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MAE 640 Rocket Propulsion II

Lecture 01A-2 Fundamental Concepts

A. UAH Propulsion Research Center
B. Conservation of Momentum and Thrust
C. Conservation of Energy and Exit Velocity
D. Nozzle Operation
E. Thrust Coefficient Toolbox
F. Comments on Homework Problems

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01A-2_A – UAH Propulsion Research Center

UAH Propulsion Research Center Vision & Mission

Vision: The PRC will be a major generator of talent and innovative solutions in propulsion and energy related technologies.

Mission: PRC connects the academic research community with industry & government to advance basic science and technology development related to propulsion and energy.

The University of Alabama in Huntsville (UAH) earned first place in project safety and third place overall in competition at a COVID-shortened national 2020 NASA Student Launch.

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Solid Rocket Motor

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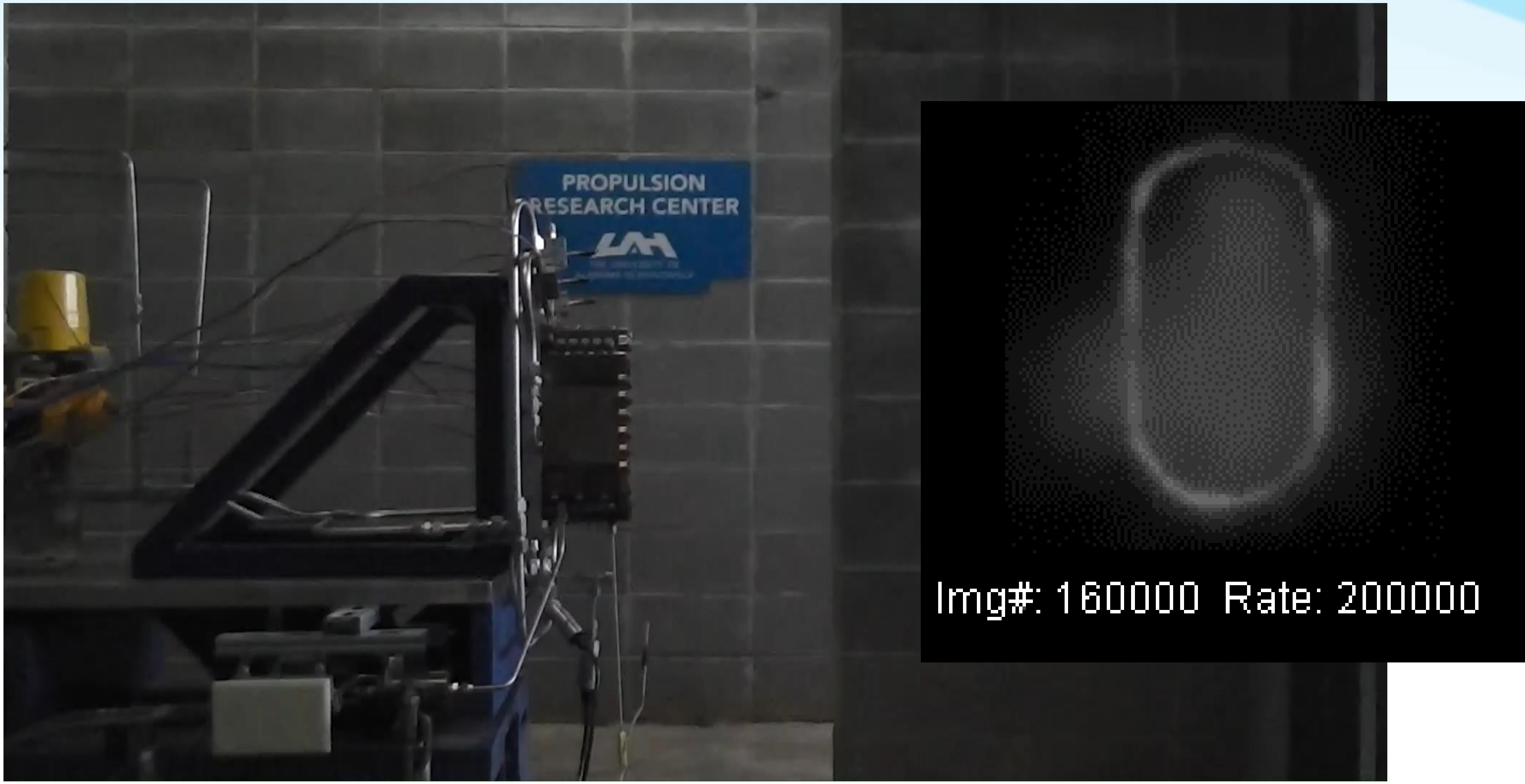
Rotating Detonation Engine



Unruh, E., Venters, J., Hemming, M., Lineberry, D., Xu, K, and Frederick, R., “Experimental Study of a Racetrack-Type Rotating Detonation Rocket Engine with Shear-Coaxial Injectors Run on Gaseous Methane and Oxygen,” AIAA Paper 2021-3683, 2021.

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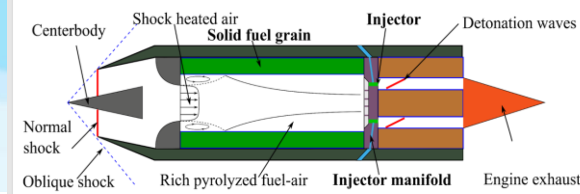
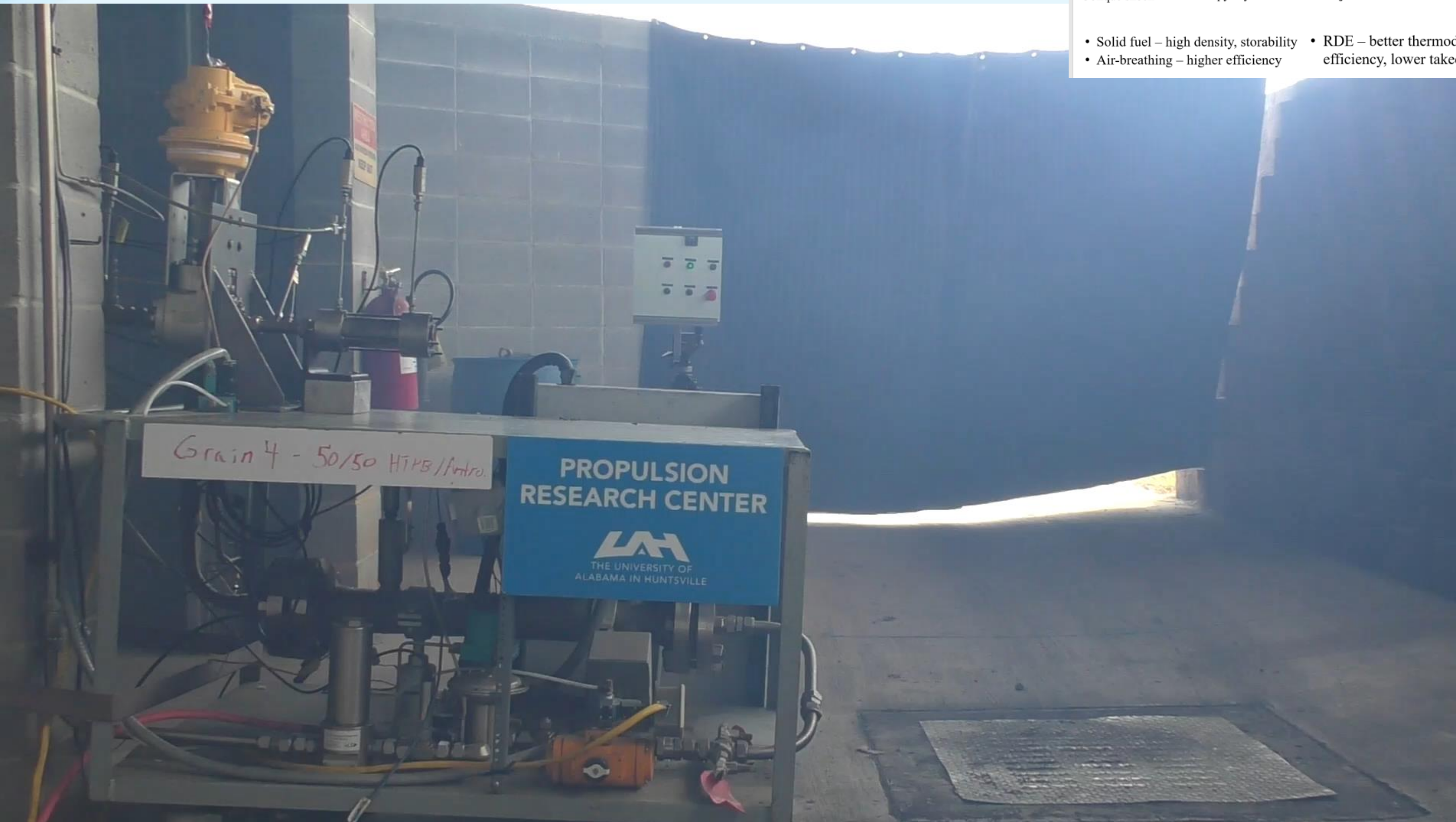
Ramjet Fuel Connected Pipe



- Solid fuel – high density, storability
- Air-breathing – higher efficiency
- RDE – better thermodynamic efficiency, lower takeover Mach



UAH Propulsion Research Center

Liquid Rocket Engine Testing

Course Objectives

Course Description

- Aerothermodynamics of rocket propulsion systems; rocket propellants and combustion; heat transfer and cooling problems. Application to ramjets and hybrid systems. Prerequisite: MAE 540 or permission of instructor.

Course Objectives

- Students will be able to define key rocket propulsion terms.
- Students will be able to calculate component and systems performance using rocket propulsion principles.
- Students will be able to use thermochemcial codes, design equations, and relevant technical literature to design a rocket combustor or propulsion system to meet specific design objectives.

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Module Learning Objectives - Example

Module 01 – Fundamental Concepts

- Students will be able to demonstrate basic knowledge of propulsion terminology and the results of the last class project
- Students will be able to calculate the performance of an over-expanded nozzle that has separated flow
- Students will be able to derive the thrust and exit velocity equations for a converging-diverging nozzle from the conservation of momentum and conservation of energy equations.

Module Components - Example

Module 01 - Fundamental Concepts

- **Module Checklist**
  - ☐ Attend (and or view) Lectures 1A and 1B
  - ☐ Review Course Syllabus
  - ☐ Review textbook chapter 1, 2, 3 and 4
  - ☐ Complete Quiz 1
  - ☐ Attend or Review Office Hours/Help Session
  - ☐ Complete Homework 01 (01HW)

01A-2 B– Conservation of Momentum

Conservation of Momentum

Shooting of a Gun

Conservation of Momentum

Shooting of a Gun

m

$V_b = 1000$ m/s

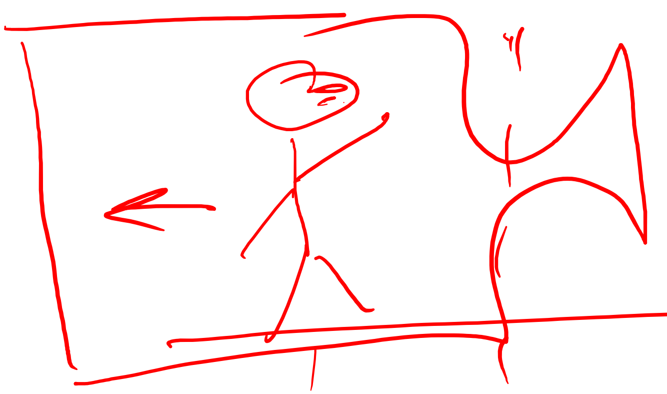
$M_o = M_o|_0 = 0$

$Mom_f = 0 = 100m(V_p) + m(1000)$

1000 m/s

$\frac{m}{\ }$

$V_p =$



-10

$V_p = \frac{-1000}{100} = -10$

$V_p = \frac{1}{\ }$

Conservation of Momentum

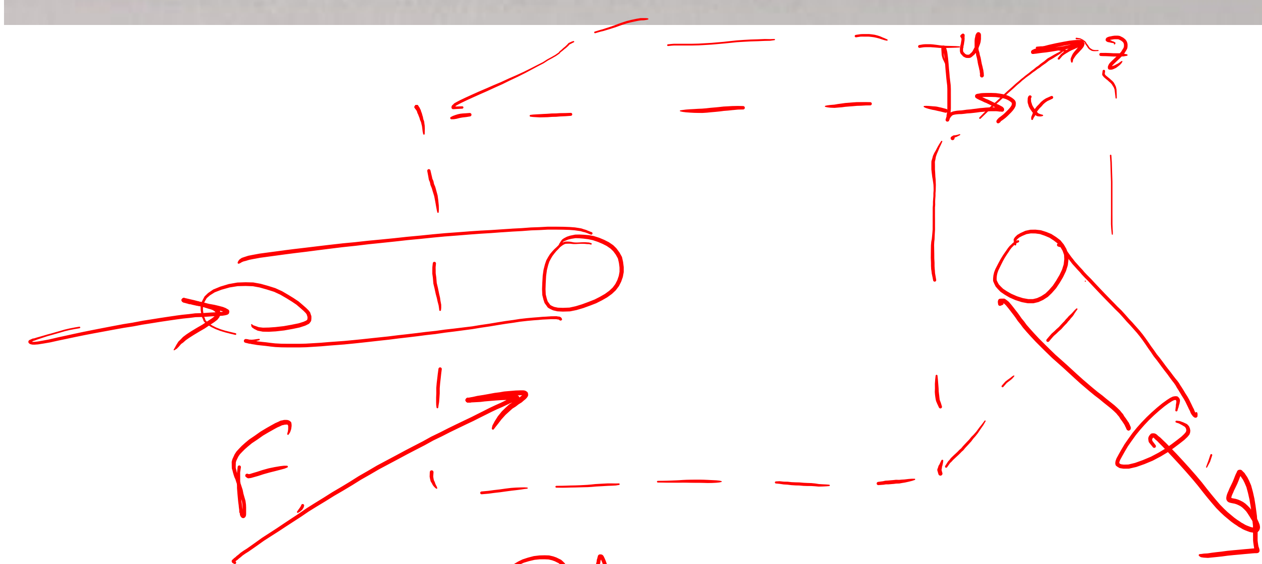
CONTROL VOLUME

Applied to a Control Volume – General Equation

CHANGES INSIDE

MOMENTUM THROUGH WALLS

$$\frac{d}{dt}(m\mathbf{V})_{\text{syst}} = \sum \mathbf{F} = \frac{d}{dt}\left(\int_{CV} \mathbf{V}\rho \, d\mathcal{V}\right) + \int_{CS} \mathbf{V}\rho(\mathbf{V}_r \cdot \mathbf{n}) \, dA$$



F = PA

F = FORCES ON BOX

CHANGE IN MOMENTUM INSIDE BOX

Conservation of Momentum

CONTROL VOLUME

MUST DEFINE BOUNDARIES OF C.V.

Applied to a Control Volume – ~~General~~ Equation

$$\frac{d}{dt}(m\mathbf{V})_{\text{syst}} = \sum \mathbf{F} = \frac{d}{dt}\left(\int_{CV} \mathbf{V}\rho \, d\mathcal{V}\right) + \int_{CS} \mathbf{V}\rho(\mathbf{V}_r \cdot \mathbf{n}) \, dA$$

+ OUT
− IN

$$\bar{V}\rho(\bar{V}_r \cdot \bar{n})\, dA$$

$\bar{V}$

$(\bar{V} \cdot \bar{n})$

The following points concerning this relation should be strongly emphasized:

1. The term $\mathbf{V}$ is the fluid velocity relative to an *inertial* (nonaccelerating) coordinate system; otherwise Newton's second law must be modified to include noninertial relative acceleration terms (see the end of this section).
2. The term $\Sigma\, \mathbf{F}$ is the *vector* sum of all forces acting on the system material considered as a free body; that is, it includes surface forces on all fluids and solids cut by the control surface plus all body forces (gravity and electromagnetic) acting on the masses within the control volume.
3. The entire equation is a vector relation; both the integrals are vectors due to the term $\mathbf{V}$ in the integrands. The equation thus has three components. If we want only, say, the x component, the equation reduces to

$$\sum F_x = \frac{d}{dt}\left(\int_{CV} u\rho \, d\mathcal{V}\right) + \int_{CS} u\rho(\mathbf{V}_r \cdot \mathbf{n}) \, dA \qquad (3.36)$$

and similarly, $\Sigma\, F_y$ and $\Sigma\, F_z$ would involve v and w, respectively. Failure to account for the vector nature of the linear momentum relation (3.35) is probably the greatest source of student error in control volume analyses.

For a fixed control volume, the relative velocity $\mathbf{V}_r \equiv \mathbf{V}$, and Eq. (3.35) becomes

$$\boxed{\sum \mathbf{F} = \frac{d}{dt}\left(\int_{CV} \mathbf{V}\rho \, d\mathcal{V}\right) + \int_{CS} \mathbf{V}\rho(\mathbf{V} \cdot \mathbf{n}) \, dA} \qquad (3.37)$$

Again we stress that this is a vector relation and that $\mathbf{V}$ must be an inertial-frame velocity. Most of the momentum analyses in this text are concerned with Eq. (3.37).

$\bar{V} \cdot \bar{n}\,(+)$
OUT

$\bar{r} \cdot \bar{n}\,(-)$
IN

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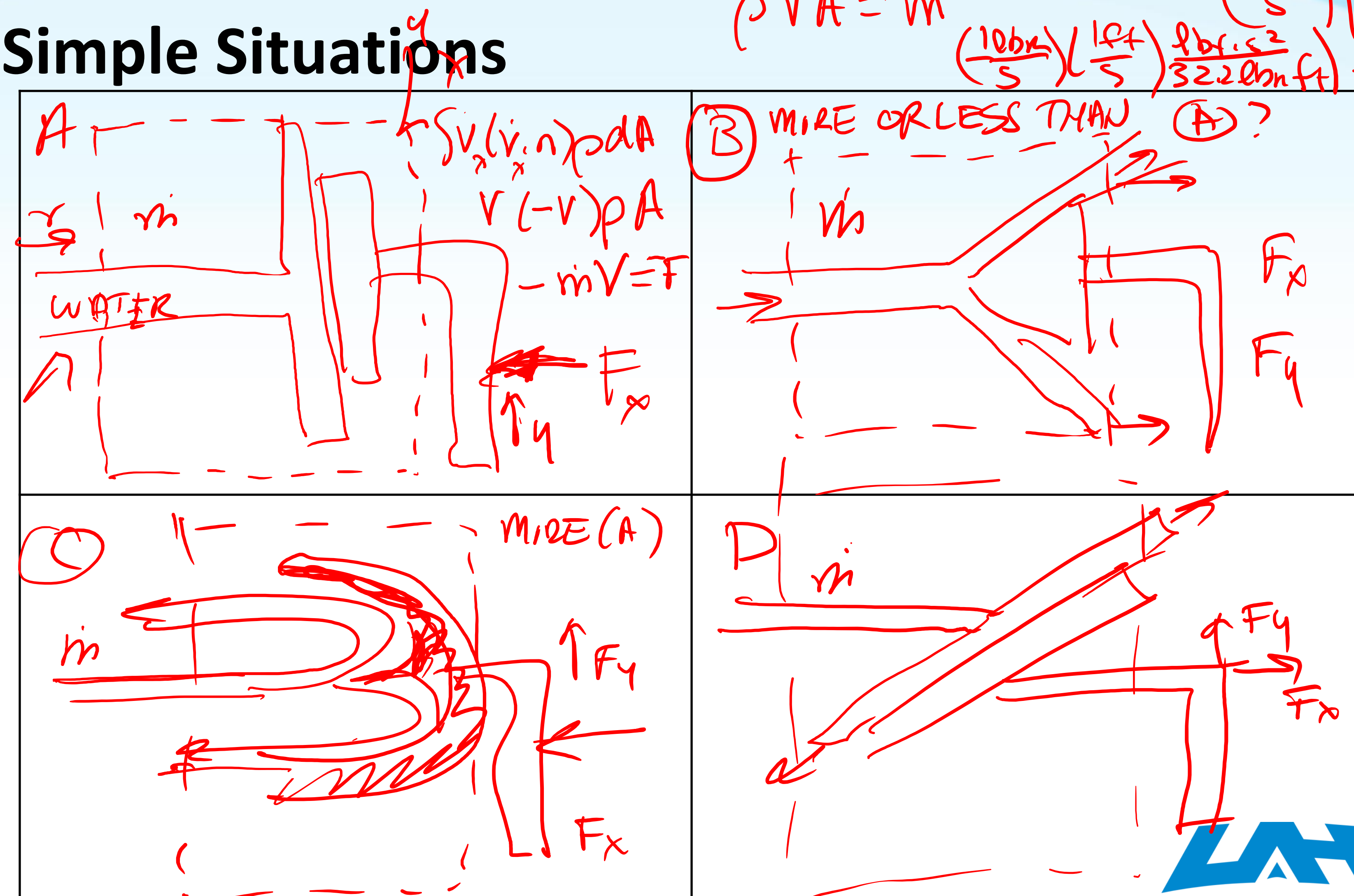
Conservation of Momentum

$\rho V A = \dot{m}$

$F = \dot{m} V = \left(\frac{1\,\text{lbm}}{s}\right)\left(\frac{1\,\text{ft}}{\text{sec}}\right)$

$\left(\frac{10\,\text{lbm}}{s}\right)\left(\frac{1\,\text{ft}}{s}\right)\frac{\text{lbf}\cdot s^2}{32.2\,\text{lbm ft}} = \frac{10}{32.2}\,\text{lbf}$

Simple Situations



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Conservation of Momentum

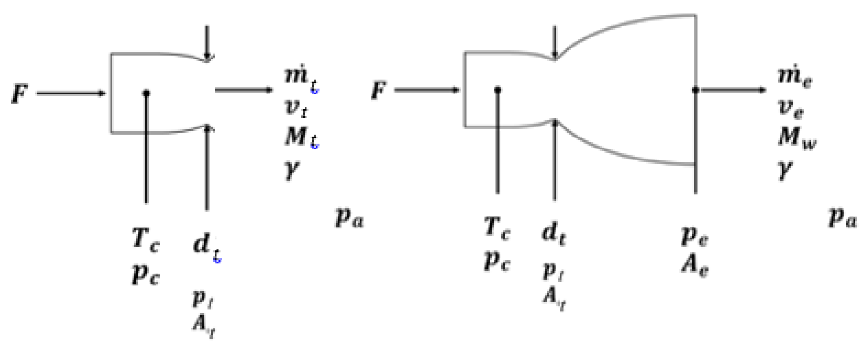
Simple Situations

Conservation of Momentum

Homework Problem – SP01-B

1. **Name:**
2. **Given:** Rocket motor with a converging nozzle, and then a second configuration adding a diverging nozzle.
3. **Find:**
   a. Starting with the complete linear momentum (Equation 3.37 in Appendix B) equation for a control volume, derive the <u>thrust equation</u> in a systematic manner for the rocket with the converging nozzle. Document each simplifying assumption, define the control volume, and use the symbols found in the schematic or consistent with the course textbook. Appendix B shows the basic starting equation with some explanations.
   b. Repeat the process in for the rocket with a converging-diverging nozzle; determine the force that the diverging section of the nozzle has on the circular ring of material around the rocket throat. You will need to draw a separate control volume for this analysis.
   c. Comment of the ratio of the thrust of the second rocket over the first for a typical supersonic converging-diverging nozzle. When is the diverging section adding to the overall thrust of the rocket motor?
4. **Schematic:**

Converging **Converging-Diverging**



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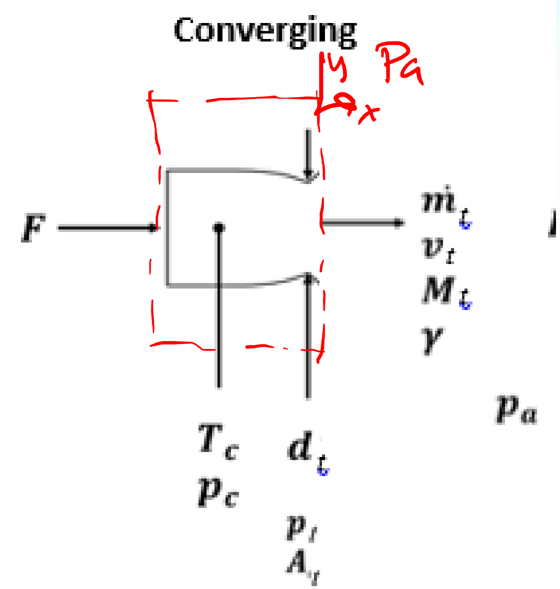
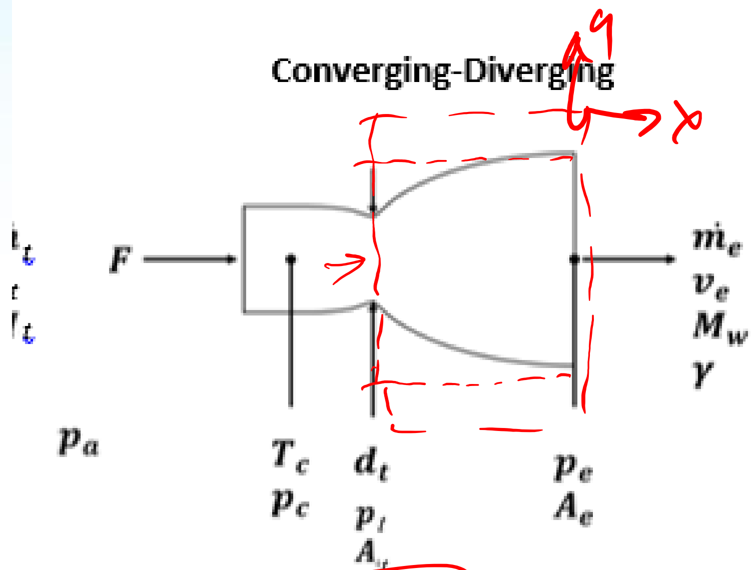
Conservation of Momentum

Homework Problem – SP01-B

4. Schematic:





FORCES

F

PRESSURE

$P_t \neq P_a$

MOMENTUM

$\boxed{\dot{m} V_t}$

$\dot{m} V_e$

FORCES

RH. $P_e A_e$

MOMENTUM

OUT ~~C~~ (RHS)

IN LHS

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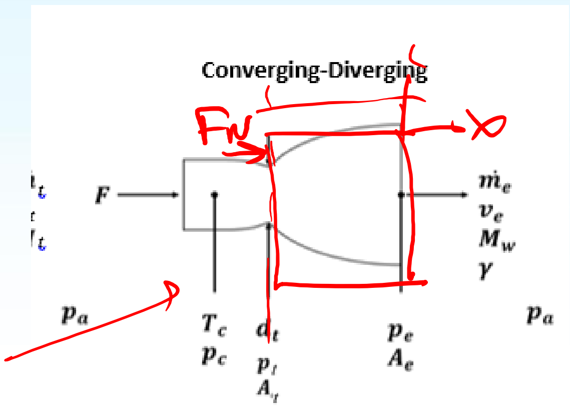
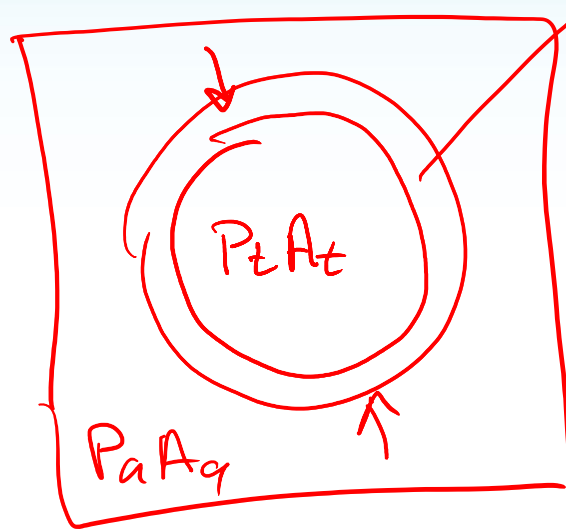
Conservation of Momentum

Homework Problem – SP01-B



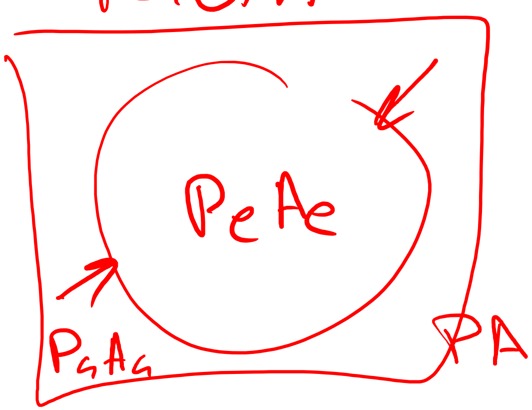
LEFT END

O-RING



F_{NOZZLE}

RIGHT END



FORCES (3 PRESSURE ~~FORC~~ FORCES)

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01A-2_C Conservation of Energy & Exit Velocity

Conservation of Energy

FLOW SYSTEMS

(THERMO I)

DRAW C.V.

Steady State Energy Equation

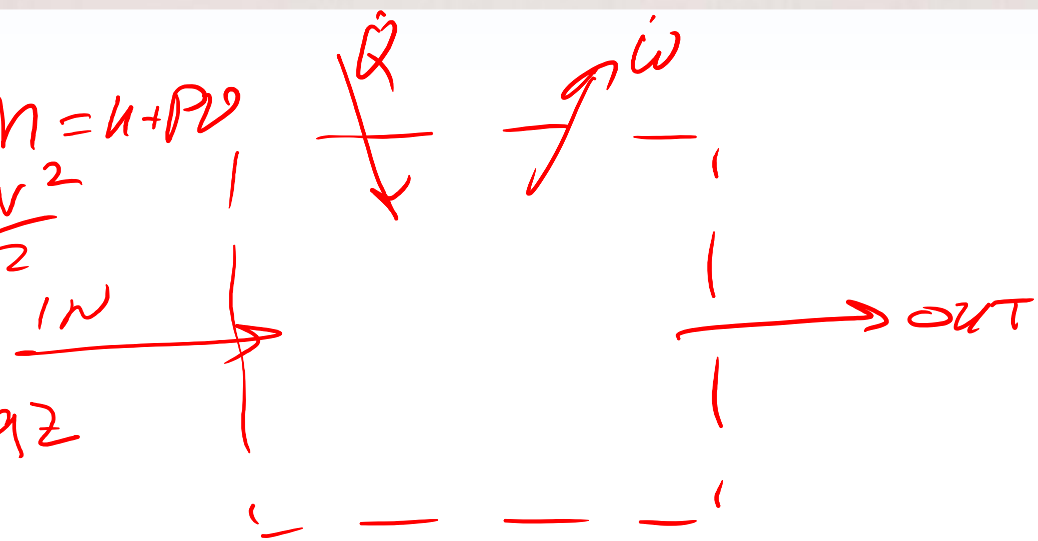
CONTROL VOLUME

$$\dot{Q} - \dot{W} = \underbrace{\sum \dot{m}_e \left(h_e + \frac{\mathbf{V}_e^2}{2} + g z_e \right)}_{\text{for each exit}} - \underbrace{\sum \dot{m}_i \left(h_i + \frac{\mathbf{V}_i^2}{2} + g z_i \right)}_{\text{for each inlet}} \quad \text{(kW)} \qquad \text{(4-19)}$$

Thermal = $h = u + Pv$

Kinetic = $\frac{V^2}{2}$

Potent Energy = gz



TURBINES

NOZZLES

VALVES

COMPRESSORS

PUMPS

etc.

Cengel, Y.A and Boles, M.A., "Thermodynamics, - An Engineering Approach," ISBN 0-07-010356-9

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Conservation of Energy

Steady State Energy Equation

$$\dot{Q} - \dot{W} = \underbrace{\sum \dot{m}_e \left(h_e + \frac{\mathbf{V}_e^2}{2} + gz_e \right)}_{\text{for each exit}} - \underbrace{\sum \dot{m}_i \left(h_i + \frac{\mathbf{V}_i^2}{2} + gz_i \right)}_{\text{for each inlet}} \quad \text{(kW)} \qquad (4\text{-}19)$$

since $\theta = h + \text{ke} + \text{pe}$ (Eq. 4-13). Equation 4-19 is the general form of the first-law relation for steady-flow processes.

For single-stream (one-inlet, one-exit) systems the summations over the inlets and the exits drop out, and the inlet and exit states in this case are denoted by subscripts 1 and 2, respectively, for simplicity. The mass flow rate through the entire control volume remains constant ($\dot{m}_1 = \dot{m}_2$) and is denoted $\dot{m}$. Then the conservation of energy equation for *single-stream steady-flow systems* becomes

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^2}{2} + g(z_2 - z_1) \right] \quad \text{(kW)} \qquad (4\text{-}20)$$

Cengel, Y.A and Boles, M.A., “Thermodynamics, - An Engineering Approach,” ISBN 0-07-010356-9

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Conservation of Energy

S.S. Energy Equation – Applied to Rocket Nozzle

$$\dot{Q} - \dot{W} = \sum \underbrace{\dot{m}_e \left(h_e + \frac{\mathbf{V}_e^2}{2} + gz_e \right)}_{\text{for each exit}} - \sum \underbrace{\dot{m}_i \left(h_i + \frac{\mathbf{V}_i^2}{2} + gz_i \right)}_{\text{for each inlet}} \quad (\text{kW}) \qquad (4\text{-}19)$$

A.T.A.M.O

$$v_e^2 = \frac{2\gamma R_u T_c}{\mathfrak{M}(\gamma - 1)} \left[1 - (p_e/p_c)^{(\gamma-1)/\gamma}\right] + V_o^2$$

Equation 4.23 in the textbook

Cengel, Y.A and Boles, M.A., "Thermodynamics, - An Engineering Approach," ISBN 0-07-010356-9

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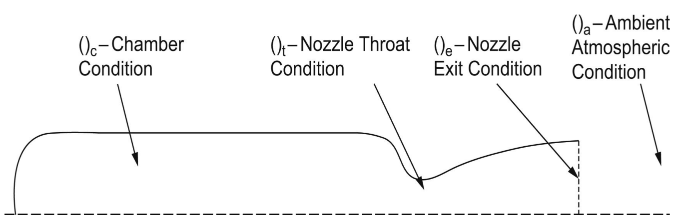
01A-2 D– Nozzle Operation

4.2 Rocket Performance Fundamentals

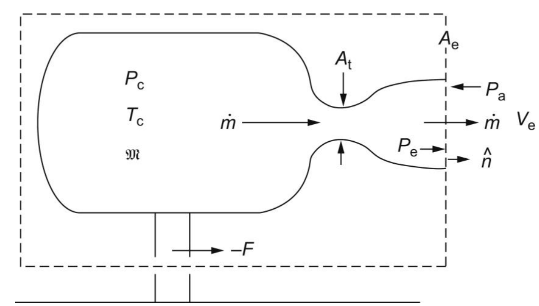
Rocket Thrust Calculation

Conservation of Momentum for a Control Volume

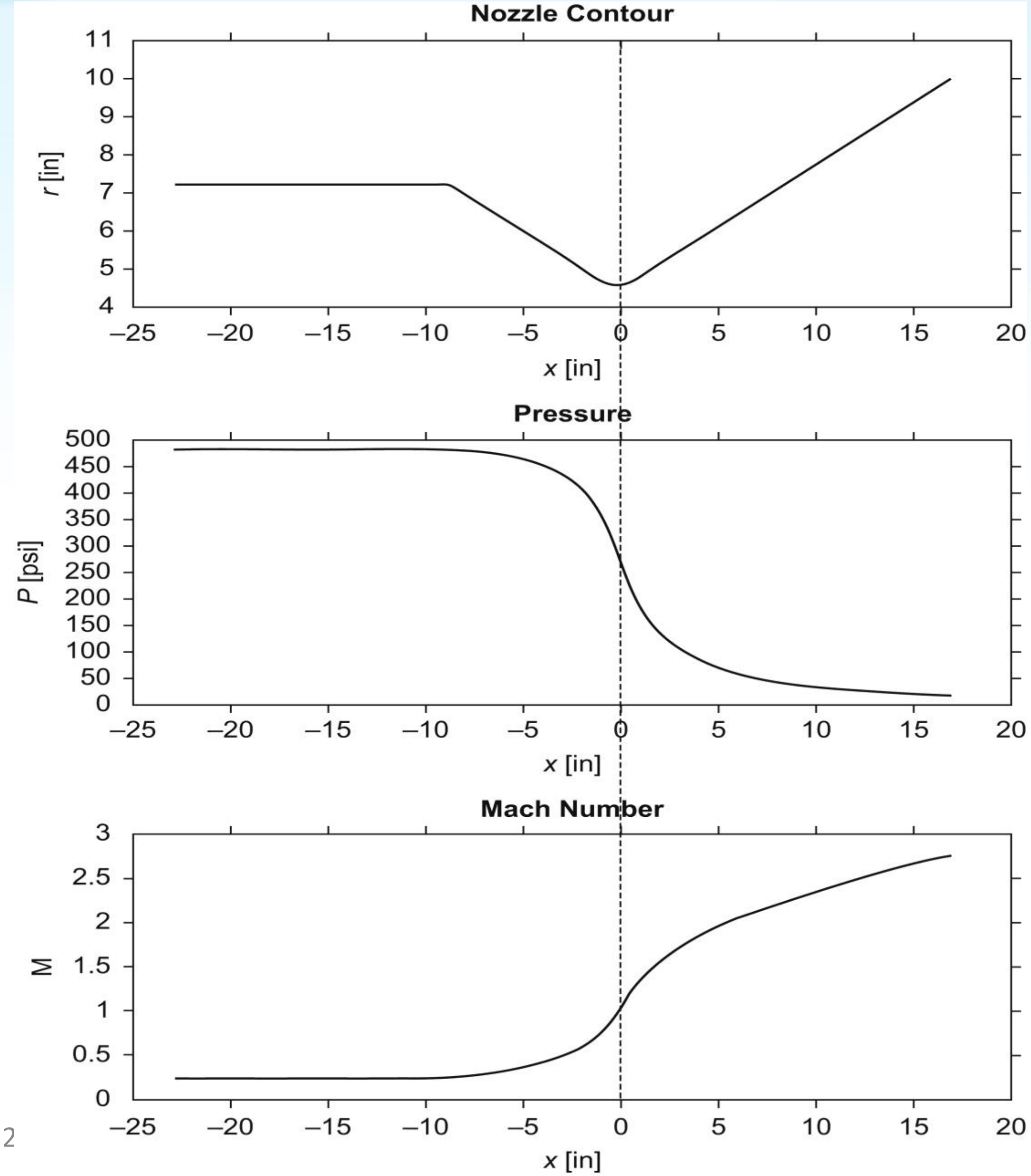
Isentropic Flow and Nozzle Thermodynamics



$$F = \dot{m}v_e + (p_e - p_a)A_e$$



4.1 Review of Compressible Flow



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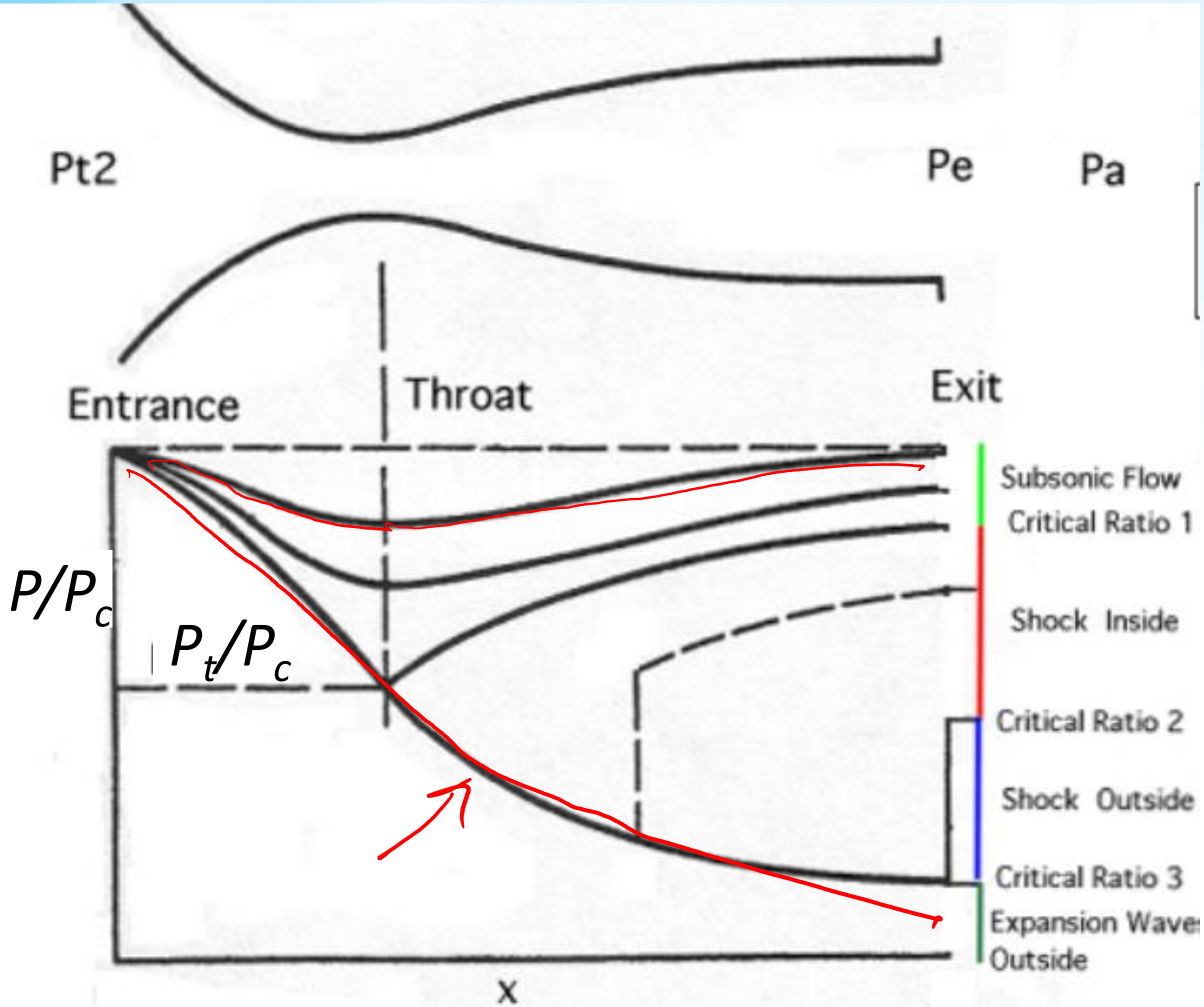
Nozzle Startup



Stagnation to static pressure

$$p_c/p = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)}$$

At the Throat

$$p_c/p_t = \left(1 + \frac{\gamma - 1}{2} 1^2\right)^{\gamma/(\gamma-1)} =$$

$$= \left[\frac{\gamma + 1}{2}\right]^{\gamma/(\gamma-1)}$$

For $\gamma = 1.2$

$$\frac{P_t}{Pc} = 0.565$$

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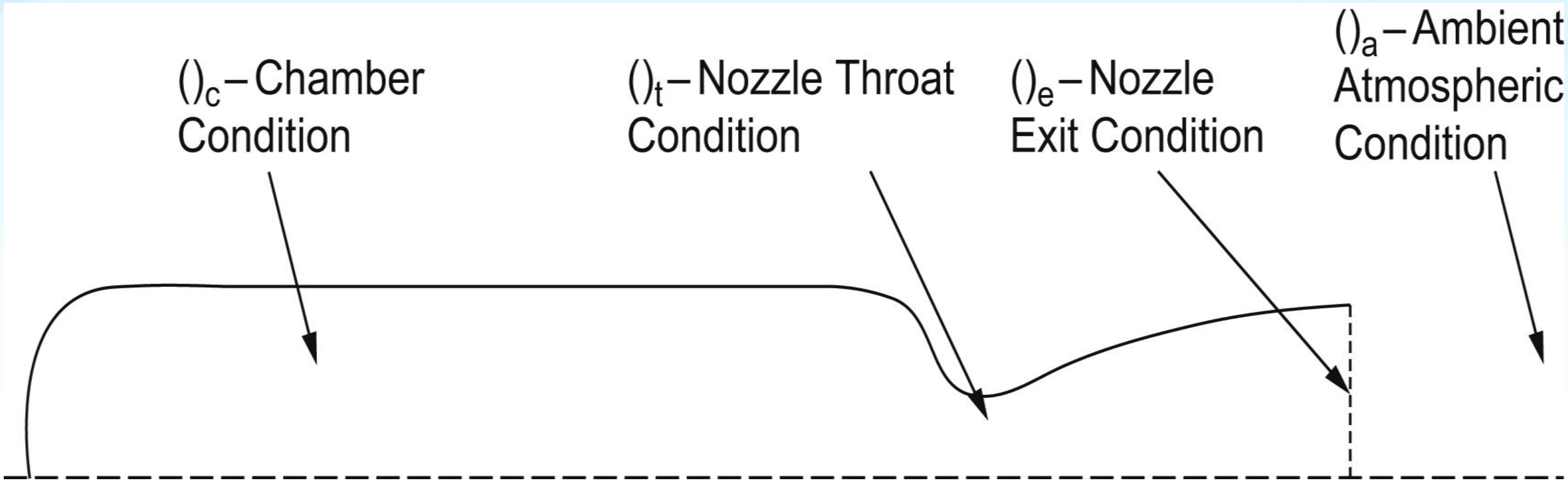
Nozzle Startup

Nomenclature



Isentropic Flow Equations

$$p_c/p = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)}$$

$$T_c/T = \left(1 + \frac{\gamma - 1}{2} M^2\right)$$

$$M = v/a = \frac{v}{\sqrt{\gamma R T}}$$

$$\frac{A}{A_t} = \frac{1}{M}\left\{\frac{2 + (\gamma - 1)M^2}{(\gamma + 1)}\right\}^{\frac{\gamma+1}{2(\gamma-1)}}$$

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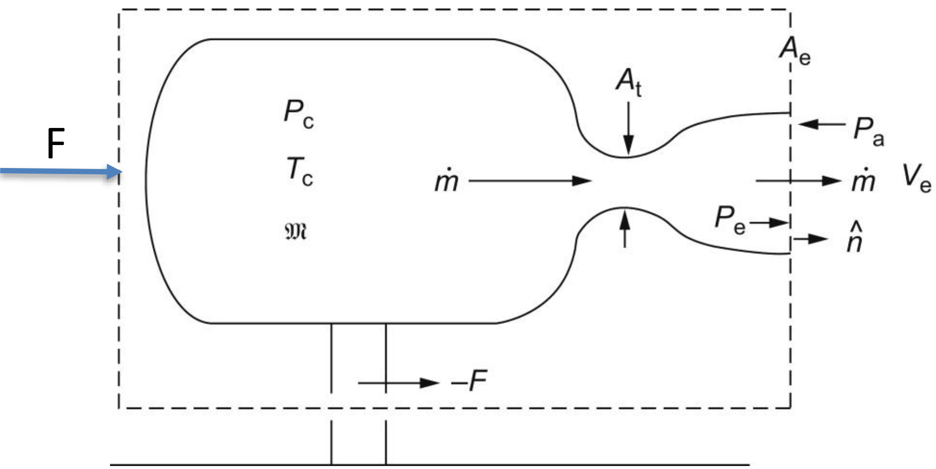
4.2 Rocket Performance Fundamentals

- Momentum Equation for Control Volumes (Fluids I)

$$F + \int_{cs} p \cdot \mathbf{n} dA = \int_{cs} \rho \mathbf{v}(\mathbf{v} \cdot \mathbf{n}) dA$$

$$F = \dot{m} v_e + (p_e - p_a) A_e$$

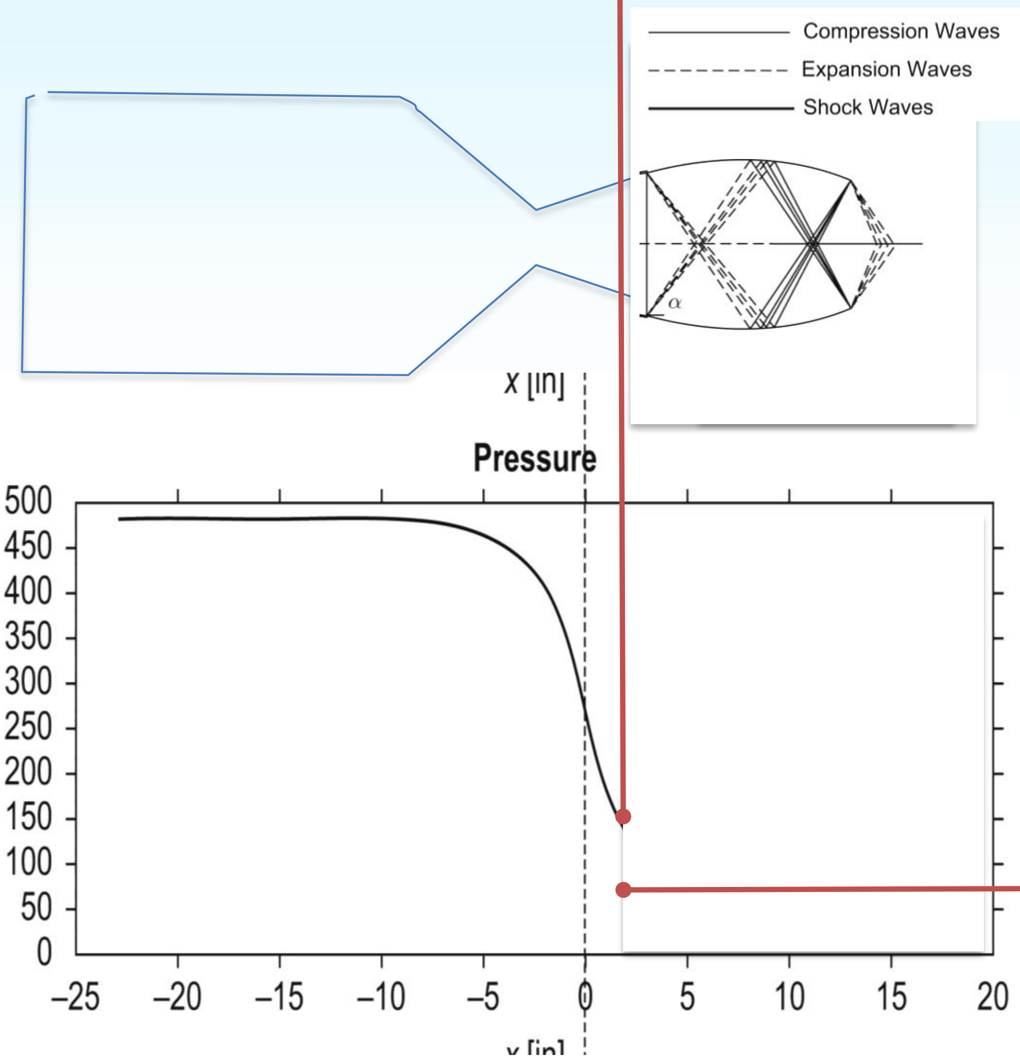


Implications

- $\dot{m} v_e$ is the "*Jet Thrust*" or "*Momentum Thrust*"
- $(p_e - p_a) A_e$ is the "Pressure Thrust"
- In General p_e is not equal to p_a
- $P_{a = o\ (vacuum)}$ is maximum thrust for that area ratio
- $F = F_v - p_a A_e$

$$F = \dot{m}v_e + (p_e - p_a)A_e$$

$P_e > P_a$ *underxpanded*



p_e

p_a

Underexpanded flow, $P_e > P_a$

Saturn 1B with 8 H1 engines,

Apollo 7 mission

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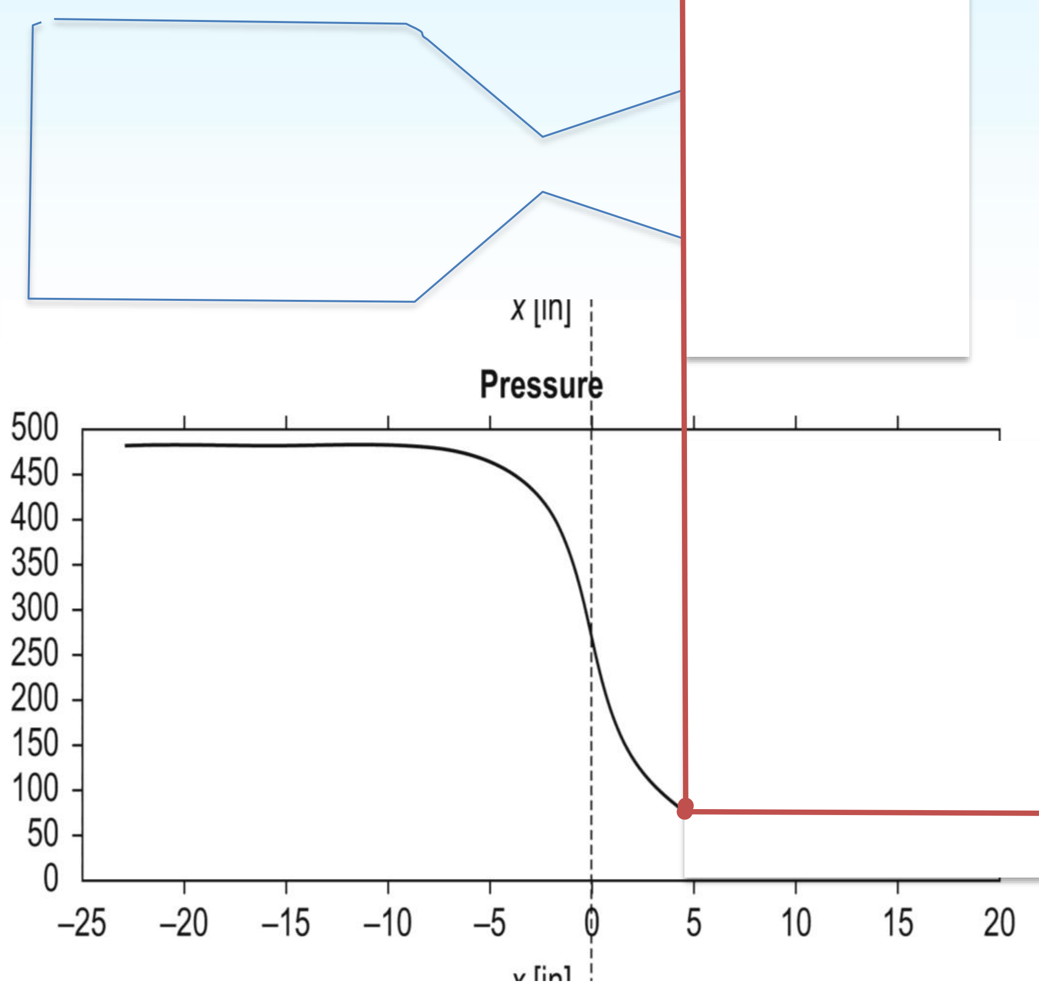
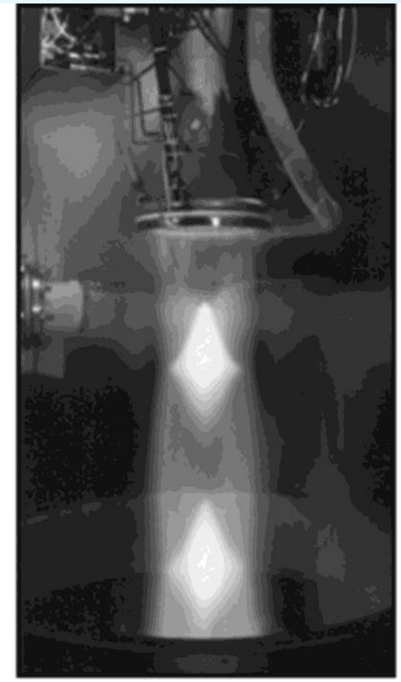
$P_e = P_a$ *perfectly expanded*

p_e



p_a

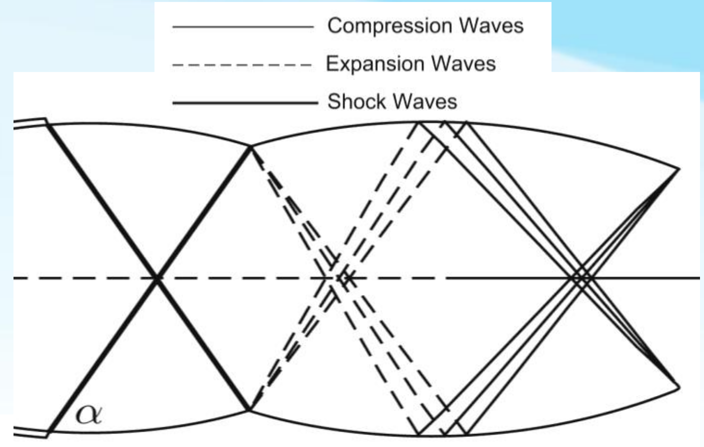


Perfcetly expanded flow,

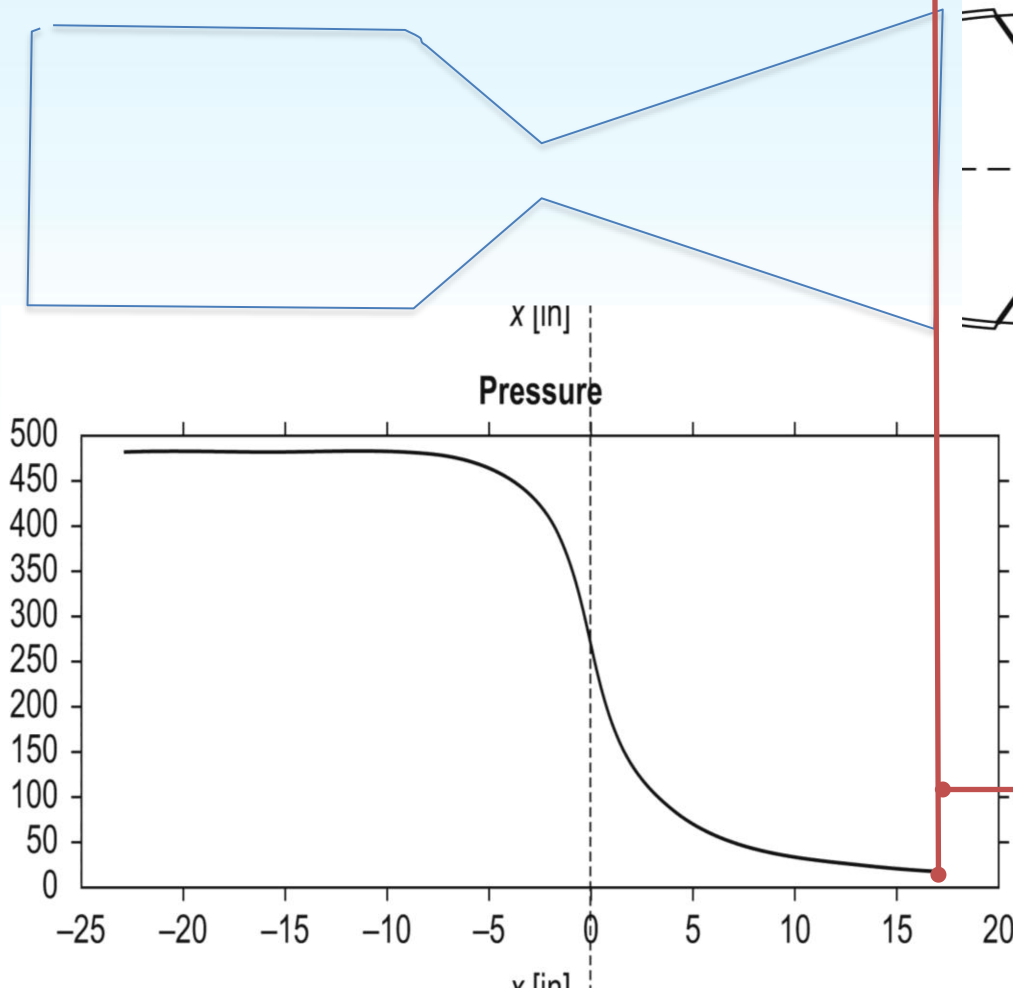
$\boldsymbol{P_e \sim P_a}$

RL 10 engine w/o NE

$P_e < P_a$ *overexpanded*



p_e



p_a

Overexpanded flow, $P_e < P_a$

Vulcain engine, hot-firing at DLR P5 ground test facility

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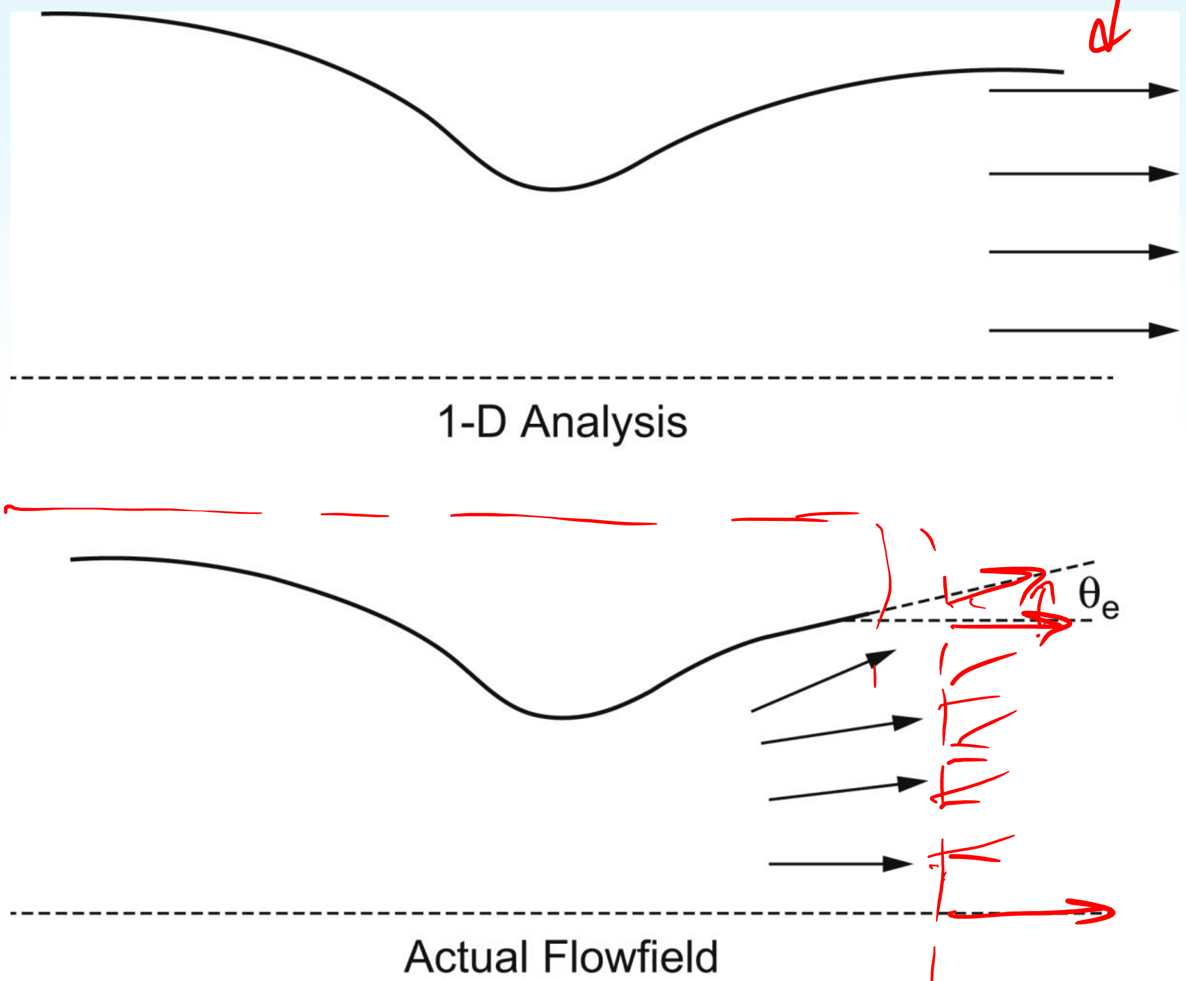
Two-Dimensional Effects

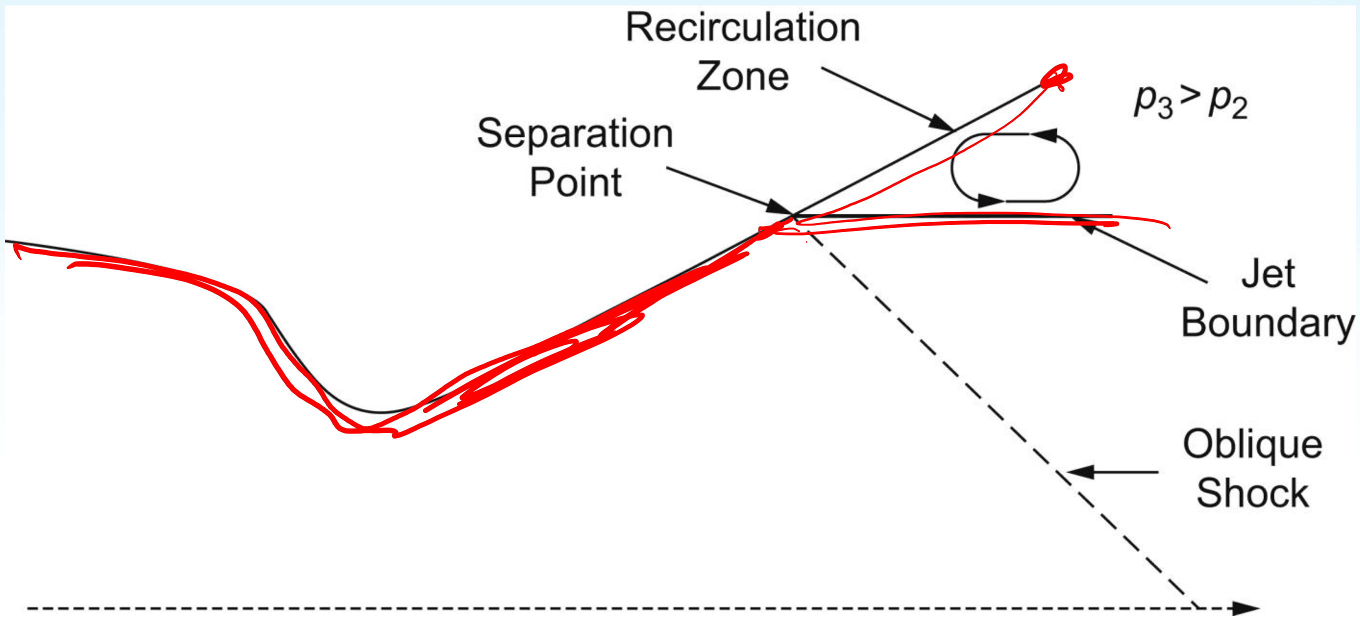
1-D AXIAL VELOCITY



$$\int_{cs} \bar{U}(\vec{V}\cdot\hat{n})\rho\, dA$$

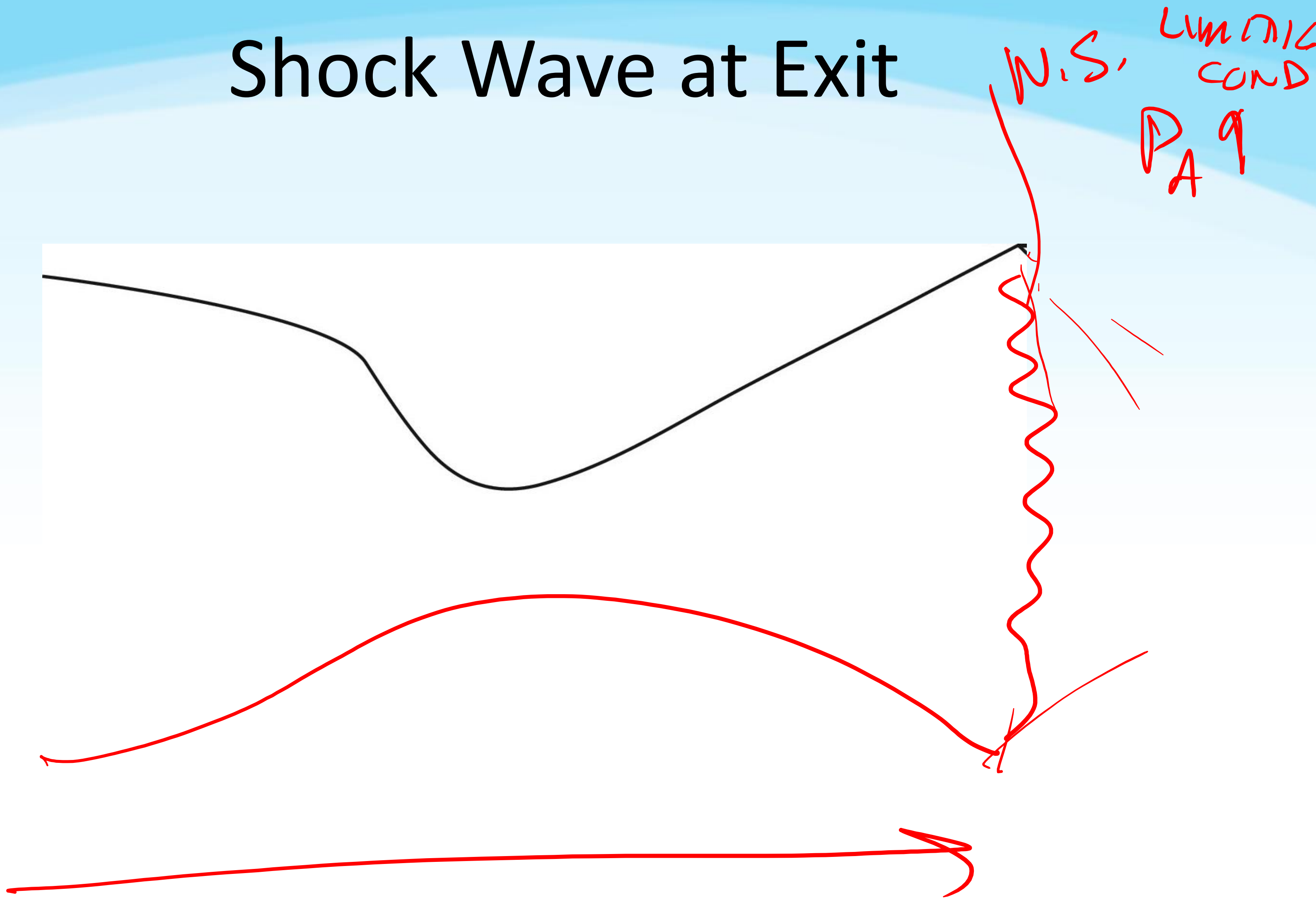
p_e

Flow Separation



p_e

Shock Wave at Exit



p_e

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Summary of Expansion States and Pressure Thrust

$$F = \dot{m}v_e + \boxed{(p_e - p_a)A_e}$$

Pressure Thrust

1. $p_e > p_a$. This is the case for an *underexpanded* nozzle, where we obtain positive pressure thrust.
2. $p_e < p_a$. This is the case for an *overexpanded* nozzle, where we obtain negative pressure thrust.
3. $p_e = p_a$. This is the case for a *perfectly expanded* nozzle where we obtain no pressure thrust.

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4.2 Rocket Performance Fundamentals

$$F = \dot{m}v_e + (p_e - p_a)A_e$$

Thermodynamic Approach

Given:
$p_c \;\; p_a \;\; T_c \;\; \gamma \;\; A_t \;\; Ae/A_t \;\; \mathfrak{M}$

Find: Thrust, F

?

Isentropic Choked Flow

$$\dot{m} = p_c A_t \sqrt{\frac{\gamma \mathfrak{M}}{R_u T_c}} [2/(\gamma+1)]^{\frac{\gamma+1}{2(\gamma-1)}}$$

Isentropic, Perfect Gas

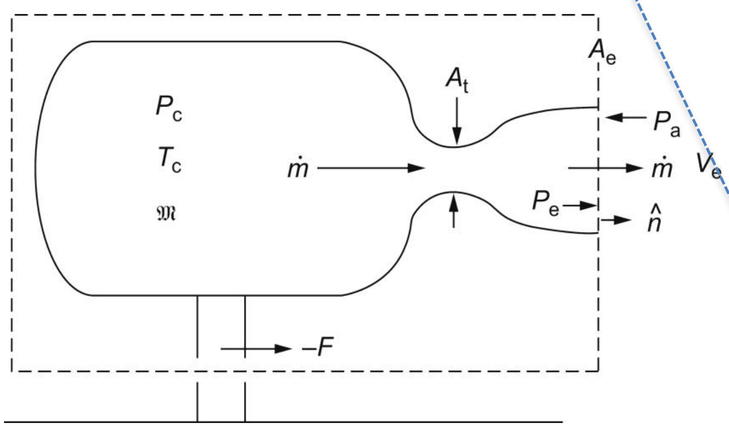
$$v_e^2 = \frac{2\gamma R_u T_c}{\mathfrak{M}(\gamma-1)}[1 - (p_e/p_c)^{(\gamma-1)/\gamma}]$$

Isentropic, Perfect Gas

$$p_c/p_e = \left(1 + \frac{\gamma-1}{2}M_e^2\right)^{\gamma/(\gamma-1)}$$

Isentropic, Perfect Gas (Supersonic Mach #)

$$\frac{A_e}{A_t} = \frac{1}{M_e}\left\{\frac{2 + (\gamma-1)M_e^2}{(\gamma+1)}\right\}^{\frac{\gamma+1}{2(\gamma-1)}}$$



01A-2 F – Thrust Coefficient Toolbox

4.2 Rocket Performance Fundamentals

Thrust Coefficient

- Best Thing Since Sliced Bread

- $F = c_f \, p_c \, A_t$

$$c_f = \frac{F}{p_c A_t} = \left[\frac{2\gamma^2}{\gamma - 1}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}\left(1 - (p_e/p_c)^{(\gamma-1)/\gamma}\right)\right]^{1/2} + (p_e/p_c - p_a/p_c)\varepsilon$$

- $c_f = c_f\,(\gamma, \varepsilon, p_c/p_a)$

- So if we know $\gamma, \varepsilon, p_c/p_a$ and, P_c *and* A_t , then we can calculate thrust

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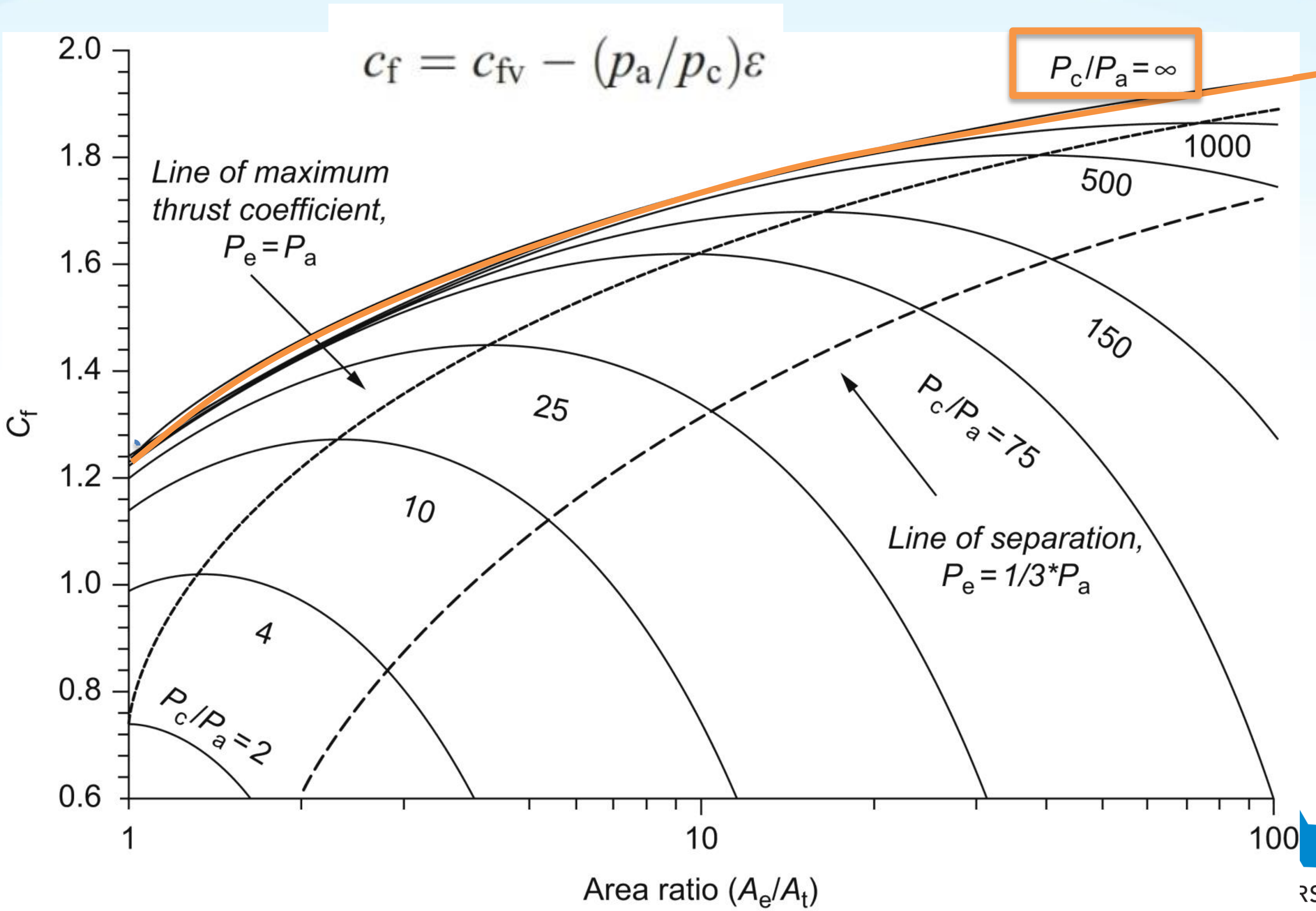
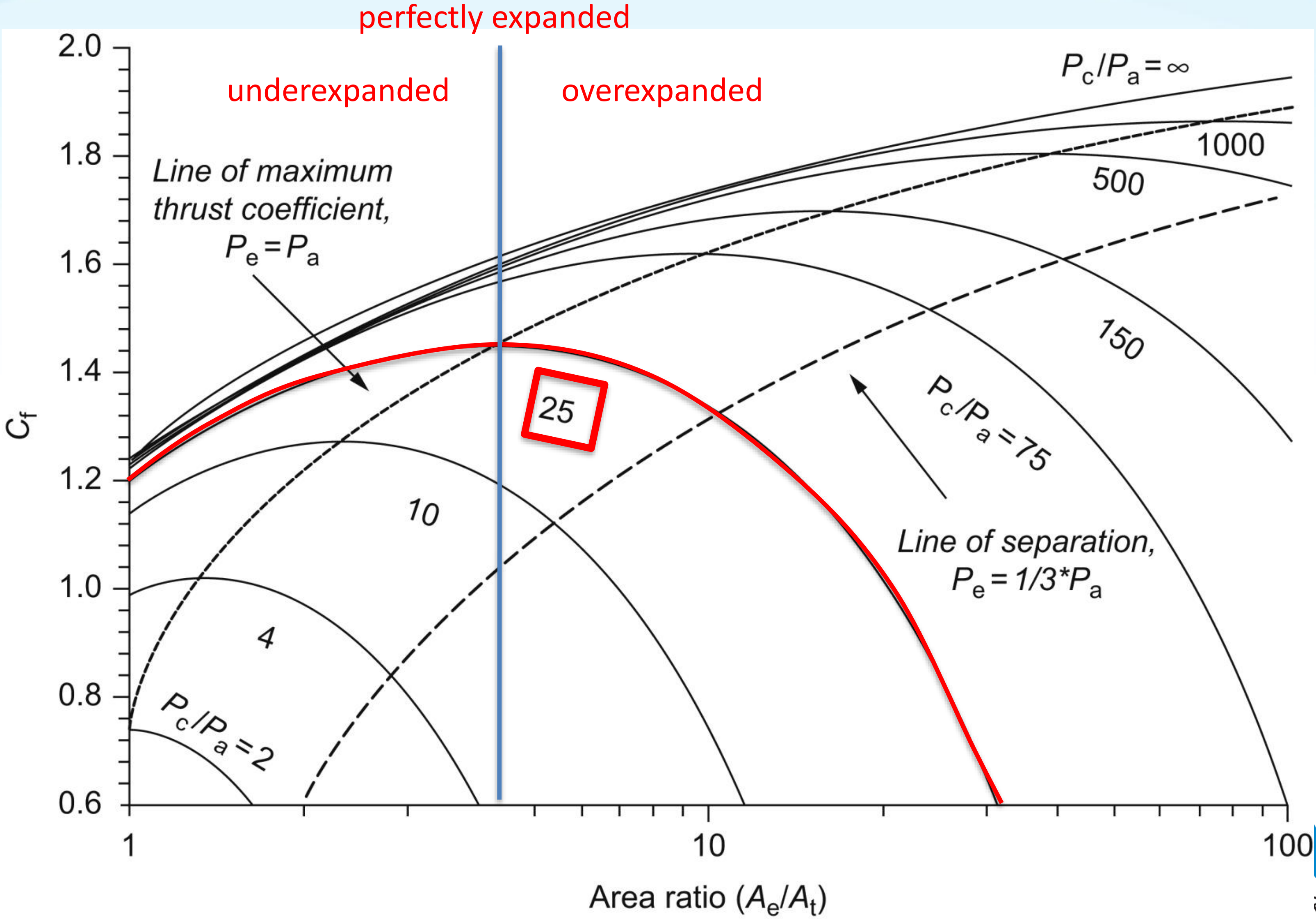
4.2 Rocket Performance Fundamentals

Thrust Coefficient



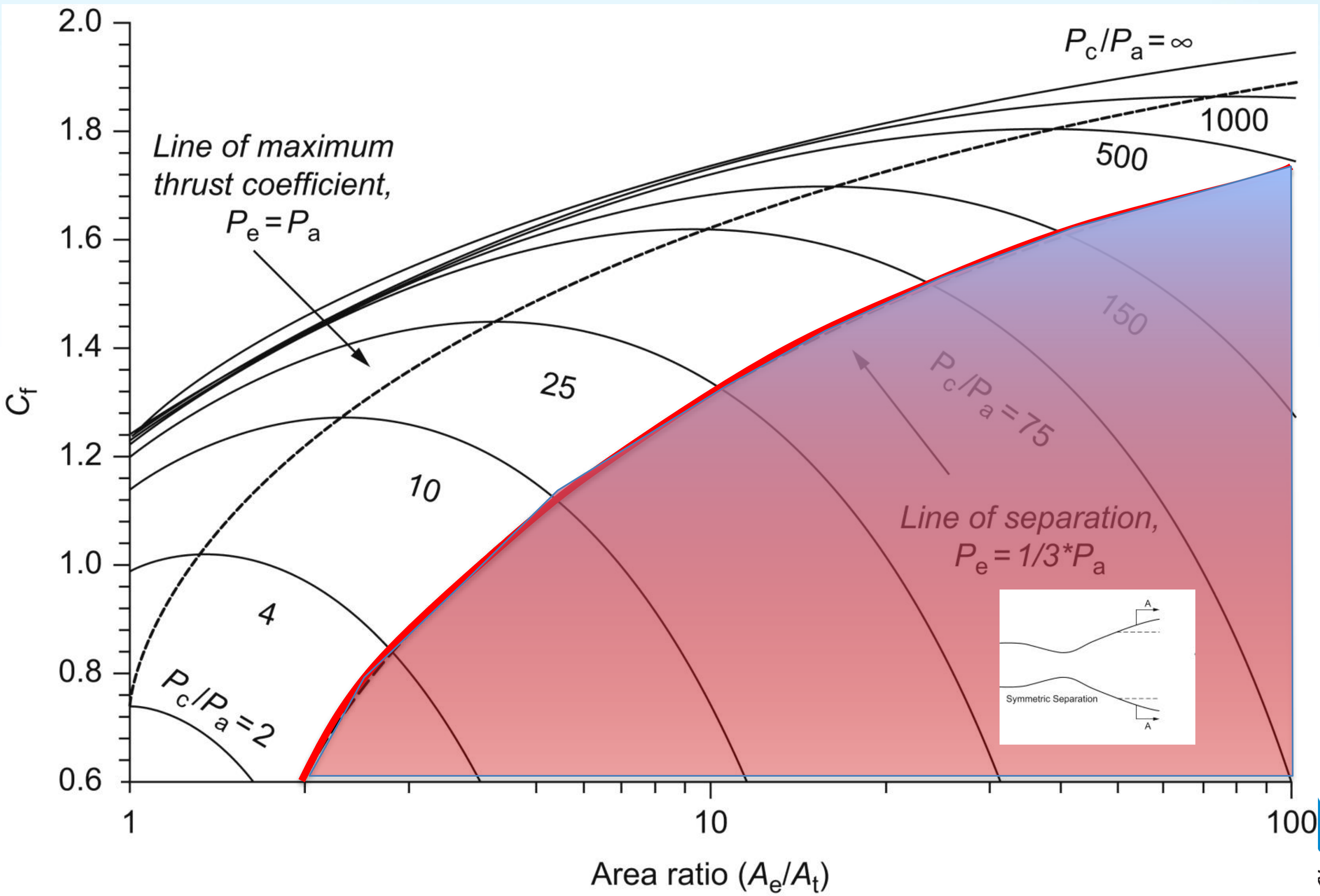
4.2 Rocket Performance Fundamentals

Thrust Coefficient



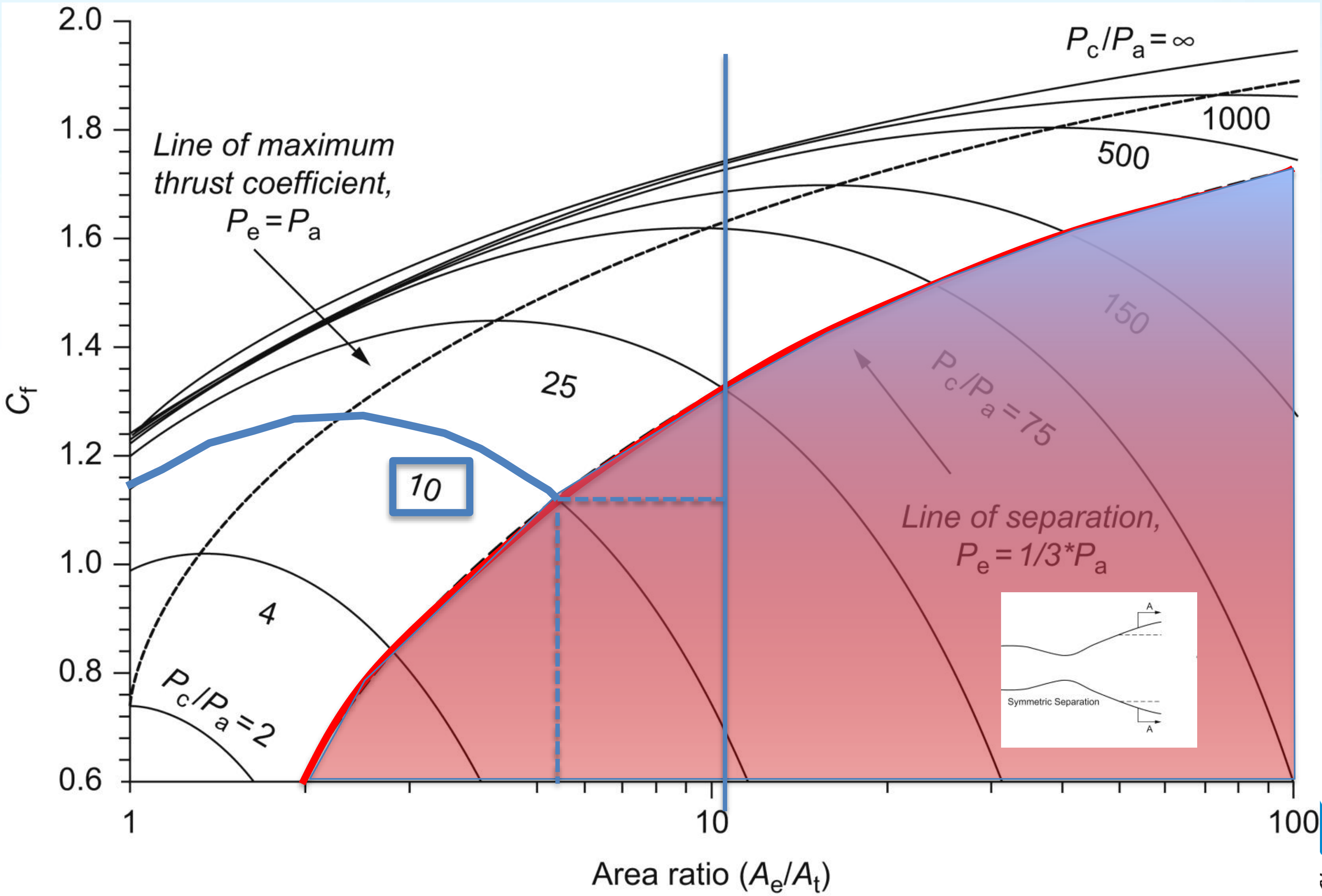
4.2 Rocket Performance Fundamentals

Thrust Coefficient



4.2 Rocket Performance Fundamentals

Thrust Coefficient



Spreadsheet Demonstration

	A	B	C	D	E	F	G	H	I	J	K	L
1				Robert Frederick								**To Calcualte Supersonic Mach Number**
2				UAH Propulsion Research Center								*=Comissions(k,area_ratio)*
3												**To cacluatie Thrust Coefficient**
4				K=	1.2							*=CF(k,Ae/At,P1/P3)*
5	*Enter Values in Green*											
6			Pc/Pa=									**Commands that you use to edit and run macros are found in the Code group of**
7	Ae/At	M2,super	M2, Sub									1. Click the File tab, and then click Options.
8	1	1										2. Click the Customize Ribbon category.
9	1.1	1.347693										3. Under Customize the Ribbon, in the Main Tabs list, click Developer, and then click OK.
10	1.2	1.493824										4. Return to Spreadsheet
11	1.3	1.603789										5. To see Marcos go to DEVELOPER ===>> VISUAL BASIC
12	1.4	1.694233										
13	1.5	1.771858										
14	1.8	1.95706										
15	2	2.055096										
16	3	2.397132										
17	4	2.619447										
18	8	3.121903										
19	10	3.278341										
20	12	3.405197										
21	14	3.512018										
22	15	3.559743										
23	19	3.723073										
24	20	3.758505										
25	30	4.039113										
26	40	4.239402										
27	50	4.395827										
28	80	4.72936										
29	90	4.813962										
30	100	4.89003										
31	100	4.89003										
32	100	4.89003										
33	100	4.89003										
34	100	4.89003										
35	100	4.89003										
36	100	4.89003										
37												
38												

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01A-2 D– Nozzle Operation

Required Homework Format

9-Step Homework Format Requirement

Required Homework Format (See Example at end of this Syllabus)
In the solution of problems, you are required to:

1. **Name:** Provide name of the student.
2. **Given**: State briefly and concisely (in your own words) the information provided.
3. **Find:** State the information that you have to find.
4. **Schematic**: Draw a schematic representation of the system and control volume if applicable.
5. **Assumptions:** List the simplifying assumptions that are appropriate to the problem and implied by the equations used.
6. **Basic Equations**: Outline the basic equations needed to do the analysis. Use the proper symbol from the book where applicable.
7. **Analysis:** Manipulate the basic equations to the point where it is appropriate to substitute numerical values. Substitute numerical values (using a consistent set of units) to obtain a numerical answer. Include appropriate units in calculations. If multiple repetitive calculations are done on a spreadsheet for example, show at least one example calculation in detail, including all units. The significant figures in the answer should be consistent with the given data. Check the answer and the assumptions made in effecting the solution to make sure they are reasonable.
8. **Answer**. Label the answer(s) with a box and an arrow from the right-hand margin.
9. **Comment**: Write a comment at the end of the homework that reflects on the limitations of the solution, the reasonableness of the solution, or something that you learned by doing the problem.

All nine formatting elements must be specifically shown in Each HW to receive full credit unless otherwise specified.

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01 Homework Assignment

- <u>Textbook Problems</u>

  2.6, 3.8, 4.24, 4.30
- <u>Special Problems</u>

  SP01A Annotated Bibliography

  Berg, P., Loeblich, W., and Frederick, R., "Using CEQUEL for Thermochemistry Calculations in a Graduate Rocket Propulsion Course at UAH," 2023 AIAA SciTech, January 26, 2023.

  SP01B Derive Basic Thrust Equation

  SP01C Derive Basic Exit Velocity Equation

Remember to upload you entire assignment in one file. If you work by hand and do not have a scanner, there are phone aps that you can use to take picture and pdf the pictures into one file. We just need to be able to clearly see all the requested homework in one file.

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Homework 01 - Problem 2.6

1. Name : Instructor
2. Given:

A small interceptor is launched horizontally from an aircraft flying at $M = 0.8$ at an altitude of 40,000 ft. The rocket motor operates over a one second duration after release from the aircraft. The missile velocity history during this time is given by

$$V = V_o\left(1 + 2\sin\left(\pi\,{}^{t}\!/_{2}\right)\right) \qquad 0 \le t \le 1$$

where V_o is the aircraft velocity at the time of release. Guidance experts indicate that the missile will have adequate agilty to intercept its moving target as long as its velocity is at least 1000 f/s. Assume that we can neglect drag during the brief boost phase. During the coast pahse, assume the following:

Missile Mass = 300 lb.

3. Find:

a) The range at the end of the boost phase.

b) The total range of the missile.

Assigned Problems:

- <u>Textbook Problems</u> 2.6, 3.8, 4.24, 4.30

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Homework 01 - Problem 2.6

Homework 01 - Problem 3.8

Assigned Problems:
- Textbook Problems
  2.6, 3.8, 4.24, 4.30

HEISTER PROBLEM 3.8 (1/4)

1. NAME: ROBERT FREDERICK

2. GIVEN: AIR-LAUNCHED MISSILE; OPERATIONAL ALTITUDE = 20,000 ft; SOLID ROCKET: $C^* = 5000$ ft/s; $\gamma = 1.2$; $\varepsilon_{max} = 30$
$m_p = 250$ lbm, $d_t = 2.0$ in, MISSILE DESIGNED TO "SHOOT UP" SO NOZZLE SHOULD BE ON VERGE OF SEPARATION AT LAUNCH. (ASSUME SEPARATION PRESSURE IS 1/3 OF LOCAL AMBIENT PRESSURE).

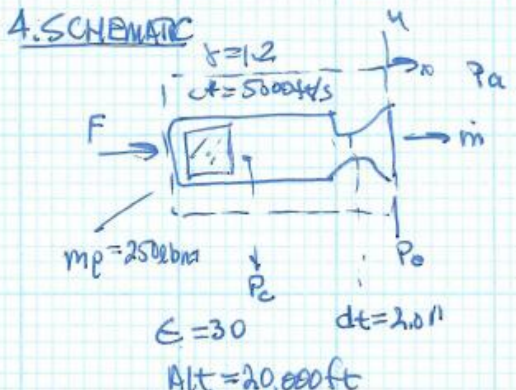
MISTAKE IN SOLUTION PART C.

3. FIND: (a) CHAMBER PRESSURE THAT SATISFIES INITIAL NOZZLE SEPARATION CRITERIA.

(b) ASSUMING P_c IS CONSTANT AT 20,000 ft, FIND THE MOTOR THRUST AND BURNING TIME

(c) DETERMINE THE SEA-LEVEL THRUST USING P_c FROM PART (a)

4. SCHEMATIC



5. ASSUMPTIONS
1. NOZZLE AREA RATIO OF 30.
2. ISENTROPIC FLOW IN NOZZLE
3. FROZEN FLOW IN NOZZLE
4. ONE-DIMENSIONAL FLOW
5. ATMOSPHERIC PROPERTIES FROM 1976 NASA STANDART ATMOSPHERE

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Homework 01 - Problem 3.8

Assigned Problems:

- Textbook Problems
  2.6, 3.8, 4.24, 4.30

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Homework 01 - Problem 4.24

Assigned Problems:

- <u>Textbook Problems</u>

  2.6, 3.8, 4.24, 4.30

HEISTER PROBLEM 4.24

1/2

1. NAME: ROBERT FREDERICK

2. GIVEN: HYBRID ROCKET MOTOR

$\dot{m}_{ox} = 10\ lbm/s$; $\dot{m}_f = 3 - 0.6(t/t_b)$; $t_b = 50\ sec$

$\dot{m}_f = lbm/s$

$\gamma = 1.2$

$C^* = 4800 + 800(t/t_b) - 800(t/t_b)^2$

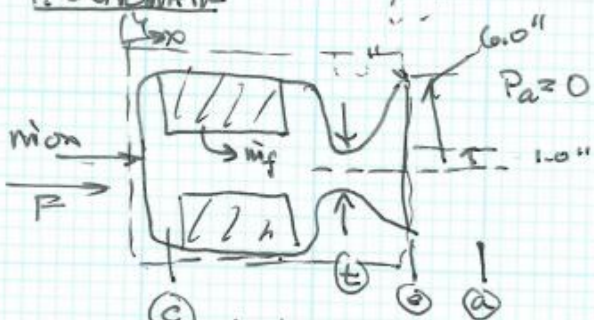
$P_a = 0$ (vacuum)

3. FIND: (a) The initial thrust and Isp OF THE ENGINE

(b) EXPRESSIONS FOR THE THRUST AND Isp AT ARBITRARY TIMES

(c) THE MAXIMUM ISP AND ITS TIME OF OCCURRENCE

4. SCHEMATIC



$\gamma = 1.2$

5. ASSUMPTIONS

(a) ISENTROPIC FLOW

(b) ONE-DIMENSIONAL FLOW

(c) NO THROAT EROSION

(d) COMPLETE COMBUSTION

(e) STEADY-STATE

6. BASIC EQUATIONS

Homework 01 - Problem 4.30

Assigned Problems:
- <u>Textbook Problems</u> 2.6, 3.8, 4.24, 4.30

1/3

PROBLEM 4.30

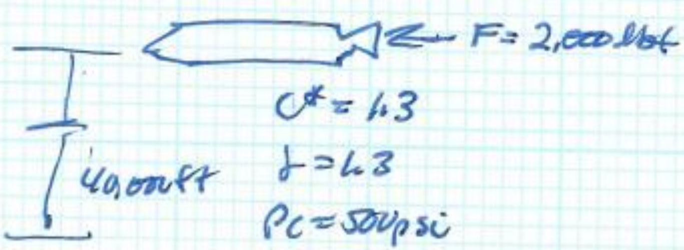
1. NAME: DR. FREDERICK, UAH

2. GIVEN: PROBLEM 4.30 HEISTER

A ROCKET PROPELS A OBJECT IN A HORIZONTAL ALTITUDE OF 40,000 FT, $\gamma = 1.3$, $C^* = 4800$ ft/s, $F_{DES} = 2000$ lbf, $P_c = 500$

3. FIND (a) D_t, D_e
(b) $\dot{m}$
(c) I_{sp}
(d) CF
(e) repeat (a)-(d) ASSUMING SEA LEVEL OPERATION

4. SCHEMATIC



5. ASSUME
1. OPTIMAL EXPANSION AT ALTITUDE
2. SAME NOZZLE AT SEA LEVEL
3. STEADY, ADIABATIC EXPANSION
4. CONSTANT SPECIFIC HEATS

Homework 01 – Special Problems

Other Discussion

Other Discussion

Other Discussion

Homework 01 - Problem 2.6

1. Name : Instructor
2. Given:

A small interceptor is launched horizontally from an aircraft flying at $M = 0.8$ at an altitude of 40,000 ft. The rocket motor operates over a one second duration after release from the aircraft. The missile velocity history during this time is given by

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Missile Mass = 300 lb.

3. Find:

a) The range at the end of the boost phase.

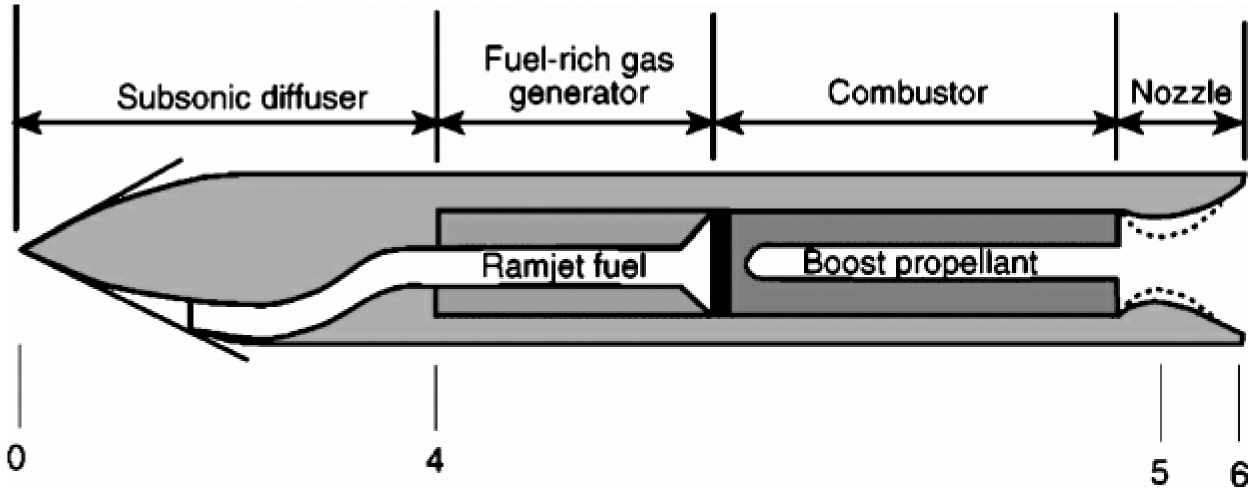
b) The total range of the missile.

Homework

Course Project

Solid Fuel Ramjet Booster/Combustor Design

The course project for the spring 2023 class will use the principles of solid rockets, hybrid rockets to compare designs among: [A] pure solid propulsion, [B] hybrid, and a [C] solid boost/ramjet combustor design for a supersonic mission to achieve the greatest range. The instructor provides additional instructional material and students research supplementary technical papers on the ramjet component of this project that are not contained in the textbook. The instructor provides a Project Requirement Document that describes the mission requirements, guidelines and assumptions, and a list of technical symbols for the project



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