NTP SYSTEM SIMULATION AND
DETAILED NUCLEAR ENGINE MODELING

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MODELING AND ENGINEERING SIMULATION OF NUCLEAR THERMAL ROCKET SYSTEMS

- Modular Thermal Fluid Solver with Neutronic Feedback
- Main Component Modules:
  - Pipes, Valves, Mixer
  - Nozzle Skirt
  - Pump, Turbine
  - Reflector, Reactor Core
- Hydrogen (Para- and Dissociated) Property Package
  - $10 \leq T \leq 10,000 \text{ K}$
  - $0.1 \leq P \leq 160 \text{ bar}$
- Models Developed for NTVR, NERVA and XNR 2000
- CFD and Heat Transfer Models for Main NTR Components

A detailed program for modeling of full system nuclear rocket engines is developed. At present time, the model features the expander cycle. Axial power distribution in the reactor core is calculated using 2- and 3-D neutronics computer codes. A complete hydrogen property model is developed and implemented. Three nuclear rocket systems are analyzed. These systems are: a 75,000 lbf NERVA class engine, a 25,000 lbf cermet fueled engine and INSPI's nuclear thermal vapor rocket.

NUCLEAR THERMAL ROCKET SIMULATION SYSTEM

The main program links all the component modules and iterates to arrive at the user specified thrust chamber pressure and temperature and thrust level. Reactor power and propellant flow rate are among outputs of the simulation program. Fuel elements in the core module are prismatic with variable flow area ratio. Each module divides the relative component into $N$ segments.
Axial temperature distribution of NTVR fuel surface and propellant in an average power rod. Reactor power is adjusted to achieve the thrust chamber temperature and pressure of 2750 K and 750 psi, respectively.

Normalized axial power distribution in C.C composite fuel matrix NTVR, calculated by DOT-2 S2 code. The axial power shape factor is an input for the simulation code.
Specific Impulse vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust

Chamber Temp.
- 3000K
- 2750K
- 2500K

Parametric study of thrust chamber pressure and temperature impact on sp of NTVR. At higher pressures sp is less sensitive to thrust chamber temperature.

Turbine Pressure Ratio vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust

Chamber Temp.
- 3000K
- 2750K
- 2500K

Turbine pressure ratio is sensitive to both thrust chamber pressure and temperature. For thrust chamber pressure of 1200 psi and temperature of 3000 K, the turbine pressure ratio of 1.26 is well within the range of available technology.
Axial temperature profiles for NERVA-75,000 lbf engine are presented. The maximum fuel temperature is 3490 K at .7 m from the core entrance.

Axial temperature distribution in XNR 2000 core is presented. XNR 2000 features a two path folded flow core fueled with CERMET. The maximum fuel temperature is 3000 K at about 85% from the entrance to the inner core region.
INSPI-NTVR Core Axial Flow Profile
Tc = 2750K  Pc = 750psi  F=75000lbf

Temperature (K)

Normalized Length

INSPI-NTVR Core Axial Flow Profile
Tc = 2750K  Pc = 750psi  F=75000lbf

Axial Power Shape Factor

Normalized Length
INSPI-NTVR Core Axial Flow Profile
Tc = 2750K  Pc = 750psi  F=75000lbf

INSPI-NTVR Core Axial Flow Profile
Tc = 2750K  Pc = 750psi  F=75000lbf
Core Exit Mach # vs Chamber Pressure
INPSI-NTVR @ 75000lbf Thrust

Turbine Pressure Ratio vs Chamber Pressure
INPSI-NTVR @ 75000lbf Thrust
Turbine Blade Speed vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust

Turbine Blade Diameter vs Chamber Pressure
INSPI-NTVR @ 75000lbf Thrust
P&W XNR2000 Core Axial Flow Profile
Tc = 2750K  Pc = 750psi  F=25000lbf

Normalized Length

Temperature (K)

Normalized Length

Axial Power Shape Factor

Normalized Length

Inner/Outer Core Boundary
P&W XNR2000 Core Axial Flow Profile

Tc = 2750K  Pc = 750psi  F=25000lbf

Pressure (MPa)

Normalized Length

P&W XNR2000 Core Axial Flow Profile

Tc = 2750K  Pc = 750psi  F=25000lbf

Mach Number

Normalized Length
NERVA Core Axial Flow Profile

\[ T_c = 2750K \quad P_c = 750\text{psi} \quad F = 75000\text{lbf} \]

![Temperature Profile](image1)

![Axial Power Shape Factor](image2)
Pump Pressure Rise vs Chamber Pressure
NERVA @ 75000lbf Thrust

![Graph showing pump pressure rise vs chamber pressure for different chamber temperatures (3000K, 2750K, 2500K).]

EVALUATION OF PARA- AND DISSOCIATED HYDROGEN PROPERTIES AT T = 10 - 10,000 K

- NASA/NIST Property Package
  (13.8 < T < 10,000 K and .1 < P < 160 bar)
  Molecular Weight, Density
  Enthalpy, Entropy
  Specific Heats, Specific Heat Ratio
  Thermal Conductivity, Viscosity

- Hydrogen Property Generator Code Features
  Linear Interpolation
  Natural Cubic Spline
  Least Square Curve Fitting with Pentad Spline Joint Functions

- Graphical Representation of Properties

The hydrogen property generator utilizes two interpolation techniques and a least-square curve fitting routine with a pentad spline function which links least-square fitted pieces together. The property generator package is incorporated into the NTR simulation code and also into a system of CFD-HT codes.
At higher temperatures, the heat capacity data displays smooth behavior. The sharp increase in $C_p$ value at temperatures above 2000 K is due to hydrogen dissociation.

Heat capacity of hydrogen near the critical point shows large gradient and oscillatory behavior. At $p = 2.35$ MPa the property package indicates a sharp peak for $C_p$. 

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The hydrogen property package is a combination of two subpackages covering the temperature ranges 10 - 3000 K and 3000 - 10,000 K, respectively. The large change of gradients in hydrogen viscosity at 3000 K indicates a non-physical flaw in the model.
Cp Versus Temperature for Para- and Dissociated Hydrogen

Thermal Conductivity Versus Temperature for Para- and Dissociated Hydrogen
Thermal Conductivity Versus Temperature for Para- and Dissociated Hydrogen

- Multigroup Cross-sections Generated by COMBINE (ENDFB-V)
- MCNP (4.2) for Complex Geometries
- BOLD VENTURE (3-D, Diffusion) for Power Profile and Reactivity Calculations
- ANISN (1-D, $S_n$) for Analysis of Heterogeneous Boundaries
- DOT IV (1, 2-D, $S_n$) for Analysis of Reflector
- XSDRNPM (1-D, $S_n$), TWODANT (2-D, $S_n$), NJOY, AMPX for Cross-comparison
VENTURE MCNP % DIFF

VENTURE,COMBINE (R&W)
MCNP4d (B&W)

0.96
0.96
0.94
0.94
0.94
0.94
0.97
0.97
0.97
0.97
0.95
0.95
0.95
0.95
1.06
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STREAMLINE OF JET-INDUCED FLOW IN CYLINDRICAL CHAMBER
Flow Pattern of A Jet-induced Flow in A Chamber
U-velocity Contour of Jet-induced Flow in A Chamber

V-velocity Contour of Jet-induced Flow in A Chamber
Grid System for a Hole of Nuclear Reactor Core

Velocity Fields for a Hole of Nuclear Reactor Core
Pressure Drop Correlation Comparison

Nusselt Number (Nu) and Pressure Drop (∆P) Correlation Comparison with CFD Analysis

(1) CFD Analysis

Energy Equation

\[
\frac{\partial (e + \sigma_T)u + \tau_{zz} - K_e \frac{\partial T}{\partial x}}{\partial x} + \frac{\partial ((e + \sigma_T)u + \tau_{zz} - K_e \frac{\partial T}{\partial y})}{\partial y} = S_i
\]

Numerical Algorithm: MacCormack hybrid implicit-explicit, finite volume method

Conductive Heat Flux

\[
q_u = -K_e \frac{\partial T}{\partial x} \bigg|_{x=R}
\]

Convective Heat Flux

\[
q_c = h_c (T_w - T_i)
\]

\[
T_w = \frac{\int T_c w T_d A}{\int \rho C_p w T_d A}
\]

Convective Heat Transfer Coefficient

\[
h_c = \frac{K_e \left[ \frac{\partial T}{\partial x} \right] \bigg|_{x=R}}{T_w - T_i}
\]

Nusselt Number

\[
Nu = \frac{h_c D}{K_e}
\]
**Diffusion Approximation**

\[ q'' = -\frac{4}{3} \chi \frac{\partial T}{\partial t} - \frac{16 \pi a^2 T^4}{3a} \]

\[ \chi = \frac{16 \pi a^2 T^4}{3a} \]

Using the perfect gas law,

\[ \chi = \frac{16 \pi a^2 T^4}{3a} \]

**WHERE**
- \( a \): Rosseland Mean Opacity
- \( \sigma \): Stefan-Boltzmann Constant
- \( \sigma_0 \): Photon Collision Cross Section per Molecule
- \( \kappa \): Boltzmann's Constant
- \( P \): Gas Pressure
- \( T \): Gas Temperature

**Approximation by Using 1-D Equation of Radiative Transfer**

\[
\begin{align*}
\int_{x}^{y} \alpha \cdot \exp(-\alpha(x-x')) dx' &= q' - q \\
q' - q &= \pi \left( i'(r') - i(r) \right)
\end{align*}
\]

**WHERE**
- \( \alpha \): Radiation Intensity in the Positive Direction (From Gas to Boundary)
- \( i'(r') \): Radiation Intensity in the Negative Direction (From Boundary to Gas)
- \( i(r) \): Source Function (\( \omega dT/\Delta T \))

**Nusselt number & Prandtl number**

\[
Re = \frac{\rho u D}{\mu (T_b - T_i)} \\
Pr = \frac{\rho(\gamma_1 k T_i)}{A i(T_i)}
\]

(III) Pressure Drop

**Compressible Flow**

\[
\Delta P = \frac{Re^2 T_m}{P_a} \left( ln \frac{P_i}{P_f} + \frac{2f \Delta Z}{D} \right)
\]

\[
\Delta P = \frac{C_9 (T - 1)^2}{2}
\]

\[
G = \frac{P_i + P_f}{2}
\]

\[
T_m = \frac{T_i + T_f}{2}
\]

\[
P_m = \frac{P_i + P_f}{2}
\]

**Incompressible Flow**

\[
\Delta P = \frac{2f \Delta Z}{\rho_i V_i^2} \left( \frac{T_i + T_f}{2} \right) + \rho_i V_i^2 \left( \frac{T_f}{T_i} - 1 \right)
\]

\[
f = 0.0011 + \frac{1}{Re^{0.24}}
\]
(II) Nußelt Number Correlations

(1) Colburn Equation
\[ \text{Nu} = 0.023 Re^{0.8} Pr^{0.4} \]

(2) Dittus-Boelter Equation
\[ \text{Nu} = 0.023 Re^{0.8} Pr^{0.33} \]

(3) Sieder- Tess Equation
\[ \text{Nu} = 0.027 Re^{0.8} Pr^{0.14} \left( \frac{D}{D_w} \right) \]

(4) Petukov Equation
\[ \text{Nu} = \frac{Re Pr (l)}{X} \left( \frac{f}{2} \right) \]
\[ X = 1.07 + 12.7 \left( \frac{Pr}{Pr+1} \right) \left( \frac{f}{2} \right) \]
\[ f = 0.0014 + \frac{1}{8} Re^{-0.13} \]

(5) Karman-Boelter-Martinelli Equation
\[ \text{Nu} = \frac{Re Pr \sqrt{f}}{0.833 \left( 5Pr + 5\ln (5Pr + 1) + 2.5\ln \left( Re \sqrt{\frac{f}{4}} \right) \right)} \]
\[ f = 0.0014 + \frac{1}{8} Re^{-0.32} \]

Axial Distance Correction
\[ \text{Nu}(x) = \text{Nu} \left( 1 + \frac{x}{D} \right)^{-0.15} \sqrt{\frac{T_1}{T_w}} \]
\[ \text{Nu}(x) = \text{Nu} \left( 1 + \frac{2ln \frac{D}{D_w}}{b} \right) \]

Figure 6.2 Velocity distribution for a fully developed turbulent flow in tube. (Re=1.6 E+4)
Figure 6.17 Nusselt number vs. axial position for a developing isothermal pipe flow at a Reynolds number of 53000. 
(Nu)ref is the Nusselt number evaluated at Z/D=20.

Figure 6.15 Heat transfer rates obtained by Navier-Stokes solver for various boundary cell size. A 60x60 grid is used. 
(Tin=4000 K, T_w=1800 K, P=1 atm, and P_m=0.5 atm)
Figure 6.16 Heat transfer rates obtained by Navier-Stokes solver for various boundary cell size. A 60x80 grid is used. 
\(T_r=4000 \text{ K}, T_s=1800 \text{ K}, P_m=10 \text{ atm}, \text{ and } P_{ms}=9.5 \text{ atm}\)

Figure 6.19 Comparative result between diffusion approximation and 1-D integral approximation for varying the gas opacity due to different flow conditions.