PASSIVE AND ACTIVE COOLING ANALYSIS OF DECAY HEAT COOLING OF NUCLEAR THERMAL PROPULSION SYSTEMS

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Methods for decay heat removal are analyzed with the goal of reducing propellant consumption using TRansient Investigation COde for Reactor DEvelopments and Research (TRICORDER) tool developed by Ultra Safe Nuclear Corporation. TRICORDER is used to perform two-dimensional steady state conduction analysis to determine system radiative capabilities. 2-D results show significant reductions in cooldown time over legacy estimates. TRICORDER is also used to simulate three-dimensional transient active cooling through fuel and tie tube channels in order to evaluate hydrogen flow profiles. Legacy flow profiles are tested and deemed to be wasteful of hydrogen. Methods for reducing hydrogen consumption through more efficient flow profiles are discussed, and an example improved profile is simulated and commented upon.

I. INTRODUCTION

Nuclear Thermal Propulsion (NTP) systems’ modes of operation include short periods of reactor operation followed by extended cooldown periods. During the cooldown periods, the reactor is still producing decay heat that must be accounted for through cooling. This is initially done using active cooling consisting of passing the hydrogen coolant/propellant through the core and exhausting the hydrogen to environment. Once the NTP system can be cooled passively, the propellant is no longer used and radiative heat transfer to the environment is the mode of heat removal. The passive cooling involves radiating heat to the environment while maintaining the system below the temperature limits of the NTP components.

Extended active cooling requires the NTP system to contain larger qualities of propellant that negatively impacts the system performance and lowers average specific impulse (ISP). Thus, the increased understanding of propellant requirements needed for decay heat cooling would enable favorable cooling strategies reducing the amount of propellant needed. The purpose of this study is to gain a greater understanding of both active and passive cooling of NTP systems after reactor shutdown.

II. METHODOLOGY

The NTP system was analyzed for both passive and active cooling strategies using steady-state and transient thermal hydraulic analysis. Both analyses involve NTP system components such as the fuel element and tie tubes. The components’ geometries are provided in Fig. 1 and listed in Table I. The analyses were conducted using the TRansient Investigation COde for Reactor DEvelopments and Research (TRICORDER) tool developed by Ultra Safe Nuclear Corporation was used for the modeling.

II.A. TRICORDER

TRICORDER is a multiphysics design tool for NTP systems involving steady state and transient analysis. TRICORDER is developed in the Multiphysics Oriented Simulation Environment (MOOSE) Framework (Ref. 1) and utilizes several MOOSE built-in modules. TRICORDER has current capabilities to simulate coupled heat transfer in solids, compressible flow in 1-D channels, and point reactor kinetics.

![Fig. 1. Schematic of the NTP system components used in the analyses.](image)

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Coolant Channel</td>
<td>1</td>
</tr>
<tr>
<td>Fuel Inner Cladding</td>
<td>2</td>
</tr>
<tr>
<td>Fuel Meat</td>
<td>3</td>
</tr>
<tr>
<td>Fuel Outer Cladding</td>
<td>4</td>
</tr>
<tr>
<td>Tie Tube Coolant Supply</td>
<td>5</td>
</tr>
</tbody>
</table>

**TABLE I.** NTP system component listings.
| Tie Tube Inner Metal | 6 |
| Tie Tube Moderator | 7 |
| Tie Tube Outer Metal | 8 |
| Tie Tube Coolant Return | 9 |
| Tie Tube Insulator | 10 |
| Tie Tube Structure | 11 |

II.B. PHYSICS MODELING

For both modeling approaches, the time to passive cooling is limited by the lowest maximum temperature limit of the NTP system components. In this analysis, the tie tube moderator is limiting temperature with a maximum temperature of 900 K. This is due to the moderator being made of zirconium hydride (ZrH). Above this temperature, ZrH begins to lose significant amounts of hydrogen. This in turn degrades the structural integrity of the tie tube and make it a less effective moderator.

Both passive and active simulations require a model for decay power for either boundary conditions or post processing. For the both steady state and transient simulations, the power level was correlated to time required for active cooling using the following relationship in Eq. (1) from Denig and Eades (Ref. 2).

\[
\frac{P(t)}{P_0} = 0.1104 \left[ t^{-0.2436} - (t_{fp} + t)^{-0.2436} \right] \quad (1)
\]

The transient simulations utilized Eq. (1) for boundary conditions of the heat sources over time.

II.B.1. Passive Cooling (Steady State Modeling)

The passive cooling was simulated using TRICORDER’s steady-state heat conduction modeling for the 2-D core geometry and components shown in Fig. 2.

\[
\dot{q} = \varepsilon_0 (T_i^4 - T_e^4) A_{surf} \quad (2)
\]

The emissivity of the radiating surface is set to 0.95 assuming a high-performance radiative paint is used on the radiator surface. The heat sources for the different components are provided as percentages and applied by decay heat to implement the heating. The power generation percentages were generated using MCNP of the same geometry. It is assumed that all decay heat generated is conducted through the core to the outer boundary and radiatively transferred. Additionally, it is assumed that axial heat conduction is negligible.

The 2-D simulations were run for multiple power levels (decay heat) until the maximum power level was found that was within the temperature limit.

II.B.2. Active Cooling (Transient Modeling)

The active cooling was simulated using TRICORDER’s 3-D heat conduction and 1-D compressible flow modeling for the unit cell core geometry shown in Fig. 3. The components modeled in the unit cell are portions of the tie tube and fuel.

The solid heat transfer component was solved using Newton’s Method and the compressible flow component was solved using Preconditioned Jacobian Free Newton – Krylov. The Picard Iterative process was used between the subdivided solid and the fluids components. The time...
stepping was done using adaptive time stepping for both components.

Due to the significant differences in geometry of the fuel and tie tubes flow regions, different friction factor and heat transfer correlations were used for each region. The circular fuel channels use the Haaland correlation for friction factors (Ref. 3) and the Dittus-Boelter correlation for heat transfer coefficients. The tie tube supply channels use the Darcy-Weisbach correlation for friction factors and Gnielinski correlations for heat transfer coefficient (Ref. 4). The annular tie tube return channels use the Darcy-Weisbach correlations for friction factors and the Dirker-Meyer correlation (Ref. 5) for heat transfer coefficients.

The boundary conditions and initial conditions for the transient simulations include both spatial and time dependent qualities such as the propellant flow rate (hydrogen flow profile), chamber (operating) pressure, and decay power over time. All spatial boundary conditions are treated as symmetric boundaries (adiabatic) with the exception of fuel and tie tube channels simulated using the compressible flow module. These boundary conditions for each of these quantities were obtained from the Small Nuclear Rocket Engine (SNRE) design (Ref. 6 and 7). The different profiles for each quantity are obtained from the SNRE report.

The shutdown period (first 30 seconds), which are not specified in the SNRE report, must be articulated. This is done by fitting a quadratic profile between known flowrates at 0 and 30 seconds so that this period matches the 95.5 kg of hydrogen used during this time period per the SNRE report (Ref. 7).

For determining the hydrogen flow rate profile for time after 30 seconds, the estimated decay hydrogen consumption (Fig. 4) and the integral of propellant flow over time (Fig. 5) are used and extracted using WebPlotDigitizer (Ref. 8).

Since the SNRE core operated at a lower power level than the example core, interpolation was used to find effective estimated cooldown mass (Fig. 4) and time (Fig. 5). WebPlotDigitizer was used to fit the profile shape for the run in Fig. 5 to the new effective cooling time (Ref. 8). A numerical derivative was taken which yields the profile presented in Fig. 6.

The pressure profile is obtained through SNRE data presented in Fig. 7.
Chamber temperature and thrust from Fig. 7 were used to calculate pressure after shutdown. A negative pressure ramp was used to plot the pressure decrease until it reaches the engine conditioning hold.

The decay power profile used for the heat sources is made of three regions: a reactor point kinetics calculated initial behavior (< 1 second), a linear transition region (1 < t < 10 seconds), and the Eq. (2) relation (t > 10 seconds) and is shown in Fig. 9 (Ref. 2).

The resultant temperature profile can be seen in Fig. 10. The profile shows core temperature at different radial locations. The results confirm intuition that temperature decreases with increasing radial position. Centrally located tie tubes, which are shown to be the most limiting, are slightly below 900 K, meaning the power level is the maximum that can be safely radiated. Thus, the radiative threshold is 29.15 kW, which corresponds to a necessary cooling time of 28490 seconds (7.91 hours). This is a significant improvement upon the SNRE estimated radiative threshold of roughly 7 kW with its estimated cooling time of, 82815.97 (23.00 hours). Decreased cooling time will save large amounts of hydrogen.
III-B. TRANSIENT ANALYSIS OF ACTIVE COOLING

The results from the TRICORDER analysis of the SNRE hydrogen profile can be seen in Fig. 11. The profile succeeded in keeping core components below critical temperatures. However, the maximum observed temperature in the tie tube moderator (ZrH) was found to be well below the temperature limit during the majority of the active cooling mode. An attempt to improve the hydrogen usage was tested where the SNRE hydrogen profile that was uniformly reduced by 35.4%. The reduced profile uses a total hydrogen mass of 608.38 kg which saves 332.72 kg of hydrogen. A comparison of maximum fuel and tie tube moderator temperatures for the baseline SNRE and the reduced SNRE are shown in Fig. 11. Unfortunately, the reduced profile fails at 1e5 seconds (hrs) by going over the tie tube moderator temperature limit. An optimization method used to direct transient analysis could be used to locate an optimized reduced SNRE profile, which would offer non-trivial hydrogen savings.

Fig. 11. Core temperatures for the SNRE and Lowered SNRE hydrogen profiles.

IV. CONCLUSIONS

A two-dimensional conduction simulation was successfully implemented. The 2-D results provided a more precise estimate for the radiative threshold and showed significant reduced required cooling time from the times suggested in the SNRE report. A successfully implemented transient decay heat removal simulation evaluated the SNRE hydrogen flow profile as adequate but un-optimized and demonstrated a process for the simulation of future profiles. The failure of the lowered SNRE profile demonstrates the process for moving towards an optimized hydrogen flow profile.

NOMENCLATURE

\[ q \] decay power

\[ \varepsilon \] emissivity

\[ \sigma \] Stefan-Boltzmann

\[ A_{\text{surf}} \] radiating surface area

\[ T_{H/0} \] temperature of the environment.

\[ t_{fp} \] time at full power

\[ P_0 \] full power

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