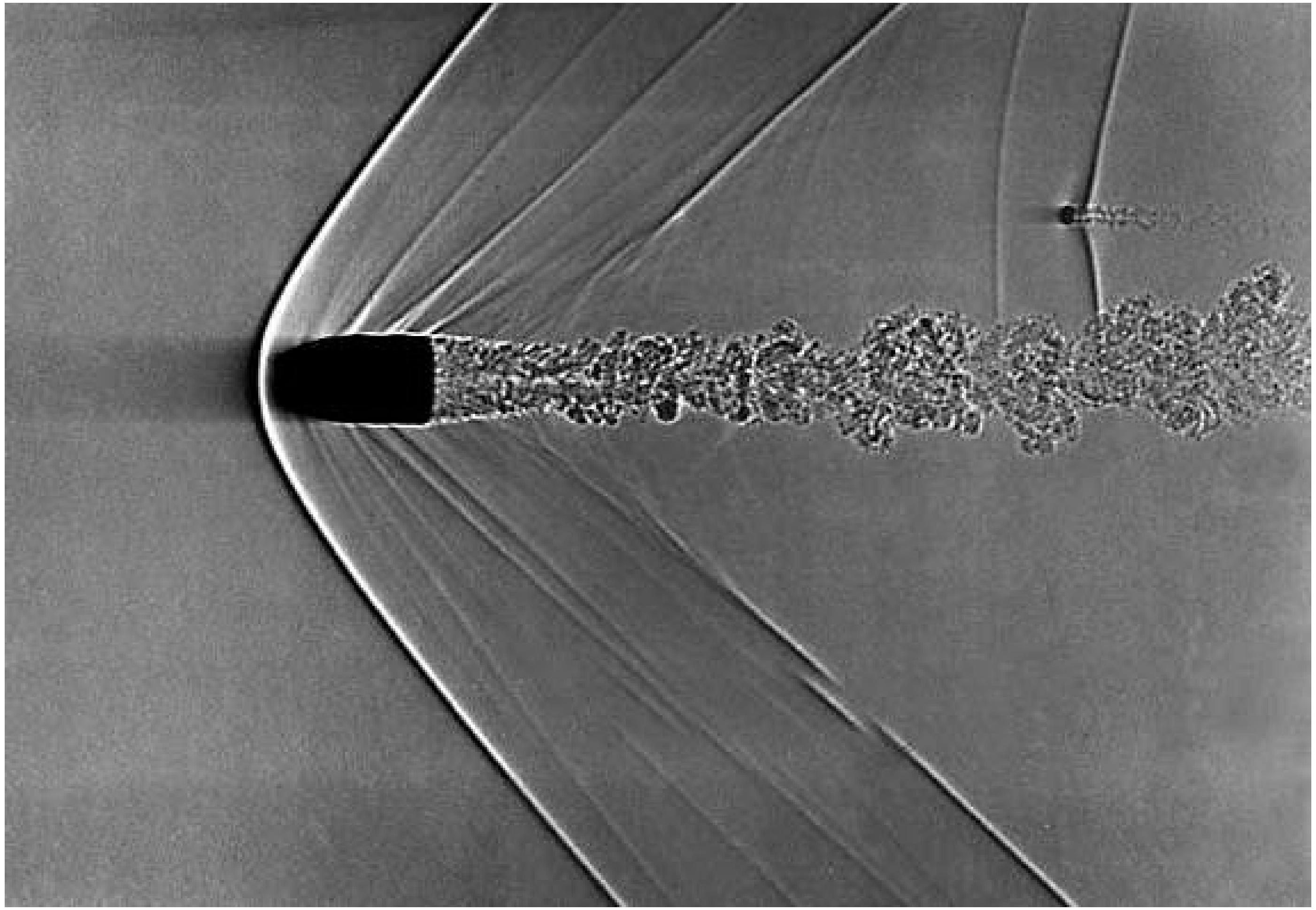
SESA3029 Aerothermodynamics
1.1 Introduction to the module

Prof. Neil Sandham

Outline for this session

- Part A:
  - – Introduction to high speed flow
  - – Definition of Mach number
  - – Classification of flow regimes
  - – Module overview
- Part B:
  - – Review of isentropic flow

Bullet (approx Mach 2)

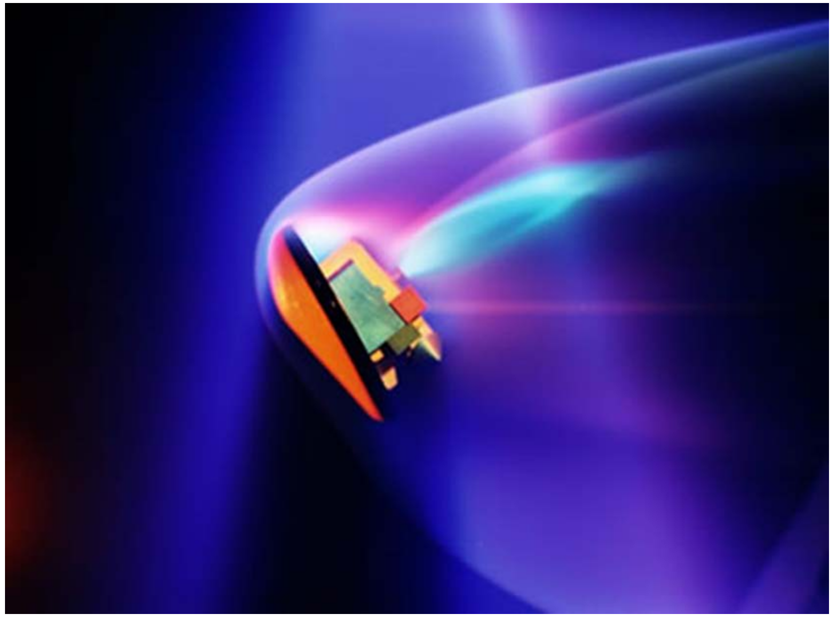


Mach number $M = \frac{V}{a}$

- V=velocity
- a=sound speed
  - For a perfect gas $a^2 = \gamma RT$
  - R is the gas constant (e.g. 287 J/(kg K) for air at standard conditions)
  - T is the absolute temperature
  - Diatomic gas γ=1.4 (ratio of specific heats c_p/c_v)
- e.g. air at T=288K a=340.2 m/s (761 mph)

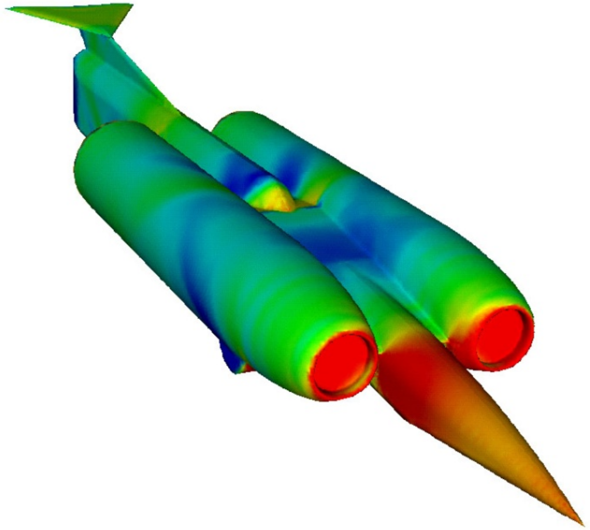
Flow regimes

- M<0.3 Effectively incompressible
- M<1 Subsonic
- M>1 Supersonic
- 0.8<M<1.2 Transonic (e.g. for wings)
- M>5 (approximately) Hypersonic



Mars lander at M=10 (ONERA experiment using electron beam fluorescence)

Thrust SSC
Mach 1



SESA3029 Aerothermodynamics: Module overview

1. Basic Toolkit (isentropic flow, normal shocks etc)

2. Oblique shocks and expansion waves

3. Nozzle flows and method of characteristics

4. High speed aerodynamics

5. Heat transfer

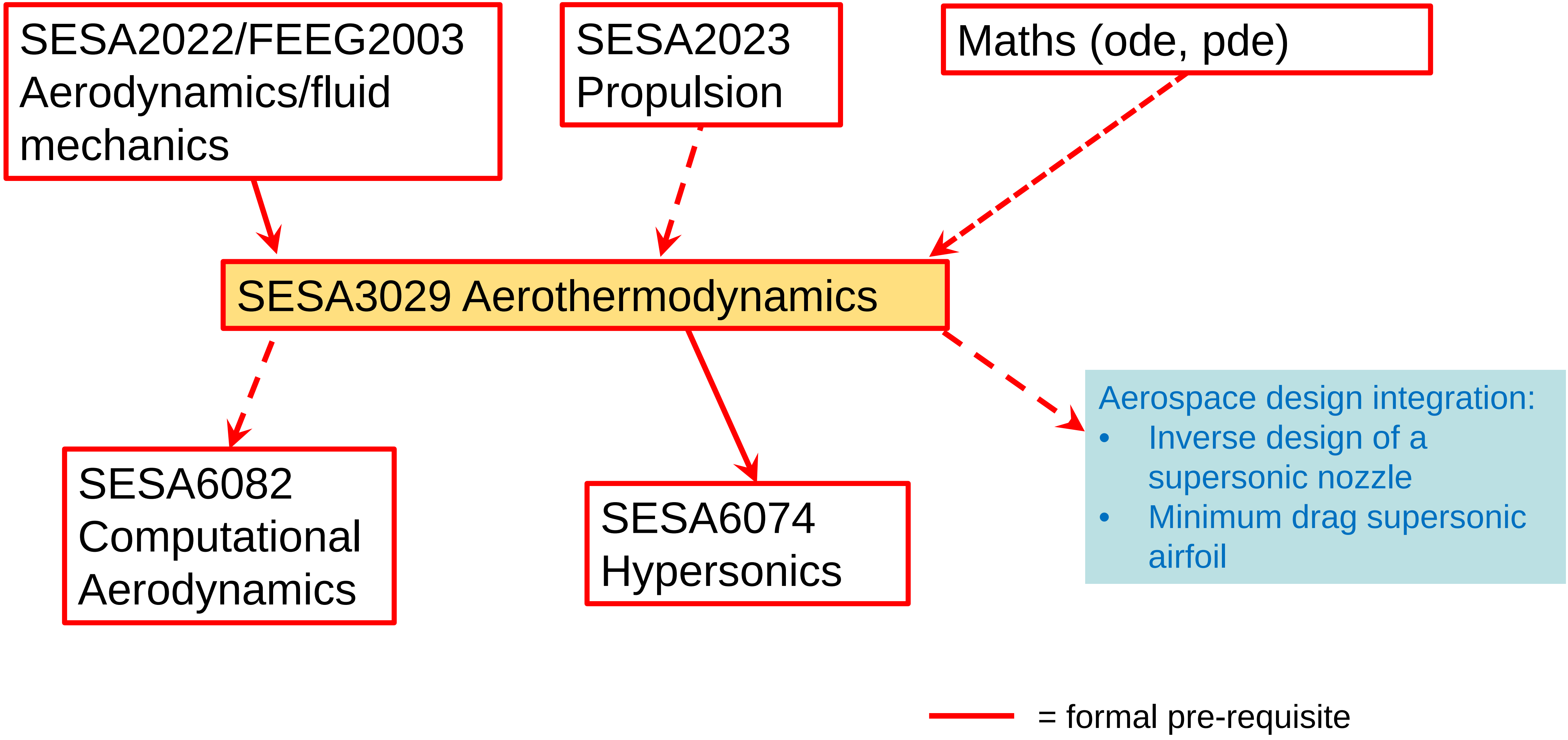
SpaceX Starship Hopper

Design examples:

- Inverse design of a supersonic nozzle
- Minimum drag airfoil shape

SR71

Relation to other modules



Assessment

- 20% coursework
  - 5 Blackboard tests (2% each), maximum 3 attempts at each test (different numbers each time), highest mark counts
  - 10% MoC nozzle design exercise
- 80% exam
  - In person exam

SESA3029 Aerothermodynamics

Module guide
Semester 1
AY 2023/24
Exam 80% Coursework 20%
Module lead:
Professor Neil Sandham

University of Southampton

In each week of semester you should:

Attend the lectures for this week's topic :

Review lecture slides and use background reading if needed:

Complete coursework before deadline:

Semester week	Monday date	Lecture topics	Background reading	Coursework
1	02-Oct	1.1 Module overview, key thermodynamic concepts, isentropic flow 1.2 key aerodynamic concepts, 1.3 normal shock waves and use of shock tables	Revision: e.g. Anderson 1.1, 7.1, 7.2, 7.5, 8.3, 8.4, 8.6,	
2	09-Oct	1.4 Application to pitot probe in compressible flow (sub- and supersonic) 2.1 Oblique shock relations 2.2 Oblique shock chart, example calculations	Anderson 8.7, 9.1, 9.2	
3	16-Oct	2.3 Shock reflections (regular and Mach), slip lines and shock/shock interactions 2.4 Expansion waves, Prandtl-Meyer function, examples 2.5 Shock-expansion method, centre of pressure and aerodynamic coefficients	Anderson 9.4, 9.5, 9.6, 9.7	Test 1 due 17th October
4	23-Oct	Class example: Diamond airfoil ; 2.6 Laval nozzle: effect of back pressure on Mach and pressure distributions 2.7 Under and over-expanded cases, supersonic wind tunnel	Anderson 10.2 10.3	
5	30-Oct	3.1 Euler equations/homentropic flow 3.2 Eigenvalues, eigenvectors and characteristics; Riemann invariants and the MoC unit process 3.3 MoC implementation: boundary conditions and applications	SESA3029 Lecture notes (handout), you can also look at Anderson 13.2, 13.3 but we follow a different derivation	Test 2 due 31st Oct
6	06-Nov	3.4 MoC Minimum length nozzle example 4.1 Euler equations for CFD 4.2 Flow patterns and wave drag; area rule, sweepback, supercritical sections	Anderson 11.7 11.9	
7	13-Nov	4.3 Compressible potential flow 4.4 Linearised potential flow and the Prandtl-Glauert transformation 4.5 Ackeret theory for supersonic airfoils	Anderson 11.2, 11.3, 11.4, 11.6	MoC coursework due 14th Nov (Hard deadline!)
8	20-Nov	4.6 Optimal airfoil shape for supersonic flight, 4.7 Test #3 Q&A 5.1 Conduction heat transfer	Anderson 12.1, 12.3	
9	27-Nov	5.2 Convective heat transfer 5.3 Turbulent flow, Reynolds' analogy 5.4 Radiation heat transfer	Bergman et al. 1.2.2, 6.1; 6.3, 6.5, 7.2; 1.2.3, 12.1, 12.2	Test 3 due 28th Nov
10	04-Dec	5.5 Heat diffusion eq., 1D finite differences 5.6 Transient 1D finite differences 5.7 2D finite differences	Bergman et al. 2.3, 2.4, 4.4; 5.3, 5.10; 4.4, 4.5 + Anderson CFD 4.2; 4.3, 4.4	Test 4 due 5th Dec
11	11-Dec	5.8 Heat exchangers -log-mean method 5.9 Heat exchangers - NTU method; 5.10 Test#4 Q&A, heat exchanger examples	Bergman et al. 11.2, 11.3; 11.4; 11.5, 8.6	
Christmas Vacation				
15	08-Jan	Revision lectures x3	Past exam papers	Test 5 due 8th Jan (Hard deadline for all tests)
Semester 1 exam period: 2h in person exam				

See links on Bb to lectures and coursework (5 tests contribute 2% each, MoC coursework contributes 10% to final mark)

Revision: From the end of November, an additional examples sheet, past exam papers with numerical solutions and hints are made available on Blackboard. Worked examples are done in lectures, including revison lectures.

Updated 21 September 2023

Blackboard site:
- Module information
- Lecture overview
- Background reading,
- Lecture slides
- Coursework info
- Discussion board

Lecturers:
- Prof J. Kim: sections,1,2
- Prof N. Sandham: L1.1 and sections 3,4
- Prof R. Deiterding section 5

Outline for this session

- Part A:
  - Introduction to high speed flow
  - Definition of Mach number
  - Classification of flow regimes
  - Module overview
- Part B:
  - Review of isentropic flow

Warm up: entropy and isentropic flow

- For a reversible process (heat transfer over infinitesimal temperature differences) entropy changes are given by

$$\boxed{\mathrm{d}s = \left(\frac{\delta q}{T}\right)_{\mathrm{rev}}}$$

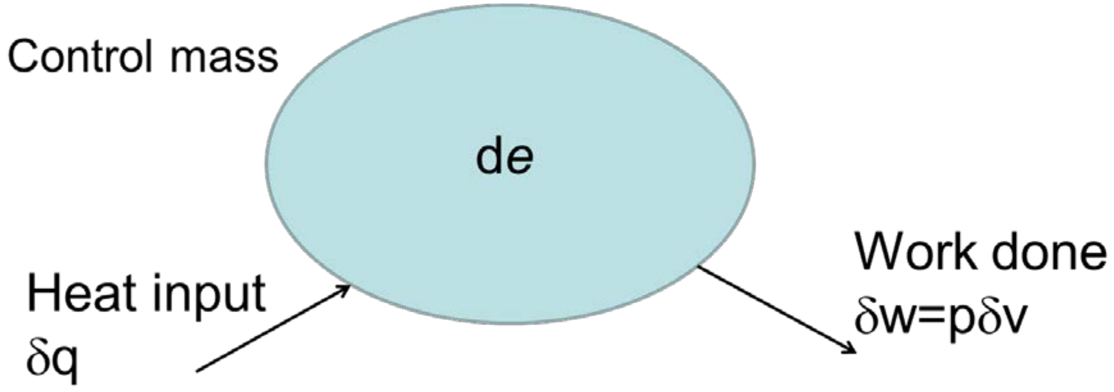
- Second law: irreversible processes lead to (additional) **production** of entropy, so in general

$$\mathrm{d}s \geq \left(\frac{\delta q}{T}\right)$$

Reversible heat addition for a closed system

First law

$$de = \delta q - \delta w$$
$$= Tds - pdv$$



$$\boxed{\begin{aligned} Tds &= de + pdv \\ &= dh - vdp \end{aligned}}$$

(using $h=e+pv$)

Gibbs relations

Calculation of entropy

$$Tds = dh - vdp$$

perfect gas

$$ds = c_p \frac{dT}{T} - R\frac{dp}{p}$$

Integrate from state 1 to state 2 only arbitrary 2 points

$$\boxed{s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{p_2}{p_1}\right)}$$

Isentropic flow ds=0

$$0 = c_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{p_2}{p_1}\right)$$

$$\ln\left(\frac{p_2}{p_1}\right) = \frac{c_p}{R}\ln\left(\frac{T_2}{T_1}\right)$$

$$= \frac{\gamma}{\gamma - 1}\ln\left(\frac{T_2}{T_1}\right)$$

(using $R=c_p-c_v$ and dividing by c_v)

hence

$$\left(\frac{p_2}{p_1}\right) = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\left(\frac{p_2}{p_1}\right) = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{p_2}{p_1}\frac{\rho_1}{\rho_2}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\left(\frac{p_2}{p_1}\right)^{1-\frac{\gamma}{\gamma-1}} = \left(\frac{\rho_2}{\rho_1}\right)^{\frac{-\gamma}{\gamma-1}}$$

$$\left(\frac{p_2}{p_1}\right) = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma}$$

For isentropic flow

$$\boxed{\left(\frac{p_2}{p_1}\right) = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}}$$

Things to know

- Definition of Mach number
- Classification of flow regimes (subsonic, transonic, supersonic, hypersonic)
- Manipulate isentropic flow relations in combination with perfect gas relation
- For isentropic flow $p \sim \rho^{\gamma} \sim T^{\frac{\gamma}{\gamma-1}}$

Additional reading: Anderson 7.2.4 and 7.2.5