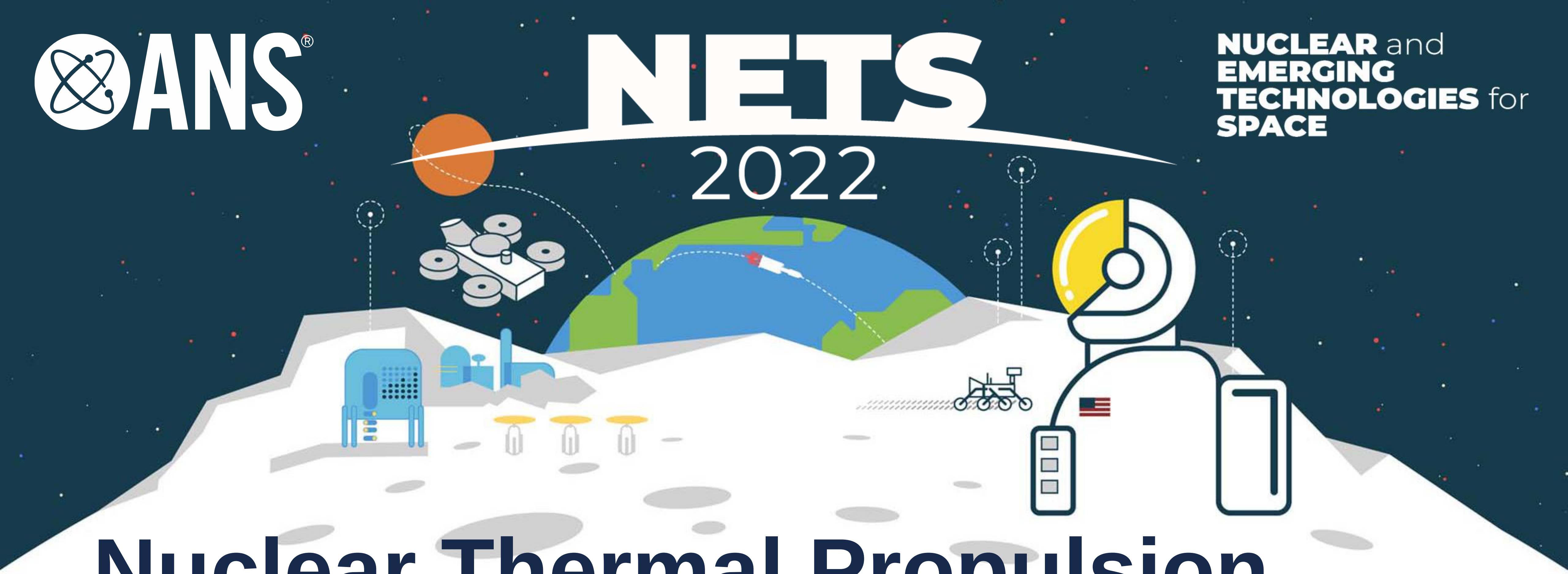

Nuclear Thermal Propulsion Turbomachinery Modeling

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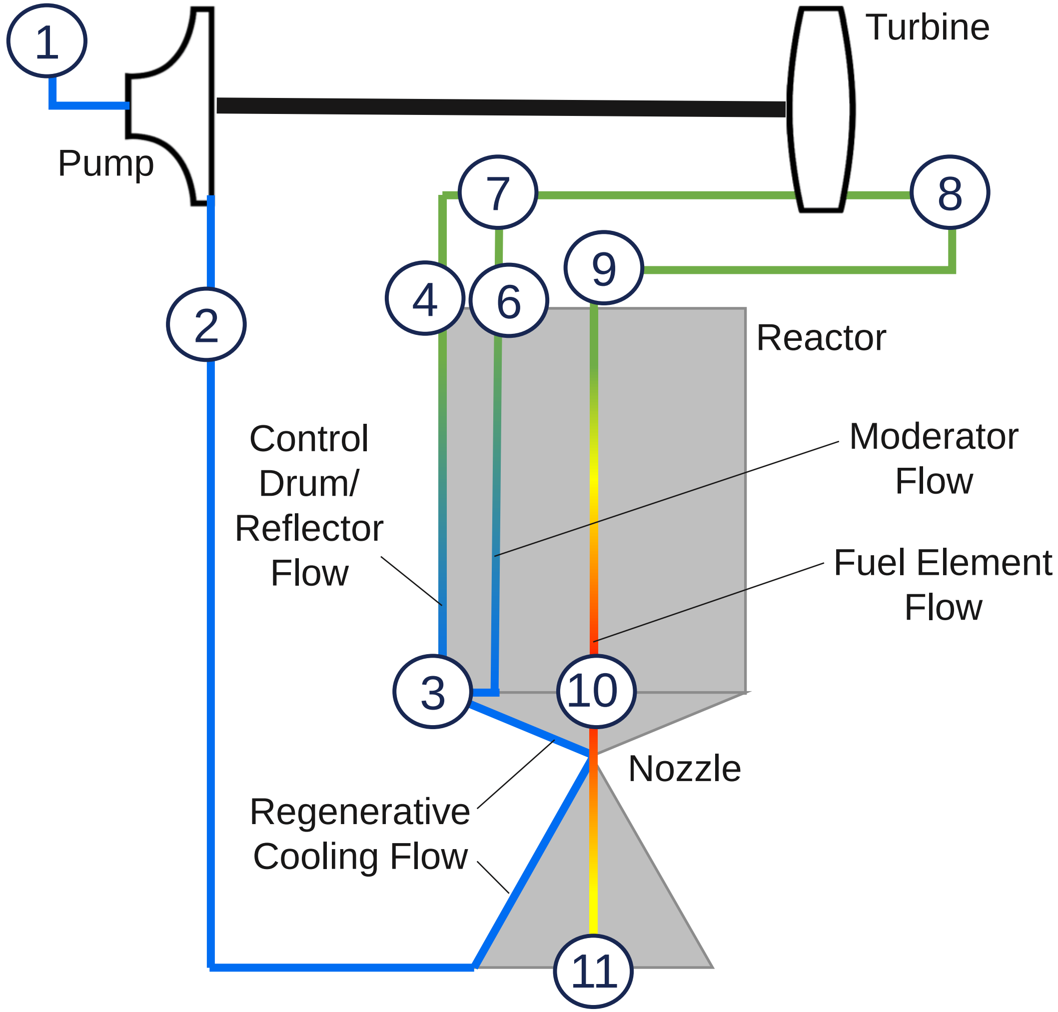
Agenda

- Introduction to Nuclear Thermal Propulsion (NTP) Modeling
- Component Level Modeling
- System Integration
- Transient Consideration
- System Mass Modeling
- Conclusions/Future Work

Nuclear Thermal Propulsion (NTP) Modeling Overview

NTP is a monopropellant system that relies on convective heat transfer from a reactor to the propellant to enable high in-space thrust and specific impulse

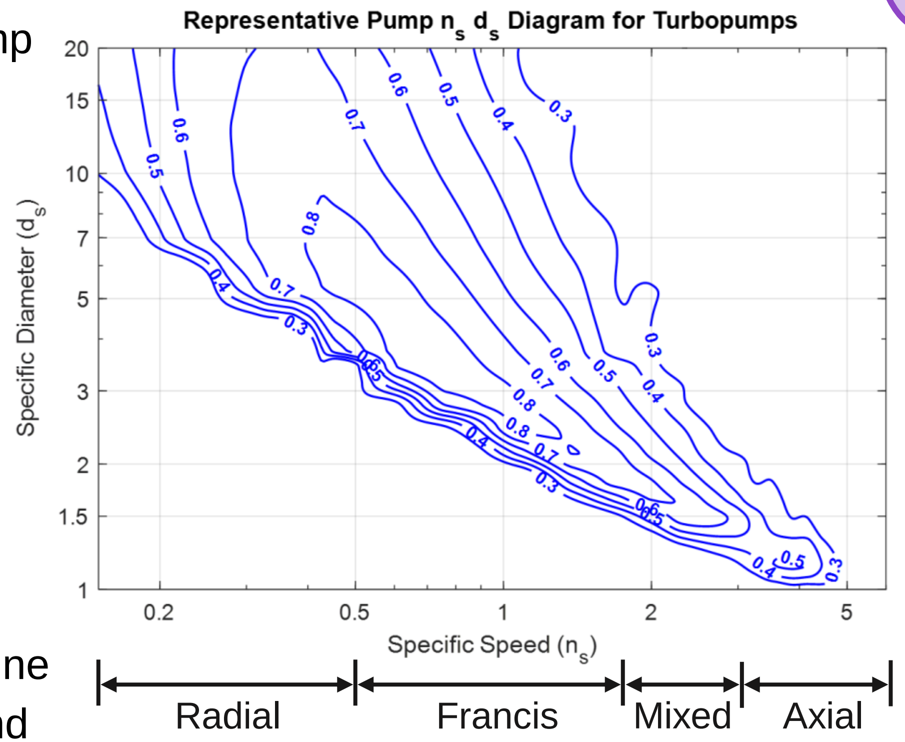
- NTP engines provide thrust levels comparable to chemical engines while doubling the specific impulse with a hydrogen propellant.
- The propellants used are only limited by the material compatibilities.
- Heat is produced via nuclear fission and the heat distribution along the flow channels must be considered.
- The non-nuclear engine may leverage components previously developed through liquid chemical rocket engine development programs.
- Both bleed and expander cycles are applicable.

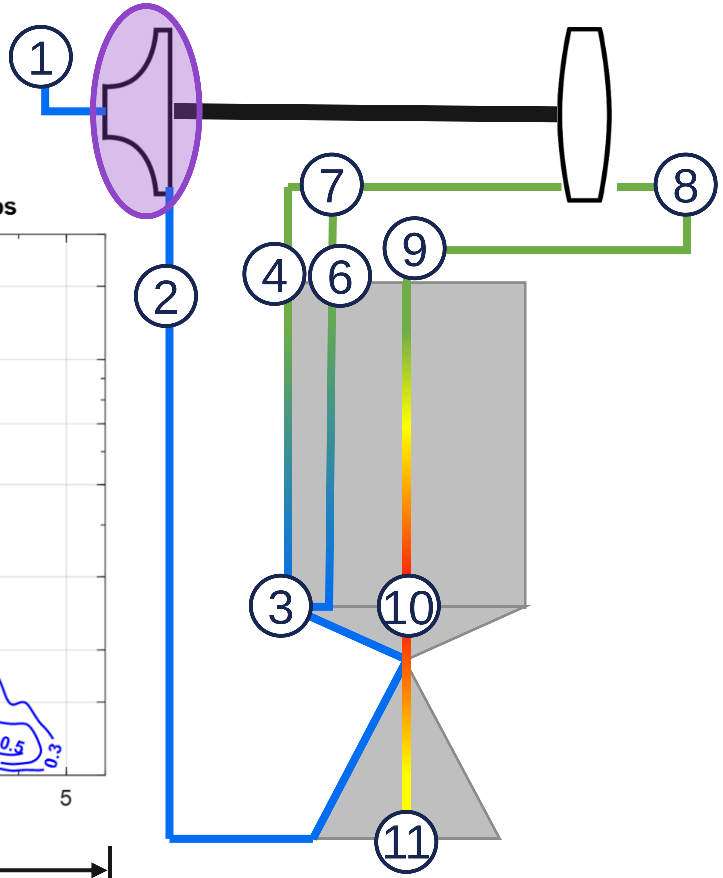


Pumps

Non-dimensional parameter approach (affinity relations)

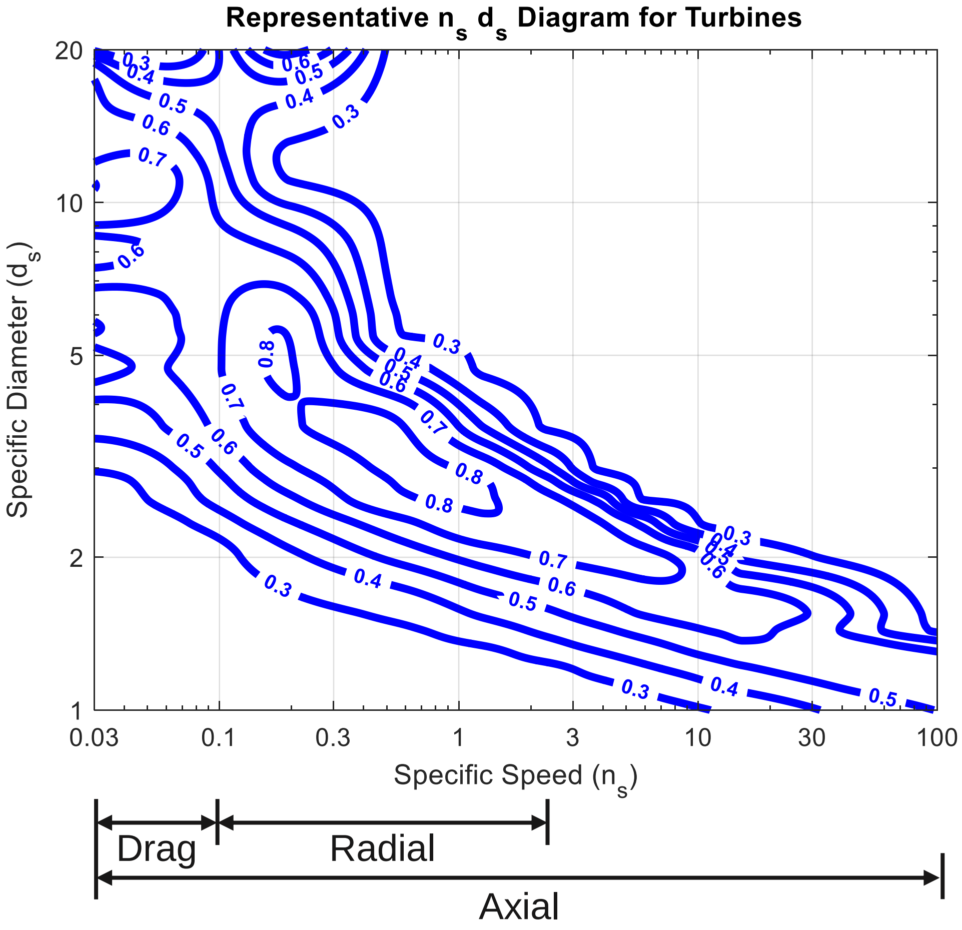
- **Three pump definition parameters:**
  - Change in pressure: ΔP
  - Physical pump diameter: D_p
  - Pump specific speed – characterizes pump type and pump rotational velocity: n_{sp}
- **Pump speed:**
  - $\omega = \dfrac{n_{sp}\left(g_0 H_p\right)^{3/4}}{\sqrt{\dot{\forall}_p}} = \dfrac{n_{sp}\Delta P^{\ 3/4}}{\rho^{1/4}\sqrt{\dot{m}_p}}$
- **Specific diameter:**
  - $d_{sp} = \dfrac{D_p\left(g_0 H_p\right)^{1/4}}{\sqrt{\dot{\forall}_p}} = \dfrac{D_p[\rho\Delta P]^{1/4}}{\sqrt{\dot{m}_p}}$
- The n_{sp} and D_p values are changed to determine the highest pump efficiency to automatically find the pump parameters.

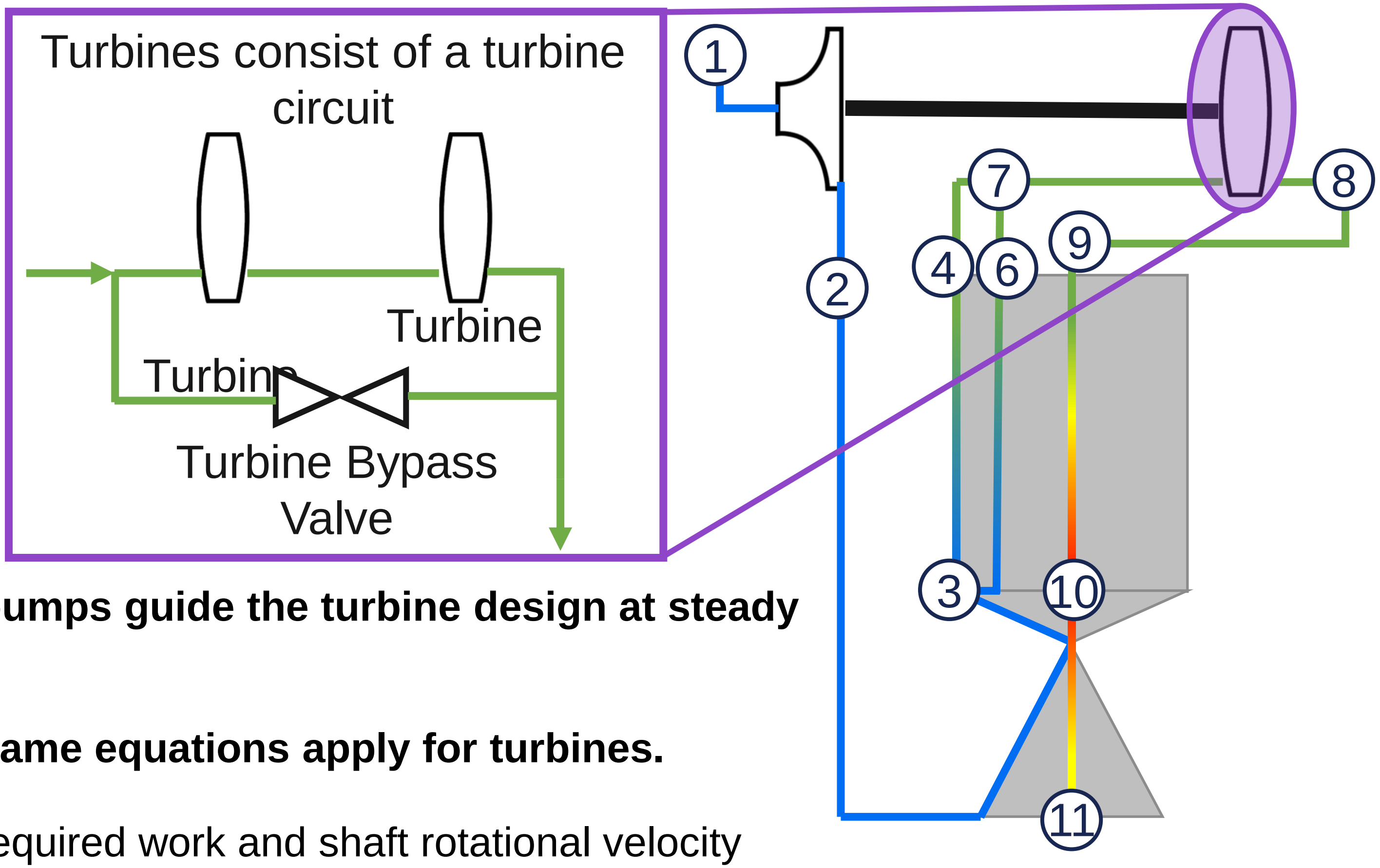




Turbines

Non-dimensional parameter approach (affinity relations)

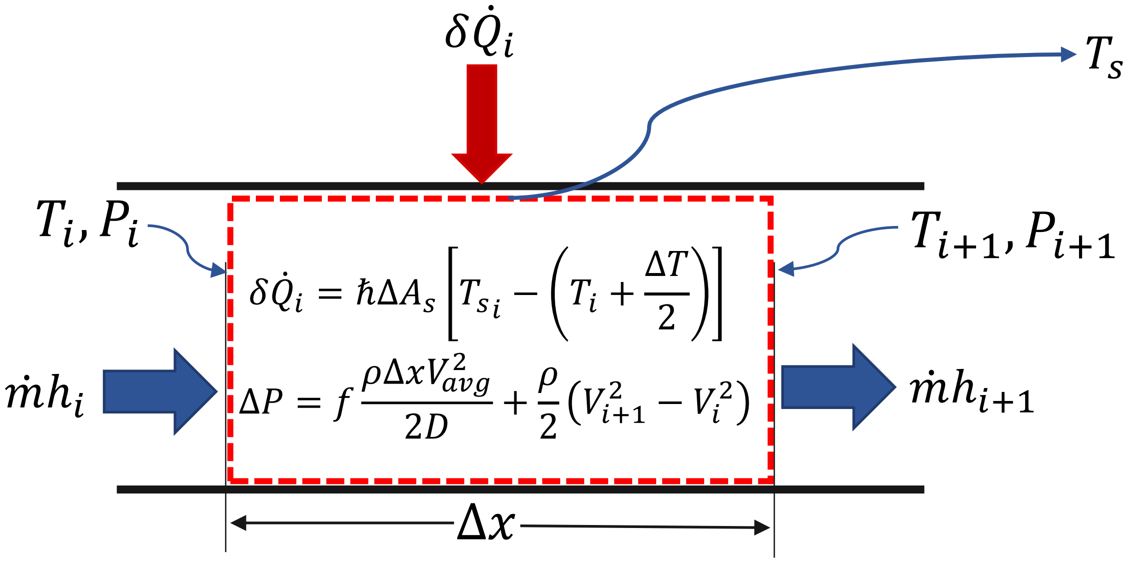




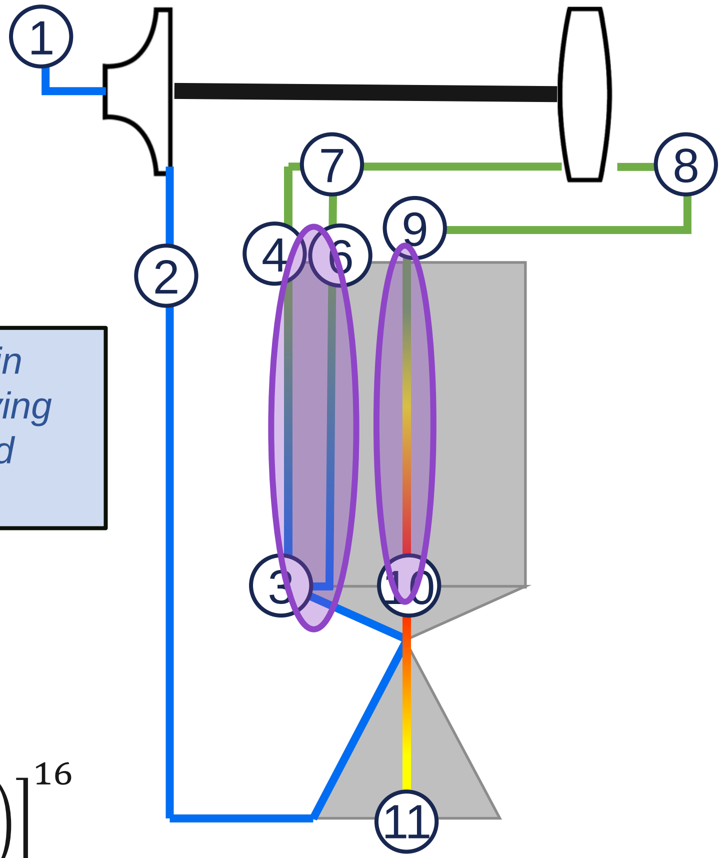
- **The pumps guide the turbine design at steady state.**
- **The same equations apply for turbines.**
- The required work and shaft rotational velocity guide the mass flow rate.
- The resulting efficiency guides the pressure ratio.

Reactor Heat Transfer

1st Law of Thermodynamics enthalpy approach with upwind nodal temperature determination [2-6]



$$T_s = \frac{T_i \exp\left(\frac{\hbar \pi D \Delta x}{\dot{m} c_p}\right) - T_{i+1}}{\exp\left(\frac{\hbar \pi D \Delta x}{\dot{m} c_p}\right) - 1}$$



Both pressure losses and changes in temperatures are calculated with varying heat transfer rates and variable fluid properties.

$$Nu_i = 0.025 Re^{0.8} Pr^{0.4} \left[1 + 0.3 \left(\frac{D}{x}\right)^{0.7} \right] \left(\frac{T_i}{T_s}\right)^{0.55}$$

$$f = 8\left[\left(\frac{8}{Re}\right)^{12} + \frac{1}{(A+B)^{1.5}}\right]^{1/12}$$

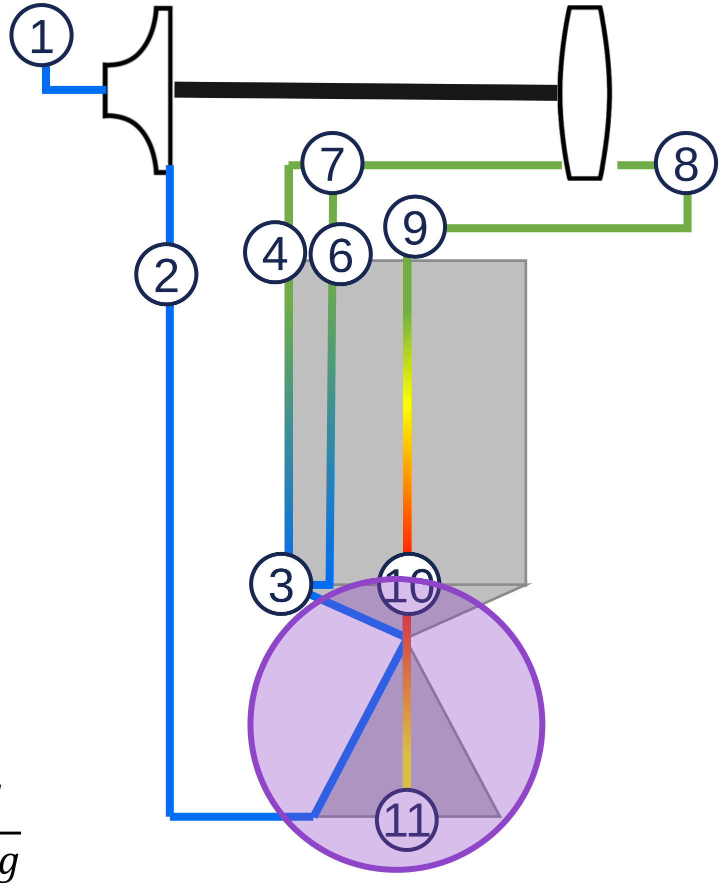
Where: $A = \left[2.457 \ln\left(\frac{1}{\left(\frac{7}{Re}\right)^{0.9} + 0.27\frac{\varepsilon}{d}}\right)\right]^{16}$

and $B = \left(\frac{37530}{Re}\right)^{16}$

Nozzle

Driving temperature difference is that which is between the plume and regenerative cooling flow

- **Bartz Correlation [7]:**
  - $\hbar_x = \frac{0.026}{D_t^{0.2}} \left(\frac{\mu^{0.2} c_p}{Pr^{0.6}}\right)_0 \left(\frac{\dot{m}}{A_t}\right)^{0.8} \left(\frac{D_t}{r_c}\right)^{0.1} \left(\frac{A_t}{A_x}\right)^{0.9} \sigma$
  - Where:
    - $\sigma = \left\{\left[\frac{1}{2}\frac{T_w}{T_0}\left(1 + \frac{\gamma-1}{2}M^2\right) + \frac{1}{2}\right]^{0.8-\frac{s}{5}} \left[1 + \frac{\gamma-1}{2}M^2\right]^{\frac{s}{5}}\right\}^{-1}$
    - $\mu = \mu_0 \left(\frac{T}{T_0}\right)^s$
    - s was determined from using temperatures and viscosities of a reference state and a state of interest inside the Power-Law Force equation.



- **Standard Compressible Flow Relations [8]:**

$$\frac{T_0}{T_e} = 1 + \frac{\gamma - 1}{2} M_e^2$$

$$\frac{P_0}{P_x} = \left(1 + \frac{\gamma - 1}{2} M_x^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{A^*}{A_x} = M_x \left[\frac{\frac{\gamma + 1}{2}}{1 + \frac{\gamma - 1}{2} M_x^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

$$\dot{m} = P_0 A^* \sqrt{\frac{\gamma}{RT_0}} \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

$$I_{sp} = \frac{F}{\dot{m}g}$$

$$F = \eta_{noz}[\dot{m}v_e + (P_e - P_a)A_e]$$

System Integration

Standalone components defined by a set of parameters with fluid states as inputs and outputs

Example:

$\dot{m}, T_1, P_1$ → **Governing Equations** → $\dot{m}, T_2, P_2$

$$\omega = \frac{n_{sp}\left(g_0 H_p\right)^{3/4}}{\sqrt{\dot{\forall}_p}} = \frac{n_{sp}\Delta P^{\,3/4}}{\rho^{1/4}\sqrt{\dot{m}_p}}$$

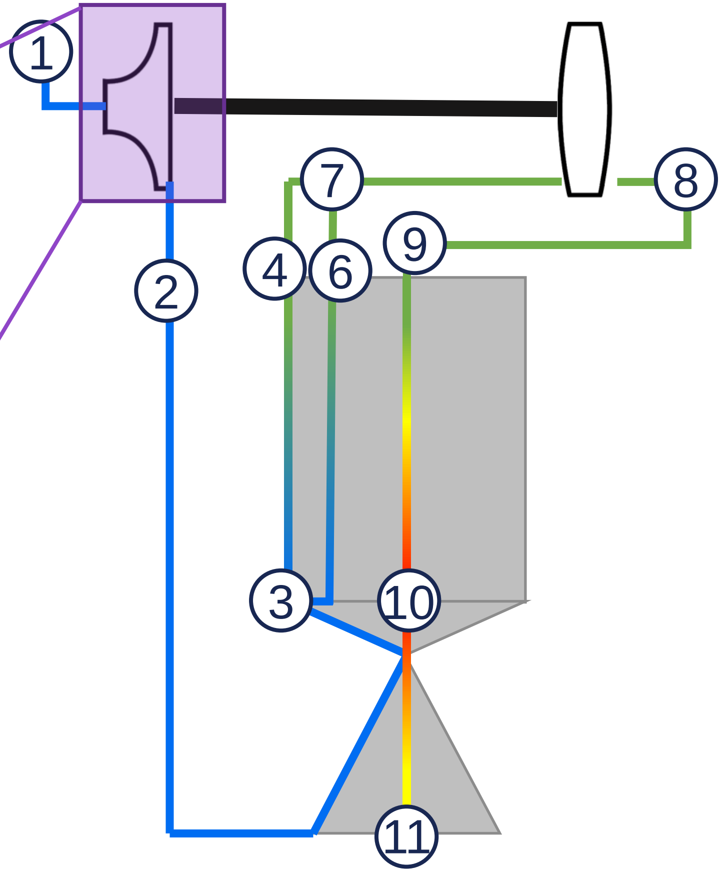
$$d_{sp} = \frac{D_p\left(g_0 H_p\right)^{1/4}}{\sqrt{\dot{\forall}_p}} = \frac{D_p[\rho\Delta P]^{1/4}}{\sqrt{\dot{m}_p}}$$

Parameters

$D, \Delta P, n_s$

Operating Characteristics

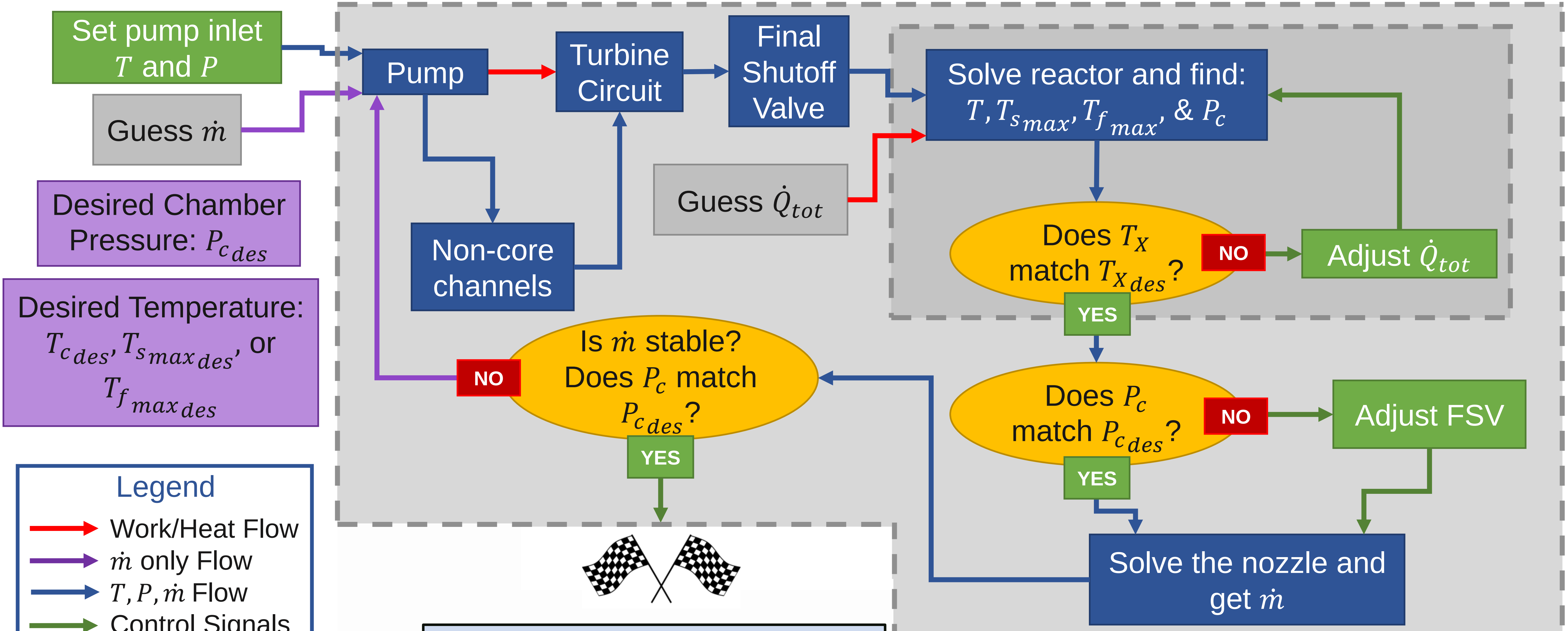
$\dot{W}, \eta, \omega$



Based on the component parameters and fluid state inputs, the component provides its operating characteristics and fluid outputs INDEPENDENT of the model itself.

Iterative Solution

The NTP system performance is solved by performing double iteration



Reactor converges on temperature ***separately*** *from the engine which converges on $\dot{m}$ and P_c.*

Transient Analysis

The iterative model provides performance parameters at different conditions for transient analysis

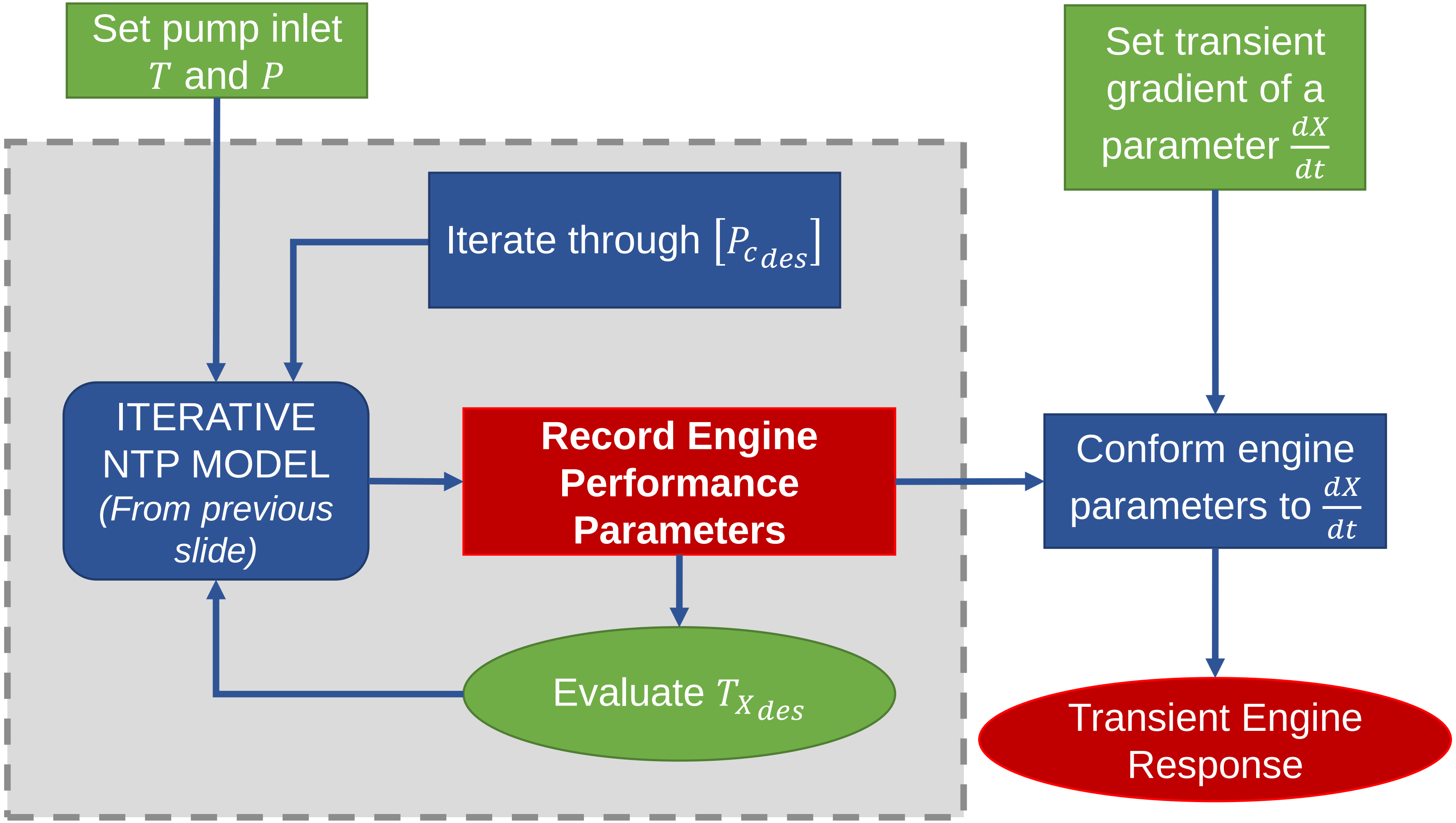
Desired Chamber Pressure VECTOR: $[P_{c_{des}}]$

Desired Temperature:

$$T_{c_{des}} = T_{c_{des}}(x, y, z)$$
$$T_{s_{max_{des}}} = T_{s_{max_{des}}}(x, y, z)$$
$$T_{f_{max_{des}}} = T_{f_{max_{des}}}(x, y, z)$$

AS FUNCTIONS OF ENGINE PARAMETERS x, y, and z

The Iterative NTP Model provides a psuedotransient engine response that needs to be conformed to a $\frac{dX}{dt}$



Engine Mass Estimations

If engine materials are known, mass can be estimated

- Engine mass estimating relationships are used for various components based on reference components and their operation regimes.
- The reactor masses should be evaluated using other reactor/neutronics software.

$$m_{duct} = m_{duct_{ref}} \left(\frac{P_{max}}{P_{max_{ref}}}\right)^{0.3} \left(\frac{\rho_{mat}}{\rho_{mat_{ref}}}\right)^{1} \left(\frac{\sigma}{\sigma_{ref}}\right)^{-1} \left(\frac{\dot{m}}{\dot{m}_{ref}}\right)^{0.625} \left(\frac{\rho}{\rho_{ref}}\right)^{-0.625}$$

$$m_{tp} = 1.5 \left(\frac{W_{tp}}{\omega}\right)^{0.6}$$

$$m_{nozzle} = m_{nozzle_{ref}} \left(\frac{P_c}{P_{c_{ref}}}\right)^{1} \left(\frac{\rho_{mat}}{\rho_{mat_{ref}}}\right)^{1} \left(\frac{\sigma}{\sigma_{ref}}\right)^{-1} \left(\frac{AR}{AR_{ref}}\right)^{1} \left(\frac{d_t}{d_{t_{ref}}}\right)^{2}$$

$$m_{struct} = m_{struct_{ref}} \left(\frac{F}{F_{ref}}\right)^{0.92068}$$

$$m_{misc} = m_{misc_{ref}} \left(\frac{\rho_{mat}}{\rho_{mat_{ref}}}\right)^{1} \left(\frac{\sigma}{\sigma_{ref}}\right)^{-1} \left(\frac{d_t}{d_{t_{ref}}}\right)^{1}$$

Conclusion

Standalone component based NTP model

- The outlined procedure could be used for low/medium fidelity analysis of the NTP engine system at the component level.
- Transient analysis of varying fidelity can be implemented.
- Variable fluid properties can be incorporated if a fluid property library such as CoolProp is implemented.
- The level of detail of the model can vary.
- The pump depends on the desired chamber pressure.
- The turbine depends on the required pump work and inlet fluid properties.

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