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THERMAL-HYDRAULIC MODELING OF POROUS BED REACTORS*

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Optimum design of nuclear reactor core requires an iterative approach between the thermal-hydraulic, neutronic and operational analysis. This paper will concentrate on the thermal-hydraulic behavior of a hydrogen cooled, small particle bed reactor (PBR).

The PBR core, modeled here, consists of a hexagonal array of fuel elements embedded in a moderator matrix. The fuel elements (see Figure 1) are annular packed beds of fuel particles held between two porous cylindrical frits. These particles, 500-600 μm in diameter, have a uranium carbide core, which is coated by two layers of graphite and an outer coating of zirconium carbide. Coolant flow, radially inward, from the cold frit through the packed bed and hot frit and axially out the channel, formed by the hot frit, to a common plenum.

A fast running 1-D lumped-parameter steady state code (FTHP) was developed to evaluate the effects of design changes in fuel assembly and power distribution. Another objective for the code was to investigate various methods of coolant control to minimize hot channel effects and maximize outlet temperatures.

The flow system is modelled as multiple parallel flows connected to common inlet and outlet headers. The coolant flow rate enters the core from the bottom and is distributed to each fuel element through inlet channels, as it is flowing axially upwards. Each inlet channel is connected to the surrounding fuel elements inlet plenum by narrow slots (0.1 cm). Flow through each

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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED fuel element is radially inwards toward the outlet channel. This imposes a constraint on the pressure drop across each flow path.

In the numerical method used to solve the above problem, the unit cell is divided into 10 axial zones and 9 radial zones. The fuel bed is subdivided into four equally spaced radial nodes. The power distribution as a function of r and z is obtained from 2-D neutron transport calculations.

Local flow is adjusted to the axial power distribution to maintain a uniform outlet temperature. Having the flow, the axial resistance of the cold frit is determined by solving a system of nonlinear equations.

The inlet and outlet channels, the inlet slot and inlet plenum are evaluated using the Fanning equation for pressure drop and the Colebrook[1] equation for friction factor. The two frits zones are based on an equation developed by Hill.[2]

In the packed bed, the pressure drop uses an Achenbach[3] correlation which is similar to Ergun[4] equation but includes an additional term for the transition region between viscous and turbulent flow.

An alternative approach was formulated to check the prediction of FTHP. In that method, we analyze thermal-hydraulic behavior for the unit cell using the two dimensional Brinkham-Forchheimer extended Darcy equations within the porous region, while Navier-Stokes equation governs the fluid motion in the fluid region. The solution method is based on the control volume approach with the power law scheme used for discritization of the fluxes at the control volumes boundaries. The resulting difference equations for the continuity, momentum and energy equations are solved by SIMPLER[5] algorithm.

Table 1 (a) illustrates, for a PBR of 200 MWt power, the axial pressure distribution, inlet frit porosity and Mach number at the outlet. Table 1(b) shows the radial nodal average coolant temperature, film temperature drop and heat transfer coefficient.

In Summary, the results of parametric thermal-hydraulic analysis of particle bed reactors have demonstrated the following:

(i) Careful design of the outlet channel to operate at Mach numbers less than 0.3, would maintain the total pressure drop in the core to less than 6% of the system pressure. The film temperature drop is also kept under 100 K with an average heat flux not exceeding 400 W/cm^2.

(ii) High bed power densities appear practical at reasonable operating pressures (e.g., approximately 70 atm). (Corresponding overall reactor power densities are approximately one-third of bed power density). Such power densities allow very high power outputs with small diameter reactors.

(iii) Proper porosity control in the cold frit, eliminating the problems of hot spots by maintaining uniform outlet temperature is feasible.

(iv) Only a small portion of the PBR core operates at high temperature, primarily the hot frit and a portion of the fuel particles (about 30 % are above 2000 K).

References

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Table 1 Thermal Hydraulic Parameters of Design Example

a) Axial Along an Average Single Element

Axial Position	Inlet Frit Porosity#		Inlet Pressure (atm)	Outlet Pressure (atm)	Mach No. in Outlet Duct
	Uniform Power Density	NonUniform Power Density*			
1	0.462	0.197	59.72	59.50	.18
2	0.579	0.271	59.73	59.52	.16
3	0.740	0.295	59.73	55.55	.14
4	0.919	0.451	59.74	59.58	.12
5	1.00	1.00	59.75	59.59	.11
6	0.896	0.734	59.77	59.60	.09
7	0.704	0.484	59.79	59.61	.07
8	0.539	0.302	59.83	59.62	.05
9	0.421	0.268	59.87	59.62	.04
10	0.359	0.172	59.93	59.63	.02

b) Radial at a Core Mid-Plane

Radial Position	Coolant Temperature (K)	Film Temperature Drop (K)	Heat Transfer Coefficient (KW/m^2-K)
1 (Inlet)	754	182	8.5
2	1584	120	13.0
3	2247	86	18.0
4 (Outlet)	2735	56	27.3

*Based on 2-D neutron transport calculations without fuel zoning

#Other thermal hydraulic parameters are based on the uniform power density

BASELINE FUEL ELEMENT & MODERATOR BLOCK

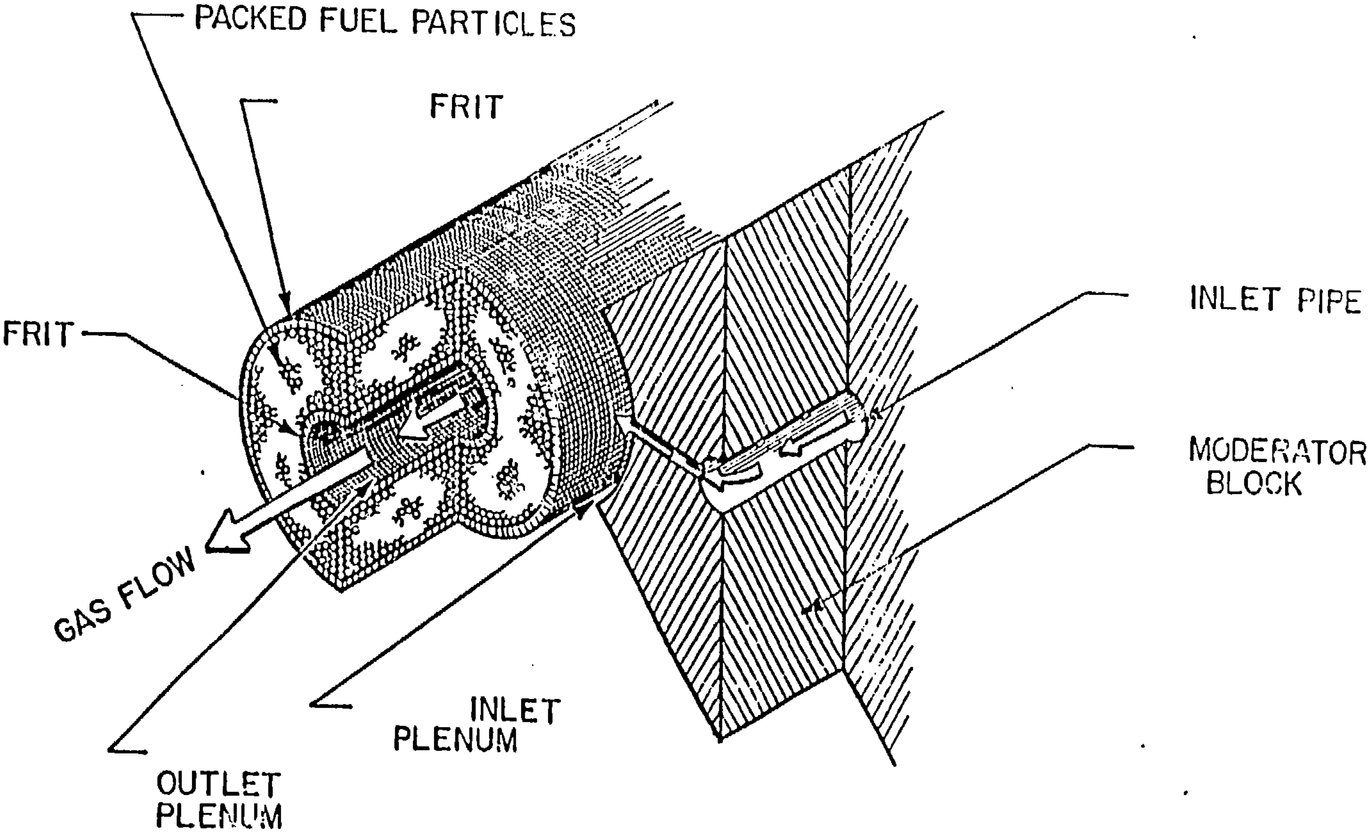

Figure 1