Rocket Nozzle Equations

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Contents

Nomenclature

A	Area
c	Speed of sound
$\dot{m}$	Mass flow rate
M	Molecular mass
Ma	Mach number
$mol\%$	Mole percentage
P	Pressure
R'	Universal gas constant
R	Specific gas constant
T	Temperature
v	Velocity
ϵ	Nozzle area ratio
γ	Ratio of specific heats
ρ	Density

Subscripts

a	Ambient
c	Chamber
e	Exit
t	Throat
x,y	Given position
0	Stagnation

1 Thermodynamic Relations [1]

1.1 Gas Constant

$$R = \frac{R'}{M} \tag{1.1}$$

1.2 Sonic Velocity

$$c = \sqrt{\gamma R T} \tag{1.2}$$

1.3 Isentropic Flow Relation

$$\frac{T_x}{T_y} = \left(\frac{P_x}{P_y}\right)^{\frac{\gamma}{\gamma-1}} \tag{1.3}$$

1.4 Isentropic Total To Static Temperature Relation

$$0 = \frac{T}{T_0}\left[1 + \frac{1}{2}(\gamma - 1)\,Ma^2\right] \tag{1.4}$$

1.5 Isentropic Total To Static Pressure Relation

$$0 = \frac{P}{P_0}\left[1 + \frac{1}{2}(\gamma - 1)\,Ma^2\right]^{\frac{\gamma}{\gamma-1}} \tag{1.5}$$

1.6 Isentropic Nozzle Area Ratio

The Isentropic Nozzle Area Ratio Calculation

$$\frac{A_y}{A_x} = \frac{Ma_x}{Ma_y}\sqrt{\left\{\frac{1 + \left[\frac{\gamma-1}{2}\right]Ma_y^2}{1 + \left[\frac{\gamma-1}{2}\right]Ma_x^2}\right\}^{\frac{\gamma+1}{\gamma-1}}} \tag{1.6}$$

1.7 Isentropic Mach Number

Equations (1.4) and (1.5) can be rearranged to solve for the Mach Number

$$Ma = \sqrt{\frac{2}{\gamma - 1}\left(\frac{T_0}{T} - 1\right)} \tag{1.7}$$

$$Ma = \sqrt{\frac{2}{\gamma - 1}\left(\frac{P_0}{P}^{\frac{\gamma-1}{\gamma}} - 1\right)} \tag{1.8}$$

2 Isentropic Flow [1]

2.1 Isentropic Exit Velocity

$$v_e = \sqrt{\frac{2\gamma}{\gamma - 1} RT_0 \left[1 - \left(\frac{P_e}{P_0}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{2.1}$$

2.2 Choked Mass Flow Rate

$$\dot{m} = A_t P_0 \gamma \frac{\sqrt{\frac{2}{\gamma+1}^{\frac{\gamma+1}{\gamma-1}}}}{\sqrt{\gamma R T_0}} \tag{2.2}$$

2.3 Thrust

$$F = \dot{m} v_e + (P_e - P_a) A_e \tag{2.3}$$

References

[1] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements*, 9th ed. Wiley, 2017.