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MASS OPTIMIZATION OF POWER SYSTEM FOR SPACE APPLICATIONS

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A Brayton cycle coupled to a direct cooled nuclear reactor is being designed and optimized for a space surface power application. Robust models for the various Brayton cycle components were developed and integrated. Separately, a nuclear reactor model which provides an optimized reactor mass for given flow conditions was developed. Then mass correlations for the size of the recuperative heat exchanger and radiator panel, along with the reactor mass model, were integrated with the cycle model, and an optimization algorithm was developed to find the least massive power system. The optimization routine is being used to explore the effects of turbine inlet temperature, cycle pressures, and other various cycle parameters on the full system mass.

I. INTRODUCTION

Future goals in space exploration will require surface power systems with a high power output, long lifetime, and high power density. NASA has identified a system capable of producing 40 kWe for 10 years as an ideal target for manned exploration of Mars. Due to significant launch costs, it is desired to minimize the system mass. An electrical system consisting of a Brayton power cycle and a direct-cooled fission reactor is being optimized for this application.

Power cycle component models were carefully constructed and integrated; a reactor model was developed in conjunction with this effort that considered both thermal and neutronic performance. The reactor and power cycle models are coupled through flow conditions, cycle efficiency, and the desired electrical power output. The full system optimization considers the tradeoffs between the high cycle efficiency related to a larger power conversion system and high thermal input related to a larger nuclear reactor.

II. POWER CYCLE MODELING

A Brayton cycle model with optimization capabilities was created in MATLAB to allow for minimization of the system mass. To enable studies that span a range of conditions, cycle configurations, and fluids, models for each cycle component were constructed separately and carefully, ensuring that they were robust and accurate as well as computationally efficient. The component models were integrated to create a simple, recuperated Brayton cycle, see Figure 1.

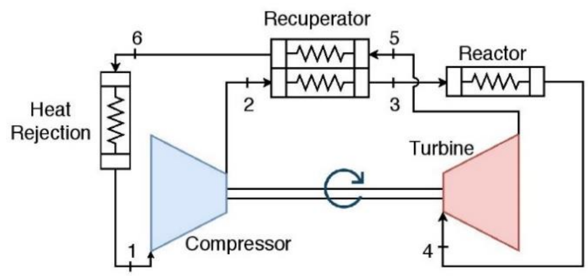

Fig. 1. Simple, recuperated Brayton cycle schematic

II.A. Component Modeling and Integration

The modeled power cycle components were the recuperator, compressor, turbine, and radiator. The counter-flow recuperator was modeled using a total conductance and the sub-heat exchanger technique[1]. This method has proven useful because, for a particular geometry, the conductance of a heat exchanger is a relatively accurate predictor of its mass. The compressor and turbine were modeled using the efficiency contours presented by O.E. Balje[2]. This information provides the efficiency of a turbomachine when given the specific speed and specific diameter, which are the dimensionless quantities representing the angular velocity and the diameter of the impeller, respectively. An equation-based representation of these contours was created for both the compressor and turbine.

Heat rejection for the power system occurs via a radiator in a secondary loop that is integrated with the main power cycle working fluid loop. The radiator model utilizes the radiative heat transfer equation from the radiator panel to the surroundings along with a pinch point temperature difference between the temperature of the radiator panel and the temperature of the working fluid leaving the radiator component.

The cycle model inputs are coolant mass flow rate, the low side pressure (p_1), the highest temperature in the cycle (T_4, leaving the reactor and entering the turbine), the compression ratio of the compressor (PR_c), the conductance of the recuperator (UA), the panel area of the radiator (A_{panel}), the heat rejection temperature (T_{rej}), the type of fluid, and an indicator that sets the desired method for determining fluid properties. Properties can be determined either by using FIT[3], a computationally efficient MATLAB toolbox add-in of fluid interpolation tables for CO_2, or REFPROP[4], the NIST Reference Fluid Thermodynamic and Transport Properties Database. Then, all of the component models are integrated to simulate the cycle.

II.B. Component Mass Correlations

Due to the relatively compact nature of the turbomachinery, the system mass optimization included only the radiator, reactor, and recuperator component masses.

A reasonable relationship for radiator mass is a multiplier on the required surface area of the radiator panel. Sandia National Lab, which is a partner on this project, suggested that heat pipe radiator heat rejection systems using current technology would have a mass density between 6 and 7.5 kg/m^2 (Ref. 5). Results found in several literature sources have confirmed this range[6, 7, 8]. A final value of 6.75 kg/m^2 was chosen to provide the baseline correlation for the cycle optimization.

As previously mentioned, conductance is the metric that must be correlated to recuperator mass. The industry partner on this project, Creare LLC, used their experience with recuperative heat exchangers and their proprietary design model of microtube and shell heat exchangers with carbon dioxide to create recuperator designs within the expected operating range for this application. The resulting design points provide mass versus conductance data that are used to relate these two metrics. The baseline correlation used is shown in Eq. (1). The “slope” value is a measure of how the mass changes with the size of the heat exchanger. The “intercept” value is a constant mass required by such things as the heat exchanger headers[9].

$$m_{recuperator} = 4.83\,\frac{kg\,K}{kW}\,UA + 23.59\;kg \qquad (1)$$

The correlation given by Eq. (1) is appropriate for the near term, legacy recuperator design which corresponds to a stainless-steel shell and microtube heat exchanger. This design leads to recuperator temperature limitations of 550°C. Mass reduction options associated with multiple recuperator units operating in parallel and insulated shell options are being discussed as future technologies to reduce component mass. The use of Inconel to allow for higher cycle temperatures is also being discussed as an overall system mass reduction option.

A simulation for the nuclear reactor is being developed by the authors in the Nuclear Engineering Department at the University of Wisconsin, Madison. The power cycle model passes information to the reactor simulation, including the required reactor heat output, the fluid type, mass flow rate, pressure, and temperature of the reactor coolant/power cycle working fluid. The fuel type must also be specified; Uranium Oxide is used for optimizations consistent with near-term technology options. The reactor model calculates the fuel fraction required to generate the required heat output. This is done by considering the core radius that is required to remain critical for the lifetime of the reactor as well as coolant requirements associated with temperature limitations. The geometry of the reactor is then used to find a mass which is passed back to the power cycle model.

III. POWER CYCLE OPTIMIZATION

The cycle model is integrated with an optimization algorithm to allow comprehensive design studies. The optimization begins by considering one potential radiator size and looks at the resulting tradeoffs between the size of the nuclear reactor and recuperative heat exchanger. For a given power output, the size of these two components are inversely related as shown in Figure 2.

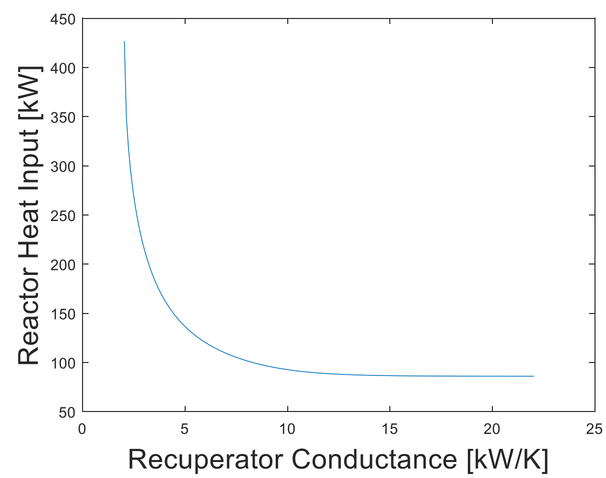

Fig. 2. Required reactor heat input with respect to recuperator size, given a radiator of 100 m^2 and a power output of 40 kW

Adding more recuperation (i.e., conductance) transfers more of the waste heat from the hot fluid stream to the cold fluid stream. This effectively preheats the fluid before it enters the reactor and increases the cycle efficiency. As the cycle efficiency increases, the required reactor heat input decreases. Figure 3 shows the combined mass of the radiator and recuperator as the cycle recuperation is increased. A minimum combined mass is apparent.

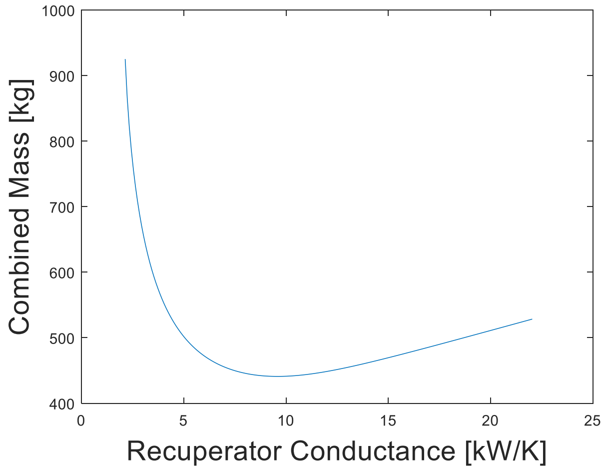

Fig. 3. Combined mass of reactor and recuperator as a function of recuperator size

Finally, the optimization repeats this process for a range of radiator sizes in order to find the cycle design with the lowest total combined mass considering the recuperator, radiator, and reactor.

IV. OPTIMUM CYCLE ANALYSIS

For the near-term optimum cycle, the high-side recuperator temperature was limited to 550°C to allow for use of a stainless-steel shell and tube heat exchanger consistent with those currently built at Creare. The nuclear fuel used was Uranium Oxide. With these parameters, the optimization was run, and the cycle that minimized mass was found as shown in Figure 4 on a *T-s* diagram. A more detailed analysis was carried out on this cycle to make sure each cycle components is realistic.

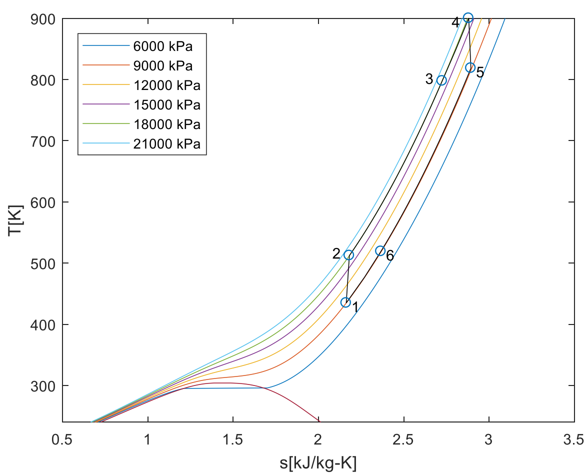

Fig. 4. T-s diagram of mass optimum Brayton cycle at parameters p_1=9,000 kPa, T_4=900 K, PR_c=2, T_{rej}=200 K, 40 kW of output power, supercritical CO_2 as the working fluid, and FIT as the property database

The optimum cycle design was found to have a recuperator conductance (*UA*) of 32.1 kW/K, radiator panel area of 82 m^2, and a mass flow rate of 1.33 kg/s. Using the mass correlations discussed in the previous section, the design of each component was converted to a mass. The mass of the recuperator, radiator, and nuclear reactor were 178.5 kg, 554.8 kg, and 318 kg respectively, with a total combined mass of 1051 kg. The characteristics of the turbomachinery in this cycle can be found in Table 1. For this cycle, the shaft speed was 3700 revolutions per second.

TABLE I. Turbomachinery parameters in optimum cycle

Turbomachine	Parameter	Value
Compressor	Diameter [cm]	2.60
	Tip Mach Number	0.86
	Head Coefficient	0.60
	Flow Coefficient	0.07
	Efficiency	0.85
Turbine	Diameter [cm]	2.68
	Tip Mach Number	0.71
	Efficiency	0.90
	Effective Nozzle Area [cm^2]	0.49
	Velocity Ratio	0.68

The parameters associated with the turbomachinery in the optimum cycle seem realistic and comparable to designs of turbomachinery built by Creare. Specifically, it is important to be sure the tip Mach numbers do not exceed 1 and the turbomachinery efficiencies seem reasonable. The recuperator effectiveness was also found to be a realistic and achievable value of 91.4%.

The cycle efficiency is relatively low, at 24% and the back work ratio is relatively high, at 68%. This is a result of optimizing the cycle for mass. Due to the radiative T^4 temperature dependence, mass optimization with respect to the radiator size drives the compressor state points away from the vapor dome and towards higher temperature in order to allow a smaller radiator panel to operate at higher temperatures. Compression of fluid near the vapor dome with a corresponding high density, would improve both values; for this reason, future work will examine alternative fluids/mixtures for which the critical temperature is more appropriate.

V. FUTURE OPTIMIZATION ITERATIONS

The creation of robust cycle components and a robust optimization routine allows for the optimization to be iterated to complete studies on the implications of several cycle parameters. Sensitivity studies of component assumptions along with parametric studies of the cycle parameters are used to explore the full potential of the supercritical CO_2 cycle.

V.A. Sensitivity Studies

In order to develop the cycle components, some modeling assumptions were made; the impact of these assumptions on the results must be understood through sensitivity studies. The sink temperature for the radiation rejection was chosen to be 200 K based on literature from similar research studies[10, 11]. In the radiator model, the pinch point temperature difference between the radiator panel surface and the working fluid leaving the radiator component was assumed constant at 10 K.

The compressor head coefficient is an input to the cycle and leads to the compressor flow coefficient and the compressor efficiency. The head coefficient of a radial compressor is typically in the range of 0.35 to 0.65. A value of 0.6 which leads to a compressor efficiency of 85.38% was chosen for the initial optimization study.

Pressure drops throughout the system were set to 2.7% in the reactor, 1% in the radiator, 1.5% in the recuperator hot side, and 0.52% in the recuperator cold side based on values found in literature[12, 13]. Sensitivity studies over a range of sink temperatures, radiator pinch point temperatures, compressor head coefficients, and component pressure drops will be completed to establish a confidence level in these values.

V.B. Parametric Studies

Parametric studies will be run to observe the effects of turbine inlet temperature, absolute pressure values, and pressure ratio. To observe the effects of higher turbine inlet temperatures, recuperator designs utilizing Inconel will be considered. To fully explore the optimization space, longer term component technology options will also be considered, including the effects of including insulation and multiple units in the recuperative heat exchanger, and the use of a more exotic nuclear fuel, Tungsten Cermet.

A preliminary parametric study of the effects of the turbine inlet temperature has been completed. To observe cycles with higher temperature values, the data provided by Creare for Inconel heat exchangers was utilized. Note, that Inconel is not a current/legacy design at Creare.

In the applicable range of operation, the mass per conductance conversions at 550°C, 650°C, and 750°C are shown in Eq. (2), Eq. (3), and Eq. (4), respectively. These relations were developed similar to Eq. (1).

$$m_{recuperator}\,(550°C) = 2.03\,\frac{kg\,K}{kW}\,UA + 8.48\,kg \qquad (2)$$

$$m_{recuperator}(650°C) = 2.89\,\frac{kg\,K}{kW}\,UA + 13.14\,kg \qquad (3)$$

$$m_{recuperator}(750°C) = 5.77\,\frac{kg\,K}{kW}\,UA + 32.01kg \qquad (4)$$

The correlations change drastically due to the strong dependence between material strength and temperature. As a result, there is a tradeoff between a higher cycle efficiency and a need for more robust components at elevated cycle temperatures. Using linear interpolation at temperatures between these correlation values, a parametric study was run for turbine inlet temperatures between 900 K and 1100 K, as shown in Figure 5.

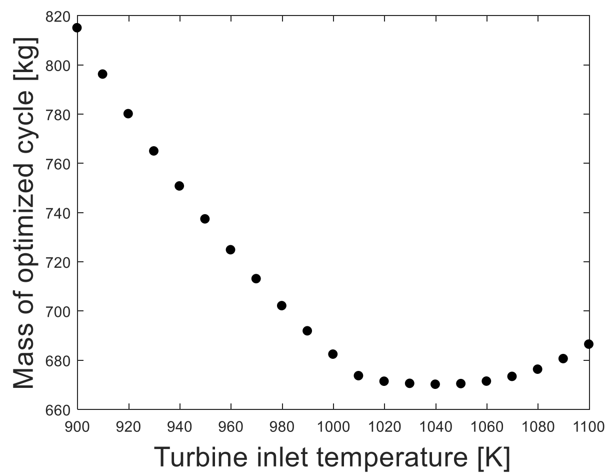

Fig. 5. Minimum masses of cycles with p_1=9,000 kPa, PR_C =2, and T_{rej} =200 K, and 40 kW of output power at various turbine inlet temperatures

From this study, it is clear there is an optimum turbine inlet temperature. Taking a closer look at the component masses associated with the optimum cycle at each turbine inlet temperature provides some explanation for this, see Figure 6.

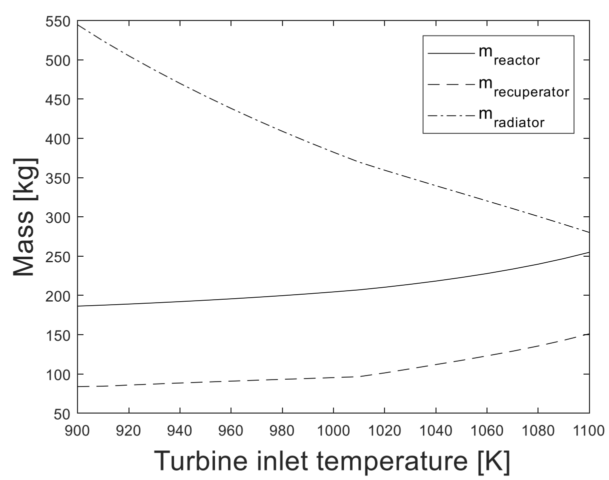

Fig. 6. Component masses of optimum cycle for various turbine inlet temperatures

The T^4 temperature dependence allows the radiator to remove more heat with a smaller area at higher temperatures, resulting in a significantly smaller radiator.

However, higher temperatures require a more massive reactor as it is operating closer to its temperature limits and a more robust and heavier recuperator due to the decline in material strength. As shown in Figure 5, approximately 1040 K seems to be the optimal turbine inlet temperature.

VI. CONCLUSION

A minimum-mass power system design is being optimized for Mars surface power. The optimization is intended to explore trade-offs between the power cycle and reactors' performances and masses. A robust model for the power cycle has been created and is being used to explore the potential benefits of sCO_2 Brayton cycle use for space power applications.

The future work of this project is completion of the necessary parametric and sensitivity studies to develop one final optimum cycle for the supercritical CO_2 working fluid. Following full analysis of supercritical CO_2 in the simple, recuperated cycle, the project focus may shift to exploration of other fluids, mixtures, and cycle configurations.

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