

Review of 1.5-Dimensional Thermal-Hydraulic and POWER System Analysis Methodologies for Nuclear Thermal Propulsion

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Nomenclature		C_p	Specific heat capacity at constant pressure ($J/kg \cdot K$)
Abbreviations		A	Area (m^2)
NTP	Nuclear Thermal Propulsion	q''	Heat flux (W/m^2)
FE	Fuel Element	q	Heat generation rate (W)
ME	Moderator Element	η	pump efficiency (-)
		h	Pump head (m)
		Q	pump power (W)
Symbols			
T	Temperature (K)		
R	Thermal resistance (K/W)	Subscripts	
P	Pressure (Pa)	i	Node index, $i = 1, \dots, N$
ρ	Density (kg/m^3)	N	Total number of nodes
$\dot{m}$	Mass flow rate (kg/s)	b	Bulk

1. Introduction

Nuclear thermal propulsion (NTP) heats hydrogen propellant using nuclear fission energy and expands it through a nozzle to generate thrust. With approximately twice the specific impulse of chemical rockets, NTP is considered a promising technology for Mars and deep-space missions [1].

NTP analysis requires coupled consideration of neutron and gamma transport, heat transfer, hydrogen flow, and system components. To reduce the computational cost of repeated high-fidelity analyses, Krecicki and Kotlyar applied an integrated framework coupling SERPENT, 1.5-dimensional THERMO, and POWER [1]. SERPENT calculates neutron and gamma transport and the resulting power distributions, THERMO performs 1.5-dimensional thermal-hydraulic analysis of the fuel and moderator elements, and POWER couples the major components of the expander cycle to determine system temperatures, pressures, and mass flow rates. This review focuses on the assumptions, reduced-order models, and coupling procedures used to simplify and analyze the NTP system.

2. NTP System and Major Core Components

2.1 Basic Principles of the Expander Cycle

The target study adopts an expander cycle for the NTP system, and the overall system configuration and hydrogen flow paths are shown in Fig. 1.

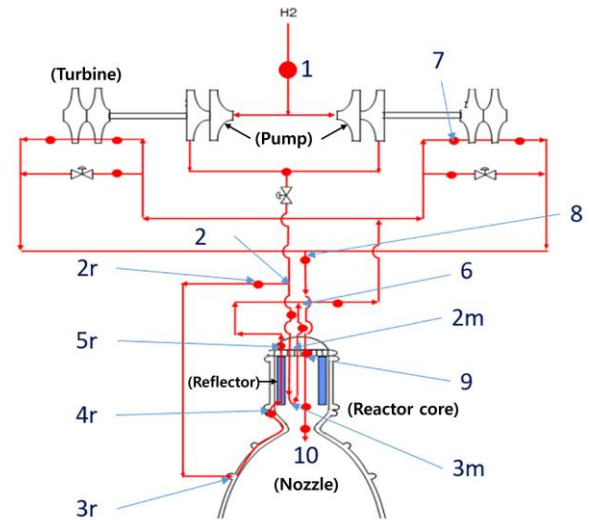


Fig. 1. Large NERVA expander cycle [2].

Hydrogen from the tank is pressurized by the pump at Point 1 and then divided at Point 2 into the nozzle/reflector cooling path and the moderator-element path. The nozzle/reflector flow follows the 2r–3r–4r–5r path, while the moderator flow passes through 2m–3m and then through the return channel, absorbing heat while cooling the corresponding structures. The two streams merge at Point 6, after which a portion of the hydrogen passes through the turbine at Point 7, where its enthalpy decreases to provide the power required to drive the pump. The turbine outlet flow and the bypass flow recombine at Point 8 and enter the fuel element at Point 9. Finally, the hydrogen is heated to a high temperature in the fuel

element and discharged through Point 10 into the nozzle to generate thrust [1].

2.2 Fuel element

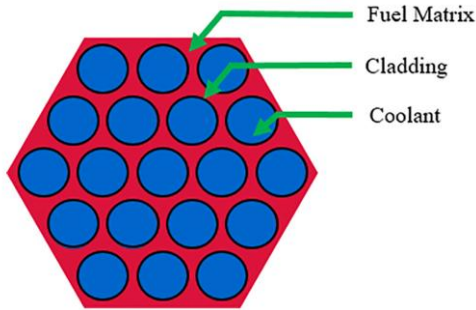


Fig. 2. Fuel element cross section.

The fuel element (FE) is the primary heat-generating component of the NTP system, where fission energy is produced and transferred to the hydrogen propellant. In the target study, the FE is based on the KIWI-4BE design and has a hexagonal configuration containing 19 hydrogen coolant channels [1]. In THERMO, the actual hexagonal geometry is simplified as an equivalent annulus to calculate radial heat conduction and heat transfer to the coolant channels [1].

In the thermal-hydraulic analysis, the fuel centerline temperature is used as a major thermal constraint. Because the reactor power is adjusted to prevent the fuel centerline temperature from exceeding its allowable limit, this parameter constrains the allowable fuel-element power and ultimately the propulsion performance [1]. In addition, THERMO neglects axial heat conduction in the solid and considers only radial heat conduction, while the power distribution within each fuel element is assumed to be uniform [1].

2.3 Moderating element

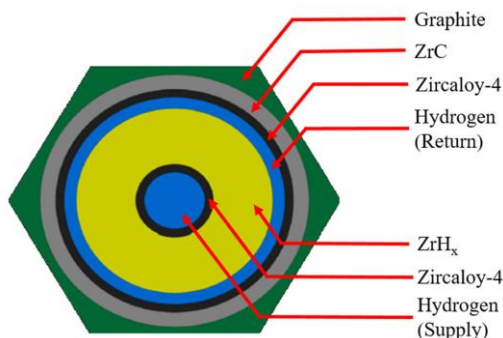


Fig. 3. Moderating element cross section.

The moderator element (ME) serves to slow down neutrons in the LEU-based core and thereby support criticality, while also providing cooling and thermal insulation to maintain the internal ZrH_x within its allowable temperature range. In the target study, hydrogen flows through a two-pass configuration consisting of a supply channel and a return channel.

Hydrogen in the supply channel cools the central ZrH_x , after which the flow reverses direction and passes through the return channel, where it absorbs heat while cooling the internal and external ME structures before returning out of the core [1].

To protect the ZrH_x from the high-temperature FE, a porous ZrC insulation layer is placed around the outer region of the ME [1]. In addition, accurate calculation of heat transfer in the ME return channel requires the temperature distribution of the adjacent FE, indicating that the thermal-hydraulic analyses of the FE and ME cannot be performed independently. Therefore, THERMO performs a coupled FE–ME analysis in which the thermal boundary conditions between the two elements are iteratively updated [1].

3. 1.5-Dimensional Thermal-Hydraulic Analysis Using THERMO

THERMO is a 1.5-dimensional thermal-hydraulic code used to analyze the thermal-hydraulic behavior of the fuel and moderator elements in NTP systems. It combines radial heat conduction in the solid with axial convection of hydrogen to calculate the temperature and pressure distributions, while the complex element geometries are simplified using an equivalent-annulus representation [1].

3.1 Radial conduction model

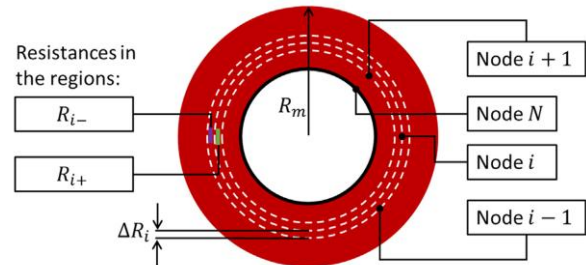


Fig. 4. Radial conduction resistance network.

In THERMO, the complex geometries of the actual fuel and moderator elements are simplified as an equivalent annulus for heat-transfer calculations. Axial heat conduction within the solid is neglected, and only radial heat conduction is considered. At each axial layer, the radial domain is divided into multiple nodes to calculate the steady-state temperature distribution [1].

A finite-difference method is applied to the radial heat conduction analysis, and a heat balance equation is formulated using the internal heat generation of each node and the thermal resistance between adjacent nodes [1,3]. As shown in Fig. 4, the temperature of radially discretized node i is calculated as follows.

$$T_i = \frac{q_i + \sum_j \left(\frac{T_j}{R_{ij}} \right)}{\sum_j \left(\frac{1}{R_{ij}} \right)} \quad (1)$$

Here, q_i represents the heat generated in node i , and R_{ij} denotes the thermal resistance between node i and the adjacent node j . This radial heat conduction method is commonly applied to both the fuel element and the moderator element [1].

By assembling the nodal heat-balance equations, the system can be expressed in a tridiagonal matrix form as follows:

$$\begin{bmatrix} \frac{1}{R_{1-}} + \frac{1}{R_{1+}} & -\frac{1}{R_{1+}} & 0 & 0 & \dots & 0 \\ -\frac{1}{R_{2-}} & \frac{1}{R_{2-}} + \frac{1}{R_{2+}} & -\frac{1}{R_{2+}} & 0 & \dots & 0 \\ \vdots & \dots & \ddots & \ddots & \dots & \vdots \\ 0 & \dots & 0 & -\frac{1}{R_{(N-1)-}} & \frac{1}{R_{(N-1)-}} + \frac{1}{R_{(N-1)+}} & -\frac{1}{R_{(N-1)+}} \\ 0 & \dots & 0 & 0 & -\frac{1}{R_{N-}} & \frac{1}{R_{N-}} + \frac{1}{R_{N+}} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_{N-1} \\ T_N \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_{N-1} \\ q_N + \frac{T_b}{R_{N+}} \end{bmatrix} \quad (2)$$

The resulting matrix equation is solved to obtain the nodal temperature distribution. Because thermal conductivity varies with temperature, the calculated temperature distribution is used to update the thermal conductivities and corresponding thermal resistances. The temperature distribution is then recalculated, and this iterative procedure is repeated until convergence is achieved [1].

3.2 Axial convection and pressure drop models

In THERMO, axial heat conduction within the solid is neglected, and axial heat transport is accounted for through convection by the hydrogen coolant [1]. At each axial layer, the heat transferred from the solid to the coolant is determined from the radial heat conduction analysis and is then used to calculate the hydrogen outlet bulk temperature of that layer.

The hydrogen outlet bulk temperature at each axial layer is calculated as follows [1]:

$$T_{b,out} = T_{b,in} + \frac{A}{\dot{m}C_p} q'' \quad (3)$$

Where $T_{b,in}$ and $T_{b,out}$ are the hydrogen inlet and outlet bulk temperatures of the corresponding axial layer, respectively; A is the heat-transfer area; q'' is the heat flux transferred to the hydrogen; $\dot{m}$ is the hydrogen mass flow rate; and C_p is the specific heat capacity of hydrogen at constant pressure. The outlet bulk temperature calculated for one layer is used as the inlet condition for the next axial layer, and this procedure is repeated sequentially along the flow direction to determine the axial distribution of the hydrogen bulk temperature [1].

The pressure drop in each thermal-hydraulic channel is calculated by accounting for friction, form, and acceleration losses, while the pressure loss due to gravity

is neglected [1]. Accordingly, the hydrogen outlet temperature and pressure calculated at each axial layer are used as the inlet conditions for the subsequent layer.

3.3 Coupled Analysis of the Fuel and Moderator Elements

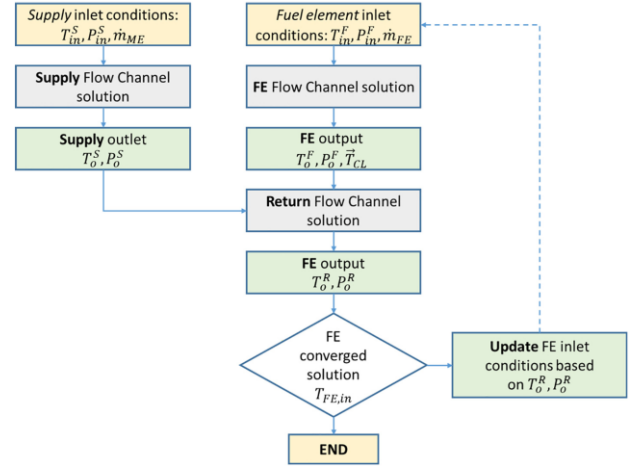


Fig. 5. Iterative scheme to calculate the heat transfer from fuel to moderating elements.

Figure 5 illustrates the coupled FE–ME thermal-hydraulic analysis procedure performed in THERMO. First, the moderator supply channel is calculated, and its outlet temperature and pressure are used as the inlet conditions for the return channel [1].

The fuel element (FE) is analyzed using the 1.5-dimensional thermal-hydraulic model with initially assumed inlet temperature and pressure. Radial heat conduction and axial hydrogen convection are calculated at each axial layer to determine the fuel centerline temperature and axial temperature distribution. The resulting FE temperature distribution is then applied as the thermal boundary condition for the moderator return channel [1].

The return-channel outlet conditions are subsequently used through the overall system flow path to determine updated FE inlet temperature and pressure. These updated inlet conditions are compared with the previous values, and the calculation is repeated until the FE inlet temperature and pressure converge [1].

4. Overall Computational Framework for the NTP System

POWER is a system analysis code developed to analyze the overall NTP expander cycle by coupling the pump, piping, nozzle/reflector, moderator elements, turbine, and fuel elements within a single system [1]. It calculates the temperature, pressure, and mass flow rate at each system state point and iteratively adjusts the major system variables to satisfy the specified operating conditions.

The POWER analysis uses axial power distributions obtained from SERPENT, a Monte Carlo-based neutron

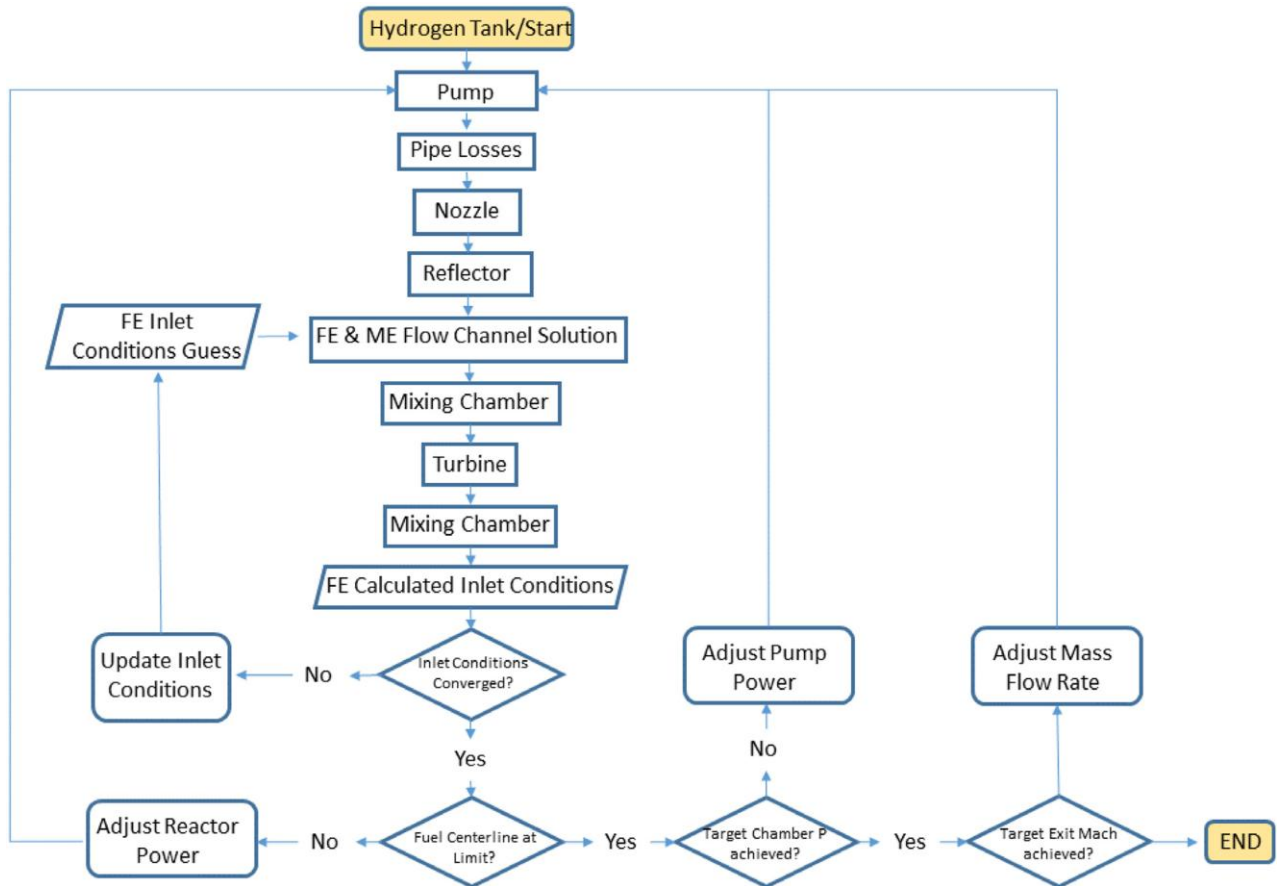


Fig. 6. POWER code calculation sequence.

and gamma transport code. SERPENT calculates the axial power distributions in the fuel elements, moderator elements, and reflector, which are then transferred to THERMO as heat-source inputs [1].

Figure 6 illustrates the overall calculation and iterative convergence procedure implemented in POWER. Based on the calculated thermal-hydraulic states of the individual components, the reactor power, pump power, and total mass flow rate are iteratively adjusted until the specified operating conditions are satisfied [1].

4.1 Pump

Hydrogen from the tank enters the pump, and the pump outlet pressure and temperature are calculated from the specified mass flow rate and inlet conditions. The pressure rise across the pump is calculated using the pump head and the inlet hydrogen density as follows [1]:

$$P_{out} = \rho_{in} h_{calc} + P_{in} \quad (4)$$

Where P_{in} and P_{out} are the pump inlet and outlet pressures, respectively; ρ_{in} is the hydrogen density at the pump inlet; and h is the pump head.

For pump powers different from the reference operating point, the pump head is adjusted using the pump affinity law [1]:

$$h_{calc} = h_k \cdot \left(\frac{Q_p}{Q_k} \right)^{2/3} \quad (5)$$

Where h_k and Q_k are the pump head and pump power at the reference operating point, respectively, and Q_p is the adjusted pump power. This relation is used to determine the corresponding pump head under off-design pump-power conditions.

The pump outlet temperature, accounting for the energy transferred to the hydrogen, is calculated as follows [1]:

$$T_{out} = T_{in} + \frac{Q_p \eta_p}{\dot{m} c_p} \quad (6)$$

Where η_p is the pump efficiency.

4.2 Pipe losses

The piping is assumed to be adiabatic, with no additional heat transfer to or from the hydrogen. The pressure drop along the pipe is calculated by accounting for frictional losses and pressure changes associated with fluid acceleration, while the pressure loss due to gravity is neglected [1].

$$P_{out} = P_{in} - \frac{f l v^2}{2 D_{eH} \rho} - (\rho_{in} v_{in}^2 - \rho_{out} v_{out}^2) \quad (7)$$

Table 1: POWER large NERVA sub-function vs NPSS.

Function	T _{in} [K]	P _{in} [MPa]	$\dot{m}$ [kg/s]	T _{out} [K]	T _{out} [K]	P _{out} [MPa]	P _{out} [MPa]
				NPSS	POWER	NPSS	POWER
Pump	22	0.22	6.34	38	40.1	15.65	15.66
Turbine	387	13.61	3.86	353	351	8.38	8.38
Mixing Chamber	387, 353	13.61, 8.38	2.48, 3.86	367	366	8.38	8.38
Nozzle	39	15.35	7.53	171	172	14.29	14.29
Reflector	171	14.29	7.53	260	259	13.61	13.62

Where f is the friction factor, l is the pipe length, D_{eH} is the hydraulic diameter, and v is the hydrogen flow velocity [1]. This pipe pressure-loss calculation is applied to the section between Point 1-2 in Fig. 1.

4.3 Nozzle and Reflector Cooling

The nozzle and reflector cooling paths are axially divided to calculate the hydrogen temperature rise and pressure loss. The heat transferred to the nozzle regenerative cooling flow is assumed to be 10% of the total reactor power, and the axial power distribution in the nozzle is assumed to be uniform. The axial power distribution in the reflector is directly obtained from the SERPENT calculation results. This calculation is applied to the Point 2r–5r section shown in Fig. 1.

4.4 Mixing Chamber

The reflector outlet flow and the ME return-channel outlet flow are recombined, and the mixing section is assumed to be an adiabatic mixing chamber. The hydrogen temperature after mixing is calculated from energy conservation by accounting for the mass flow rate and thermal state of each stream [1].

$$T_{out} = \frac{\dot{m}_1 c_{p,1} T_{in,1} + \dot{m}_2 c_{p,2} T_{in,2}}{\dot{m}_1 c_{p,1} + \dot{m}_2 c_{p,2}} \quad (8)$$

4.5 Turbine

A portion of the mixed hydrogen passes through the turbine, where it loses enthalpy and provides the power required to drive the pump. The pump and turbine are connected by the same shaft, and the turbine is assumed to operate at a constant pressure ratio regardless of the mass flow rate [1]. The turbine outlet pressure is determined from the specified pressure ratio, while the outlet temperature is calculated as follows [1]:

$$T_{out} = T_{in} - \frac{Q_p \eta_t}{\dot{m} c_p} \quad (9)$$

The turbine outlet temperature and the average specific heat are iteratively updated until convergence is achieved. The turbine calculation corresponds to Point 7 in Fig. 1.

4.6 Validation of the POWER Code

Krecicki and Kotlyar validated the major functions of the POWER code by comparing its results with previously reported Numerical Propulsion System Simulation (NPSS) results [1,4]. In this review, the POWER–NPSS comparison results for the large NERVA system presented in [1] are summarized in Table 1. The two sets of results showed overall good agreement. Although some discrepancies may arise from differences in the hydrogen property libraries, the largest difference was reported for the pump outlet temperature, at approximately 3 K. This difference is small relative to the overall temperature range of the engine cycle, indicating that the component outlet-state calculations performed by POWER are in good agreement with the corresponding NPSS results [1].

5. Conclusion

This review examined the 1.5-dimensional thermal-hydraulic and system analysis methodologies for NTP systems. THERMO simplifies the fuel and moderator elements using an equivalent-annulus representation and analyzes radial heat conduction and axial hydrogen convection, while POWER couples the major system components and iteratively determines the operating conditions of the overall expander cycle. This framework enables efficient analysis of the complex NTP system through reduced-order thermal-hydraulic modeling and system-level coupling. In addition, the POWER component calculations showed good agreement with previously reported NPSS results [1,4].

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