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FUEL ELEMENT TO MODERATOR ELEMENT HEAT TRANSFER ANALYSIS

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This paper concerns an issue in Nuclear Thermal Propulsion (NTP) reactor design, namely, the heat flow between Fuel Elements (FE) and Moderator Elements (ME) in a reactor. This question is important as this heat flow is used to drive the propellant turbopumps, and must be properly matched for successful operation of these rocket reactors. The current NASA GCD NTP design requires insight into this issue.

I. Introduction

The Fuel Element/Moderator Element (FE/ME) design was used in the Small Nuclear Reactor Engine (SNRE) [1] where the ME provides structural support for the reactor core, neutron moderating ZrHx (x=1.89), cooling of this moderator with cryogenic hydrogen flow through axial passages; further this heated hydrogen drives propellant turbopumps. In the original design study [1] (the reactor was not built), an estimated 6% of the FE heat flowed to the ME, and this heat conducts (Figure 1) from the FE through multiple materials in the ME, including moderator and high performance insulator layers, annular support tube (tie tube), all with intervening gaps.

In a high-fidelity numerical simulation of the SNRE engine [2], again 6% of FE heat to the ME was calculated. Figure 2 shows this calculated temperature profile; note the

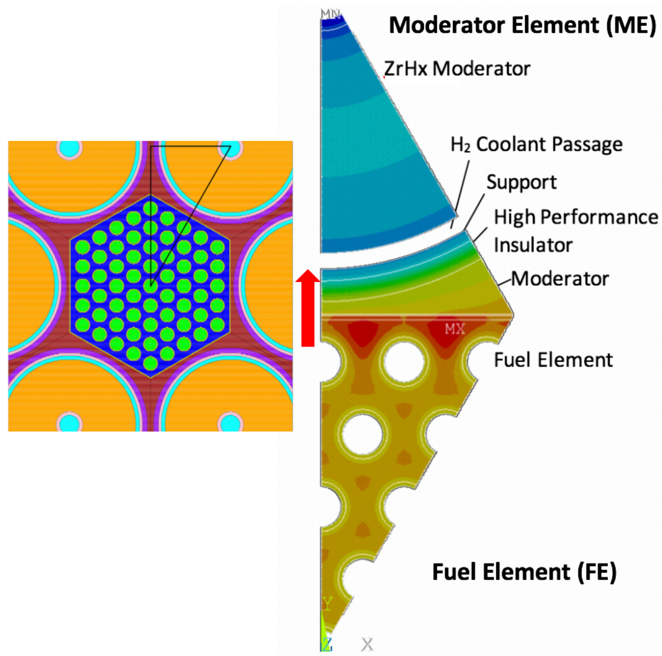

Fig. 1. Fuel Element/Moderator Element configuration (left) showing symmetric calculation region. ANSYS thermal simulation (right) of 2-D FE/ME section. Moderator Element layers are indicated. Red arrow indicates heat flow to ME.

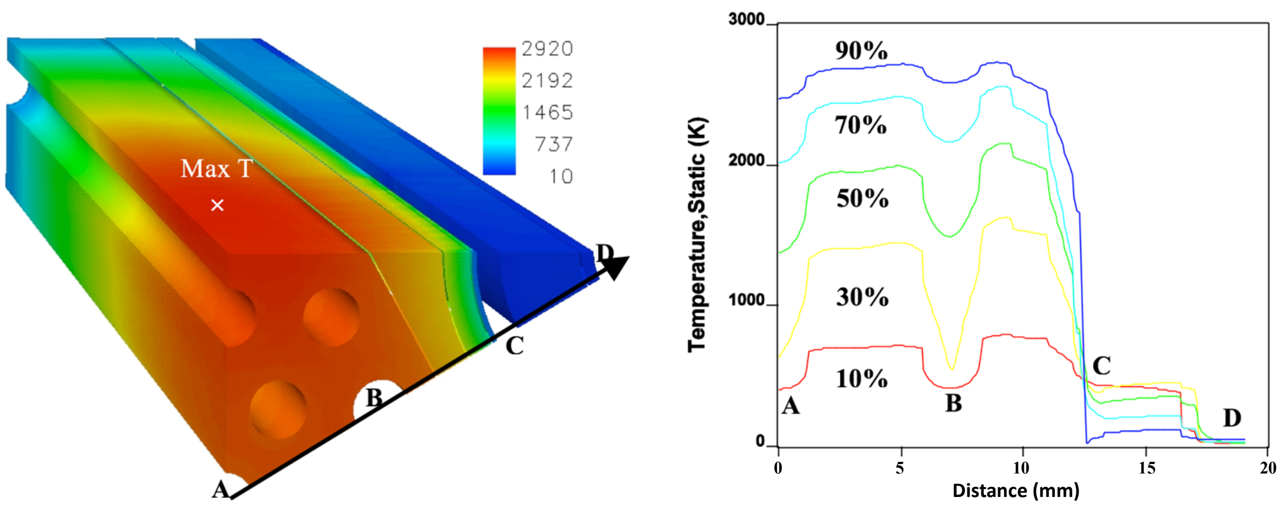

Fig. 2. Temperature distribution through SNRE fuel element (FE) and moderator element (ME) based on fluid/thermal simulations from [2]. The FE to ME heat flux is to the left of C, and is a high temperature gradient through a high performance thermal insulator.

high temperature gradient through the thermal insulator. However, this model assumed heat conduction through uniform thickness gaps (6.35×10^{-5} m) filled with stagnant hydrogen gas—no radiative heat transfer.

II. ANALYSIS

The dominant heat transfer effect is conduction in the high performance insulator, but, realistically, the heat flow through gaps is more complex than conduction. This paper aims to quantify the relevant effects through 1-D heat equation analysis and ANSYS 2-D thermal simulations (Figure 1). The heat transfer effects to be considered are:

1) Radiative heat transfer, particularly across the FE-ME gaps in the hottest parts of the FE.

2) FE thermal expansion will narrow gaps; conduction through hydrogen in a gap transitions to contact thermal conductivity between FE and ME claddings.

3) As gaps narrow to the mean free path of the filler gas, a 'temperature jump' occurs [3, p. 136] which limits conduction. What is the location and area of this condition, any reduction or diversion of heat transfer, and resulting temperature peaks?

4) Due to the presence of moderators, the edges of FE are exposed to higher neutron fluxes than at FE centers. MCNP simulations indicate a resulting linear increase in volumetric heat deposition rate starting 2.5 mm from the FE edge that peaks at double the rate near the edge.

5) Heat deposition within the ZrHx moderator, contributes additional heat to drive the turbopumps. The current MCNP prediction is 4% of total reactor power deposited into the ZrHx moderator.

There are two additional issues that may be difficult to resolve,

1) Tolerances in FE/ME dimensions may open or close gaps between components, so understanding and calculating heat transfer sensitivity is important.

2) Closed gaps experience a contact thermal conductivity which is dependent on surface finish, applied pressure and is difficult to predict.

Differences in axial thermal expansion between the ME material layers plus the FE, could result in binding and stress during operation, exacerbated by the wide range of thermal cycles. To avoid these stresses, the design may dimension FEs and MEs to simply avoid gap closing, thereby solving the issues of contact thermal conductivity and 'temperature jumps'.

II.A. 1-D Heat Equation

The first analysis method is a 1-D heat equation that includes conduction through material layers, plus conduction and radiation at gaps. Heat flux is conserved from the temperature peak near the fuel element edge, through material layers and gaps to the outer moderator passage. Realistic values of layer thickness, thermal conductivity, k, and emissivity, ε, have been used. Further, heat deposition rates for each material layer are taken from MCNP simulation results.

Figure 3 shows a typical temperature profile. The results indicate that substantial temperature jumps occur across gaps, particularly the FE to ME gap and between moderator layer and insulator layer. Further, radiation contributes significantly (20-40%) to heat transfer across the hottest gaps, but the levels are sensitive to emissivity values, ε.

II.B. 2-D Heat Equation on Fuel Element Sections

The second analysis method is ANSYS thermal simulations of 2-D fuel element sections; typical temperature predictions are shown in Figure 1. Thermal simulations on 2-D radial sections of a FE/ME are believed to be very cost effective and realistic, as heat transfer is predominantly in a radial direction. Further, the effect of hydrogen flow and cooling is adequately captured by specifying the wall temperature of the coolant tubes and the ME support tube. These simulations include conduction through material layers and gaps—no radiative heat transfer. Properties for each material include temperature dependent thermal conductivity, $k(T)$.

Table I shows simulation predictions on five radial sections along the FE/ME, from coldest to hottest. The results indicate that the dominant heat flow is at the hottest sections of the fuel.

3-D fluid/thermal simulations, as in Reference [2] for the SNRE engine, are not currently available for current

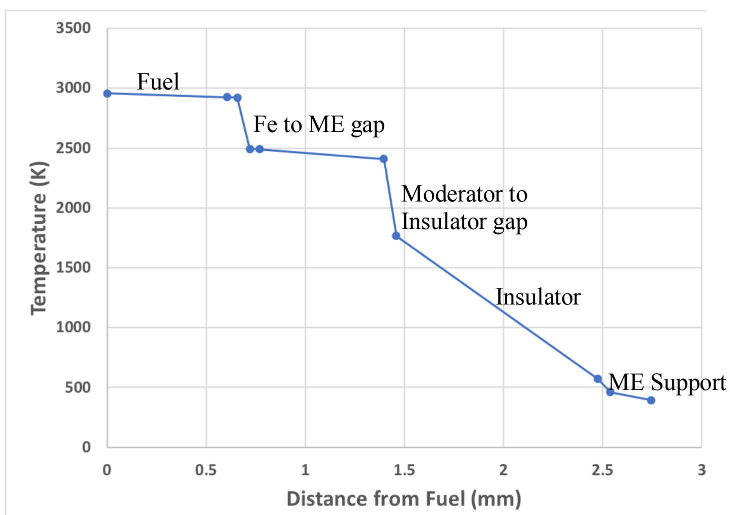

Fig. 3. Temperature profile predicted by 1-D heat equation. The reference heat flux is 3×10^6 W/m^2 at the hottest section of the FE/ME.

TABLE I. Five 2-D sections of FE/ME with thermal simulation predictions exactly as shown in Figure 1. The first four columns indicate imposed conditions, while the last four columns show predictions.

Coolant Channel Temperature (K)	Support Tube Temperature (K)	Fuel Heat Deposition (W/m^3)	Edge Heating Factor	Predicted Peak Temperature (K)	Predicted Heat Flux (W/m^2)	Normalized Heat Flux	Fraction of Section Heat Deposition (%)
200	400	3.0E+09	2	600	-3.3E+05	-0.04	-0.8
800	400	6.0E+09	2	1018	9.0E+05	0.11	1.1
1750	400	9.0E+09	2	2072	3.9E+06	0.49	3.1
2250	400	9.0E+09	2	2553	5.1E+06	0.64	4.1
2850	400	9.0E+09	2	3124	7.9E+06	1.00	6.4

engine designs. They should provide a third model of this heat transfer process.

III. CONCLUSIONS

How can reactor designs respond?

From a design perspective, the ‘control knob’ to achieve the desired FE to ME heat transfer is the thickness and quality of the high performance insulator (Figure 1).

The NERVA/Rover program included substantial efforts to develop high performance thermal insulators [4]. In the ME, the design intent [4, p. 31] was not only to “protect the tie tube (ME) from excessive temperatures,” and “reduce heat flux from the fuel”, but to “meter the heat flow to the support system coolant such that the gas exit conditions were proper for turbine operation.“

ACKNOWLEDGMENTS

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