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KINETIC - A SYSTEM CODE FOR ANALYZING
NUCLEAR THERMAL PROPULSION ROCKET ENGINE TRANSIENTS*

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Abstract

A system code suitable for analyzing Nuclear Thermal Propulsion (NTP) rocket engines is described in this paper. The code consists of a point reactor model and nodes to describe the fluid dynamics and heat transfer mechanism. Feedback from the fuel, coolant, moderator and reflector are allowed for, and the control of the reactor is by motion of controls element (drums or rods). The worth of the control element and feedback coefficients are predetermined. Separate models for the turbo-pump assembly (TPA) and nozzle are also included. The model to be described in this paper is specific for the Particle Bed Reactor (PBR). An illustrative problem is solved. This problem consists of a PBR operating in a blowdown mode.

INTRODUCTION

Kinetics System Code is a collection of computer programs written for the purpose of analyzing start-up transients in PBR Reactors. These programs are broadly divided into modules such as nucleonics, hydraulics, heat transfer, control rods, plus specific items such as TPA assemblies, valves, and nozzles.

The solution for the transient is obtained by organizing the equations into an initial value problem. This system is then solved with an integrator routine, which uses the Gear method (Gear 1971) for solving stiff initial value systems. The use of this integrator automatically controls the solution accuracy.

The test problem to be solved as an example requires modules for nucleonics, heat transfer, hydraulics, feedback and control rods. Since it operates in the blowdown mode, the TPA is omitted. The nozzle is treated in the hydraulics section. An intermodule information flow diagram is given for this test problem in Figure 1. The driving functions for the sequence consist of a power trace consisting of a 5-decade, 5-second exponential ramp to power plus a linear pressure ramp for the inlet pressure to 18 MPA in the same time frame.

FIGURE 1. Test Problem Diagram

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Heat Transfer

The reactor system is nodalized for this calculation. Each node consists of a solid material with passages for the coolant. Heat sources are from fission and (n, γ) interaction. The form of Equations (9) and (10) for heat transfer follows from the following assumptions. There are no abutting nodes in this system except in the fuel bed where coolant convection totally dominates the heat transfer. The only non-fuel bed nodes are one each in the reflector and moderator. This eliminates conduction terms in Equation (9). The thermal inertial term in the coolant is assumed to be negligible. Equation (10) is the space dependent equation along the coolant passage. This is used to determine the coolant temperatures and H_{OUT} in Equation (9). The heat transfer coefficient h [Equation (2)] is determined using the Achenbach correlation (Achenbach 1982) developed for particle beds or Dittus-Boelter (El-Wakil 1971) for the reflector and moderator.

$$MC_p^s \dot{T}_s = Q - \dot{m}(H_{out} - H_{in}) \quad (9)$$

$$hP(T_s - T_c)dx = \dot{m}C_p^c dT_c \quad (10)$$

Definitions for 9 and 10

M = Mass of node

C_p^s = Heat capacity of node

C_p^c = Heat capacity of coolant

T_s = Temperature of node

T_c = Temperature of coolant

Q = heat source in node

$\dot{m}$ = Coolant mass flow rate

H = enthalpy of coolant

h = Heat transfer coefficient

p = Coolant channel perimeter

x = Distance from channel inlet

Hydraulics

The system is also nodalized for this calculation which is actually a computer algorithm using pressure drop correlations to determine the pressures from the input source to the nozzle. Quasi-steady state conditions are assumed. The path is through the reflector, moderator, fuel element in that order. The first two are simple one node systems. The element is more complicated as the flow splits for passage through the frits and fuel bed. A flow map for the element is shown in Figure 2. A balanced flow and pressure map is found iteratively which equals the input pressure and satisfies the nozzle equation. This map is a unique function of the temperature map from heat transfer and the input pressure. It is thus also a quasi-steady state solution consistent with the temperatures.

FIGURE 2. Fuel Element Coolant Flow Diagram

Physics

The physics equations are conveniently in initial value form and can be used directly. The basic equations are commonly called the point kinetics equations (Duderstadt and Hamilton 1976).

$$\dot{n} = \frac{(k+k_f)(1-\beta)-1}{\tau} n + \sum_{i=1}^6 \lambda_i C_i \quad (1)$$

$$\dot{C}_i = \frac{\beta_i k n}{\tau} - \lambda_i C_i \quad i=1, \dots, 6 \quad (2)$$

Definitions for Equations 1 and 2

n = neutron population	k = multiplication constant
C_i = i th precursor population	k_f = feedback delta k
τ = prompt neutron lifetime	$\beta = \sum_{i=1}^6 \beta_i$
λ_i = i th precursor time constant	
β_i = i th delayed neutron fraction	

Actually it is more accurate to call them fundamental mode kinetics as the parameters are determined using the full geometry of the reactor. We are using six groups of delayed neutron precursors. The set of equations used in the code to represent the physics model are (1), (5), and (8).

$$\omega = \frac{\dot{n}}{n} \quad Y_i = \frac{\lambda_i \tau C_i}{n} \quad (3)$$

$$\tau \omega = (k+k_f)(1-\beta)-1 + \sum_{i=1}^6 Y_i \quad (4)$$

$$\dot{Y}_i = k + k_f \beta_i \lambda_i - (\lambda_i + \omega) Y_i \quad (5)$$

$$\tau \dot{\omega} = k(1-\beta) + \sum_{i=1}^6 \dot{Y}_i \quad (6)$$

$$\dot{\omega} = \gamma_1 (\omega_T - \omega) + \gamma_2 (n_T - n) \quad (7)$$

$$k(1-\beta) = \tau [\gamma_1 (\omega_T - \omega) + \gamma_2 (n_T - n)] - \sum_{i=1}^6 \dot{Y}_i \quad (8)$$

These equations are similar to the MIT/SNL control laws (Bernard et al. 1987). n_T is the desired population or power trace. ω_T is the corresponding period n_T/n_T . γ_1 and γ_2 are tracking constants regulating how closely the calculated power follows n_T . Equation (8) determines the reactivity required for this purpose. The feedback k_f is included in the power Equation (1) for determining ω . The solution for k thus consists of the reactivity required for both holding the reactor on the power trace and compensating for the feedback. Here k_f is set to zero.

FIGURE 3. Reactor and Coolant Flow.

FIGURE 4. Feedback Delta k.

FIGURE 5. Control Drum Angular Velocities.

FIGURE 6. Control Drum Rotation.

The cold frit and the nozzle require "tuning" for this calculation as they are not predetermined. This process varies the nozzle diameter and the axially dependent frit permeabilities to satisfy the following conditions at some point in time: the mean cold frit pressure drop is set at a fraction of the system pressure (1 MPa in the example), the mixed mean outlet temperature is prescribed, the axial flow splits are proportional to the axial power distribution. The time selected is the end of the sequence when a steady state is achieved.

Feedback

Feedback coefficients for canister coolant density, fuel density, Doppler, and moderator temperature are used. The reactivity change is assumed to be linear over the temperature range for the fuel density and moderator temperature feedbacks. The canister coolant density feedback is linear with coolant density, and the fuel Doppler assumes a $T^{-1/2}$ dependence for the reactivity coefficient, giving a $T^{1/2}$ dependence for the reactivity feedback.

Control Drums

The control loop is open for this problem and control rod position merely echoes the reactivities. Eventually this loop must be closed using some electro-mechanical inertial system to model drum responses. This loop will have a significant impact on transient simulations.

Problem Description

The problem is a start-up transient, specified in terms of initial conditions, pressure boundary conditions, and power history. The hydrogen coolant is supplied by pressurized tank farm. The fuel element configuration and reactor configuration are typical of a PBR NTP rocket engine.

The transient used in the example is controlled via linearly ramping the inlet pressure from initial pressure up to design pressure, and reactivity insertion by the control drums. The safety rods are assumed to be withdrawn. The control law uses a target power trace, which the control algorithm follows.

Transient History

Power history: 5 decades at a rate of 1 decade/s, which is an exponential power increase at a constant period. Power at end of transient is Design Power. This corresponds to a reactor period of 0.2326 s.

Inlet Pressure History: from initial pressure (0.1 MPa) to final pressure of 18 MPa linearly in 5 seconds. This controls the mass flow rate indirectly via the pressure drops in the system.

Test Problem Results

Figures 3-7 show a selection of results from the test problem. Power, flow, feedback, and control drum motion traces are shown as indicated. A temperature map for the fuel bed is given at 6.0 sec. in Figure 7.

FIGURE 7. Fuel Temperature Distribution.

CONCLUSIONS

The KINETIC code system is a viable transient analysis algorithm for studying the start-up and shutdown behavior of PBR based NTR engine. The flexibility of the code will allow the investigation of: TPA start strategies, reactor design variation to minimize feedbacks, and Engine shutdown strategies.

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References

- Achenbach, E. (1982) Heat Transfer and Pressure Drop of Pebble Beds Up to High Reynolds Number, Proc. 7th Int. Heat Transfer Conf. EP1, Munich.
- Bernard, John A., Kwans Kwok, David D. Lanning, Allan F. Henry, and John E. Meyer (1987) Application of the Reactivity Constraint Approach to the Transient Control of Spacecraft Reactors, Proceeding 4th Symposium on Space Nuclear Power Systems, Albuquerque, NM.
- Duderstadt, James J. and Louis J. Hamilton (1976), Nuclear Reactor Analysis, John Wiley and Sons, NY.
- El-Wakil, M. M. (1971) Nuclear Heat Transport, Intext, Scranton.
- Gear, C. William (1971) Numerical Initial Value Problems in Ordinary Differential Equations, Englewood Cliffs, N.J., Prentice Hall.

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