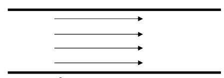
One Dimensional Flow

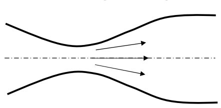
- The first flow situation we will investigate is that of One Dimensional, Inviscid, Adiabatic Flow.
- This type flow can be visualized as that through a constant area pipe:

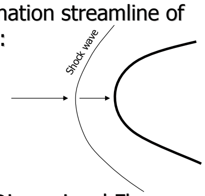


- At first, this case seems trivial since incompressible flow would require that nothing happen.
- This "trivial" solution also occurs in compressible flow, but it is not the only possibility.
- The solutions to this flow will be the building block of for other flow situations.

One Dimensional Flow [2]

- There are also a number of 'nearly' one dimensional flow situations.
- For example the flow in a converging/diverging duct or the flow along the stagnation streamline of a blunt body in supersonic flow:

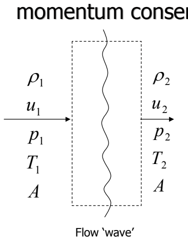




- These are cases of Quasi-One Dimensional Flow which will be discussed in later chapters.

1-D Flow Equations

- For 1-D flow, the velocity reduces to a single component, u, which we will align with the x axis.
- We will only consider steady flow, so the mass and momentum conservation equations become:



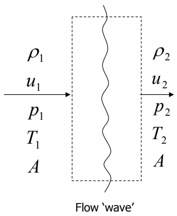
$$\oiint_S \rho \overline{V} \cdot \hat{n} dS = 0$$

$$\oiint_S \rho \overline{V}\left(\overline{V} \cdot \hat{n}\right) dS + \oiint_S p \hat{n} dS = 0$$

$$\oiint_S \rho \left(e + \tfrac{1}{2} V^2\right) \overline{V} \cdot \hat{n} dS + \oiint_S p\left(\overline{V} \cdot \hat{n}\right) dS = 0$$

1-D Flow Equations [2]

- For the flow through the control volume shown, we allow for the possibility of a flow disturbance in the form of a wave – either a pressure or shock-wave.
- By integrating over the inflow/outflow boundaries:



$$\oiint_S \rho \overline{V} \cdot \hat{n} dS = 0$$

$$-\rho_1 u_1 A + \rho_2 u_2 A = 0$$

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

$$\oiint_S \rho \overline{V}\left(\overline{V} \cdot \hat{n}\right) dS + \oiint_S p \hat{n} dS = 0$$

$$-\rho_1 u_1^2 A - p_1 A + \rho_2 u_2^2 A + p_2 A = 0$$

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

1-D Flow Equations [3]

- And for the energy equation:

$$\oiint_S \rho\left(e + \tfrac{1}{2}V^2\right)\overline{V} \cdot \hat{n} dS + \oiint_S p\left(\overline{V} \cdot \hat{n}\right) dS = 0$$

$$-\rho_1\left(e_1 + \tfrac{1}{2}u_1^2\right)u_1 A - p_1 u_1 A + \rho_2\left(e_2 + \tfrac{1}{2}u_2^2\right)u_2 A + p_2 u_2 A = 0$$

$$-\rho_1 u_1\left(e_1 + \frac{p_1}{\rho_1} + \tfrac{1}{2}u_1^2\right) + \rho_2 u_2\left(e_2 + \frac{p_2}{\rho_2} + \tfrac{1}{2}u_2^2\right) = 0$$

- But, from the mass conservation (continuity) equation, $\rho_1 u_1 = \rho_2 u_2$. Thus:

$$e_1 + \frac{p_1}{\rho_1} + \tfrac{1}{2}u_1^2 = e_2 + \frac{p_2}{\rho_2} + \tfrac{1}{2}u_2^2$$

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

1-D Flow Equations [3]

- If the inflow conditions are known, that leaves us 5 unknowns at the outflow: $p_2, \rho_2, u_2, T_2, h_2$.
- So far we only have 3 equations – so we need two more relations to obtain a solution.
- The enthalpy and temperature are, of course, related:

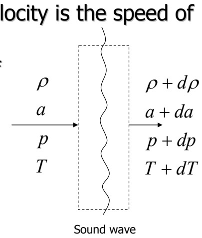
$$\boxed{h_2 = c_p T_2}$$

- This thermally perfect relation adds one equation – and the perfect gas law give us the needed 5th.

$$\boxed{p_2 = \rho_2 R T_2}$$

Speed of Sound

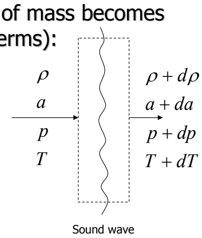
- A special case of 1-D flow is that of a very weak pressure wave – i.e., a sound wave.
- In this case, put the control volume in motion with the wave so that the inflow velocity is the speed of sound, a.
- Also allow for the possibility of a change in flow properties across the wave.
- Since a sound wave is weak, express these changes as differential quantities.



Speed of Sound [2]

- In this case, the conservation of mass becomes (after dropping higher order terms):

$$\rho a = (\rho + d\rho)(a + da)$$
$$= \rho a + \rho da + a d\rho + d\rho \rho d$$
$$da = -a\frac{d\rho}{\rho}$$



- And momentum becomes:

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

Speed of Sound [3]

- Combine the two equations by eliminating da:

$$a\frac{d\rho}{\rho} = \frac{dp + a^2 d\rho}{2\rho a}$$
$$a = \frac{1}{2a}\frac{dp}{d\rho} + \frac{a}{2}$$
$$a^2 = \frac{dp}{d\rho}$$

- This last expressions is a differentiation and to be precise, it should be a partial differentiation with one other property held constant.
- Since the flow is adiabatic and inviscid, it is natural to require isentropic (constant entropy) flow.

Speed of Sound [4]

- Thus, the speed of sound can be written as:

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

- Also note, that given our previous definition of the compressibility factor, the speed of sound can also be written as:

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

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

- Thus we see the close relationship between compressibility and the speed of sound.

Speed of Sound [5]

- While the previous equations are interesting in understanding flow behavior, they don't help much in actual calculations.
- To obtain a useful equation, apply our isentropic relation: $\left(\frac{p_2}{p_1}\right) = \left(\frac{\rho_2}{\rho_1}\right)^\gamma \Rightarrow \frac{p_2}{\rho_2^\gamma} = \frac{p_1}{\rho_1^\gamma}$
- If the grouping of properties at the two locations can be separated, they must separately equal a constant. Thus: $p = C\rho^\gamma$
- As it turns out, we don't really need to know the value of the constant, C.

Speed of Sound [6]

- Instead, it can be eliminated when we perform the differentiation:

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

- And thus, $a = \sqrt{\frac{\gamma p}{\rho}}$
- Also, the perfect gas low can be used to obtain:

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

- Note this dependence on temperature, and thus the speed of the random motion of the particles, also makes good sense.

Forms of the Energy Equation

- Before going on, it is important to spend a little time considering different forms of the energy eqn.

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

- As before, if the properties at two locations can be separated, they must each equal a constant.
- For this case, we will give the constant a name – the total enthalpy. $\boxed{h + \tfrac{1}{2}u^2 = h_o}$
- We indicate this 'total' property with a subscript zero since it is also the value at zero velocity.
- From incompressible flow, we might also call this the 'stagnation' enthalpy.

Forms of the Energy Equation [2]

- We can also use the relationship between enthalpy and temperature to write either of:

$$c_p T_1 + \tfrac{1}{2}u_1^2 = c_p T_2 + \tfrac{1}{2}u_2^2 \qquad c_p T + \tfrac{1}{2}u^2 = c_p T_o$$

- Further, if the relation between the speed of sound and temperature is introduced…

$$c_p T = \frac{\gamma R T}{\gamma - 1} = \frac{a^2}{\gamma - 1}$$

- Then, we get:

$$\frac{a_1^2}{\gamma - 1} + \frac{u_1^2}{2} = \frac{a_2^2}{\gamma - 1} + \frac{u_2^2}{2} \qquad \frac{a^2}{\gamma - 1} + \frac{u^2}{2} = \frac{a_0^2}{\gamma - 1}$$

Forms of the Energy Equation [3]

- All the previous equations are valid forms of the adiabatic energy equation.
- One form relates the properties at two points in a flow to each other while the other form relates the properties at any point to the reference, total conditions.
- This is useful since, for <u>adiabatic</u> flow, the total flow conditions of h_o, T_o, and a_o <u>do not change</u>!
- We will later see that these 1-D equations are also valid in 2 and 3-D if the velocity is replaced with the total velocity magnitude: $u \rightarrow V$

Forms of the Energy Equation [4]

- For external flows, the total or stagnation conditions are the preferred reference values.
- In internal flows, like engines, there is another set of reference conditions often used. These are the **sonic conditions** – or those that would occur at the speed of sound.
- Using an asterisk to denote sonic conditions, one form of the energy equation is:

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

- Note that by definition: $u* = a*$

Forms of the Energy Equation [5]

- Similarly, the sonic temperature can be introduced:

$$c_pT+\tfrac{1}{2}u^2=c_pT*+\tfrac{1}{2}a*^2$$

- Note also that the sonic and total conditions can be related: $$\frac{a_0^2}{\gamma-1}=\frac{a^2}{\gamma-1}+\frac{u^2}{2}=\frac{\gamma+1}{2(\gamma-1)}a*^2$$
- Thus: $$\boxed{\frac{a*^2}{a_0^2}=\frac{T*}{T_0}=\frac{h*}{h_0}=\frac{2}{\gamma+1}}$$
- If follows that these sonic conditions, like the total conditions are flow constants.

Mach Relation

- Some final, and probably the most useful, forms of the energy equation involve the Mach number.

$$\frac{a^2}{(\gamma-1)}+\tfrac{1}{2}V^2=\frac{a_0^2}{(\gamma-1)}$$

- Rearrange to get the ratio of total to local temperature on one side:

$$\frac{a_0^2}{a^2}=\frac{T_0}{T}=1+\frac{(\gamma-1)}{2}\frac{V^2}{a^2}$$

- Now, introduce the Mach number to get the first of our "Mach Relation" equations:

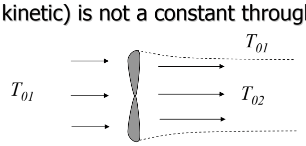
$$\boxed{\frac{T_0}{T}=1+\frac{(\gamma-1)}{2}M^2}$$

Limits of Adiabatic Flow Assumption

- All of the equations to this point are valid for any adiabatic flow – which is pretty much all aerodynamic flow cases.
- However, there are some important situations where the above equation doesn't work:
  - Obviously, whenever there is heat addition – the most common of which is actively cooled hypersonic and space reentry flows.
  - Whenever there is a propeller, compressor, or turbine.
  - Two merging flows from separate sources.
- In these cases, the equations don't work because the total enthalpy is not a constant – and thus neither is the total temperature.

Limits of Adiabatic Flow Assumption [2]

- This brings up an important point – the total (and sonic) conditions are reference conditions, they don't necessarily correspond to a point in the flow.
- However, all points in a flow have a total and sonic temperature associated with them – these are a measure of the energy at the point.
- In the cases mentioned, the energy (internal plus kinetic) is not a constant throughout:



$T_{02} > T_{01}$

Isentropic Flow Relations

- While the previous equations are good for any adiabatic flow, there are also many cases when the flow is also reversible – and thus isentropic.
- From our previous isentropic flow relations:

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

- These equations relate the properties at one locations to that of another – as long as the flow between the two points is isentropic!
- Thus, this equation will not work in a viscous boundary layer or across a shock wave.

Isentropic Flow Relations [2]

- We can use these equations to also calculate the total pressure and total density:

$$\frac{p_0}{p} = \left(\frac{T_0}{T}\right)^{\gamma/\gamma-1} \qquad \frac{\rho_0}{\rho} = \left(\frac{T_0}{T}\right)^{1/\gamma-1}$$

- As with the total enthalpy and temperature, these reference quantities don't have to be actual points in the flow.
- Thus, the total pressure is the pressure the flow would have **IF** it were isentropic brought to rest.
- Similarly, the total density is the density the flow would have **IF** isentropically brought to rest.

Isentropic Flow Relations [3]

- Using these relations, we can then write:

$$\boxed{\frac{p_0}{p} = \left(1 + \frac{(\gamma-1)}{2}M^2\right)^{\gamma/\gamma-1}} \qquad \boxed{\frac{\rho_0}{\rho} = \left(1 + \frac{(\gamma-1)}{2}M^2\right)^{1/\gamma-1}}$$

- And the sonic pressure and temperature can be found from:

$$\frac{p^*}{p_0} = \left(\frac{T^*}{T_0}\right)^{\gamma/\gamma-1} = \left(\frac{2}{\gamma+1}\right)^{\gamma/\gamma-1}$$

$$\frac{\rho^*}{\rho_0} = \left(\frac{T^*}{T_0}\right)^{1/\gamma-1} = \left(\frac{2}{\gamma+1}\right)^{1/\gamma-1}$$

Dynamic Pressure

- When non-dimensionalizing forces and pressures in compressible flow, it is still convenient to use the dynamic pressure. I.e.:

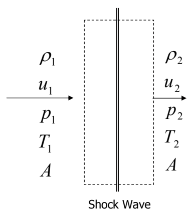
$$q = \frac{1}{2}\rho V^2 \qquad C_L = \frac{L}{qS} \qquad c_p = \frac{(p - p_\infty)}{q}$$

- However, remember that Bernoulli's equation **does not** apply in compressible flow!
- To reinforce this, we can rewrite the dynamic pressure in terms of pressure and Mach number:

$$q = \frac{1}{2}\rho V^2 = \frac{1}{2}\frac{\gamma p}{\gamma p}\rho V^2 = \frac{\gamma}{2}\frac{pV^2}{a^2} = \boxed{\frac{\gamma}{2}pM^2}$$

Normal Shock Relations

- Finally, let's return to our original problem and look at the case when a shock wave is present.



- In particular, this is called a <u>normal</u> shock because it is perpendicular to the flow.
- The conservations equations in 1-D are still:

$$\rho_1 u_1 = \rho_2 u_2$$
$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$$
$$h_1 + \tfrac{1}{2} u_1^2 = h_2 + \tfrac{1}{2} u_2^2$$

Normal Shock Relations [2]

- Let's start by dividing the two sides of the momentum by the mass conservation equation:

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

- And, by rearranging and introducing the speed of sound:

$$u_2 - u_1 = \frac{p_2}{\rho_2 u_2} - \frac{p_1}{\rho_1 u_1} = \frac{a_2^2}{\gamma\, u_2} - \frac{a_1^2}{\gamma\, u_1}$$

- But, from one form of our energy equation:

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

Normal Shock Relations [3]

- Or, when written for the two points involved:

$$a_1^2 = \frac{\gamma + 1}{2} a^{*2} - \frac{\gamma - 1}{2} u_1^2 \qquad a_2^2 = \frac{\gamma + 1}{2} a^{*2} - \frac{\gamma - 1}{2} u_2^2$$

- Note that since the flow is adiabatic, the sonic speed of sound, a^*, is the same at both points.
- Substituting these two equations into our previous equation – and rearranging – gives:

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

- Which looks complex - until you notice the common factor $(u_2 - u_1)$.

Normal Shock Relations [4]

- This equation is automatically satisfied if nothing happens in the control volume, i.e. $u_2=u_1$.
- This is the trivial case, but it is nice to know our equations will give that result.
- The more interesting case is when $(u_2-u_1)\neq 0$, which allows us to divide through by this factor.

$$1=\frac{\gamma+1}{2\gamma u_1 u_2}a^{*2}+\frac{\gamma-1}{2\gamma}$$

- Or, when rearranged, simply:

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

Characteristic Mach Number

- Another way of writing this result is in terms of the characteristic Mach number: $M^* = u/a^*$.

$$\boxed{M_1^* = 1/M_2^*}$$

- Note that this is not a "true" Mach number which is the ratio of local velocity to local speed of sound.
- This relationship tells us something very important
  - If the flow is initially subsonic, $u_1<a^*$, then it will become supersonic $u_2>a^*$.
  - Of, if the flow is initially supersonic, $u_1>a^*$, then it will become subsonic, $u_2<a^*$.

Characteristic Mach Number [2]

- The first possibility, a flow spontaneously jumping from subsonic to supersonic, isn't physically possible - we will show this in a little bit.
- The second case, jumping from supersonic to subsonic is exactly what a normal shock does.
- Why? Usually because there is some disturbance or condition downstream which the flow cannot negotiate supersonically. I.e:
  - When there is a blunt body the flow must go around
  - When a nozzle has an exit pressure condition which requires subsonic flow

Characteristic Mach Number [3]

- The previous characteristic Mach relation, while informative, is not very useful in application.
- Instead, relate the characteristic Mach to the true Mach number by using:

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

- When simplified, this becomes:

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

- Thus the two values are (relatively) simply related.

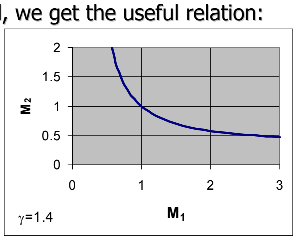
Mach Jump Relation

- Substituting into our characteristic Mach relation:

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

- Or, when simplified, we get the useful relation:

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



Mach Jump Relation [2]

- It is important to note the limits of the expression as $M_1 \rightarrow 1$ and $M_1 \rightarrow \infty$.

$$Lim_{M_1\rightarrow 1}(M_2)=\sqrt{\frac{1+\frac{(\gamma-1)}{2}}{\gamma-\frac{(\gamma-1)}{2}}}=1$$

$$Lim_{M_1\rightarrow \infty}(M_2)=\sqrt{\frac{\gamma-1}{2\gamma}}=0.378 \text{ (in air)}$$

- Thus, if we are sonic, the normal shock becomes very week and nothing happens.
- If we go hyper-hypersonic, the flow reaches a fixed post-shock Mach number.

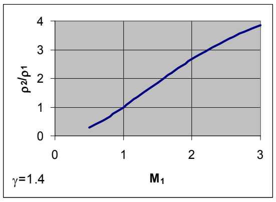
Density/Velocity Jump Relation

- To get the shock jump relations for our remaining flow properties, start with continuity:

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

- Thus, the density and velocity jumps are inversely related and given by:

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



Density/Velocity Jump Relation [2]

- Once again, if M_1=1, the shock wave becomes very weak and nothing happens.
- At very high speeds, however:

$$Lim_{M_1\to\infty} \frac{\rho_2}{\rho_1} = \frac{(\gamma+1)}{(\gamma-1)} = 6 \quad \text{for air}$$

- Thus, when you hear some people talk about hypersonic vehicles compressing air to the density of steel….
- Well, not quite. Not even close actually. But it sure sounds impressive.

Pressure Jump Relation

- Next, turn to momentum conservation to get a relation for pressure. First rearrange terms:

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

- And them manipulate to get Mach numbers and our previous velocity jump expression:

$$\frac{p_2 - p_1}{p_1} = \frac{\rho_1 u_1^2}{p_1}\left(1-\frac{u_2}{u_1}\right) \Rightarrow \frac{p_2}{p_1} - 1 = \frac{\gamma u_1^2}{a_1^2}\left(1-\frac{u_2}{u_1}\right)$$

- Or, just

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

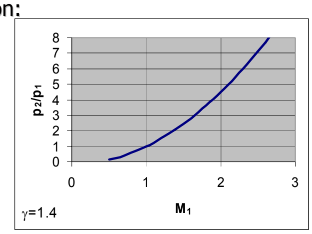
Pressure Jump Relation [2]

- Finally, insert our definition for characteristic Mach number….

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

- And, on simplification:

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



Pressure Jump Relation [3]

- Once again if M_1=1, nothing happens.
- Note that this time however, as $M_1 \rightarrow \infty$, the pressure also does: $$Lim_{M_1 \rightarrow \infty} \frac{p_2}{p_1} = \infty$$
- Thus, while the density might not be huge, the pressures can be.
- Finally, the easiest way to get the temperature jump is through the perfect gas law:

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

- So, temperatures also get very large!

Entropy Change

- And last, consider the change in entropy across a normal shock wave.
- Using our previous definition and the perfect gas law:

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{p_2}{p_1}\right) = c_p \ln\left(\frac{p_2}{p_1} \cdot \frac{\rho_1}{\rho_2}\right) - R \ln\left(\frac{p_2}{p_1}\right)$$

- Or with a little extra manipulation:

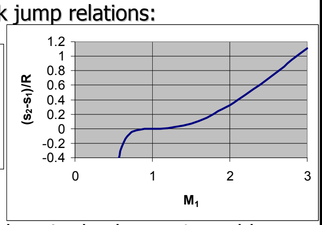
$$s_2 - s_1 = c_p \ln\left(\frac{\rho_1}{\rho_2}\right) + (c_p - R) \ln\left(\frac{p_2}{p_1}\right)$$

$$s_2 - s_1 = c_p \ln\left(\frac{\rho_1}{\rho_2}\right) + c_v \ln\left(\frac{p_2}{p_1}\right)$$

Entropy Change [2]

- Now, insert our shock jump relations:

$$s_2 - s_1 = c_p \ln\left(\frac{2+(\gamma-1)M_1^2}{(\gamma+1)M_1^2}\right) + c_v \ln\left(1+\frac{2\gamma}{\gamma+1}\left(M_1^2-1\right)\right)$$



- Now we see that a subsonic shock, M_1<1 would produce a decrease in entropy – something not allowed by the 2nd Law of Thermodynamics.
- Thus only supersonic shocks are possible.

Total Pressure Jump

- One final thing to note is this special case where a flow is:
  - isentropically accelerated from rest to M_1
  - jumps through a shock
  - and then isentropically slows back down to rest.
- The only entropy change occurs at the shock, thus, we can write for the initial and final states:

$$s_2 - s_1 = c_p \ln\left(\frac{T_{02}}{T_{01}}\right) - R\ln\left(\frac{p_{02}}{p_{01}}\right)$$

- Or, since the flow is adiabatic, $T_{01} = T_{02}$. Thus:

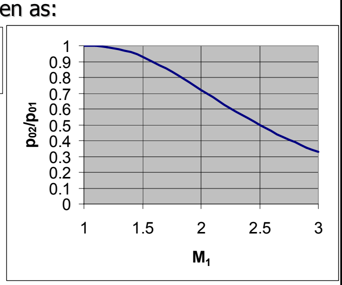
$$s_2 - s_1 = -R\ln\left(\frac{p_{02}}{p_{01}}\right)$$

Total Pressure Jump [2]

- This can be rewritten as:

$$\frac{p_{02}}{p_{01}} = \frac{\rho_{02}}{\rho_{01}} = e^{-(s_2-s_1)/R}$$

- Thus we see the close relationship between entropy changes and total pressure loss.



- As a result, flow efficiency in inlets and nozzles is often measured by this total pressure ratio.