \frac{RT_A \ln\left(r_p\right)}{q - \Delta h}; \eta_{t,e} = \frac{w_{actual}}{w_{ideal}} = \frac{q - \Delta h}{RT_A \ln\left(r_p\right)} = \frac{UA \cdot \Delta T - \Delta h}{RT_A \ln\left(r_p\right)} \tag{5}$$

2.2.3 Pressure Ratio

An interesting characteristic of the ideal CAC is that the pressure lift is decoupled from the temperature lift – i.e., if the latter is kept constant, the pressure ratio has no impact on the system's COP. The pressure ratio will determine the entropy gap which will consequently define the total net power consumption and the heat load (Figure 5a).

3. THEORETICAL ANALYSES

In this section we present a set of theoretical thermodynamic analyses to evaluate the feasibility of the CAC cycle, its sensitivity to certain parameters – especially the isentropic and isothermal efficiencies – and how it compares to conventional reversed Brayton cycle and Vapor Compression Cycles. In the following analyses, all cycles are assumed to have the working fluid at 10ºC at the compressor suction, and 45ºC at the expander/expansion device suction, as such the Carnot efficiency is a single reference to all analyses. Pressure drop and heat losses are neglected, and for the saturated subcritical cycles, the superheat and subcooling are assumed to be zero. For simplicity, all analyses will consider the cooling COP only, while the heating COP can be inferred by analogy. Finally, the total pressure ratio for the CAC was fixed in 5 while the isentropic pressure ratio was adjusted accordingly to meet the abovementioned saturation temperatures.

3.1 Reversed Brayton Cycle vs. Carnot-Equivalent Air Cycle

The first important conclusion from this comparison, is that the CAC cycle is considerably more sensitive to the isothermal than the isentropic efficiency. The rate of COP degradation with respect to isothermal efficiency is an order of magnitude greater than it is with respect to isentropic efficiency, as illustrated in Figure 5b. The isentropic efficiency imposes a lower penalty on the CAC because the isentropic work occurs at a smaller pressure ratio compared to the RBC. The second conclusion of this analysis is that the CAC is demonstrably more efficient than RBC, independent of the compression and expansion efficiencies. In the ideal case, the CAC COP approaches the Carnot efficiency and is approximately 5 times greater than the RBC. Physically, that occurs since the CAC essentially eliminates the greatest irreversibility contributor in RBC – the "the superheat horn" (Qian, et al. 2016).

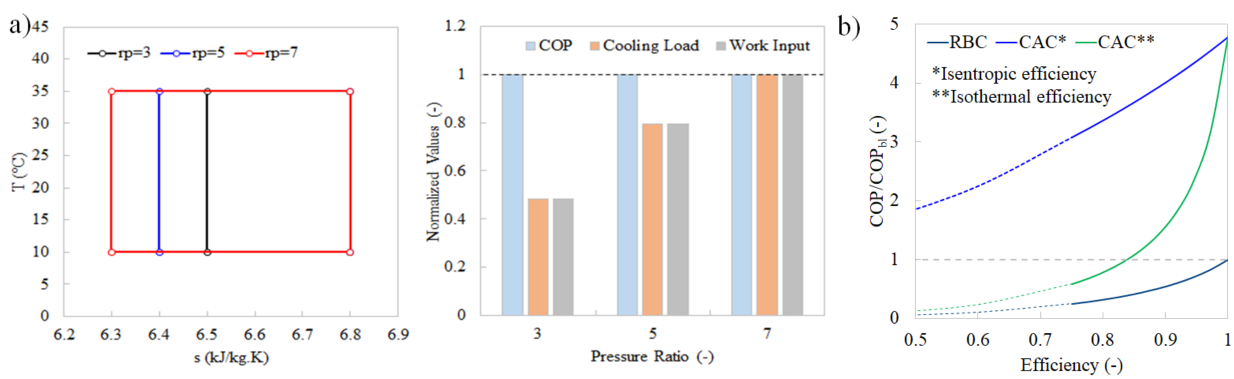

Figure 5: a) CAC pressure ratio analysis; b) RBC vs. CAC sensitivity to compression/expansion efficiencies.

3.2 VCC vs. CAC

In this analysis, the CAC is compared against VCC's using R410A, R454B, R1234yf and Propane as refrigerants. Even though the CAC has greater pressure ratio compared to the VCC cycles, the "superheat horn" is minimized since the isentropic processes occur at a reduced pressure ratio, while most of the work is done isothermally (Figure 6).

The CAC has a much faster COP degradation, particularly with respect to the isothermal efficiency, however, it can theoretically achieve the Carnot COP while conventional VCC's will, at best, fall short by at least 30% (Figure 7a). The irreversibility associated with "superheat horn" and expansion losses in VCC's are of the order of 10-20% each (Qian *et al.* 2016), which is consistent with the values found in this work since no other irreversibility sources were accounted for. If an isothermal efficiency of nearly 100% can be achieved, that means the CAC would always outperform any VCC (Figure 7b).

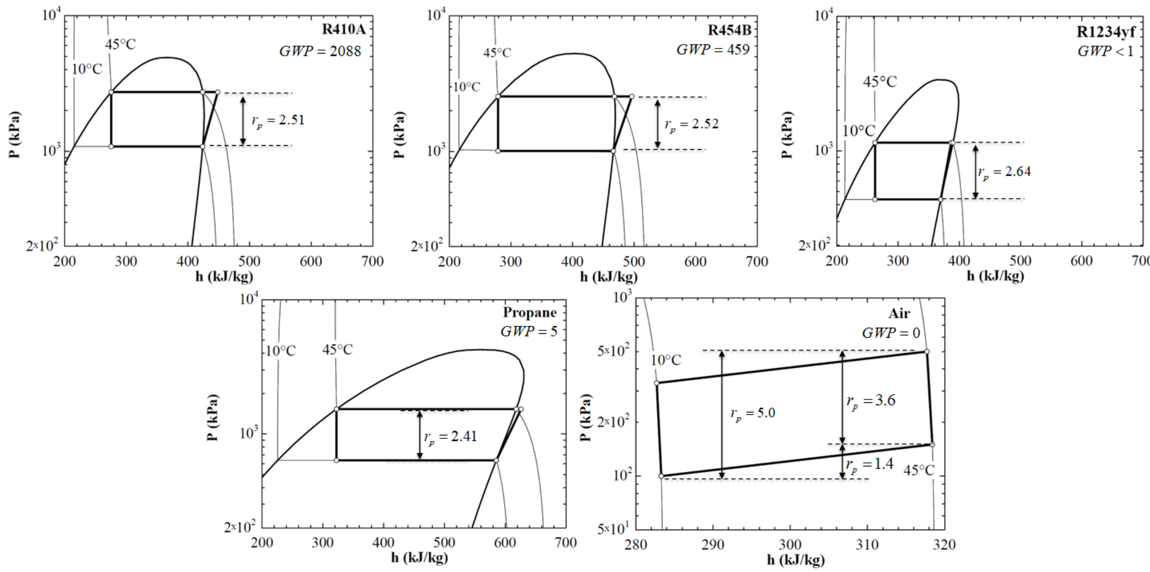

Figure 6: P-h diagrams for ideal cycles (100% isentropic/isothermal efficiencies).

Although such high isothermal efficiencies can be a challenge to achieve, researchers have reported values greater than 0.9 as shown in Table 2. Another challenge for CAC, is the compressor/expander sizes. Since it operates at much lower pressures (near atmospheric), for similar mass flow rates (MFR), the CAC will have an order of magnitude greater volumetric flow rates (VFR) than the refrigerant counterparts (Figure 7a).

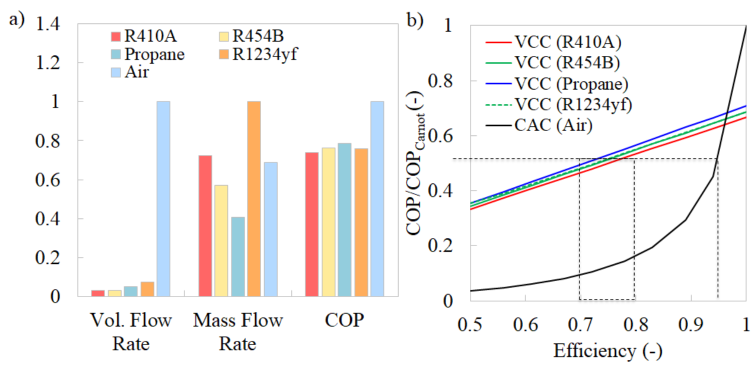

Figure 7: CAC vs. VCC: a) Normalized refrigerant flow rate and COP for same capacity and 100% work efficiency; b) COP as function of work efficiency.

4. CONCLUSIONS

In this paper, we proposed leveraging the increasingly improved isothermal technology to both compression and expansion in an air cycle. Combining the isentropic and isothermal processes we theoretically achieve the ideal Carnot efficiency. The literature on air cycles has explored many configurations of the reversed Brayton cycle, but they still fall short on COP, and are suitable to narrow applications. The herein proposed configuration can be applied to any heat pump application with potential to outperform any subcritical vapor compression cycle with virtually no global warming potential. The air cycle may be configured in closed or open loops; with the latter, the working fluid may be the conditioning air itself or the outdoor air which may address ventilation concerns that have become a critical issue during the COVID-19 Pandemic. The most important take away lessons from this study are:

- Isothermal compression/expansion are better than conventional isentropic counterparts, since the heat rejection/gain and work occur simultaneously, minimizing the superheat "horns".
- The isothermal efficiency is a function of how effective the heat transfer is, i.e., the overall heat

transfer conductance UA.

- The CAC temperature lift is decoupled from the pressure lift – the latter determines the system size (capacity and power), while the former determines the system's efficiency (i.e., COP).
- The CAC COP is more sensitive to the isothermal efficiency rather than the isentropic efficiency.
- The CAC outperforms a conventional RBC regardless of the compression/expansion efficiencies. The isentropic efficiency imposes a lower penalty on the CAC because the isentropic work occurs at a smaller pressure ratio compared to the RBC. In the ideal case, the CAC COP is approximately 5 times greater than the RBC.
- The isothermal compression needs to be at least 90% in order for the system to become truly competitive against conventional VCC, however many researchers have consistently reported isothermal efficiencies comfortably greater than 90%, which makes the proposed approach viable and promising.
- In addition to the isothermal efficiency challenge, the volumetric flow rates for the same capacity are an order of magnitude larger for CAC compared to VCC, which will result in larger compressors/expanders.

NOMENCLATURE

A,B,C,D	State points	-
C	Generic constant	-
CAC	Carnot-Equivalent Air Cycle	-
COP	Coefficient of Performance	-
c_p	Specific heat	kJ/kg.K
h	Specific enthalpy	kJ/kg
k	Isentropic coefficient	-
n	Polytropic coefficient	-
P	Pressure	kPa
q	Heat	kJ/kg
Q	Heat transfer rate	W
R	Ideal-gas constant	kJ/kg.K
RBC	Reversed Brayton Cycle	-
r_p	Pressure ratio	-
s	Specific entropy	kJ/kg.K
T	Temperature	K or °C
v	Specific volume	m³/kg
VCC	Vapor Compression Cycle	-
w	Work	kJ/kg
W	Power	W

Greek Letters

η	Efficiency	-
θ	Temperature ratio (compression)	-
ξ	Temperature ratio (expansion)	-

Subscripts

p	Polytropic	-
s	Isentropic	-
t	Isothermal	-

REFERENCES

Bell, Ian H., Vincent Lemort, Eckhard A. Groll, James E. Braun, and Galen B. King. 2012. "Liquid-flooded compression and expansion in scroll machines e Part I: Model development." *International Journal of Refrigeration* 35: 1878-1889.

Carnot Compression. n.d. Carnot Compression. Accessed June 24, 2021. https://carnotcompression.com/.

Cherry, Mark A., Robert A. Alderman, and Hans Shillinger. 2015. CENTRIFUGAL GAS COMPRESSOR METHOD AND SYSTEM. United States of America Patent US 20150023807 A1. January 22.

Coney, M. W., P. Stephenson, A. Malmgren, C. Linnemann, R. E. Morgan, R. A. Richards, R. Huxley, and H. Abdallah. 2002. "Development Of A Reciprocating Compressor Using Water Injection To Achieve Quasi-Isothermal Compression." *International Compressor Engineering Conference.* West Lafayette, IN.

Dib, Ghady, Philippe Haberschill, Romuald Rulliere, and Remi Revellin. 2021. "Thermodynamic investigation of quasi-isothermal air compression/expansion for energy storage." *Energy Conversion and Management* 235.

Fleming, J. S., L. Li, and B. J. C. Van der Wekken. 1998. "Air Cycle Cooling and Heating Part II: A Mathematical Model For The Transient." *International Journal of Energy Research* 22: 463-476.

Goetzler, Bill, Matt Guernsey, and Theo Kassuga. 2019. *Grid-interactive Efficient Buildings Technical Report Series.* U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy.

Guanwei, Jia, Xu Weiqing, Cai Maolin, and Shi Yan. 2018. "Micron-sized water spray-cooled quasi-isothermal compression for compressed air energy storage." *Experimental Thermal and Fluid Science* 96: 470-481.

He, Wei, and Jihong Wang. 2018. "Optimal selection of air expansion machine in Compressed Air Energy Storage: A review." *Renewable and Sustainable Energy Reviews* 87: 77-95.

Hou, Shaobo, and Hefei Zhang. 2009. "An open reversed Brayton cycle with regeneration using moist air for deep freeze cooled by circulating water." *International Journal of Thermal Sciences* 48: 218-223.

Hou, Y., H.L. Zhao, C.Z. Chen, and L.Y. Xiong. 2006. "Developments in reverse Brayton cycle cryocooler in China." *Cryogenics* 46: 403-407.

Igobo, Opubo N., and Philip A. Davies. 2014. "Review of low-temperature vapour power cycle engines with quasi-isothermal expansion." *Energy* 70: 22-34.

J. Park, P. I. Ro, S. D. Lim, A. P. Mazzoleni, and B. Quinlan. 2012. "Analysis and optimization of a quasi-isothermal compression and expansion cycle for ocean compressed air energy storage (OCAES)." *Oceans* 1-8.

Kim, Woohyun, and James E. Braun. 2010. "Impacts of Refrigerant Charge on Air Conditioner and Heat Pump Performance." *International Refrigeration and Air Conditioning Conference at Purdue, July 10-15, 2010.* West Lafayette, IN.

Kim, Y. M., D. K. Shin, and J. H. Lee. 2014. "A Scroll Expander With Heating Structure and Their Systems." *International Compressor Engineering Conference at Purdue, July 12-15.* West Lafayette, IN.

Li, Shuangshuang, Shugang Wang, Zhenjun Ma, Shuang Jiang, and Tengfei Zhang. 2017. "Using an air cycle heat pump system with a turbocharger to supply heating for full electric vehicles." *International Journal of Refrigeration* 77: 11-19.

Nobrega, C.E.L., and L.A. Sphaier. 2013. "Desiccant-assisted humidity control for air refrigeration cycles." *International Journal of Refrigeration* 36: 1183-1190.

Patil, Vikram C., Pinaki Acharya, and Paul I. Ro. 2020. "Experimental investigation of water spray injection in liquid piston for near-isothermal compression." *Applied Energy* 259.

Qian, Suxin, Dennis Nasuta, Adam Rhoads, Yi Wang, Yunlong Geng, Yunho Hwang, Reinhard Radermacher, and Ichiro Takeuchi. 2016. "Not-in-kind cooling technologies: A quantitative comparison of refrigerants and system performance." *International Journal of Refrigeration* 62: 177-192.

Qin, Chao, and Eric Loth. 2014. "Liquid piston compression efficiency with droplet heat transfer." *Applied Energy* 114: 539-550.

Ren, Teng, Weiqing Xu, Maolin Cai, Xiaoshuang Wang, and Minghan Li. 2019. "Experiments on Air Compression with an Isothermal Piston for Energy Storage." *Energies* 12.

Spence, Stephen W.T., W. John Doran, and David W. Artt. 2004. "Design, construction and testing of an air-cycle refrigeration system for road transport." *International Journal of Refrigeration* 27: 503-510.

Spence, Stephen W.T., W. John Doran, David W. Artt, and G. McCullough. 2005. "Performance analysis of a feasible air-cycle refrigeration system for road transport." *International Journal of Refrigeration* 381-388: 28.

Thomas, T.F. 1948. "The Air Cycle Heat Pump." *Proceedings of the Institution of Mechanical Engineers* 30-51.

Weiqing, Xu, Du Ziyue, Wang Xiaoshuang, Cai Maolin, Jia Guanwei, and Shi Yan. 2020. "Isothermal piston gas compression for compressed air energy storage." *International Journal of Heat and Mass Transfer* 155.

Yang, Liang, Han Yuan, Jing-Wei Peng, and Chun-Lu Zhang. 2016. "Performance modeling of air cycle heat pump water heater in cold climate." *Renewable Energy* 87: 1067-1075.

Zhang, Chun-Lu, Han Yuan, and Xiang Cao. 2015. "New insight into regenerated air heat pump cycle." *Energy* 91: 226-234.

Zhang, Xinjing, Yujie Xu, Xuezhi Zhou, Yi Zhang, Wen Li, Zhitao Zuo, Huan Guo, Ye Huang, and Haisheng Chen. 2017. "Numerical Study of a Quasi-isothermal Expander by Spraying Water." *Energy Procedia* 142: 3388-3393.

Zhang, Zhenying, Shengjun Liu, and Lili Tian. 2011. "Thermodynamic analysis of air cycle refrigeration system for Chinese train air conditioning." *Systems Engineering Procedia* 1: 16-22.

ACKNOWLEDGEMENT

This work was funded by the Modeling and Optimization Consortium within the Center for Environmental Energy Engineering at the University of Maryland.