Compressible Flow - TME085

Lecture 3

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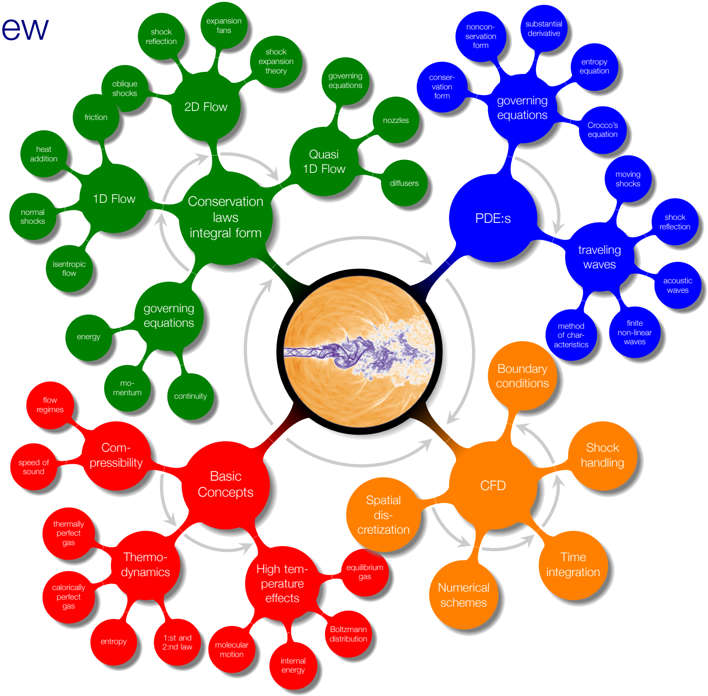
Overview



Conservation laws integral form
2D Flow
shock reflection
expansion fans
shock expansion theory
oblique shocks
Quasi 1D Flow
governing equations
nozzles
diffusers
1D Flow
friction
heat addition
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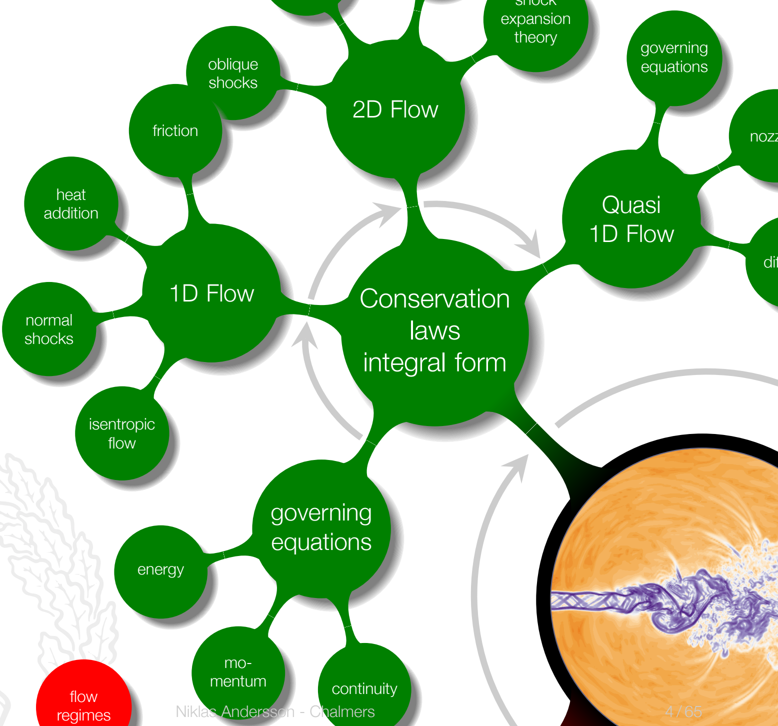
Chapter 3
One-Dimensional Flow

Overview



Conservation laws integral form
1D Flow
heat addition
normal shocks
isentropic flow
friction
oblique shocks
2D Flow
expansion theory
Quasi 1D Flow
governing equations
governing equations
energy
mo-mentum
continuity
flow regimes

Addressed Learning Outcomes

4 Present at least two different formulations of the governing equations for compressible flows and explain what basic conservation principles they are based on

5 Explain how thermodynamic relations enter into the flow equations

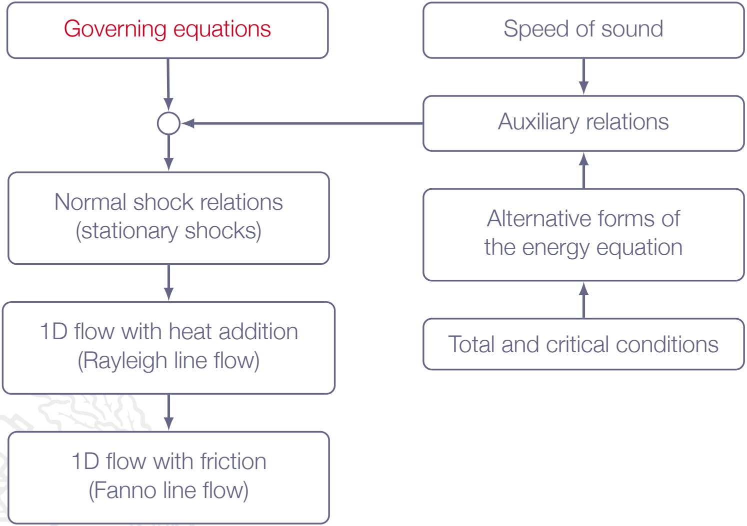
6 Define the special cases of calorically perfect gas, thermally perfect gas and real gas and explain the implication of each of these special cases

8 Derive (marked) and apply (all) of the presented mathematical formulae for classical gas dynamics

   a 1D isentropic flow*
   b normal shocks*

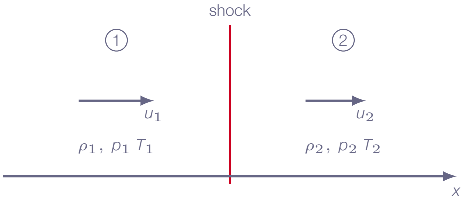
one-dimensional flows - isentropic and non-isentropic

Roadmap - One-dimensional Flow



Chapter 3.2 One-Dimensional Flow Equations

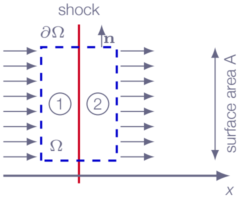
One-Dimensional Flow Equations



Assumptions:

- all flow variables only depend on x
- velocity aligned with x-axis

One-Dimensional Flow Equations



Control volume approach:

Define a rectangular control volume around shock, with upstream conditions denoted by 1 and downstream conditions by 2

One-Dimensional Flow Equations

Conservation of mass:

$$\frac{d}{dt}\iiint\limits_{\Omega} \rho d\mathscr{V} = 0 \qquad \oiint\limits_{\partial\Omega} \rho\mathbf{v}\cdot\mathbf{n}dS = \rho_2 u_2 A - \rho_1 u_1 A$$

$$\rho_1 u_1 = \rho_2 u_2$$

Conservation of momentum:

$$\frac{d}{dt}\iiint\limits_{\Omega} \rho\mathbf{v} d\mathscr{V} = 0 \qquad \oiint\limits_{\partial\Omega} \left[\rho(\mathbf{v}\cdot\mathbf{n})\mathbf{v} + p\mathbf{n}\right] dS = (\rho_2 u_2^2 + p_2)A - (\rho_1 u_1^2 + p_1)A$$

$$\rho_1 u_1^2 + p_1 = \rho_2 u_2^2 + p_2$$

One-Dimensional Flow Equations

Conservation of energy:

$$\frac{d}{dt}\iiint_{\Omega}\rho e_o d\mathscr{V} = 0 \qquad \oiint_{\partial\Omega}[\rho h_o \mathbf{v}\cdot\mathbf{n}]\,dS = \rho_2 h_{o_2} u_2 A - \rho_1 h_{o_1} u_1 A$$

$$\rho_1 u_1 h_{o_1} = \rho_2 u_2 h_{o_2}$$

Using the continuity equation this reduces to

$$h_{o_1} = h_{o_2}$$

or

$$h_1 + \frac{1}{2}u_1^2 = h_2 + \frac{1}{2}u_2^2$$

One-Dimensional Flow Equations

Summary:

$$\boxed{\begin{aligned}\rho_1 u_1 &= \rho_2 u_2 \\ \rho_1 u_1^2 + p_1 &= \rho_2 u_2^2 + p_2 \\ h_1 + \frac{1}{2}u_1^2 &= h_2 + \frac{1}{2}u_2^2\end{aligned}}$$

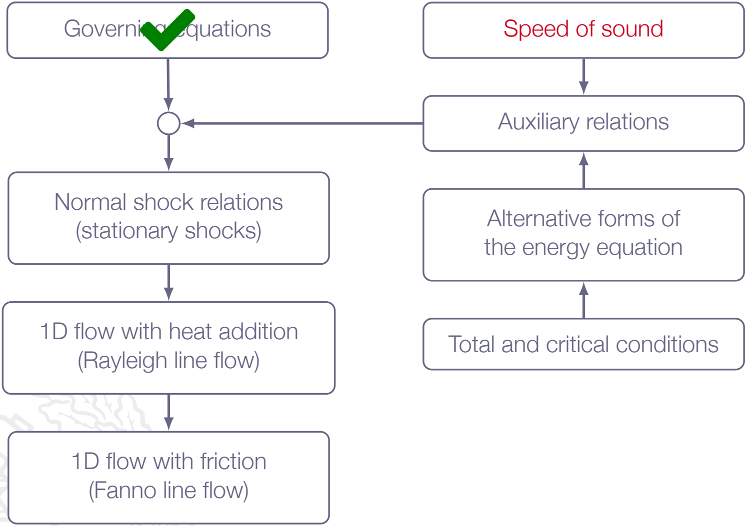
Valid for all gases!

General gas $\Rightarrow$ Numerical solution necessary

Calorically perfect gas $\Rightarrow$ analytical solution exists

Note: These equations are valid regardless of whether there is a shock or not inside the control volume

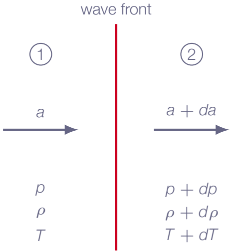
Roadmap - One-dimensional Flow



Chapter 3.3
Speed of Sound and Mach Number

Speed of Sound

Sound wave / acoustic perturbation



Speed of Sound

Conservation of mass gives

$$\rho a = (\rho + d\rho)(a + da) = \rho a + \rho da + d\rho a + d\rho da$$

products of infinitesimal quantities are removed $\Rightarrow$

$$\rho da + d\rho a = 0 \Rightarrow$$

$$a = -\rho \frac{da}{d\rho}$$

Speed of Sound

The momentum equation evaluated over the wave front gives

$$p + \rho a^2 = (p + dp) + (\rho + d\rho)(a + da)^2$$

Again, removing products of infinitesimal quantities gives

$$dp = -2a\rho da - a^2 d\rho$$

Solve for $da \Rightarrow$

$$da = \frac{dp + a^2 d\rho}{-2a\rho}$$

Speed of Sound

Now, inserting the expression for *da* in the continuity equation gives

$$a = -\rho \left[\frac{dp/d\rho + a^2}{-2a\rho} \right] \Rightarrow$$

$$a^2 = \frac{dp}{d\rho}$$

Speed of Sound

Sound waves are small perturbations in ρ, $\mathbf{v}$, p, T (with constant entropy s) propagating through gas with speed a

$$a^2 = \left(\frac{\partial p}{\partial \rho}\right)_s$$

(valid for all gases)

Speed of Sound

Compressibility and speed of sound:

from before we have

$$\tau_s = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_s$$

insert in relation for speed of sound

$$a^2 = \left(\frac{\partial p}{\partial \rho}\right)_s = \frac{1}{\rho \tau_s}$$

or

$$a = \sqrt{\frac{1}{\rho \tau_s}}$$

(valid for all gases)

Speed of Sound

Calorically perfect gas:

Isentropic process $\Rightarrow p = C\rho^{\gamma}$ (where C is a constant)

$$a^2 = \left(\frac{\partial p}{\partial \rho}\right)_s = \gamma C \rho^{\gamma-1} = \frac{\gamma p}{\rho}$$

which implies

$$a = \sqrt{\frac{\gamma p}{\rho}}$$

or

$$a = \sqrt{\gamma R T}$$

Speed of Sound

Sound wave / acoustic perturbation

- a weak wave
- propagating through gas at speed of sound
- small perturbations in velocity and thermodynamic properties
- isentropic process

Mach Number

The mach number, M, is a local variable

$$M = \frac{v}{a}$$

where

$$v = |\mathbf{v}|$$

and a is the local speed of sound

In the free stream, far away from solid objects, the flow is undisturbed and denoted by subscript ∞

$$M_\infty = \frac{v_\infty}{a_\infty}$$

Mach Number

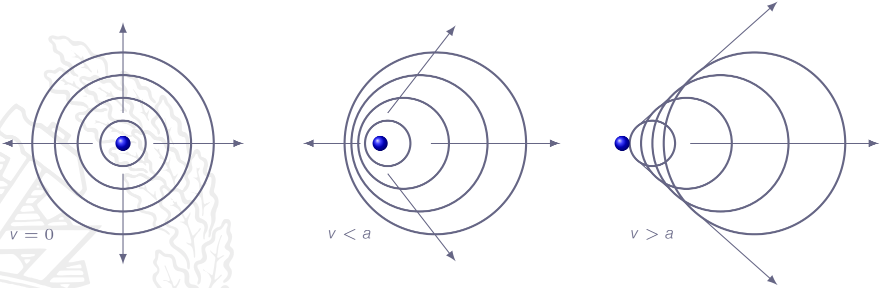
For a fluid element moving along a streamline, the kinetic energy per unit mass and internal energy per unit mass are $V^2/2$ and e, respectively

$$\frac{V^2/2}{e} = \frac{V^2/2}{C_v T} = \frac{V^2/2}{RT/(\gamma-1)} = \frac{(\gamma/2)V^2}{a^2/(\gamma-1)} = \frac{\gamma(\gamma-1)}{2}M^2$$

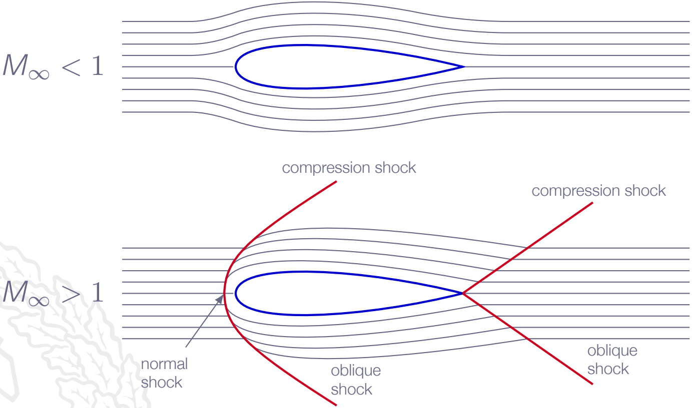
i.e. the Mach number is a measure of the ratio of the fluid motion and the random thermal motion of the molecules

Physical Consequences of Speed of Sound

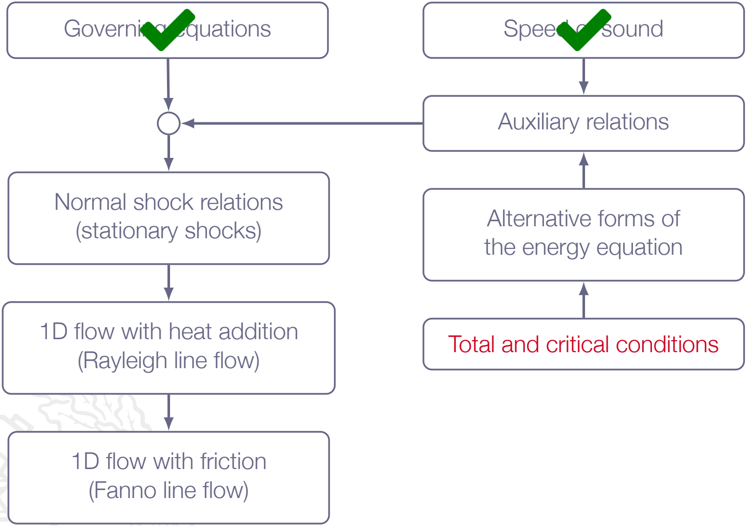
- Sound waves is the way gas molecules convey information about what is happening in the flow
- In subsonic flow, sound waves are able to travel upstream, since $v < a$
- In supersonic flow, sound waves are unable to travel upstream, since $v > a$



Physical Consequences of Speed of Sound



Roadmap - One-dimensional Flow



Chapter 3.4
Some Conveniently Defined Flow Parameters

Stagnation Flow Properties

Assumption: Steady inviscid flow

If the flow is slowed down isentropically (without flow losses) to zero velocity we get the so-called total conditions (total pressure p_o, total temperature T_o, total density ρ_o)

Since the process is isentropic, we have (for calorically perfect gas)

$$\frac{p_o}{p} = \left(\frac{\rho_o}{\rho}\right)^{\gamma} = \left(\frac{T_o}{T}\right)^{\frac{\gamma}{\gamma-1}}$$

Note that $v_o = 0$ and $M_o = 0$ by definition

Critical Conditions

If we accelerate the flow adiabatically to the sonic point, where $v = a$, we obtain the so-called critical conditions, *e.g.* p^*, T^*, ρ^*, a^*

where, by definition, $v^* = a^*$

As for the total conditions, if the process is also reversible (entropy is preserved) we obtain the relations (for calorically perfect gas)

$$\frac{p^*}{p} = \left(\frac{\rho^*}{\rho}\right)^{\gamma} = \left(\frac{T^*}{T}\right)^{\frac{\gamma}{\gamma-1}}$$

Total and Critical Conditions

For any given steady-state flow and location, we may think of an imaginary isentropic stagnation process or an imaginary adiabatic sonic flow process

- We can compute total and critical conditions at any point
- They represent conditions realizable under an isentropic/adiabatic deceleration or acceleration of the flow
- Some variables like p_o and T_o will be conserved along streamlines under certain conditions
  - T_o is conserved along streamlines if the flow is adiabatic
  - conservation of p_o requires the flow to be isentropic (no viscous losses or shocks)

Total and Critical Conditions

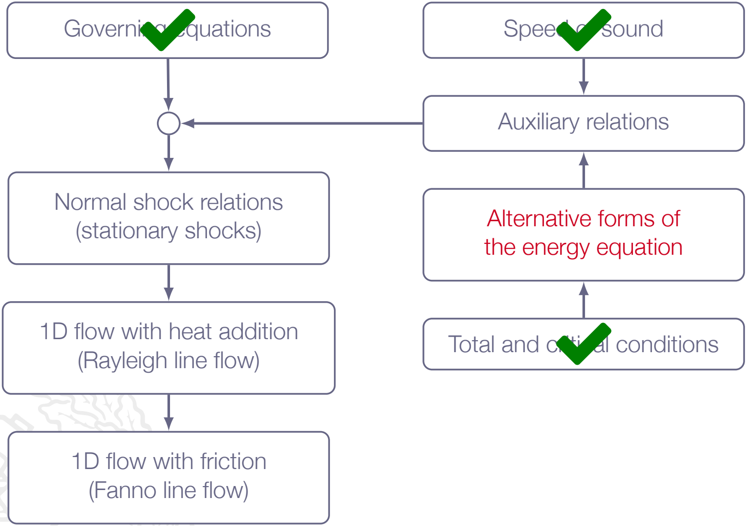
Note: The actual flow does not have to be adiabatic or isentropic from point to point, the total and critical conditions are results of an imaginary isentropic/adiabatic process at one point in the flow.

If the flow is not isentropic:

$$T_{o_A} \neq T_{o_B},\ p_{o_A} \neq p_{o_B},\ \ldots$$

However, with isentropic flow T_o, p_o, ρ_o, etc are constants

Roadmap - One-dimensional Flow



Chapter 3.5
Alternative Forms of the Energy Equation

Alternative Forms of the Energy Equation

For steady-state adiabatic flow, we have already shown that conservation of energy gives that total enthalpy, h_o, is constant along streamlines

For a calorically perfect gas we have $h = C_p T$ which implies

$$C_p T + \frac{1}{2} v^2 = C_p T_o$$

$$\frac{T_o}{T} = 1 + \frac{v^2}{2 C_p T}$$

Inserting $C_p = \dfrac{\gamma R}{\gamma - 1}$ and $a^2 = \gamma R T$ we get

$$\frac{T_o}{T} = 1 + \frac{1}{2}(\gamma - 1) M^2$$

Alternative Forms of the Energy Equation

For calorically perfect gas (1D/2D/3D flows):

$$\frac{T_o}{T} = 1 + \frac{1}{2}(\gamma - 1)M^2$$

$$\frac{\rho_o}{\rho} = \left(\frac{T_o}{T}\right)^{\frac{1}{\gamma-1}}$$

$$\frac{p_o}{p} = \left(\frac{T_o}{T}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\left(\frac{a^*}{a_o}\right)^2 = \frac{T^*}{T_o} = \frac{2}{\gamma+1}$$

$$\frac{\rho^*}{\rho_o} = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}$$

$$\frac{p^*}{p_o} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

Note: tabulated values for these relations can be found in Appendix A.1

Alternative Forms of the Energy Equation

$$M^* \equiv \frac{v}{a^*}$$

For a calorically perfect gas (1D/2D/3D flows)

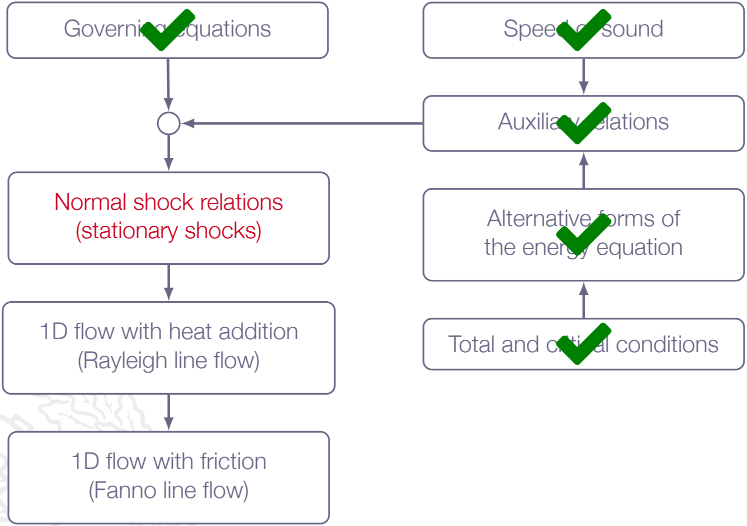
$$M^2 = \frac{2}{\left[(\gamma+1)/{M^*}^2\right] - (\gamma-1)}$$

This relation between M and M^* gives:

$$M^* = 0 \Leftrightarrow M = 0$$
$$M^* = 1 \Leftrightarrow M = 1$$
$$M^* < 1 \Leftrightarrow M < 1$$
$$M^* > 1 \Leftrightarrow M > 1$$

$$M^* \rightarrow \sqrt{\frac{\gamma+1}{\gamma-1}} \text{ when } M \rightarrow \infty$$

Roadmap - One-dimensional Flow



Chapter 3.6
Normal Shock Relations

One-Dimensional Flow Equations

$$\rho_1 u_1 = \rho_2 u_2$$

$$\rho_1 u_1^2 + p_1 = \rho_2 u_2^2 + p_2$$

$$h_1 + \frac{1}{2} u_1^2 = h_2 + \frac{1}{2} u_2^2$$

Normal Shock Relations

Calorically perfect gas

$$h = C_p T, \quad p = \rho R T$$

with constant C_p

Assuming that state 1 is known and state 2 is unknown

- 5 unknown variables: ρ_2, u_2, p_2, h_2, T_2
- 5 equations

$\Rightarrow$ solution can be found

Normal Shock Relations

Divide the momentum equation by $\rho_1 u_1$

$$\frac{1}{\rho_1 u_1}\left(p_1 + \rho_1 u_1^2\right) = \frac{1}{\rho_1 u_1}\left(p_2 + \rho_2 u_2^2\right)$$

$$\{\rho_1 u_1 = \rho_2 u_2\} \Rightarrow$$

$$\frac{1}{\rho_1 u_1}\left(p_1 + \rho_1 u_1^2\right) = \frac{1}{\rho_2 u_2}\left(p_2 + \rho_2 u_2^2\right)$$

$$\frac{p_1}{\rho_1 u_1} - \frac{p_2}{\rho_2 u_2} = u_2 - u_1$$

Normal Shock Relations

$$\frac{p_1}{\rho_1 u_1} - \frac{p_2}{\rho_2 u_2} = u_2 - u_1$$

Recall that $a = \sqrt{\frac{\gamma p}{\rho}}$, which gives

$$\frac{a_1^2}{\gamma u_1} - \frac{a_2^2}{\gamma u_2} = u_2 - u_1$$

Now, we will make use of the fact that the flow is adiabatic and thus a^* is constant

Normal Shock Relations

Energy equation:

$$C_pT_1 + \frac{1}{2}u_1^2 = C_pT_2 + \frac{1}{2}u_2^2$$

$$\left\{C_p = \frac{\gamma R}{\gamma - 1}\right\} \Rightarrow$$

$$\frac{\gamma RT_1}{(\gamma - 1)} + \frac{1}{2}u_1^2 = \frac{\gamma RT_2}{(\gamma - 1)} + \frac{1}{2}u_2^2$$

$$\left\{a = \sqrt{\gamma RT}\right\} \Rightarrow$$

$$\frac{a_1^2}{(\gamma - 1)} + \frac{1}{2}u_1^2 = \frac{a_2^2}{(\gamma - 1)} + \frac{1}{2}u_2^2$$

Normal Shock Relations

In any position in the flow we can get a relation between the local speed of sound a, the local velocity u, and the speed of sound at sonic conditions a^* by inserting in the equation on the previous slide. $u_1 = u$, $a_1 = a$, $u_2 = a_2 = a^* \Rightarrow$

$$\frac{a^2}{(\gamma-1)} + \frac{1}{2}u^2 = \frac{a^{*2}}{(\gamma-1)} + \frac{1}{2}a^{*2}$$

$$a^2 = \frac{\gamma+1}{2}a^{*2} - \frac{\gamma-1}{2}u^2$$

Evaluated in station 1 and 2, this gives

$$a_1^2 = \frac{\gamma+1}{2}a^{*2} - \frac{\gamma-1}{2}u_1^2$$

$$a_1^2 = \frac{\gamma+1}{2}a^{*2} - \frac{\gamma-1}{2}u_2^2$$

Normal Shock Relations

Now, inserting

$$a_1^2 = \frac{\gamma + 1}{2} a^{*2} - \frac{\gamma - 1}{2} u_1^2$$

and

$$a_1^2 = \frac{\gamma + 1}{2} a^{*2} - \frac{\gamma - 1}{2} u_2^2$$

in

$$\frac{a_1^2}{(\gamma - 1)} + \frac{1}{2} u_1^2 = \frac{a_2^2}{(\gamma - 1)} + \frac{1}{2} u_2^2$$

and solve for a^* gives

$$a^{*2} = u_1 u_2$$

Normal Shock Relations

$$a^{*2} = u_1 u_2$$

A.K.A. the Prandtl relation. Divide by a^{*2} on both sides $\Rightarrow$

$$1 = \frac{u_1}{a^*}\frac{u_2}{a^*} = M_1^* M_2^*$$

Together with the relation between M and M^*, this gives

$$M_2^2 = \frac{1 + \frac{1}{2}(\gamma - 1)M_1^2}{\gamma M_1^2 - \frac{1}{2}(\gamma - 1)}$$

Normal Shock Relations

Continuity equation and $a^{*2} = u_1 u_2$

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{u_1^2}{u_1 u_2} = \frac{u_1^2}{a^{*2}} = M_1^*$$

which gives

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma + 1)M_1}{2 + (\gamma - 1)M_1}$$

Normal Shock Relations

Now, once again back to the momentum equation

$$p_2 - p_1 = \rho_1 u_1^2 - \rho_2 u_2^2 = \{\rho_1 u_1 = \rho_2 u_2\} = \rho_1 u_1 (u_1 - u_2)$$

$$\frac{p_2}{p_1} - 1 = \frac{\rho_1 u_1^2}{p_1}\left(1 - \frac{u_2}{u_1}\right) = \left\{a = \sqrt{\frac{\gamma p}{\rho}}\right\} = \gamma M_1^2 \left(1 - \frac{u_2}{u_1}\right)$$

with the expression for u_2/u_1 derived previously, this gives

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_1^2 - 1)$$

Normal Shock Relations

Normal shock $\Rightarrow M_1 > 1$

$$M_1 > 1 \Rightarrow M_1^* > 1$$

$$M_2^* = \frac{1}{M_1^*} \Rightarrow M_2^* < 1$$

$$M_2^* < 1 \Rightarrow M_2 < 1$$

After a normal shock the Mach number must be lower than 1.0

Normal Shock Relations

$$M_2^2 = \frac{1 + \frac{1}{2}(\gamma - 1)M_1^2}{\gamma M_1^2 - \frac{1}{2}(\gamma - 1)}$$

- $M_1 = 1.0 \Rightarrow M_2 = 1.0$
- $M_1 > 1.0 \Rightarrow M_2 < 1.0$
- $M_1 \to \infty \Rightarrow M_2 \to \sqrt{(\gamma - 1)/(2\gamma)} = \{\gamma = 1.4\} = 0.378$

Normal Shock Relations

Are the normal shock relations valid for $M_1 < 1.0$?

Mathematically - yes!

Physically - ?

Normal Shock Relations

Let's have a look at the 2^{nd} law of thermodynamics

$$s_2 - s_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

We get the ratios (T_2/T_1) and (p_2/p_1) from the normal shock relations

$$s_2 - s_1 = C_p \ln \left[\left(1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \right) \left(\frac{2 + (\gamma-1)M_1^2}{(\gamma+1)M_1^2} \right) \right] + \\ - R \ln \left(1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \right)$$

$M_1 = 1 \Rightarrow \Delta s = 0$ (Mach wave)

$M_1 < 1 \Rightarrow \Delta s < 0$ (not physical)

$M_1 > 1 \Rightarrow \Delta s > 0$

Normal Shock Relations

$M_1 > 1.0$ gives $M_2 < 1.0$, $\rho_2 > \rho_1$, $p_2 > p_1$, and $T_2 > T_1$

What about T_o and p_o?

Energy equation:

$$C_pT_1 + \frac{u_1^2}{2} = C_pT_2 + \frac{u_2^2}{2}$$

$$C_pT_{o_1} = C_pT_{o_2}$$

calorically perfect gas $\Rightarrow$

$$T_{o_1} = T_{o_2}$$

or more general (as long as the shock is stationary):

$$h_{o_1} = h_{o_2}$$

Normal Shock Relations

2^{nd} law of thermodynamics and isentropic deceleration to zero velocity (Δs unchanged since isentropic) gives

$$s_2 - s_1 = C_p \ln \frac{T_{o_2}}{T_{o_1}} - R \ln \frac{p_{o_2}}{p_{o_1}} = \{T_{o_1} = T_{o_2}\} = -R \ln \frac{p_{o_2}}{p_{o_1}}$$

$$\frac{p_{o_2}}{p_{o_1}} = e^{-(s_2 - s_1)/R}$$

i.e. the total pressure decreases over a normal shock

Normal Shock Relations

Normal shock relations for calorically perfect gas (summary):

$$T_{o_1} = T_{o_2}$$

$$a_{o_1} = a_{o_2}$$

$$a_1^* = a_2^* = a^*$$

$$u_1 u_2 = {a^*}^2$$

(the Prandtl relation)

$$M_2^* = \frac{1}{M_1^*}$$

$$M_2^2 = \frac{1 + \frac{1}{2}(\gamma - 1)M_1^2}{\gamma M_1^2 - \frac{1}{2}(\gamma - 1)}$$

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_1^2 - 1)$$

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma + 1)M_1^2}{2 + (\gamma - 1)M_1^2}$$

$$\frac{T_2}{T_1} = \frac{p_2}{p_1}\frac{\rho_1}{\rho_2}$$

see table A.2 and figure 3.10 on p. 94

Normal Shock Relations

As the flow passes a stationary normal shock, the following changes will take place discontinuously across the shock:

ρ	increases
p	increases
u	decreases
M	decreases (from $M > 1$ to $M < 1$)
T	increases
p_o	decreases (due to shock loss)
s	increases (due to shock loss)
T_o	unaffected

Normal Shock Relations

The normal shock relations for calorically perfect gases are valid for $M_1 \leq 5$ (approximately) for air at standard conditions

Calorically perfect gas $\Rightarrow$ Shock depends on M_1 only

Thermally perfect gas $\Rightarrow$ Shock depends on M_1 and T_1

General real gas (non-perfect) $\Rightarrow$ Shock depends on M_1,p_1, and T_1

Normal Shock Relations

And now to the question that probably bothers most of you but that no one dares to ask ...

Normal Shock Relations

And now to the question that probably bothers most of you but that no one dares to ask ...

When or where did we say that there was going to be a shock between 1 and 2?

Normal Shock Relations

And now to the question that probably bothers most of you but that no one dares to ask ...

When or where did we say that there was going to be a shock between 1 and 2?

Answer: We did not (explicitly)

Normal Shock Relations

- The derivation is based on the fact that there should be a change in flow properties between 1 and 2
- We are assuming steady state conditions
- We have said that the flow is adiabatic (no added or removed heat)
- There is no work done and no friction added
- A normal shock is <u>the solution</u> provided by nature (and math) that fulfill these requirements!

Chapter 3.7
Hugoniot Equation

Hugoniot Equation

Starting point: governing equations for normal shocks

$$\rho_1 u_1 = \rho_2 u_2$$

$$\rho_1 u_1^2 + p_1 = \rho_2 u_2^2 + p_2$$

$$h_1 + \frac{1}{2}u_1^2 = h_2 + \frac{1}{2}u_2^2$$

Eliminate u_1 and u_2 gives:

$$h_2 - h_1 = \frac{p_2 - p_1}{2}\left(\frac{1}{\rho_1} + \frac{1}{\rho_2}\right)$$

Hugoniot Equation

Now, insert $h = e + p/\rho$ gives

$$e_2 - e_1 = \frac{p_2 + p_1}{2}\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right) = \frac{p_2 + p_1}{2}(\nu_1 - \nu_2)$$

which is the Hugoniot relation

Stationary Normal Shock in One-Dimensional Flow

Normal shock:

$$e_2 - e_1 = -\frac{p_2 + p_1}{2}(\nu_2 - \nu_1)$$

- More effective than isentropic process
- Gives entropy increase

Isentropic process:

$$de = -pd\nu$$

- More efficient than normal shock process

see figure 3.11 p. 100

Roadmap - One-dimensional Flow