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# Jet and Rocket Propulsion

## AE4451

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### LECTURE 17

# Overview

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- over the past few weeks, we've looked at air-breathing systems in some detail
  - types of technologies: ramjet, turbojet, turbofan
  - cycle analysis: ideal/non-ideal
  - performance metrics and progress trends
  
- today:
  - rocket propulsion systems

# Rocket propulsion systems

## Definition of a rocket propulsion system

- device that provides thrust to a vehicle by accelerating some stored matter (propellant) and exhausting it
- unlike the air-breathing systems we've studied: in rocket systems, all the propellant is carried onboard



Ariane 5's Vulcain 2 engine  
liquid oxygen/liquid hydrogen



Ariane 5 liftoff

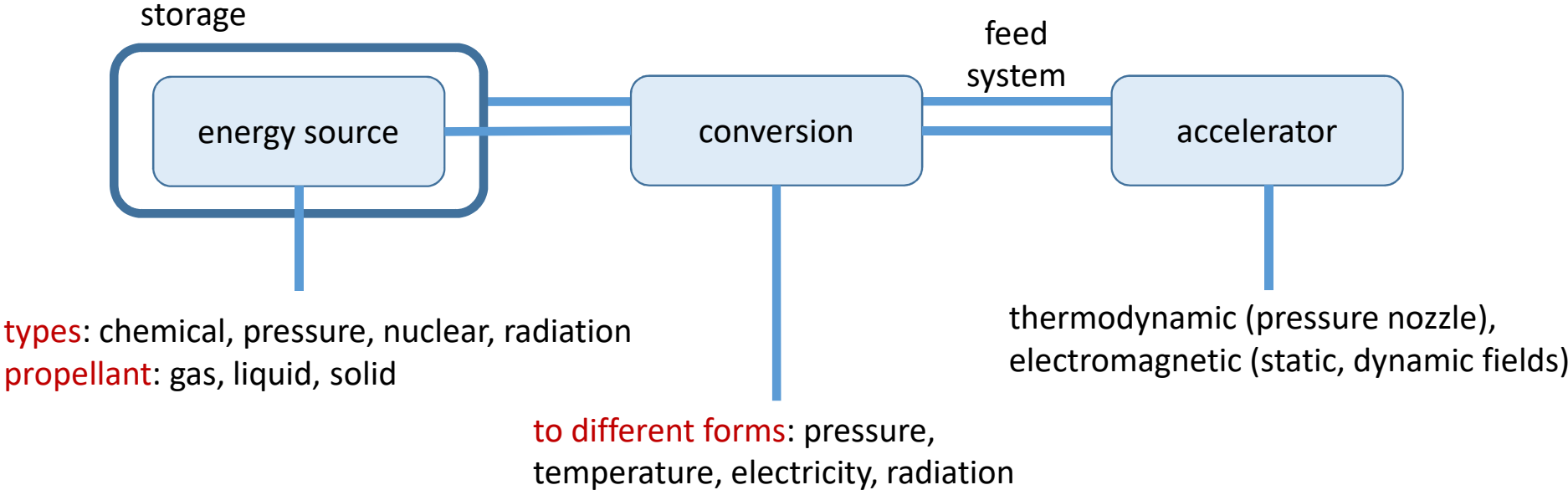
# Rocket propulsion systems

## Performance parameters

- thrust  $F$ 
  - important to consider when dealing with required acceleration for a particular maneuver, e.g. launch in gravity field
  
- total impulse
  - measure of time-integrated performance (to change vehicle momentum)  $I = \int F dt$
  
- other considerations
  - structural weight, size, shape
  - complexity, reliability
  - throttling, reusability
  - emissions, noise, etc.

# Rocket propulsion systems

## Elements



# Rocket propulsion systems

## Elements: examples

pressure rocket

### cold gas thruster



IBB cold gas thruster  
20 – 200 mN

propellant = energy source (thermal)

storage = gas (canister)

feed system = piping from storage to nozzle

energy conversion = none

accelerator = nozzle (thermal to kinetic)

- cold gas (e.g. N<sub>2</sub>) stored under pressure, accelerated across nozzle to produce thrust

chemical rocket

### bipropellant: LH<sub>2</sub>/LOX (H<sub>2</sub>/O<sub>2</sub>)



RS-25 (SSME), NASA

propellant = energy source (chemical)

storage = liquid (cryogenic tanks)

feed system = liquid pumps and piping

energy conversion = chemical to thermal (combustion)

accelerator = nozzle (thermal to kinetic)

- reaction between pressurized H<sub>2</sub> and O<sub>2</sub> in combustion chamber, acceleration across nozzle

# Rocket propulsion systems

## Elements: examples

electric rocket

### ion engine

- ionize neutral gas (e.g. Xe), accelerate ions with electric field, recombination with electrons

propellant = neutral gas

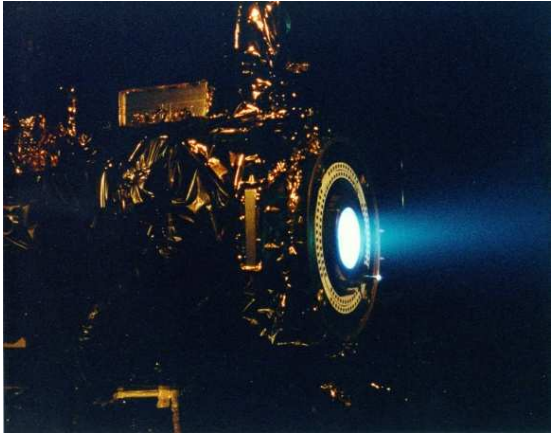
energy source = solar, nuclear

storage = gas (canister)

feed system = piping from storage

energy conversion =  
nuclear/solar to electrical

accelerator = electrostatic field



Deep Space 1, NASA (1998)



NSTAR gridded ion engine, NASA

# Rocket propulsion systems

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## Applications

- **space propulsion**
  - launch: from planetary body to orbit
  - orbit insertion: from launch orbit to mission orbit
  - maneuvering: maintain or change orbit or trajectory
  - attitude control: orientation of vehicle
- **aircraft propulsion**
  - high thrust/acceleration (sustained or boosters)
  - high speed flight (> ramjet/scramjet capability)

# Rocket propulsion systems

## Chemical rockets

- common applications
  - usual choice for high thrust requirements: launch, orbit change, aircraft propulsion
  - also used for maneuvering and attitude control
  
- propellants
  - monopropellants: exothermic decomposition of single species (liquid)
    - $N_2H_4$ ,  $H_2O_2$ ,  $N_2O$ , ...
  
  - bipropellants
    - RP-1/ $O_2$ ,  $H_2/O_2$ ,  $CH_3(NH)NH_2/N_2O_4$
  
  - ...

# Rocket propulsion systems

## Chemical rockets

- **propellant storage**
  - gas rockets: fuel/oxidizer stored as gases – requires large storage volumes
  - liquid rockets: stored as liquids – more complex but high impulse
  - solid rockets: propellant is solid – lower impulse but simpler
  - hybrid rockets: usually solid fuel + liquid oxidizer
- **motors versus engines**
  - "motor" = propellant stored inside combustion chamber
  - "engine" = storage outside combustion chamber
- **important considerations for propellant**
  - high  $I_s$  from high exhaust gas temperature, and low exhaust gas molecular weight
  - high density: lighter, smaller tanks
  - high stability desirable, also safe storage and handling
  - good performance means usually chemically active substance: corrosive, flammable, toxic

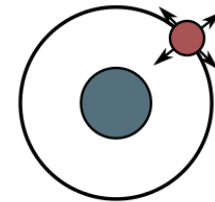
# Rocket propulsion systems

## Other rockets: applications

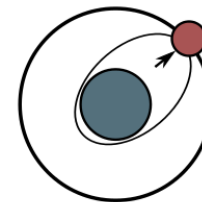
- pressure (cold gas)
  - attitude control + maneuvering: reduced thrust as pressure decreases, rendezvous

- electrical

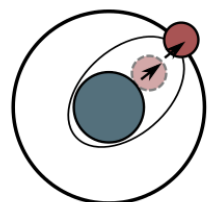
- resistojets
- arcjet thrusters - maneuvering + attitude control
- ion engines/Hall thrusters - space propulsion, now multiple orbit maneuvers
- many others



station-keeping



orbit-topping



orbit-raising

- future (?) systems

- nuclear thermal: like chemical rockets with nuclear-based heat addition, high thrust
- magnetoplasmadynamic and other electrodynamic devices, high impulse

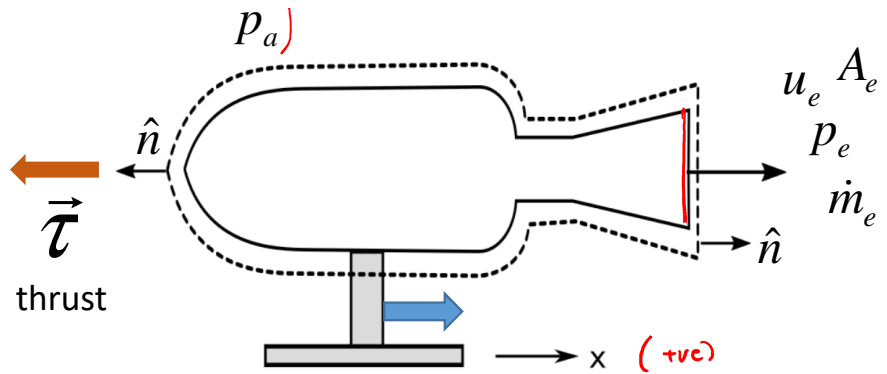
# "Non-rocket" propulsion systems

- **combined cycles**: typically combine air-breathing with rocket cycles for single-stage to orbit (SSTO)
- **solar sails**: use momentum from solar radiation
- **magnetic sails**: use magnetic fields interacting with solar particles
- **tethers**: conducting material moving through EM fields can produce currents/voltages or passing current through tether can produce forces
- **gravity assist**: sling shot effect
- warp drive, Cannae Drive (EmDrive, resonant cavity thruster – refuted)



# Rocket propulsion systems: thrust and impulse

## Static thrust



- immobile
- steady, quasi 1D flow

recall from momentum conservation

$$\begin{aligned}
 \vec{F}_{solid\ body\ on\ fluid} - \int_{open} p \hat{n} dA + \int_{open} \vec{\sigma}_{shear} dA + \int_{CV} \rho \vec{f} dV &= \frac{d}{dt} \int_{CV} \rho \vec{u} dV + \int_{CS} \rho \vec{u} (\vec{u}_{rel} \cdot \hat{n}) dA \\
 -(-\tau) - (p_e - p_a)A_e + 0 + 0 &= \frac{d}{dt} \int_{CV} \rho 0 dV + \dot{m} u_e \quad \text{(ignoring shear, body forces)} \\
 \tau &= \dot{m} u_e + (p_e - p_a)A_e \quad \text{(steady flow)}
 \end{aligned}$$

$\dot{m} = \rho u A$   
 $u_{rel} = u_e - 0$

# Rocket propulsion systems: thrust and impulse

## Equivalent exhaust velocity $u_{eq}$

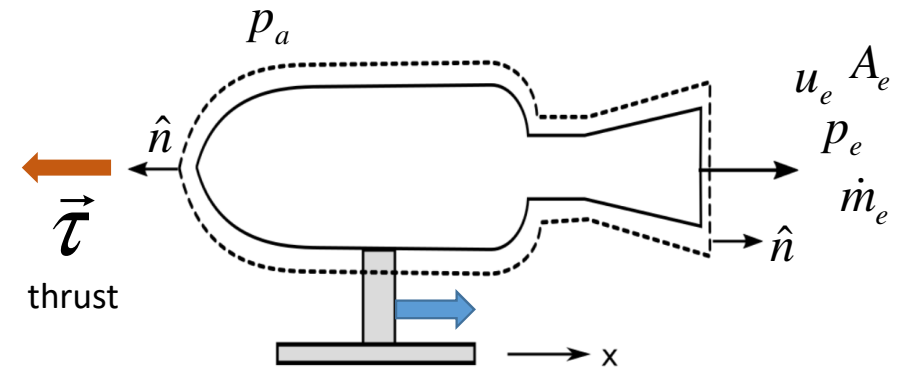
### Definition

$$u_{eq} \equiv \frac{\tau}{\dot{m}} = u_e + \frac{(p_e - p_a)A_e}{\dot{m}}$$

- combines momentum change and pressure force terms
- written for convenience

$$\tau = \dot{m}u_e + (p_e - p_a)A_e$$

$$\tau = \dot{m}u_{eq}$$



# Rocket propulsion systems: thrust and impulse

## Impulse I

### Definition

$$I = \int_{t_{start}}^{t_{end}} \tau dt$$

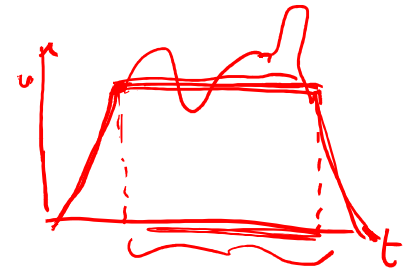
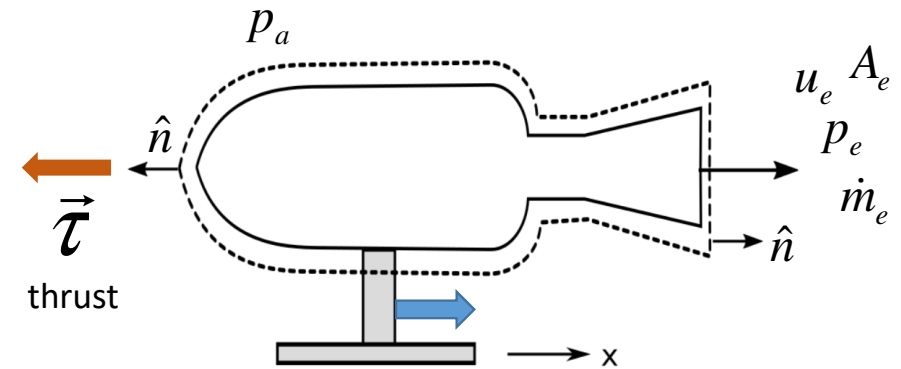
- total momentum imparted by a force (here,  $\tau$ ) acting over time

also written 
$$I = \int_{t_{start}}^{t_{end}} \dot{m} u_{eq} dt$$

- assuming steady nozzle and ambient conditions,

$$I = u_{eq} \int_{t_{start}}^{t_{end}} \dot{m} dt = u_{eq} m_p$$

$m_p$  = total mass of expelled propellant



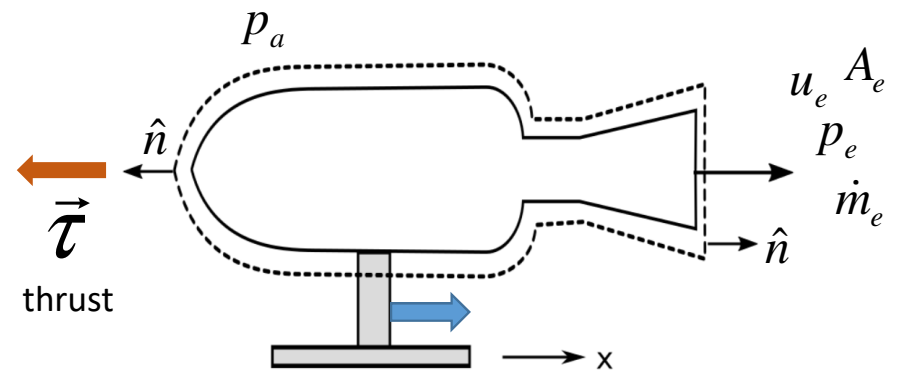
# Rocket propulsion systems: thrust and impulse

## Specific impulse $I_{sp}$

Definition

$$I_{sp} \equiv I / m_p = \underline{u_{eq}}$$

if steady  
units of velocity



- divided by propellant mass to determine rocket performance per kg of propellant it has to carry
- higher  $I_{sp}$  means less propellant required, thus
  - more payload that can be carried
  - or lighter, smaller rocket can be used

• **normalization**

- to get same value in all unit systems, typically normalize  $I_{sp}$  by Earth's gravitational constant (gravity at Earth's surface)

$g_e \approx 9.81 \text{ m/s}^2$   
**not g at rocket location**

$$I_{sp} = \left( \frac{I}{m_p} \right) / g_e = \frac{u_{eq}}{g_e}$$

if steady  
units of time (seconds)

# Rocket propulsion systems: thrust and impulse

## Liquid bipropellants: examples

Oxidizer	<sup>boiling / freezing pt</sup> BP/FP (°C)	Fuel	BP/FP (°C)	Combustor Temperature (K)	Bulk Avg. Density (g/cm <sup>3</sup> )	C* (m/s)	Isp (s)
O <sub>2</sub>	-183/-218	H <sub>2</sub>	-253/-259	3010	0.3	2420	390
O <sub>2</sub>		RP-1	~210/-50	3680	1.0	1810	300
O <sub>2</sub>		UDMH	63/-58	3600	1.0	1860	310
O <sub>2</sub>		NH <sub>3</sub>	-33/-78	3080	0.9	1800	295
F <sub>2</sub>	-188/-220	H <sub>2</sub>		3960	0.5	2560	410
F <sub>2</sub>		Hydrazine	113/1.4	4680	1.3	2210	363
N <sub>2</sub> O <sub>4</sub>	21/-12	MMH	86/-53	3390	1.2	1750	288
N <sub>2</sub> O <sub>4</sub>		RP-1		3450	1.3	1650	275

$u_{eq} = ?$  (m/s)

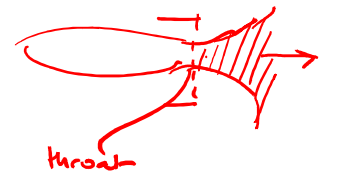
3830 x

2940

4020

2700

$$I_{sp} = \left( \frac{I}{m_p} \right) / g_e = \frac{u_{eq}}{g_e}$$



$$c^* = \frac{pA_t}{\dot{m}}$$

$c^*$  = characteristic velocity,  
measure of combustion performance without nozzle

Optimum performance; 1000psia (6.94MPa) combustor;  $p_e=p_a=14.7$  psia (1 atm)  
**UDMH**=Unsymmetrical dimethyl hydrazine (CH<sub>3</sub>)<sub>2</sub>NNH<sub>2</sub>    **Hydrazine**=N<sub>2</sub>H<sub>4</sub>  
**MMH**=Monomethyl hydrazine CH<sub>3</sub>NH-NH<sub>2</sub>    **NH<sub>3</sub>**=Ammonia  
 \***Hypergolic Mixture** (ignites on contact)

# Rocket propulsion systems: thrust and impulse

## Solid propellants: examples

Propellant	Metal (wt %)	Combustion Temperature (K)	Density (g/cm <sup>3</sup> )	Isp (s)
Double Base		2530	1.6	230
DB/AP	Al (20)	3870	1.8	265
Polyurethane-AP	Al (20)	3480	1.8	265
PBAN-AP	Al (16)	3480	1.8	263
HTPB-AP		3000	1.8	250
HTPB-AP	Al (17)	3480	1.9	265

$$u_{eq} = ? \text{ (m/s)}$$

2260

$$I_{sp} = \left( \frac{I}{m_p} \right) / g_e = \frac{u_{eq}}{g_e}$$

2450

2600

**Double Base**= homogeneous mixture nitroglycerine-nitrocellulose



**AP**=Ammonium Perchlorate **PBAN**=Polybutadiene-Acrylic Acid-Acrylonitrile Terpolymer

**HTPB**=Hydroxy-terminated Polybutadiene

# Rocket propulsion systems: thrust and impulse

## Specific impulse: ranges

- chemical rockets
  - liquid bipropellants typically have higher  $I_{sp}$  than solids
  - typically  $I_{sp} = \underline{200 - 400}$  s at sea level exhaust
  - increase by  $\sim 17\%$  for vacuum exhaust
- electrical rocket systems
  - $I_{sp} > 1000 - 3000$  s
  - thrust however limited by available power source

# Rocket propulsion systems: vehicle acceleration

## Accelerating rocket

- rocket propulsion systems are typically used to *accelerate* a vehicle

i.e.  $du / dt, u \neq \text{constant}$

- **velocity increment**

$$\Delta u \equiv u_{final} - u_{initial} \quad \text{net increase in vehicle velocity}$$

- since large amount of propellant onboard, mass of vehicle also changes with time

$$dm / dt, m \neq \text{constant}$$

# Rocket propulsion systems: vehicle acceleration

## Rocket acceleration

momentum conservation now becomes:

$$\vec{F}_{\text{solid body on fluid}} - \int_{\text{open}} p \hat{n} dA + \int_{\text{open}} \vec{\sigma}_{\text{shear}} dA + \int_{\text{CV}} \rho \vec{f} dV = \frac{d}{dt} \int_{\text{CV}} \rho \vec{u} dV + \int_{\text{CS}} \rho \vec{u} (\vec{u}_{\text{rel}} \cdot \hat{n}) dA$$

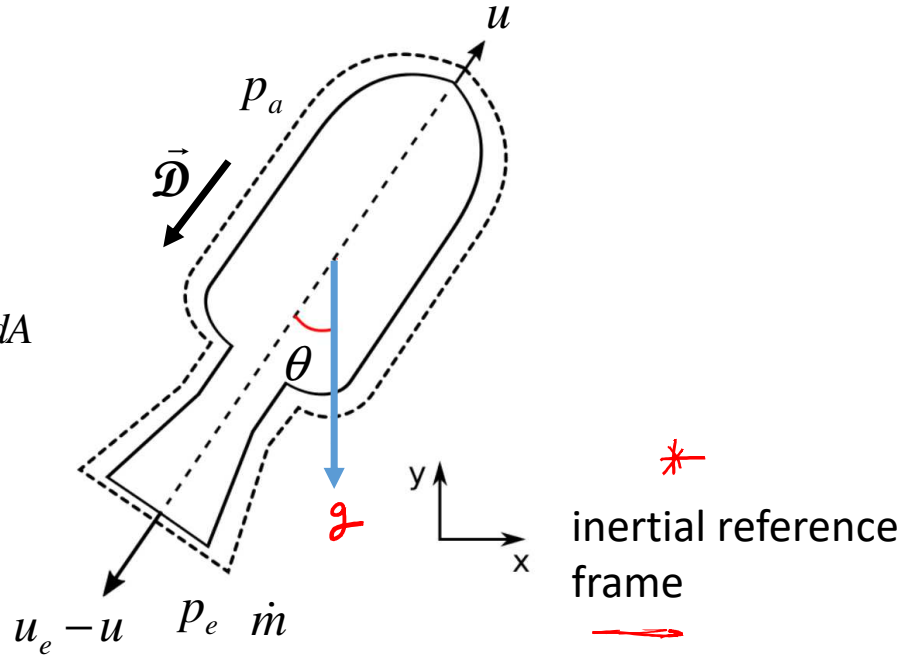
$m = \rho V$

$$0 - (-p_e + p_a)A_e - \mathcal{D} - \underbrace{mg \cos \theta}_{\text{body force contribution}} = \left( \frac{dm}{dt} u + m \frac{du}{dt} \right) + \dot{m} (u - u_e)$$

rearranging terms,

$$\frac{du}{dt} = \frac{1}{m} [\dot{m} u_e + (p_e - p_a) A_e] - g \cos \theta - \mathcal{D}/m$$

$\mathcal{D}$  = drag



# Rocket propulsion systems: vehicle acceleration

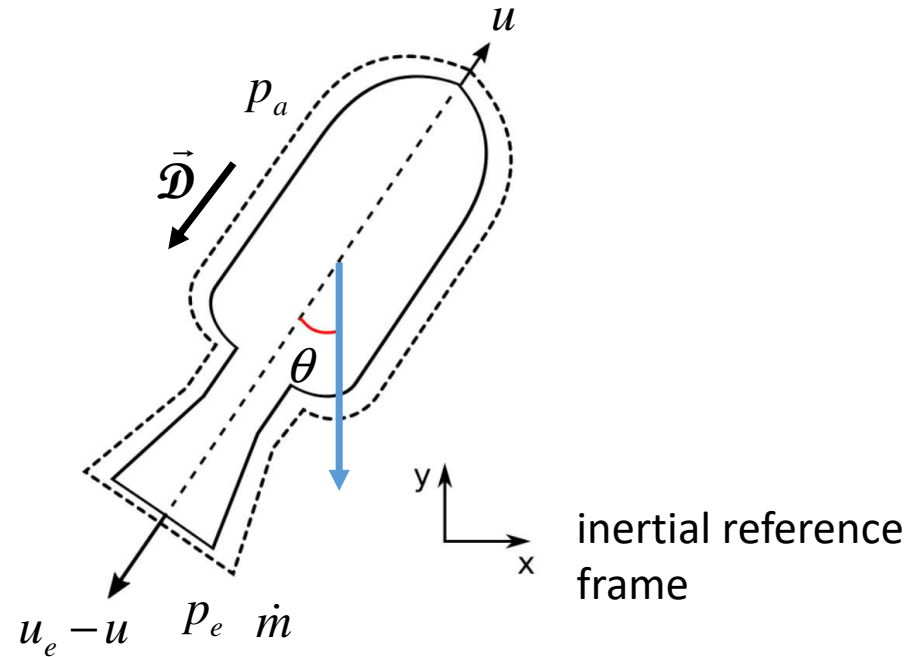
## Rocket acceleration

$$\frac{du}{dt} = \frac{1}{m} \left[ \dot{m}u_e \pm (p_e - p_a)A_e \right] - g \cos \theta - \mathcal{D}/m$$

$= \dot{m}u_{eq}$

$$\frac{du}{dt} = \frac{\dot{m}}{m} u_{eq} - g \cos \theta - \mathcal{D}/m$$

$\left( -\frac{dm}{dt} \right) / m$  negative sign for decreasing mass



$$du = -\frac{dm}{m} u_{eq} - [g \cos \theta + \mathcal{D}/m] dt$$

describes velocity change of rocket as function of time

# Rocket propulsion systems: vehicle acceleration

## Velocity increment

- to find  $\Delta u$ , integrate  $du = -\frac{dm}{m}u_{eq} - [g \cos \theta + \mathcal{D}/m]dt$

- in general, all variables can change in time

$u_{eq}, \theta, g, \mathcal{D}, m$  not constant

simplest case:  $u_{eq}$  constant and  $g, \mathcal{D}$  negligible

ideal rocket equation

$$\int_{u_{initial}}^{u_{final}} du = \Delta u = -u_{eq} \int_{m_{initial}}^{m_{final}} \frac{dm}{m} - 0$$

$$\Delta u = -u_{eq} \ln \frac{m_{final}}{m_{initial}} = u_{eq} \ln \frac{m_{initial}}{m_{final}}$$

