PROPULSIONE SPAZIALE

Chemical Rocket Propellant Performance Analysis
**Real Nozzles**

Compared to an ideal nozzle, the real nozzle has energy losses and energy that is unavailable for conversion into kinetic energy of the exhaust gas. The **principal losses** are:

1. The *divergence of the flow* in the nozzle exit sections causes a loss. The losses can be reduced for bell-shaped nozzle contours

2. Small chamber or port area cross sections relative to the throat area or *low nozzle contraction ratios* $A_1/A_t$ cause pressure losses in the chamber and reduce the thrust and exhaust velocity slightly

3. Lower flow velocity in the *boundary layer or wall friction* can reduce the effective exhaust velocity by 0.5 to 1.5%

4. *Solid particles or liquid droplets* in the gas can cause losses up to 5%

5. *Unsteady combustion* and *oscillating flow* can account for a small loss

6. *Chemical reactions in nozzle* flow change gas properties and gas temperatures, giving typically a 0.5% loss

7. There is lower performance during *transient pressure operation*, for example during start, stop, or pulsing

8. For uncooled nozzle materials, such as fiber reinforced plastics or carbon, the gradual *erosion of the throat region* increases the throat diameter during operation. In turn this will reduce the chamber pressure and thrust and cause a reduction in specific impulse

9. *Non-uniform gas composition* can reduce performance (due to incomplete mixing, turbulence, or incomplete combustion regions)
## REAL NOZZLES

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical specific impulse (vacuum conditions)</td>
<td>278.1 sec</td>
</tr>
<tr>
<td>Delivered specific impulse (vacuum conditions)</td>
<td>268.2 sec</td>
</tr>
<tr>
<td><strong>Losses (calculated):</strong></td>
<td>(9.9 sec total)</td>
</tr>
<tr>
<td>Two-dimensional two-phase flow (includes divergence loss)</td>
<td>7.4 sec</td>
</tr>
<tr>
<td>Throat erosion (reduces nozzle area ratio)</td>
<td>0.9 sec</td>
</tr>
<tr>
<td>Boundary layer (wall friction)</td>
<td>0.7 sec</td>
</tr>
<tr>
<td>Submergence (flow turning)</td>
<td>0.7 sec</td>
</tr>
<tr>
<td>Finite rate chemistry (chemical equilibrium)</td>
<td>0.2 sec</td>
</tr>
<tr>
<td>Impingement (of Al₂O₃ particles on nozzle wall)</td>
<td>0.0 sec</td>
</tr>
<tr>
<td>Shock (if turnback angle is too high or nozzle length too low)</td>
<td>0.0 sec</td>
</tr>
<tr>
<td>Combustion efficiency (incomplete burning)</td>
<td>0.0 sec</td>
</tr>
</tbody>
</table>

Calculated Losses in the Space Shuttle Booster RSRM Nozzle
**Energy Losses**

Two types of energy conversion processes occur in any propulsion system: the **generation of energy** (conversion of stored energy into available energy) and, subsequently, the **conversion into kinetic energy**, which is the **form of energy useful for propulsion**

![Diagram showing energy losses in a chemical rocket](image)

Typical energy losses for a chemical rocket

- The **combustion efficiency** for chemical rockets is a measure of the source efficiency for creating energy. Its value is typically high (approximately 94 to 99%)
- A large portion of the energy of the exhaust gases is **unavailable for conversion** into kinetic energy and leaves the nozzle as residual enthalpy
ENERGY LOSSES

Two types of energy conversion processes occur in any propulsion system: the generation of energy (conversion of stored energy into available energy) and, subsequently, the conversion into kinetic energy, which is the form of energy useful for propulsion.

Propulsive efficiency at varying velocities

- The propulsive efficiency determines how much of the kinetic energy of the exhaust jet is useful for propelling the vehicle. The propulsive efficiency is a maximum when the forward vehicle velocity is exactly equal to the exhaust velocity (residual kinetic energy of the jet is zero).
For maximum specific impulse, the optimum O/F is ≈ 2.3 for frozen equilibrium and 2.5 for shifting equilibrium.

The maximum values of $c^*$ are at slightly different O/F.

The optimum O/F is not the one for highest temperature, which is usually close to the stoichiometric value (> 3.0).

The temperature and the molecular weight at the nozzle exit increase for shifting equilibrium due to recombination reactions.

Much of the carbon is burned to CO$_2$ and almost all of the hydrogen to H$_2$O.

Performance of LOX/RP-1 as a function of O/F.
Chemical Rocket Propellant Performance Analysis

- For maximum specific impulse, the optimum O/F is \( \approx 2.3 \) for frozen equilibrium and 2.5 for shifting equilibrium.
- The maximum values of \( c^* \) are at slightly different O/F.
- The optimum O/F is not the one for highest temperature, which is usually close to the stoichiometric value (\( > 3.0 \)).
- The temperature and the molecular weight at the nozzle exit increase for shifting equilibrium due to recombination reactions.
- Much of the carbon is burned to \( \text{CO}_2 \) and almost all of the hydrogen to \( \text{H}_2\text{O} \).

Performance of LOX/RP-1 as a function of O/F (assuming shifting equilibrium during the entire expansion)
For maximum specific impulse, the optimum O/F is \( \approx 2.3 \) for frozen equilibrium and 2.5 for shifting equilibrium.

The maximum values of \( c^* \) are at slightly different O/F.

The optimum O/F is not the one for highest temperature, which is usually close to the stoichiometric value (\( > 3.0 \)).

The temperature and the molecular weight at the nozzle exit increase for shifting equilibrium due to recombination reactions.

Much of the carbon is burned to \( \text{CO}_2 \) and almost all of the hydrogen to \( \text{H}_2\text{O} \).

Performance of LOX/RP-1 as a function of O/F (shifting equilibrium and frozen expansion)
For maximum specific impulse, the optimum O/F is $\approx 2.3$ for *frozen equilibrium* and $2.5$ for *shifting equilibrium*.

The maximum values of $c^*$ are at slightly different O/F.

The optimum O/F is not the one for highest temperature, which is usually close to the stoichiometric value ($> 3.0$).

The temperature and the molecular weight at the nozzle exit increase for shifting equilibrium due to recombination reactions.

Much of the carbon is burned to CO$_2$ and almost all of the hydrogen to H$_2$O.

Performance of LOX/RP-1 as a function of O/F (shifting equilibrium, frozen expansion, and Bray’s throat freezing point)
For maximum specific impulse, the optimum O/F is ≈ 3.8 for frozen equilibrium and 4.6 for shifting equilibrium. The maximum values of $c^*$ are at slightly different O/F. The optimum O/F is not the one for highest temperature, which is usually close to the stoichiometric value (8.0). The temperature and the molecular weight at the nozzle exit increase for shifting equilibrium due to recombination reactions.

Performance of LOX/LH2 as a function of O/F (assuming shifting equilibrium during the entire expansion)
• For maximum specific impulse, the optimum O/F is \( \approx 3.8 \) for frozen equilibrium and 4.6 for shifting equilibrium.

• The maximum values of \( c^* \) are at slightly different O/F.

• The optimum O/F is not the one for highest temperature, which is usually close to the stoichiometric value (8.0).

• The temperature and the molecular weight at the nozzle exit increase for shifting equilibrium due to recombination reactions.

Performance of LOX/LH2 as a function of O/F (shifting equilibrium and frozen expansion)
For maximum specific impulse, the optimum O/F is \( \approx 3.8 \) for frozen equilibrium and 4.6 for shifting equilibrium.

The maximum values of \( c^\ast \) are at slightly different O/F.

The optimum O/F is not the one for highest temperature, which is usually close to the stoichiometric value (8.0).

The temperature and the molecular weight at the nozzle exit increase for shifting equilibrium due to recombination reactions.

Performance of LOX/LH2 as a function of O/F (shifting equilibrium, frozen expansion, and Bray’s throat freezing point)
FROZEN VS SHIFTING EQUILIBRIUM GAS COMPOSITION

- **Dissociation of molecules** requires considerable energy and causes a decrease in the combustion temperature, which in turn can reduce the specific impulse.
- Atoms or radicals such as O or H and OH are formed. As the gases are cooled in the expansion, the **dissociated species recombine** (shifting equilibrium) and release heat into the flowing gases. Only a small percentage of dissociated species persists at the nozzle exit.
**Frozen vs Shifting Equilibrium Gas Composition**

- **Dissociation of molecules** requires considerable energy and causes a decrease in the combustion temperature, which in turn can reduce the specific impulse.

- Atoms or radicals such as O or H and OH are formed. As the gases are cooled in the expansion, the **dissociated species recombine** (shifting equilibrium) and **release heat** into the flowing gases. Only a small percentage of dissociated species persists at the nozzle exit.
Frozen vs Shifting Equilibrium Gas Composition

- **Dissociation of molecules** requires considerable energy and causes a decrease in the combustion temperature, which in turn can reduce the specific impulse.

- Atoms or radicals such as O or H and OH are formed. As the gases are cooled in the expansion, the **dissociated species recombine** (shifting equilibrium) and release heat into the flowing gases. Only a small percentage of dissociated species persists at the nozzle exit.