Dynamic Model of a Space Reactor Brayton-Cycle System

Steven A. Wright

Sandia National Laboratories: PO Box 5800, MS-1146, Albuquerque, NM, 87185 sawrigh@sandia.gov

INTRODUCTION

Small innovative nuclear reactors that use Brayton power conversion systems are being considered by the National Aeronautical Space Administration (NASA) for its Jupiter Icy Moon Orbiter (JIMO) mission. This paper describes some early results of a dynamic system's model for the reactor and closed-loop Brayton cycle (CBC). This model is expected to provide a basic understanding of the dynamic behavior and stability of the coupled reactor and power generation loop.

DESCRIPTION OF THE DYNAMIC MODEL

Few reactors have ever been coupled to closed Brayton-cycle systems [1,2]. As such their behavior under dynamically varying loads, startup and shut down conditions, and requirements for safe and autonomous operation are largely unknown. In addition the reactor and power conversion system are highly coupled because the turbo-machinery provides the shaft power to force the coolant through the reactor. This strong coupling is expected to impact the design of the entire spacecraft.

The model described in this abstract is a lumped parameter model of the reactor, turbine, compressor, recuperator, radiator/waste-heat-rejection system and generator [3]. More detailed models that remove the lumped parameter simplifications are also being developed.

The reactor model uses the point reactor kinetics equations with a negative fuel-temperature feedback coefficient [4]. The reactor, recuperator, and radiator are assumed to have single average temperatures that are coupled by heat transfer to the inlet and outlet gas temperatures. The time rate of change for the fuel temperature, radiator, and recuperator temperature are determined, and they are used to updated the temperatures for each time step. In addition, the characteristic flow curves for the turbine and compressor (rotating on a single shaft), along with the generator load were used to predict the excess torque or power to spin the turbo-machinery shaft, and thus its rate of change in rotational speed. The characteristic flow curves also determine the compressor and turbine outlet temperature and pressure given the mass flow rate, the rotational speed, and the inlet and outlet temperatures [5]. No bypass valves were included in the model. Thus, the only means of control was via the electrical load or by adjusting the reactivity control in the reactor.

INITIAL RESULTS OF THE MODEL

The initial solutions were obtained for a 100 kWe class space reactor power system that had a 140 m^2 waste heat rejection radiator and a recuperator with a heat transfer area of about 40 m^2 between the high and low-pressure legs of the CBC loop. The coolant was HeXe (70mole % He). Solutions were obtained for step changes in load from 100 kWe to 90 kWe or to 20 kWe. Startup transients have also been generate using the more detailed model.

The initial results of the model indicate stable operation of the reactor-driven Brayton-cycle system and its ability to load-follow. However, the model also indicates some counter-intuitive behavior. Specifically, for fixed reactivity insertion, (with negative feedback) decreases in load resulted in higher rpm, higher flow rates, and increased reactor power levels. Operation of the reactor control system may be required to change the reactor fuel temperature to create conditions where load increases or decreases result in corresponding reactor power level increases or decreases.

Dynamic Behavior and Stability of the Closed-loop System

To explore the dynamic behavior of the reactor coupled CBC system, the dynamic equations were solved with all derivates set to zero except for the rate of change of revolutions per minute (rpm). In this manner, we were able to solve for the excess shaft power P_X for a specified rpm, load, and average fuel temperature. Figure 1 shows the excess shaft power for fixed load (100 kWe) at various fuel temperatures as a function of rpm. Note that steady-state behavior requires that the excess shaft power be zero, and that there are two points on this curve where the excess shaft power is zero.

Operations that have an rpm below the lower "zero-point" will result in a system-wide-stall, because too much load is being demanded from the system at the lower rpm. The higher rpm "zero-point" is an attractor-point. Operation of the system at any rpm above the stall point will result in increased rpm until the stable point is reached.

In summary, the dynamic model shows that a properly designed reactor and closed-Brayton-cycle system has a stable operating range that is capable of load following using only the negative feedback characteristics of the reactor.

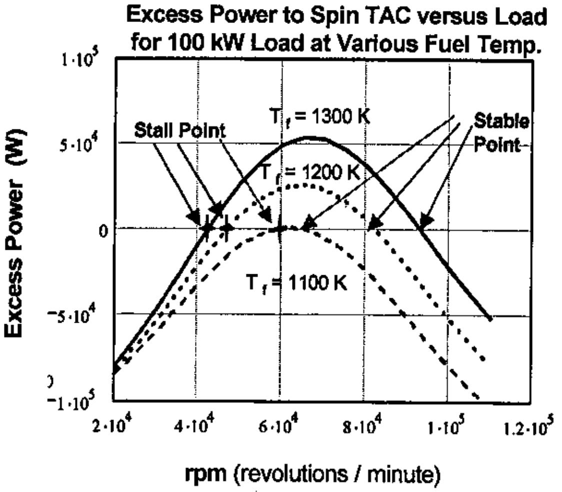

Fig. 1 Excess Shaft Power shown as a function of shaft revolutions per minute (rpm) for various load and fuel temperatures T_f.

REFERENCES

1. L. H. Suid, *The Army's Nuclear Power Program: The Evolution of a Support Agency*, Greenwood Press, NY 1990.
2. C. Rodriguez, et. al., "GT-MHR Operations and Control", Proceedings *"Development Status of Modular High Temperature Reactors and Their Future Role"*, ECN, Petten, Nov. 28-30 1994.
3. S. A. Wright, "Preliminary Results of Dynamic System Model for a Closed-Loop Brayton Cycle Coupled to a Nuclear Reactor", *Proc. 1st International Energy Conversion Engineering Conference, 17 - 21 Portsmouth*, VA, Aug. 17-21,(2003)
4. D. L. Hetrick, Dynamics of Nuclear Reactors, University of Chicago, 1971.
5. Japikse D. and Baines N. C. "*Introduction to Turbomachinery*", Concepts ETI Inc. and Oxford University Press, 1997.