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EVALUATION AND OPTIMIZATION OF A SUPERCRITICAL CARBON DIOXIDE POWER CONVERSION CYCLE FOR NUCLEAR APPLICATIONS

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1. INTRODUCTION

This paper describes work performed as part of the Next Generation Nuclear Plant (NGNP) Project at the Idaho National Laboratory (INL), to evaluate the performance of a supercritical CO_2 power cycle operating in the temperature range between 550°C and 850°C. The power cycle selected for this study is a supercritical CO_2 Brayton cycle with recompression. The current reference design for the NGNP is a High-Temperature Gas-Cooled Reactor (HTGR) operating with a 750°C reactor coolant outlet temperature. For NGNP applications, the supercritical CO_2 recompression Brayton cycle would be operated as an indirect power conversion cycle. However, for this initial study, a direct cycle was assumed to allow optimization of the power cycle loop without the added complication of connecting to a primary loop, and to allow future comparisons with other direct power conversion cycles.

The supercritical CO_2 recompression Brayton cycle was selected for evaluation because of its relatively high power conversion efficiencies for turbine inlet temperatures between 550°C and 750°C compared to the efficiencies that can be achieved using a recuperated helium Brayton cycle. The supercritical CO_2 cycle achieves these high efficiencies by taking advantage of the rapidly changing properties of CO_2 at temperatures and pressures slightly above the critical point (7.38 MPa and 31.1°C).

2. DISCUSSION

The UniSim process analysis software was used in the evaluation of the supercritical CO_2 recompression Brayton cycle. The reference design for the direct power conversion cycle assumed a reactor outlet temperature of 750°C and a reactor power of 600 MW_t. The high pressure portion of the cycle was limited to approximately 20 MPa. Realistic component operating conditions and design parameters were selected to be consistent with those assumed for the NGNP Project. In particular, the compressors and turbine were assumed to have an adiabatic efficiency of 90%, and the minimum approach temperature for all shell and tube heat exchangers in the power conversion system was conservatively assumed to be 20°C.

Table 1 summarizes the power cycle parameters and operating conditions for the reference design. For these conditions, the overall power cycle thermal efficiency was calculated to be 49.2%.

Table 1. Reference design parameters

Reactor Heat, MW_t	600
Reactor inlet pressure, MPa	20
Reactor outlet temperature, °C	750
Coolant flow rate, kg/hr (kg/s)	1.032E7 (2867)
Pressure ratio	2.3
Recompression fraction	0.435
Heat rejection rate (waste heat), kW	3.05E5
Compressor/turbine power ratio	0.268
Minimum approach temperature (all heat exchangers), °C	20
Tube and shell side pressure drop (all heat exchangers), kPa	20

Sensitivity calculations were also performed to determine the effect of reactor outlet temperature and coolant flow rate on power cycle thermal efficiency. Results of these sensitivity calculations, which showed a decrease in power cycle efficiency with both reactor outlet temperature and coolant mass flow, are discussed in the full paper.

3. CONCLUSIONS

The results of this evaluation showed that relatively high power cycle thermal efficiencies can be achieved for turbine inlet temperatures in the range of 550°C to 850°C. For a 600 MW_t reactor operating at a reference outlet temperature of 750°C, maximum system pressure of 20 MPa, and a coolant flow rate of 1.032E7 kg/hr (2867 kg/s), a maximum power cycle thermal efficiency of 49.2% was achieved.

Sensitivity calculations performed to evaluate the affect of reactor coolant outlet temperature and total mass coolant flow rate on power cycle thermal efficiency, also provided information on the optimum values for power cycle pressure ratios and recompression fractions at the different operating conditions.

The relatively high power cycle thermal efficiencies obtained for the supercritical CO_2 recompression Brayton cycle at temperatures in the range of 550°C to 850°C, combined with the simplicity and compactness of the power conversion system design make this an attractive option for high temperature reactor applications. Based on the results presented in this paper, it is anticipated that further evaluation of this concept will be pursued, including the evaluation of an indirect supercritical CO_2 power cycle design.

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Keywords: Next Generation Nuclear Plant (NGNP), supercritical CO_2, recompression Brayton cycle, power cycle thermal efficiency,

ABSTRACT

There have been a number of studies involving the use of gases operating in the supercritical mode for power production and process heat applications. Supercritical carbon dioxide (CO_2) is particularly attractive because it is capable of achieving relatively high power conversion cycle efficiencies in the temperature range between 550°C and 750°C. Therefore, it has the potential for use with any type of high-temperature nuclear reactor concept, assuming reactor core outlet temperatures of at least 550°C. The particular power cycle investigated in this paper is a supercritical CO_2 recompression Brayton Cycle. The CO_2 recompression Brayton Cycle can be used as either a direct or indirect power conversion cycle, depending on the reactor type and reactor outlet temperature. The advantage of this cycle when compared to the helium Brayton Cycle is the lower required operating temperature; 550°C versus 750°C. However, the supercritical CO_2 recompression Brayton Cycle requires a high end operating pressure in the range of 20 MPa, which is considerably higher than the required helium Brayton cycle high end operating pressure of 7 MPa. This paper presents results of analyses performed using the UniSim process analyses software to evaluate the performance of the supercritical CO_2 recompression Brayton cycle for different reactor coolant outlet temperatures and mass flow rates. The UniSim model assumed a 600 MW_t reactor power source, which provides heat to the power cycle at a maximum temperature of between 550°C and 850°C. Sensitivity calculations were also performed to determine the affect of reactor coolant mass flow rates for a reference reactor coolant outlet temperature of 750°C. The UniSim model used realistic component parameters and operating conditions to model the complete power conversion system. CO_2 properties were evaluated, and the operating range for the cycle was adjusted to take advantage of the rapidly changing conditions near the critical point. The UniSim model was then optimized to maximize the power cycle thermal efficiency at the different reactor coolant outlet temperatures and flow rates. The results of the analyses showed that power cycle thermal efficiencies in the range of 40 to 50% can be achieved over the range of temperatures and mass flow rates investigated.

1. INTRODUCTION

There have been a number of studies involving the use of supercritical CO_2 for both direct and indirect power conversion cycles. One of the more extensive studies, performed by Dostal, et.al. (2004), evaluated both direct and indirect supercritical CO_2 power cycles. Much of the focus of this work was on the sizing and performance of the heat exchangers used in the different power cycle analyses. Kato, et.al. (2004), looked at supercritical CO_2 cycles with the lower end cycle pressure well below the critical pressure to allow operation of the power cycle at a lower maximum pressure. Results of this study showed that CO_2 cycle efficiencies for a turbine inlet temperature of 650°C were comparable to those obtained for a helium-cooled gas reactor Brayton cycle operating at 850°C turbine inlet temperature. And, Sandia National Laboratories (Wright, et.al. 2010) have performed small scale testing to study key issues of compression near the critical point of CO_2.

At the Idaho National Laboratory (INL) there have been a number of studies (Harvego, et.al. 2009 and O'Brien, et.al. 2010) evaluating different power conversion cycles, including supercritical CO_2 power cycles, for use in the production of hydrogen using high-temperature steam-electrolysis. This paper describes work performed as part of the Next Generation Nuclear Plant (NGNP) Project at the INL, to evaluate the performance of a supercritical CO_2 power cycle operating in the temperature range between 550°C and 850°C, and using realistic design conditions and component operating parameters representative of those expected for NGNP. The power cycle selected for this study is a supercritical CO_2 Brayton cycle with

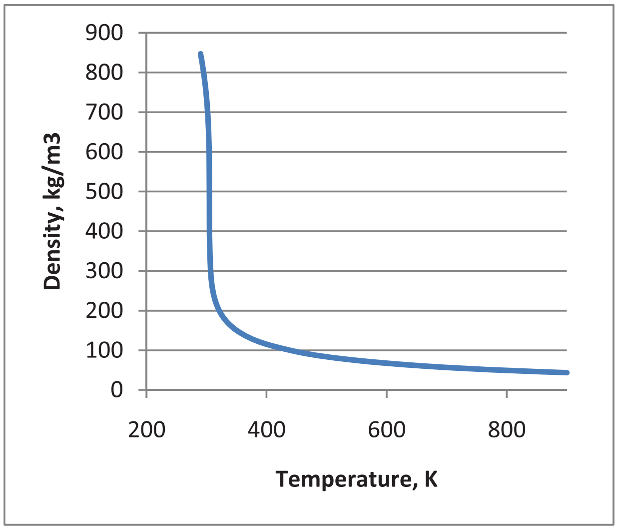

Figure 1. Carbon dioxide density near critical point.

recompression. The current reference design for the NGNP is a High-Temperature Gas-Cooled Reactor (HTGR) operating with a 750°C reactor coolant outlet temperature. For NGNP applications, the supercritical CO_2 recompression Brayton cycle would be operated as an indirect power conversion cycle. However, for this initial study, a direct cycle was assumed to allow optimization of the power cycle loop without the added complication of connecting to a primary loop, and to allow future comparisons with other direct power conversion cycles.

The supercritical CO_2 recompression Brayton cycle was selected for evaluation because of its relatively high power conversion efficiencies for turbine inlet temperatures between 550°C and 750°C compared to the efficiencies that can be achieved using a recuperated helium Brayton cycle. The supercritical CO_2 cycle achieves these high efficiencies by taking advantage of the rapidly changing properties of CO_2 at temperatures and pressures slightly above the critical point (7.38 MPa and 31.1°C). For example, Figure 1 shows the change in density as a function of temperature for supercritical CO_2 at a pressure of 7.5 MPa. As shown in the plot, the density of supercritical CO_2 rapidly increase at temperatures below about 400 K (127°C). By taking advantage of these relatively high fluid densities near the critical point, compressor work at the low-pressure end of the cycle can be considerably reduced compared to that of a power cycle using an ideal gas such as helium.

The thermal efficiency of the supercritical CO_2 recompression Brayton cycle is further enhanced by the introduction of a second compressor (recompressor) into the standard recuperated Brayton cycle before the precooler. As described later in this paper, the flow is split so that only a portion of the flow passes through the precooler, resulting in less heat rejection to the sink temperature and a corresponding increase in power cycle thermal efficiency. In addition to offering improvements in efficiency, the supercritical CO_2 recompression Brayton power conversion system is also relatively simple, compact and potentially less expensive than traditional power conversion designs. However, the required turbine inlet pressure for this concept is approximately 20 MPa compared to a maximum turbine inlet pressure of approximately 7 MPa for the recuperated helium Brayton cycle.

2. REFERENCE DESIGN AND MODEL DESCRIPTION

The UniSim process analysis software was used in the evaluation of the supercritical CO_2 recompression Brayton cycle. The reference design for the direct power conversion cycle assumed a reactor outlet temperature of 750°C and a reactor power of 600 MW_t. The high pressure portion of the cycle was limited to approximately 20 MPa to avoid the potential large irreversibility in the power conversion system high temperature recuperator, which is the result of a pinch point problem described by Dostal, et.al. (2004) and others. Realistic component operating conditions and design parameters were selected to be consistent with those assumed for the NGNP Project. In particular, the compressors and turbine were assumed to have an adiabatic efficiency of 90%, and the minimum approach temperature for all shell and tube heat exchangers in the power conversion system was conservatively assumed to be 20°C.

Figure 2 shows the UniSim model of the supercritical CO_2 recompression Brayton cycle. The calculated stream conditions (flow rates, temperatures and pressures) at different points in the system are indicated on the flow sheet.

In the reference design, the supercritical CO_2 coolant enters the reactor (upper left corner of Figure 2) at approximately 584°C and 20 MPa. After being heated in the reactor to 750°C, the coolant is expanded through the turbine to produce electric power. The coolant, at a lower temperature and pressure then passes through high-temperature and low-temperature recuperators, where it is further cooled. The coolant flow is then split into two streams (bottom of Figure 2). One stream passes through a precooler that provides additional cooling to the working fluid before it enters Compressor 1. Compressor 1 provides the driving force to circulate the fluid back through the two recuperators where heat is recovered before the working fluid is returned to the reactor inlet to complete the cycle. The second split stream at the bottom of Figure 2 passes directly to Compressor 2 (the recompressor) without any additional cooling, where it is compressed and joined with the first split stream before passing through the high temperature recuperator and returning to the reactor inlet to complete the cycle.

The calculated power conversion cycle thermal efficiency (η_{pcs}) for the conditions shown in Figure 2 is 49.2%, where η_{pcs} is defined as:

$$\eta_{pcs} = (P_{turbine} - P_{compressors})/Q_{reactor} \quad (1)$$

and,
$P_{turbine}$ = Power of the primary side turbine
$P_{compressors}$ = Compressor power (two compressors)
$Q_{reactor}$ = Reactor heat.

Table 1 summarizes the power cycle parameters and operating conditions selected for the reference design.

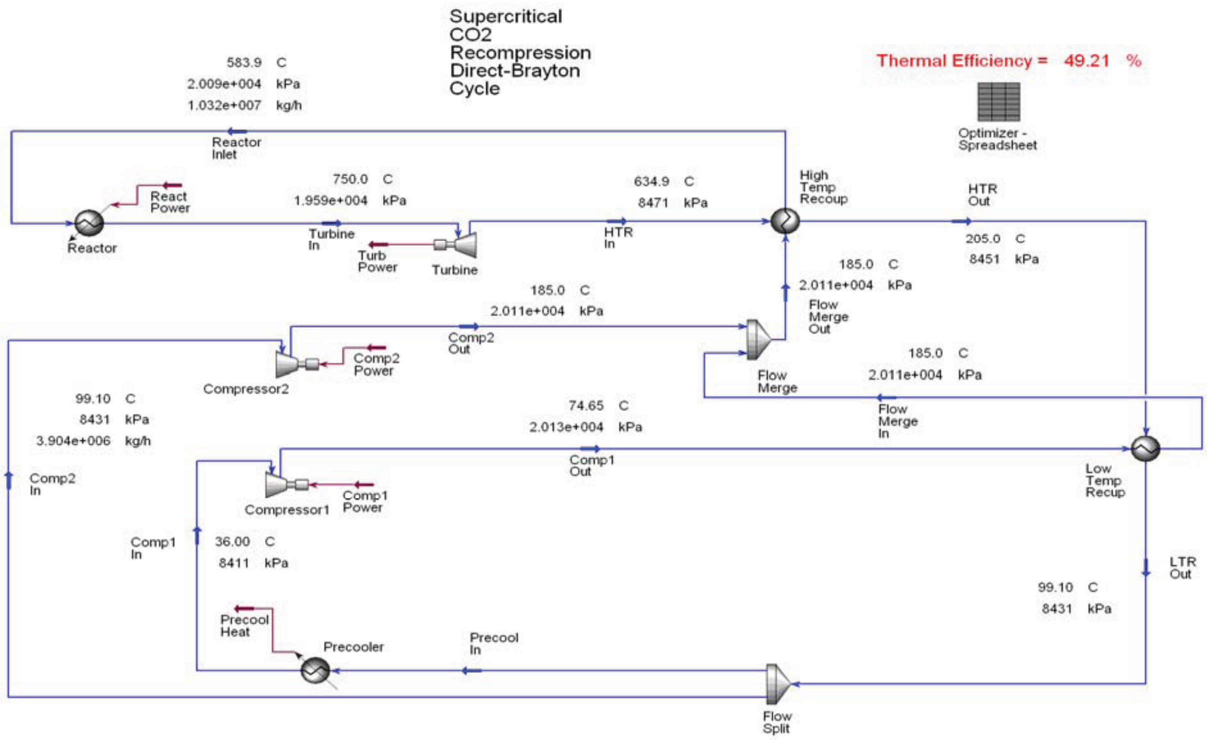

Figure 2. Process flow model of supercritical carbon dioxide Brayton cycle with recompression.

For a reactor outlet temperature of 750°C and a coolant flow rate of 2867 kg/s, the optimized pressure ratio (ratio of maximum to minimum pressures in the power cycle) giving the highest power cycle thermal efficiency was found to be 2.3. The calculated recompression fraction, which is defined to be the ratio of coolant flow to Compressor 2 (the flow bypassing the precooler) divided by the total coolant mass flow, is 0.435. With only a fraction of the total coolant flow rejecting its heat to the precooler at a sink temperature of 36°C, the power cycle heat rejection rate (waste heat) is 3.05E5 kW. This compares to a waste heat rejection rate of approximately 3.58E5 kW for an equivalent direct helium Brayton cycle powered by a 600 MW_t reactor at a reactor outlet temperature of 750°C (Harvego, et.al. 2009). The waste heat rejection rate for the supercritical CO_2 recompression Brayton cycle is, therefore, approximately 15% less than that of the equivalent recuperated helium Brayton cycle, contributing to the overall higher thermal efficiency of the supercritical CO_2 recompression Brayton cycle.

Table 1. Reference design parameters.

Reactor Heat, MW_t	600
Reactor inlet pressure, MPa	20
Reactor outlet temperature, °C	750
Coolant flow rate, kg/hr (kg/s)	1.032E7 (2867)
Pressure ratio	2.3
Recompression fraction	0.435
Heat rejection rate (waste heat), kW	3.05E5
Compressor/turbine power ratio	0.268
Minimum approach temperature (all heat exchangers), °C	20
Tube and shell side pressure drop (all heat exchangers), kPa	20

Finally, a comparison of the ratio of the net power of the two compressors to the output power of the turbine (8^{th} row in Table 1) shows a compressor-to-turbine power ratio of 0.268. This compares with a typical compressor-to-turbine power ratio of approximately 0.45 for a recuperated helium Brayton cycle, and demonstrates the reduced compression work that can be achieved by taking advantage of the higher density of supercritical CO_2 near the critical point.

4. SENSITIVITY STUDIES

To determine the effect of reactor outlet temperature and coolant flow rate on power cycle thermal efficiency, several sensitivity calculations were performed over a reactor coolant outlet temperature range of 550°C to 850°C and a coolant mass flow rate range of 1.032E7 kg/hr (2867 kg/s) to 1.3E7 kg/hr (3611 kg/s). The results of these sensitivity calculations are discussed in the following sections.

4.1 Reactor Outlet Temperature Sensitivity

Figure 3 shows the effect of reactor outlet temperature on power cycle thermal efficiency for a coolant flow rate of 1.032E7 kg/hr (2867 kg/s). As the reactor outlet temperature varies from 550°C to 850°C, the power cycle thermal efficiency increases from a minimum value of 39.2% at a reactor outlet temperature of 550°C to 51.0% at a reactor coolant outlet temperature of 850°C.

Since the reactor coolant flow rate, maximum system pressure, pressure losses, turbine and compressor adiabatic efficiencies, and heat exchanger minimum approach temperatures are fixed, the primary variable influencing power cycle efficiency is the turbine exhaust pressure. This variable was, therefore, varied to achieve the maximum power cycle thermal efficiencies shown in Figure 3. A

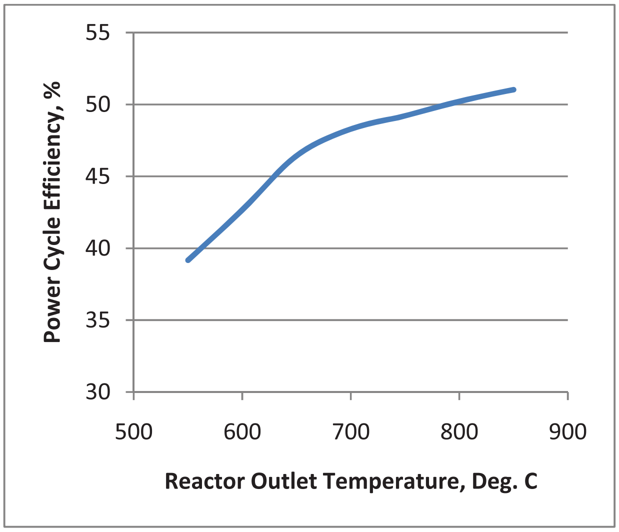

Figure 3. Power cycle efficiency versus reactor outlet temperature.

secondary requirement to maximize the power cycle efficiency was to minimize the outlet temperature from the precooler while at the same time avoiding the potential for liquid entrainment at the inlet to Compressor 1. The required precooler outlet temperatures were found to vary from 32°C at the low reactor coolant outlet temperatures, to 39°C at the high reactor coolant outlet temperatures.

Figures 4 and 5 show the optimum pressure ratio (ratio of maximum to minimum pressures in the power cycle) and recompression fraction (fraction of total coolant flow bypassing the precooler) plotted as a function of reactor coolant outlet temperature, respectively.

Figure 4 shows that the optimum power cycle pressure ratio decreases from a value of 2.9 at a reactor outlet temperature of 550°C (corresponding to a power cycle thermal efficiency of 39.2%) to a value of 2.3 at a reactor coolant outlet temperature of 850°C (corresponding to a power cycle thermal efficiency of 51.1%).

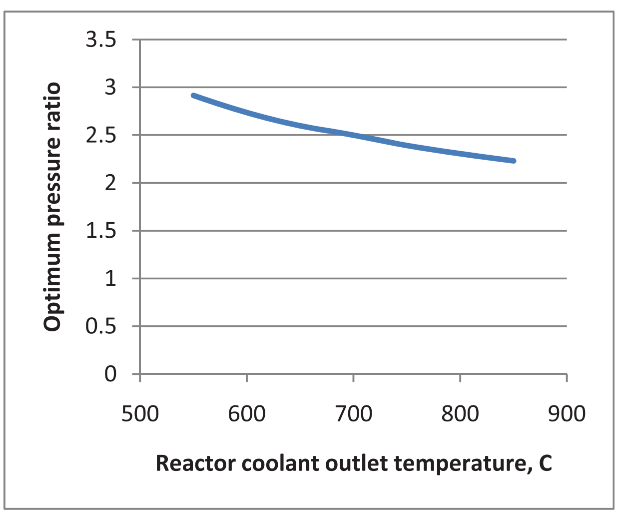

Figure 5. Pressure ratio versus reactor outlet temperature.

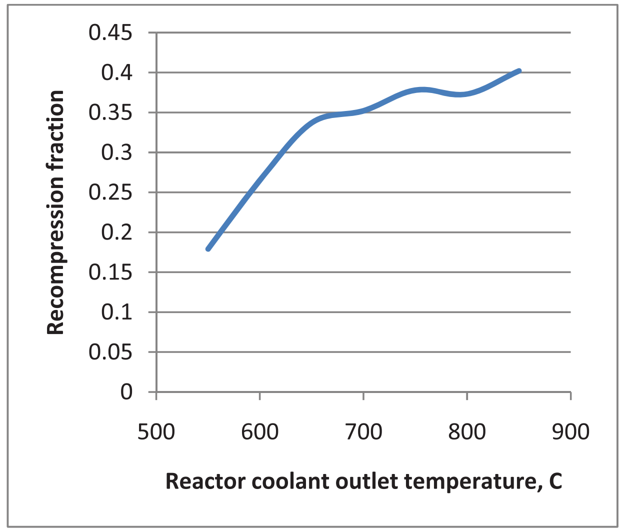

Figure 4. Recompression fraction versus reactor outlet temperature.

Figure 5 shows that the optimum recompression fraction to maximize power cycle thermal efficiency increases with increased reactor coolant outlet temperature. The similar trends in the recompression fraction in Figure 5 and the power cycle thermal efficiency in Figure 3 is to be expected because, with an increase in the recompression fraction, less coolant passes through the precooler, resulting in less waste heat rejected to the low temperature heat sink and a higher power cycle thermal efficiency. The variation in the calculated recompession fraction with reactor outlet temperature (i.e., lack of a smooth curve) can probably be attributed to the sensitivity of the recompression fraction to the rapidly changing CO_2 properties near the supercritical point.

4.2 Coolant Mass Flow Sensitivity

The second set of sensitivity calculations performed was to vary the total coolant mass flow rate while maintaining the reactor coolant outlet temperature constant at the NGNP reference temperature of 750°C. As in the previous sensitivity calculations, maximum system pressure, pressure losses, turbine and compressor adiabatic efficiencies, and heat exchanger minimum approach temperatures were held constant, and the turbine exhaust pressure was varied to maximize power cycle efficiency.

Figure 6 shows the resulting power cycle thermal efficiency plotted as a function of total coolant mass flow. These results show that the achievable maximum power cycle thermal efficiency decreases from a maximum value of 49.2% at the reference design flow rate of 1.032E7 kg/hr (2867 kg/s) to 43.7% at a coolant flow rate of 1.3E7 kg/hr (3611 kg/s).

Finally, Figure 7 shows the calculated power cycle thermal efficiency plotted as a function of waste heat rejection rate from the precooler for both sets of sensitivity calculations (variation in reactor coolant outlet temperature and variation in total coolant mass flow rate). The combined data show that the power cycle thermal efficiency decreases in a linear

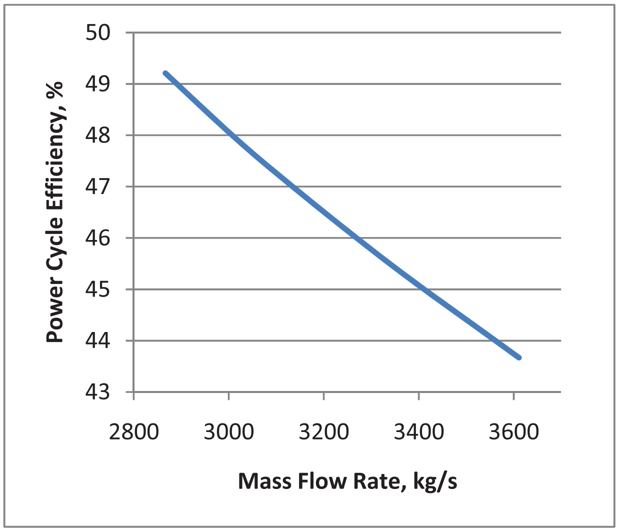

Figure 6. Power cycle efficiency versus mass flow rate.

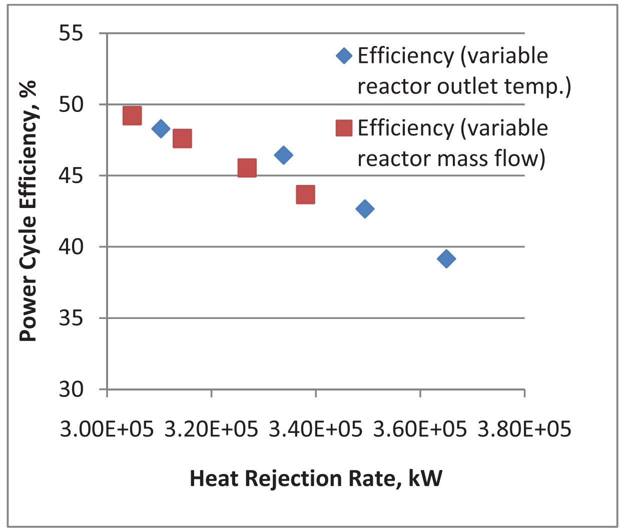

Figure 7. Power cycle efficiency versus waste heat rejection rate.

fashion as the heat rejection rate from the precooler increases.

6. CONCLUSIONS

This paper presents results of an evaluation of a supercritical CO_2 recompression Brayton cycle to determine the power cycle thermal efficiency at conditions representative of those expected in the NGNP. Although a supercritical CO_2 cycle would most likely be an indirect power conversion cycle for NGNP applications, the analyses presented in this paper were performed for a direct power conversion cycle so that the cycle performance could be optimized and compared with results from other direct power conversion cycles without the added complication of an interface between the power cycle and a primary helium cooling loop.

The results of this evaluation showed that relatively high power cycle thermal efficiencies can be achieved for turbine inlet temperatures in the range of 550°C to 850°C. For a 600 MW_t reactor operating at a reference outlet temperature of 750°C, maximum system pressure of 20 MPa, and a coolant flow rate of 1.032E7 kg/hr (2867 kg/s), a maximum power cycle thermal efficiency of 49.2% was achieved. Sensitivity studies were also performed showing the affect of reactor coolant outlet temperature and total mass coolant flow rate on power cycle thermal efficiency and the resultant optimum values for power cycle pressure ratio and recompression fraction.

The relatively high power cycle thermal efficiencies obtained for the supercritical CO_2 recompression Brayton cycle at temperatures in the range of 550°C to 850°C, combined with the simplicity and compactness of the power conversion system design make this an attractive option for high temperature reactor applications. Based on the results presented in this paper, it is anticipated that further evaluation of this concept will be pursued, including the evaluation of an indirect supercritical CO_2 power cycle design.

ACKNOWLEDGMENTS

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