INL/CON-18-45753-Revision-0

EVALUATION OF ORGANIC RANKINE CYCLES IN AN AIR-BRAYTON COMBINED CYCLE FOR MICROREACTOR APPLICATIONS

Joseph Litrel, Donna Guillen, Michael McKellar

November 2018

INL/CON-18-45753-Revision-0

EVALUATION OF ORGANIC RANKINE CYCLES IN AN AIR-BRAYTON COMBINED CYCLE FOR MICROREACTOR APPLICATIONS

Joseph Litrel, Donna Guillen, Michael McKellar

November 2018

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

EVALUATION OF ORGANIC RANKINE CYCLES IN AN AIR-BRAYTON COMBINED CYCLE FOR MICROREACTOR APPLICATIONS

Joseph Litrel and Donna Post Guillen
Idaho National Laboratory
1955 Fremont Avenue, Idaho Falls, ID 83415
Joseph.Litrel@inl.gov, Donna.Guillen@inl.gov

Michael McKellar
University of Idaho - Idaho Falls
1776 Science Center Drive, Idaho Falls, ID 83402
mmckellar@uidaho.edu

ABSTRACT

Microreactors can be used to provide electrical power up to 10 MWe for emergency situations, remote areas, or military applications. Combined cycles comprised of an air Brayton topping cycle and an Organic Rankine bottoming cycle were evaluated in HYSYS using different working fluids in the bottoming cycle and in different ambient environments. The results indicate that a bottoming ORC can increase the thermal efficiency of the air Brayton cycle from 35.8 % up to 40.2 %. Exergy analysis was also performed on the combined cycle along with a simple validation of HYSYS on the bottoming cycle. The exergy analysis shows that of available work, most is lost at the reactor or turned into work at the topping cycle. A rudimentary capital cost estimate shows that the addition of a bottoming cycle is not prohibitively expensive.

KEYWORDS
Microreactor, Combined Cycle, Nuclear Reactor, Organic Rankine Cycle, Mobile Power

1. INTRODUCTION

Recently, research has been conducted into miniature nuclear reactors (or microreactors) as a means of providing energy to grid isolated areas at the behest of the Department of Energy (DOE) and the Department of Defense (DOD) [1]. Microreactors, also known as very Small Modular Reactors (vSMR), have been identified as a potential means to provide for power demands between 1 and 10 MWe for special purpose applications. Examples include, but are not limited to, military forward operating bases, military monitoring stations, rural public communities, and mining operations [1]. Microreactors are being considered to provide energy resilience to mission-critical functions at critical national security infrastructure [2].

Many of these grid isolated installations are reliant on fossil fuels for power generation, often relying upon natural gas or diesel generators. This method of power generation incurs a large cost from not only the fuel consumption but also from the cost of fuel transport. Furthermore, the ability to transport fuel to an isolated area is dependent on many factors, causing concern for the reliability of this method of power generation.

There are myriad situations where a microreactor would be beneficial. A microreactor providing 2 MWe could supply electrical needs for approximately 1550 households, or 6000 people during emergency situations. A microreactor could also provide process heat for district heating or chemical processing. The Defense Science Board, under the DOD, has identified a reactor design that could potentially fulfill DOD needs for small power sources, a Los Alamos National Laboratory design called the Special Purpose

Nuclear Reactor [1]. Additionally, various microreactor designs are underway by industry, including Oklo, Elysium, MicroNuclear, Westinghouse, and NuScale. Furthermore, many companies, including Oklo, Elysium, MicroNuclear, and NuScale from the aforementioned list, have received small business vouchers from the Gateway for Accelerated Innovation in Nuclear (GAIN) Initiative to help the design and development of microreactors [3].

1.1 Power Cycles for Microreactors

Evaluation of power cycles in this paper is based on the Special Purpose Nuclear Reactor (SPR). The SPR is a low-enriched Uranium (19.75%) design that can supply 5 MWth (~2 MWe). Potassium heat pipes operate at 675 °C. The heat pipes outside of the core are cooled by forced air convection in order to operate a recuperated open air Brayton Cycle.

The recuperated air Brayton cycle exhausts air at approximately 140° C while the unrecuperated version exhausts air at approximately 280 °C. In less permanent configurations, the recuperated air Brayton cycle shows a large advantage in its ability to operate without water. It can directly reject heat without the need for a condenser, saving cost and complexity [1]. The proposed power conversion cycles for microreactors should have the ability to operate in various climate extremes, such as (1) Temperate, (2) Hot Desert, (3) Cold Coastal, and (4) Tropical Rainforest.

1.2 Open Air Brayton Cycle

An open air Brayton cycle is comprised of an air inlet, a compressor, a heating chamber, a turbine, an electrical generator, and an exhaust, as shown in Fig. 1. HP stands for high pressure.

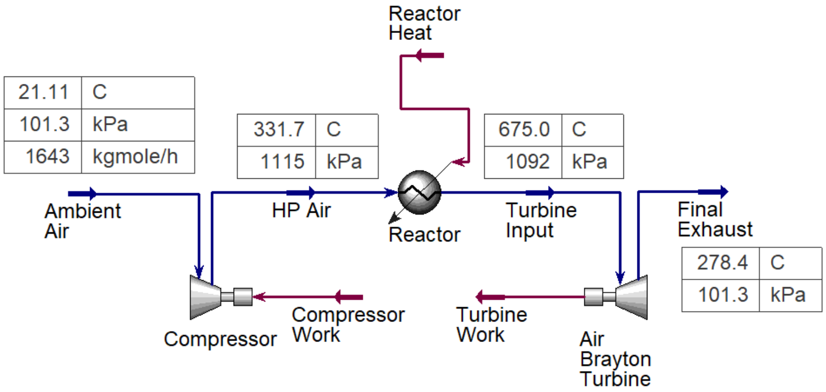

Figure 1. Open air Brayton cycle

In an open air Brayton cycle, ambient air is taken into the system after it has been filtered of particulates and other debris that may damage the system. The air is then compressed before it is sent to a heating chamber [4]. In natural gas plants, this would be a combustion chamber, whereas in our case, air is forcefully convected over the heat pipes that are connected to the core of the reactor. After the air is heated, it is expanded through a turbine which turns the shaft of an electrical generator. The exhaust of the system exits the turbine and is returned to the environment. By returning exhaust into the ambient, one can use Earth’s atmosphere as a near infinite heat sink. This eliminates all needs of cooling water for waste heat rejection.

1.3 Recuperated Air Brayton Cycle

The power cycle associated with the current iteration of the SPR is a recuperated air Brayton cycle. In this configuration, the exhaust is diverted from the exit of the turbine to a heat exchanger between the compressor and heating chamber. A recuperated air Brayton cycle outperforms an unrecuperated cycle. [1]

By recuperating the waste heat, the compressor work and the waste heat rejection both decrease. This cycle rejects its heat to the ambient air and does not require cooling water for waste heat rejection. The process diagram is shown in Fig. 2.

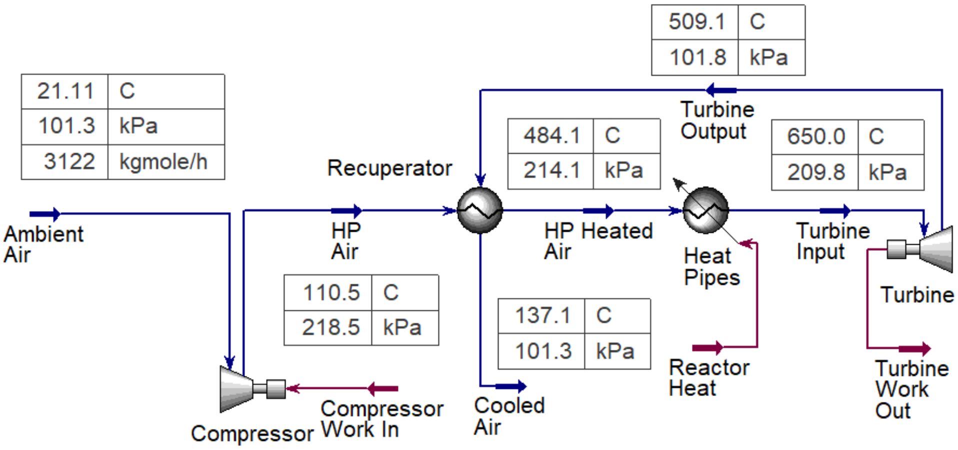

Figure 2. Recuperated air Brayton cycle

1.4 Air Brayton Combined Cycle

In many commercial power generation plants, especially those using natural gas, the power generation method of choice is the Air Brayton Combined Cycle (ABCC). In the ABCC, the heat source is provided by natural gas combustion, is used to run the topping cycle which is an open air Brayton cycle. The waste heat of the air Brayton cycle is then used by the bottoming cycle. The hot exhaust from the air Brayton cycle is passed through a Heat Recovery Steam Generator (HRSG) before it is passed to the environment. The HRSG functions as the boiler in the closed loop system that functions as the bottoming cycle for waste heat to power generation.

There are two main reasons to use an ABCC. The first is that combined cycles achieve the highest efficiency η for conversion of heat into electricity, as given by the following equations [5]

$$air\ Brayton\ Cycle\ Efficiency = \frac{W_{AB}}{Q_{in}} = \eta_{AB} \tag{1}$$

$$Heat\ to\ Rankine\ Cycle = (1-\eta_{AB})Q_{in} = Q_R \tag{2}$$

$$Rankine\ Cycle\ Efficiency = \frac{W_R}{Q_R} = \eta_R \tag{3}$$

$$Overall\ Efficiency = \frac{W_{AB}+W_R}{Q_{in}} = \frac{\eta_{AB}Q_{\ in}+\eta_R(1-\eta_{AB})Q_{in}}{Q_{in}} \tag{4}$$

$$Overall\ Efficiency = \eta_{AB} + \eta_R - \eta_{AB}\eta_R = \eta_T \tag{5}$$

Using the Carnot cycle efficiency equation from [6], an ideal combined cycle efficiency can be calculated.

$$\eta_{Carnot} = \frac{T_H - T_C}{T_H} \tag{6}$$

$$\eta_{AB} = \frac{923-413}{923} = 55.25\% \tag{7}$$

$$\eta_R = \frac{413-294}{413} = 28.81\% \tag{8}$$

$$\eta_{CC} = 0.5525 + 0.2281 - 0.5525 * 0.2281 = 65.46\% \tag{9}$$

where W is work, Q is heat, and T is temperature. The combined cycle concept is illustrated in Fig. 3.

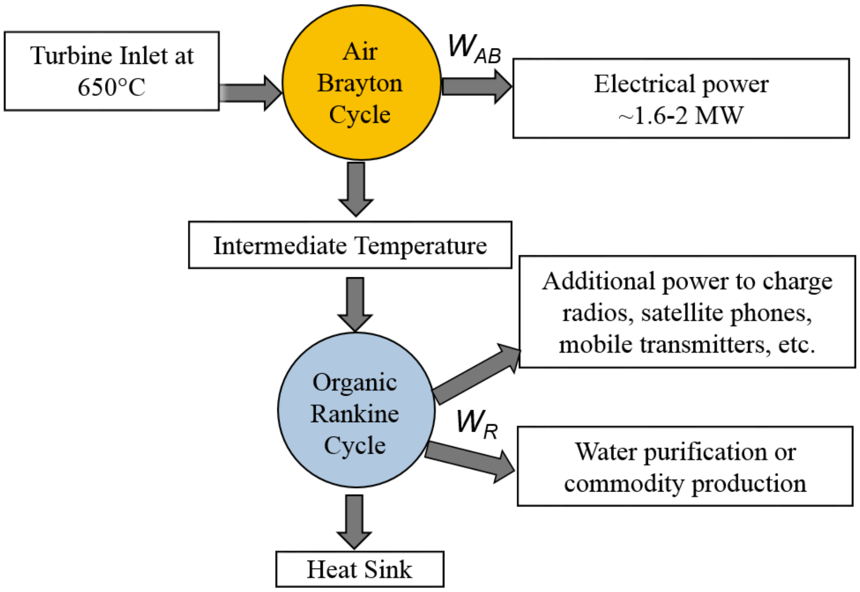

Figure 3. Heat flow in the microreactor combined cycle power conversion system

The second main reason is that the combined cycle requires a minimal amount of cooling water since much of the waste heat is rejected to the air [7].

In the combined cycle we will be evaluating, a recuperated air Brayton cycle is the topping cycle and an Organic Rankine Cycle (ORC) the bottoming cycle. Waste heat recovery would occur at the recuperative exhaust temperatures, or about 140°C. The HYSYS schematic is shown in Fig. 4.

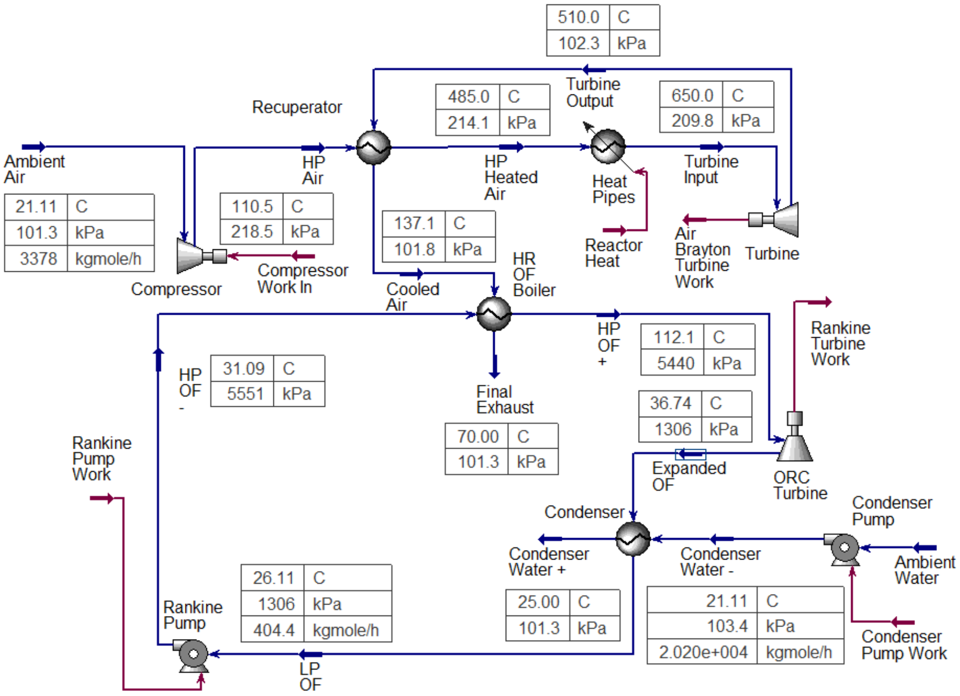

Figure 4. Process model of air Brayton cycle coupled to ORC bottoming cycle.

Because the recuperated air Brayton cycle exhausts at low temperatures, the Rankine operates at low temperatures as well. This requires the use of a different working fluid rather than water. The organic fluids used in an ORC have lower boiling temperature than water does, allowing their use in a two phase power cycle at lower temperatures [8].

By implementing the recuperative air Brayton cycle in the ABCC, energy gained from the ORC would improve overall efficiency. A combined cycle using an unrecuperated air Brayton cycle would have to meet the efficiency of standalone recuperated air Brayton cycle first before it started to show improvements in power conversion efficiency.

As an added benefit, the organic fluids commonly used in ORCs also have a lower freezing temperature than water, which may be of benefit for a remote installation in military bases or communities in places such as Alaska.

1.5 Organic Rankine Cycles

1.5.1 General operating and design guidelines

A Rankine cycle is a closed cycle system with a pump, a boiler, a turbine, and a condenser. In a Rankine Cycle, the fluid is coldest at the low pressure side of the pump. It moves through the pump, going to high pressure. At high pressure, the fluid is moved to the boiler where it is heated to a saturated vapor. Then, the vapor is diverted through a turbine where it is expanded to low pressure. The resultant vapor is then condensed into a saturated liquid, where it is then sent to the pump to close the cycle.

Zhang et al. [9] found that the thermal efficiency, exergy efficiency and power generation of the steam Rankine cycle for 150-350°C waste heat is lower than when compared to an organic working fluid. Although the steam Rankine cycles are commonly used for power conversion, they are not efficient for low temperature waste heat recovery.

It has been shown that the total efficiency of the system can be estimated using equation 4. Equation 4 is built on the assumption that all waste heat from the air Brayton cycle is transferred to the ORC, which is an unrealistic assumption. However, that fact, coupled with equation 10,

$$\frac{\partial \eta_T}{\partial \eta_B} = 1 - \eta_R \tag{10}$$

justify the decision to design the ORC around the waste heat of the recuperated air Brayton cycle instead of the unrecuperated cycle since the expected efficiency of the ORC is low. The efficiency of the ORC is not expected to surpass the efficiency of the air Brayton cycle because the ORC will operate at lower temperatures. It will also operate with less heat than the air Brayton cycle rejects. This means that mathematically speaking, highest efficiency will be most likely achieved with the recuperated air Brayton cycle, even if it sacrifices some of the efficiency of the ORC.

ORCs pose several advantages over Steam Rankine Cycles for waste heat recovery [10]:

1. Evaporation takes place at lower temperatures and pressures
2. Condensation takes place at higher than atmosphere pressures, avoiding air intake
3. Smaller temperature changes between evaporation and condensation allow single stage turbines

The ability to extract heat at low temperatures and above atmospheric pressures are very beneficial for microreactors. A microreactor with a recuperative air Brayton cycle exhausts at approximately 140° C and is designed to have a small footprint. The ability of ORCs to work at low temperatures means that there is an efficiency gain with minimal changes to the existing system by attaching a waste heat to electricity bottoming cycle. The operation of an ORC at above atmospheric pressure also entails a smaller footprint for condenser and associated components. This fact, along with no need for multiple staged turbines, ensures that the footprint of the overall system can be kept minimal.

ORC efficiencies are increased with increases in turbine inlet temperatures and decreases in condenser temperatures [11]. However, in our study, both of these vary only with the performance of the heat exchangers and the ambient conditions. Thus, these parameters can be set aside when considering the optimization of the bottoming ORC.

1.5.2 Fluid selection

Compared to water as a working fluid, organic fluids can pose significant advantages and operate without the disadvantages of water. Several problems exist when operating water in a Rankine cycle [12]:

1. Superheat is necessary to avoid condensation in the turbines
2. Risk of turbine blade erosion
3. High pressure in the boiler
4. Complex and expensive turbines

Some of the advantages provided by organic fluids include [13]:

1. Most organic fluids exist as a gas above condenser temperature after turbine exit
2. Organic fluids have higher cycle efficiencies than water at low temperatures

Several characteristics are considered when selecting a working fluid. For the microreactor application, the fluid should have fluid stability [14], minimal autoignition potential [15], low freezing point, low toxicity, and good material compatibility [16]. One should also consider the saturation vapor curve of the chosen fluid during the expansion process [17] (see Fig. 5). There are three types of fluids: wet, dry, and isentropic. Wet fluids have a negative slope, dry fluids have a positive slope, and isentropic fluids have an infinite slope. Dry and isentropic fluids have better thermal efficiencies than wet fluids because they do not condense through the turbine. Dry and isentropic fluids also eliminate concern over erosion or wear in the turbine due to condensate.

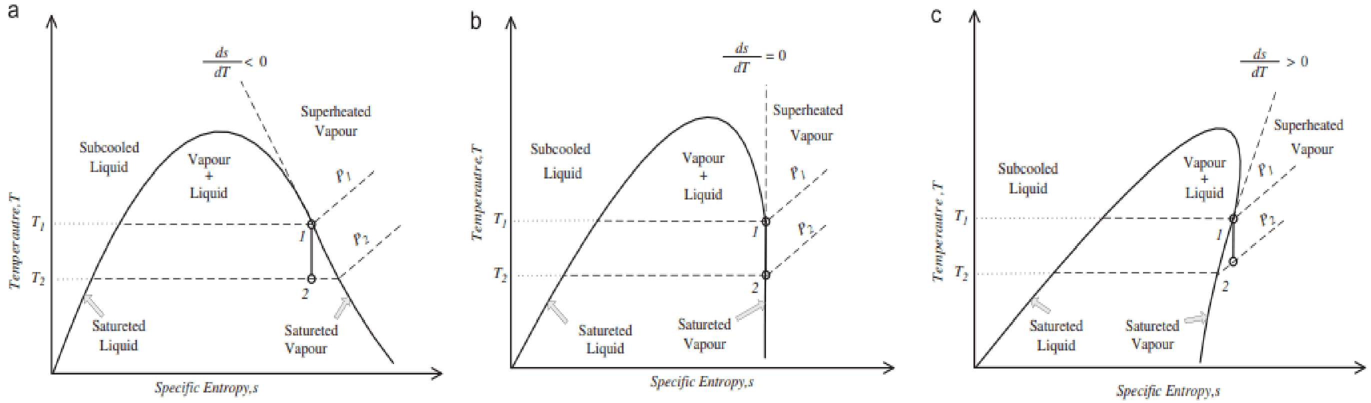

Figure 5. From [12] a) Wet Fluid, b) Isentropic Fluid, c) Dry Fluid

Furthermore, fluids should have low critical temperature and pressure, low viscosity, and high thermal conductivity [18]. Fluids of consideration should also be safe for the environment with little to no Ozone Depletion Potential and low Global Warming Potential due to phase-outs regulated in the Montreal protocol [6]. Highest thermal efficiencies are achieved with high boiling point fluids, but more heat can be transferred to fluids operating supercritically [19]. Refrigerants often make good candidates based on physical and toxicity characteristics [20].

With the previous paragraph in mind, the following organic fluids were taken into consideration:

- r134a
- r141b
- r143a
- r124a
- r21

Additional fluids were also taken into consideration, with the caveat that these fluids are explosive under certain conditions:

- R600 (butane)
- R600a (iso-butane)
- R601 (pentane)
- R601a (iso-pentane)
- Propane

Also of note, is that ammonia and CO_2 are evaluated in some cases due to their past and proposed use in Rankine or refrigeration cycles.

1.6 Effects of Environment

Along with an investigation into the net benefits of attaching a bottoming cycle to the air Brayton cycle, investigations will be made into the effects of temperature and humidity on the air Brayton cycle. These effects will obviously propagate into the ORC. The study of the effects of the ambient environment on the performance was conducted with three extreme environments compared to a temperate environment:

- Temperate: 21.11 °C + 50% Relative Humidity
- Hot Desert: 37.78 °C + 10% Relative Humidity
- Cold Coastal: -6.67 °C + 65% Relative Humidity
- Tropical Rainforest: 28.44 °C + 85% Relative Humidity

1.7 Exergy Analysis

According to Abdollahi-Demneha et al. in [21], exergy B can be calculated using the following equation in the absence of nuclear, magnetic, electrical, and surface tension effects.

$$B = B_{phys} + B_{chem} + B_{kinetic} + B_{potential} \tag{11}$$

In this study, we will only be considering physical exergy since no chemical reactions will be taking place, and the kinetic and potential effects are comparatively negligible in comparison to physical exergy. Physical Exergy can be calculated with the following equation

$$B_{phys} = (h - h_0) - T_0(s - s_o) \tag{12}$$

where h is enthalpy and s is entropy. The subscript *0* corresponds to the value for the initial state of the working fluid.

1.8 Assumptions

The assumptions used in the analysis of the recuperated air Brayton cycle are as follows:

1. Turbines operate at 90% efficiency
2. Pressure drops across heat exchangers are 2% of inlet pressures
3. Turbine inlet temperature is 650° C
4. Temperature minimum approach in the recuperative heat exchanger is 25° C
5. Temperature minimum approach in the waste heat exchanger is 25° C
6. Pumps and Compressors operate at 80% efficiency
7. Air pressure at the inlet and exit is 1 atm

2. RESULTS

2.1 Temperate Environment Combined Cycle

Starting with the recuperated air Brayton cycle, a waste heat recovery ORC was added as a bottoming cycle. Its HYSYS model is shown in Fig. 6. For purposes of modularity, the air Brayton cycle is not changed past its optimized conditions for a recuperated system in a temperate environment with no bottoming cycle attached.

This model, being a test case, is run at temperate conditions of 21.11°C and 50% relative humidity. It is assumed that a steady supply of water is available for cooling in the condenser. This case was used to test efficiencies of various organic fluids and refrigerants to determine an ideal working fluid for the ORC. Since it would be ideal to have a working fluid that works at warmer and colder ambient temperatures, we expect the best performing fluid at temperate conditions to meet this criterion. The efficiency of the recuperated air Brayton cycle is 35.77%. Table I lists the combined cycle efficiencies with the recuperated air Brayton as a topping cycle and various fluids in an ORC bottoming cycle.

Table I. Combined Cycle Efficiencies in a Temperate Environment.

Refrigerant	Total Efficiency
r134a	39.18%
r141b	38.74%
n-butane	38.70%
i-butane	38.79%
n-pentane	38.62%
i-pentane	38.66%
r143a	40.22%
r124a	38.66%
propane	39.28%
r21	39.77%
ammonia	38.48%

2.2 Combined Cycle Performance in Different Environments

At this point, the effects of the ambient conditions were examined, such as temperature and humidity, on the performance of the ABCC. For each environment, several different refrigerants were evaluated, including r143a, propane, and ammonia. This selection was based on prior history of their usage as refrigerants and expected performance in the selected temperature range.

An evaporative cooler was added to the system to more accurately reflect the effects of ambient temperature and humidity on the operation of the combined cycle, since it is expected that the microreactor will be operated in remote areas that may not have access to large amounts of cooling water. In this evaporative cooler process model, ambient water used for makeup is unrealistically at or above air temperature to conservatively estimate the power necessary for cooling.

An evaporative cooler would vastly decrease the amount of water needed to cool the ORC compared to using water at ambient temperature alone, and would vastly decrease the energy required to cool the ORC if an air cooler was used, so its use was implemented into these tests. The process model of the evaporative cooler is shown in Fig. 7. The amount of work necessary to run the evaporative cooler is found using [22].

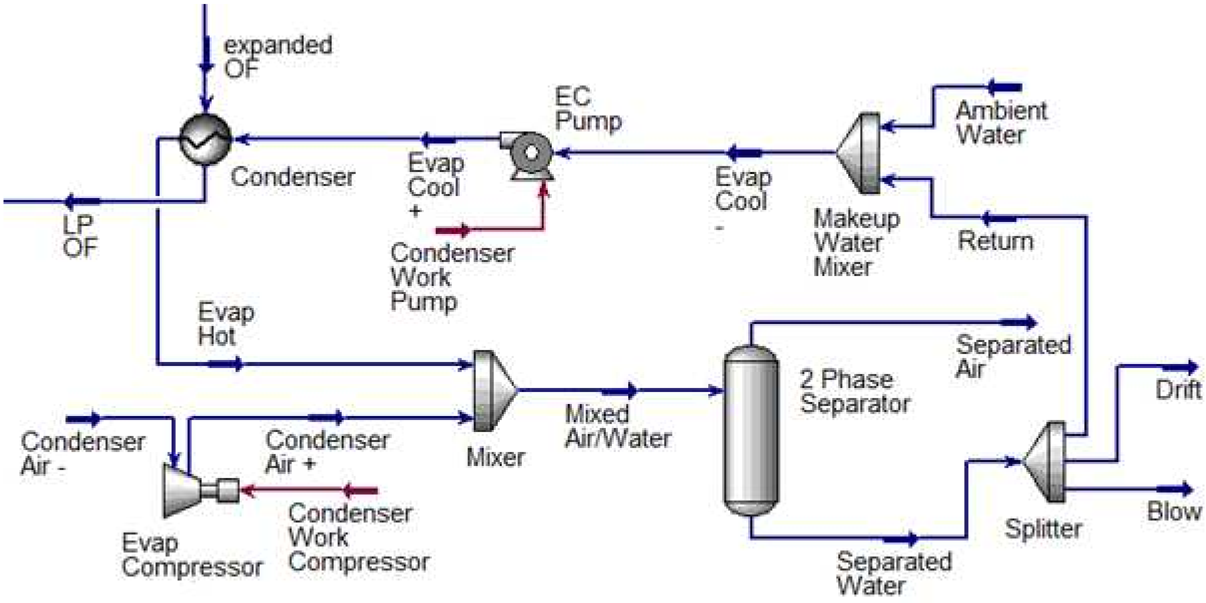

Figure 6. Process Model of Evaporative Cooler (EC)

Table II. Combined Cycle Efficiencies in Different Environments

Refrigerant	Hot Desert	Cold Coastal	Tropical Rainforest
r143a	38.54%	41.07%	38.75%
Propane	37.99%	40.89%	39.43%
Ammonia	34.77%	40.74%	35.49%
Carbon Dioxide	-	41.88%	-

In Table II, the first environment evaluated is a hot, dry environment with an air temperature of 37.78 °C and a relative humidity of 10%. In this case, the efficiency of the air Brayton cycle alone is 32.99%. In desert conditions, r143a is the top performer. However, the total efficiency of the cycle is reduced due to reduced performance of the air-Brayton. The compressor in the air Brayton cycle requires larger amounts of power to compress the air before it is heated.

The next environment is a cold, humid one with an air temperature of -6.67 °C and 60% Relative Humidity. Due to reduced power demands of the compressor in the air Brayton cycle, the efficiency of the air Brayton topping cycle alone was 40.4%. ORC performance was poor in this simulation and had minimal effects of increasing total efficiency. Carbon dioxide was evaluated due to poor performance of the three selected refrigerants and its proposed use as a working fluid for low grade waste heat recovery operations. Of the original three refrigerants, r143a performed the best, but it was outperformed by carbon dioxide.

The last environment evaluated was a hot, humid environment with an air temperature of 28.44 °C and 85% Relative Humidity. The ABC efficiency is at 34.41% in these conditions. In this environment, propane was the best performing ORC working fluid.

2.2.4 Water Usage Table by Environment

Table III lists the water usage for the recuperated ABCC with r143a. The temperate model uses water from the ambient, whereas the other three environments use evaporative cooling. It is evident that evaporative cooling massively reduces the required water by factor 50, approximately. Evaporative cooling can reduce water demands from 8.6 million liters per day to below 200,000 liters per day.

Table III. Water use in different ambient environments

Environment	**Temperate**	**Hot Desert**	**Cold Coastal**	**Tropical Rainforest**
Water Use (kg/sec)	101.08	2.16	0.51	1.89

2.2 Exergy Analysis

Exergy analysis was performed on the temperate case cycle with r143a. Exergy calculated using equation (12). Fig. 7 shows the results of exergy calculations. A majority of exergy is either lost at the reactor heat pipes or used as work at the air Brayton turbine. The work of the Rankine turbine seems comparatively small to the air Brayton turbine work, but it still has a large effect on thermal efficiency because the ORC does not require large inputs of work like the air Brayton cycle does with its compressor.

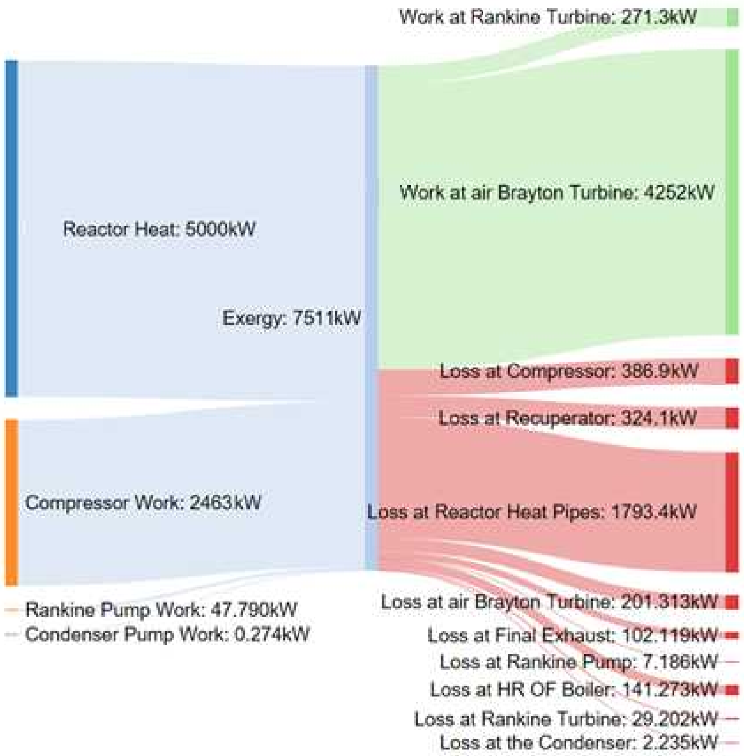

Figure 7. Sankey Exergy Diagram for air Brayton and ORC combined cycle

2.3 Preliminary Validation of HYSYS

Enthalpy and entropy were acquired from HYSYS and [23]. Exergy is calculated using equation 12. Results of the validation of the ORC are shown in Table IV. Enthalpy and entropy were used to calculate exergy changes from one state to another for the Ammonia ORC in a temperate environment. The exergy changes show fairly good agreement between HYSYS and [23], suggesting that HYSYS is correctly modeling the cycle.

Table IV. Exergy Comparison of Ammonia Rankine Cycle

	State	Pressure (Bar)	Temperature (Kelvin)	Exergy Change to Next State (kJ/kg)
From Ammonia Tables	LP OF	11.1	28.61	3.20208
	HP OF -	28.65	29.29	112.0321
	HP OF +	28.08	67.95	-115.764
	Expanded OF	11.1	28.61	0.52936
From HYSYS	LP OF	11.1	28.61	3.09472
	HP OF -	28.65	29.29	117.0496
	HP OF +	28.08	67.95	-120.07
	Expanded OF	11.1	28.61	-0.07392

HP = High Pressure; LP = Low Pressure; OF = Organic Fluid

2.4 Preliminary Cost Estimates

Using the HYSYS built-in economic analysis, equipment and installation costs were estimated for the major system components in the temperate environment combined cycle with r143a (listed in Table V). HYSYS was unable to estimate the air Brayton turbine cost due to its temperature, so using reference [24], it was found that gas turbines from 4 to 4.5 MW cost approximately \$2M in 2017 US dollars.

Table V. Estimated Costs by Component for the Temperate Combined Cycle

Component	Equipment Cost	Installed Cost
ORC Turbine	183,100	304,200
Condenser	422,900	617,600
Compressor	6,626,800	7,087,100
Turbine	2,000,000	3,300,000
Condenser Pump	11,500	69,800
Recuperator	2,523,000	4,392,800
HR (Heat Recovery) OF Boiler	152,500	302,200
Rankine Pump	57,400	101,100
Total Cost (\$)	11,977,200	16,174,800

Utilizing the cost calculations from reference [25] and the rule of six tenths, the operating costs of this cycle were estimated. When applying the rule of six tenths, power was used as the scaling factor for estimating the operating costs of the combined cycle. The estimates in Table VI are given in 2017 dollars using the national average electrical price among all sectors for 2017 from [26].

Table VI. Economics for the Temperate Combined Cycle

Item	Value
Operation and Maintenance	510,000 \$/yr
Revenue at .1033 \$/kW-hr	1,820,000 \$/yr

Profit	1,310,000 $/yr
Capital Cost	16,174,800 $
Payback Period	12.34 years

If one neglects the cost of the microreactor itself, the payback period of the power cycle is approximately 12.3 years. However, these figures are calculated using average electricity prices. In the areas where a microreactor would operate, electricity might be at a premium due to the absence of a grid connection and difficulty of power generation. For the ORC alone, the payback period is 3.94 years (Table VII). As this is lower than the payback period of the combined cycle, if the air Brayton cycle is economically viable at any electricity price, then the addition of an ORC will also be economical at that price.

Table VII. Economics of the ORC

Item	Value
Operation and Maintenance	35,000 $/yr
Revenue at .1033 $/kW-hr	245,500 $/yr
Profit	210,000 $/yr
Capital Cost	827,400 $
Payback Period	3.94 years

3. CONCLUSIONS

A recuperated air Brayton cycle paired with an ORC was evaluated for a turbine inlet temperature of 650°C for four ambient environments and several different ORC working fluids. The recuperative air Brayton cycle's performance increases with decreasing temperatures. In temperate, cold, and desert environments, r143a is the best refrigerant of the ones that were evaluated. In a tropical rainforest setting, propane is the best performer. In the cold environment, the effects of adding a bottoming ORC are negligible. Since the ORC can be neglected and the process heat from the air Brayton cycle could be used in other ways, this is an option to look at in colder climates. The exergy analysis showed what was expected, most exergy that is lost is lost at the heat pipes, and the air Brayton turbine provides much of the work of the system. The capital cost estimate of this power system, while rudimentary, shows that a majority of the cost incurred in the project comes from the air Brayton cycle, so adding an ORC may be economical.

Further work on the topic would include evaluating more refrigerants. There were only a few fluids evaluated in each ambient environment. A broader selection of working fluids may find a better performing working fluid in the various environments. Furthermore, only four environments were evaluated. Though we believe that the chosen environments are fairly representative, there are others that could be evaluated, such as a cold, dry environment, or environments at different altitudes. Next, the bottoming ORC used in this paper was a basic system. More advanced ORC systems may improve efficiency, such as regenerative ORCs. Lastly, the air Brayton cycle was unmodified beyond its optimization as a standalone unit. Better combined cycle performance may be realized with reduced performance of the air Brayton cycle, the reduction in air Brayton cycle performance leading to higher exhaust temperatures, which means higher inlet temperatures for the ORC. Additionally, cooling of the inlet air into the compressor of the air Brayton cycle could also improve efficiency.

Of note is that a bottoming ORC was evaluated for this combined cycle, but there are other methods of power generation that could be used to recoup the low-grade waste heat of the recuperating air Brayton cycle. There has been research into using Stirling engines [27], thermoelectric chemical methods [28,29], solar chimneys [30], and trilateral flash cycles (TFC) [31]. In this paper, the best performing working fluids of the ORC were those operating supercritically. The supercritical state of the working fluid created a reduction in the severity of the pinch point effect on the cycle, allowing more heat to be transferred to the working fluid. In the TFC, the working fluid operates in a single phase, eliminating the effect of a pinch point. Thus, it may be beneficial to examine a TFC instead of an ORC as a bottoming cycle.

ACKNOWLEDGMENTS

This manuscript was authored by Battelle Energy Alliance, LLC, under Contract No. DE-AC07-05-ID14517 with the U.S. Department of Energy. Support for Joseph Litrel was provided by the U.S. DOE Office of Science, Office of Workforce Development for Teachers and Scientists under the SULI program. Funding for Michael McKellar was provided by the Center for Advanced Energy Studies Visiting Summer Faculty Program.

REFERENCES

1. J.W. Sterbentz et al., "Special Purpose Nuclear Reactor (5 MW) for Reliable Power at Remote Sites Assessment Report." Idaho National Laboratory Report INL/EXT-16-40741, Revision 1 (2017).
2. Congressmen Wilson, Norcross, Hudson, Peters. "Report on a Pilot Program for Micro-Reactors Discussion Draft." Subcommittee on Energy 4th Hearing, 115th Congress 2nd Session (2018).
3. "Nuclear Energy Vouchers" GAIN: Gateway for Accelerated Innovation in Nuclear. gain.inl.gov (2018).
4. G.J Van Wylan, R.E. Sonntag, *Fundamentals of Classical Thermodynamics*, chapter 7, John Wiley and Sons, Inc., Hoboken, NJ (1973).
5. B. Zohuri, P. J. McDaniel, C. R. R. De Oliveira. "Advanced Nuclear Open Air-Brayton Cycles for Highly Efficient Power Conversion." *Nuclear Technology*, vol 192:1, pp. 48-60 (2015). DOI: 10.13182/NT14-42
6. Y. Cengel, Michael A. Boles, *Thermodynamics: An Engineering Approach*, chapter 4, McGraw Hill, USA (2002).
7. B. Zohuri. *Innovative Open Air Brayton Combined Cycle Systems for the Next Generation Nuclear Power Plants,* Nuclear Engineering ETDs University of New Mexico Digital Repository (2014).
8. T.C. Hung, T.Y. Shai, & S.K. Wang. *A Review of Organic Rankine Cycles (ORCs) for the Recovery of Low-Grade Waste Heat*, Department of Mechanical Engineering, Kaosiung Polytechnic Institute (2014).
9. X. Zhang, L. Wu, X. Wang, G, Ju, "Comparative Study of Waste Heat Steam SRC, ORC and S-ORC Power Generation Systems in Medium-Low Temperature." *Applied Thermal Engineering.* Vol 106, pp.1427-1439 (2016).
10. N. Tauveron, S. Colasson, J.A. Gruss. "Available Systems for the Conversion of Waste Heat to Electricity." *ASME 2014 International Mechanical Engineering Congress and Exposition*. IMECE2014-37984 (2014).
11. U. Kumar, M. Karimi. M. Asjad. "Parametric optimisation of the organic Rankine cycle for power generation from low-grade waste heat" *International Journal of Sustainable Energy*, Vol 35:8, pp. 774-792 (2016).
12. J. Bao, L. Zhao. "A Review of Working Fluid and Expander Selections for Organic Cycle." *Renewable and Sustainable Energy Reviews* (2013).
13. U. Drescher, D. Bruggermann. "Fluid Selection for the Organic Rankine Cycle (ORC) in Biomass Power and Heat Plants." *Applied Thermal Engineering*, Vol 2, pp. 223-228 (2007).

14. D. Ginosar, L. Petkovic, D.P. Guillen, Thermal Stability of Cyclopentane as an Organic Rankine Cycle Working Fluid, *Energy & Fuels,* Vol 25, pp. 4138 – 4144 (2011).
15. D.P. Guillen, "The Autoignition of Cyclopentane in an Ignition Quality Tester" *Journal of Materials*, Vol. 64, No. 8 (2012).
16. R.E. Niggeman, W.J. Greenlee, P. Lacey. "Fluid Selection and Optimization of an Organic Rankine Cycle Waste Heat Power Conversion System," *ASME 78-WA* (1978).
17. P. Mago, L. Chamra, K. Srinivasan, C. Somayaji. "An Examination of Regenerative Organic Rankine Cycles using Dry Fluids" *Applied Thermal Engineering.* Vol 28, pp. 998-1007 (2008).
18. V. Maizza, A. Maizza. "Unconventional working fluids in organic Rankine-cycles for waste energy recovery systems." *Applied Thermal Engineering,* Vol 21, pp.381–390 (2001).
19. B. Saleh, G. Koglbauer, M. Wendland, J. Fisher. "Working Fluids for Low-Temperature Organic Rankine Cycles." *Energy,* vol 32, pp. 1210-1221 (2007).
20. M.J. Lee, D.L. Tien, C.T. Shao. "Thermophysical capability of ozone safe working fluids for an organic Rankine-cycle system" *Heat Recovery System & CHP.* Vol 13, pp. 409–418 (1993).
21. F. Abdollahi-Demneha, M. Moosaviana, M. Omidkhahb, H. Bahmanyara "Calculating Exergy in Fowsheeting Simulators: A HYSYS Implementation." *Energy,* vol 36, pp. 5320-5327 (2011).
22. C. Leeper, A. Stephen, "Wet Cooling Towers: 'Rule of Thumb' Design and Simulation," EGG-GTH-5775 (1981).
23. "NH3 Tables Calculator," http://www.ammonia-properties.com (2018).
24. "Gas Turbine Prices by KW," http://www.nyethermodynamics.com/trader/kwprice.htm (2018)
25. M. McKellar et al. "Power Cycles for the Generation of Electricity From a Next Generation Nuclear Plant," Idaho National Laboratory Report TEV-674 (2010).
26. "Electric Power Monthly," U.S. Energy Information administration, https://www.eia.gov (2018)
27. A. V. Mehta et al. "Waste Heat Recovery Using Stirling Engine," *International Journal of Advanced Engineering Technology,* Vol 3, pp. 305-310 (2012).
28. M. Rahmini et al., "Electrical power production from low-grade waste heat using a thermally regenerative ethylenediamine battery" *Journal od Power Sources,* Vol 351, pp. 45-50 (2017).
29. K. Ono, R. O. Suzuki, "Thermoelectric Power Generation: Converting Low-Grade Heat into Electricity" *JOM,* 1998 December issue, pp. 49-51 (1998).
30. B. Ghorbani et al., "Electricity Production with Low Grade Heat in Thermal Power Plants by Design Improvement of a Hybrid Dry Cooling Tower and a Solar Chimney Concept" *Energy Conversion and Management ,* Vol. 94, pp. 1-11 (2015).
31. M. A. Iqbal et al., "Power Generation from Low Grade Heat using Trilateral Flash Cycle," *Energy Procedia,* Vol. 110, pp. 492-497, (2017).