ME 323: FLUID MECHANICS-II

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Introduction

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Fluid Mechanics I and II

ME 323: Fluid Mechanics-II

- Similitude (scaling, dimensional analysis, etc.)
- **Viscous incompressible fluid flow ($\mu \neq 0$)**
  - Boundary layer concept, friction drag, flow separation, etc.
  - Laminar & turbulent flows, RANS formulations
  - flow through pipes, piping network, etc.
  - Pressure drop (head loss: major/minor)
- Lift and drag on bodies immersed in fluid
- **Inviscid Compressible flow ($\mu = 0$)**
- Open channel flow

ME 321: Fluid Mechanics-I

- Fluid properties
- Fluid statics
- Fluid dynamics (ideal fluid, $\mu = 0$)

  [Euler Eq., Bernoulli Eq., momentum principle, etc.]
- Potential flow (inviscid, irrotational flow)

Course Contents (ME 323)

1. Dimensional analysis and similitude
2. Real fluid flow: head losses in pipes and fittings
3. Flow in multiple-pipe systems

MMR

4. Introduction to boundary layer; Displacement, momentum and energy thicknesses
5. Lift and Drag forces on immersed bodies.

MA

6. *Compressible flow; Speed of sound wave*
7. *Stagnation states for the flow of an ideal gas*
8. *Flow through converging-diverging nozzles*
9. *Normal shock wave*

MTH

10. Open channel flow
11. Best hydraulic channel cross-sections; Hydraulic jump; Specific energy; Critical depth.

MA

Text Book (s):

- F. M. White, Fluid Mechanics, 7th Edition, 2011, ISBN: 978-007-131121-2.
- Munson, Okiishi, Huebsch, Rothmayer, Fundamentals of Fluid Mechanics, 7th Edition, 2013, ISBN: 978-1-118-18676.
- M.C. Potter, D.C. Wiggert, Mechanics of Fluids, 3rd Edition, 2010, ISBN: 978-0-495-43857-1.
- Class lectures will be available at ***toufiquehasan.buet.ac.bd***

Reference books: (for further reading)

ii. Fox and McDonald, Introduction to Fluid Mechanics, 9th Edition, 2015, ISBN: 978-1118912652.

iii. J. F. Douglas, J. M. Gasiorek, J. A. Swaffield, L. B. Jack, Fluid Mechanics, 5th Edition, 2005, ISBN- 978-0-13-129293-2.

and

Relevant other books.

Compressible fluid mechanics deals with the speed of flow which is atleast comparable to the speed of sound.

Can you physically feel the ***speed of sound*** ???

It is around 340 m/s at standard condition (~ 1200 km/hr or 760 mi/hr)

How strong are the cyclones/Hurricanes/Typhoons?

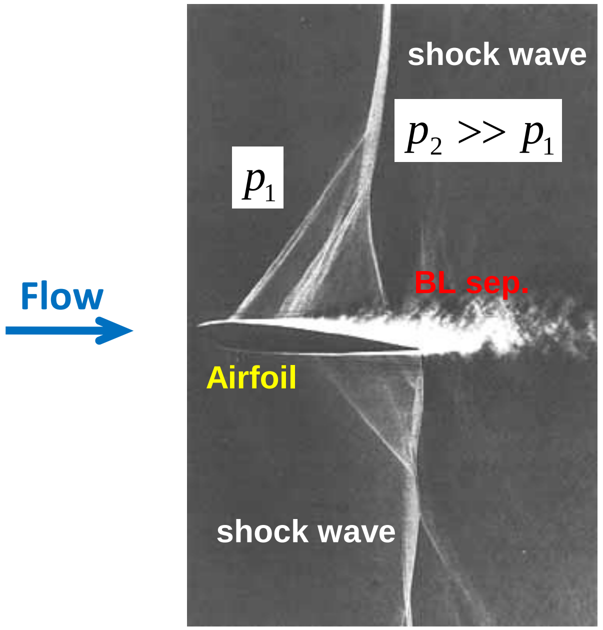
Saffir-Simpson scale

Category	Wind velocity *(for 1-minute sustained maximum wind)*	Examples
1	119 - 153 km/hr (33-43 m/s)	Florence, USA (2018) Aila, BD (2009)
2	154 - 177 km/hr (43-49 m/s)	
3	178 - 208 km/hr (49-58 m/s)	Katrina, USA (2005)
4	209 - 251 km/hr (58-70 m/s)	Michael, USA (2018) Sidr, BD (2007)
5	> 251 km/hr (>70 m/s)	Patricia, USA, Mexico (2015)

Source: SSHWS; National Hurricane Center, USA (2012)

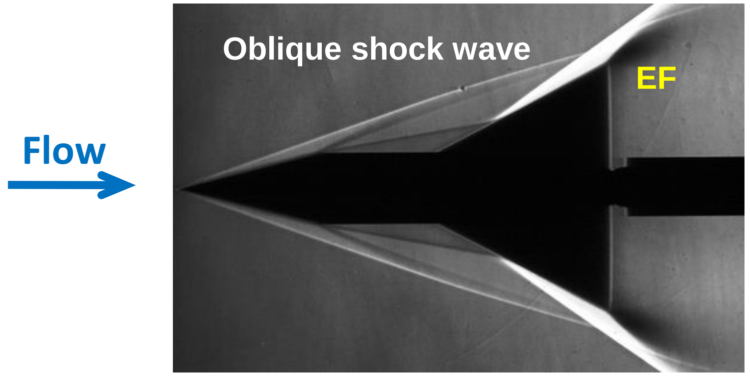
Mostly incompressible flows (velocity << 340 m/s)

Some examples of Compressible Flow



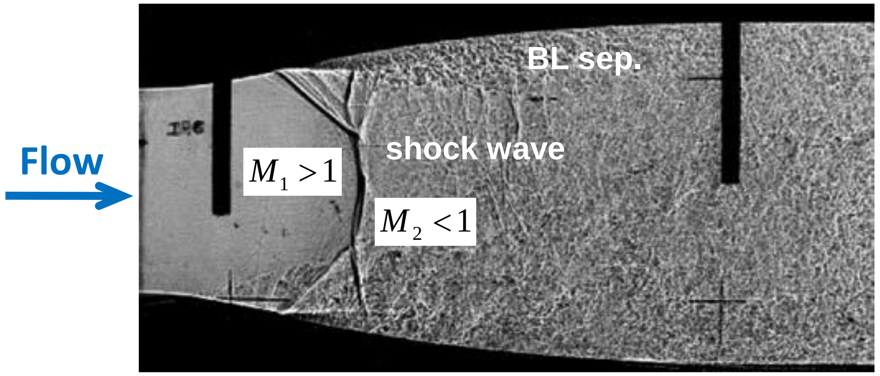
$$\boxed{\frac{\partial \rho}{\partial x}}$$

Schlieren photograph (density gradient) of **high speed** (transonic) flow over an airfoil.
The nearly **vertical** ***shock wave*** is followed by ***boundary layer separation*** that adversely affects lift, drag, and other flight parameters.

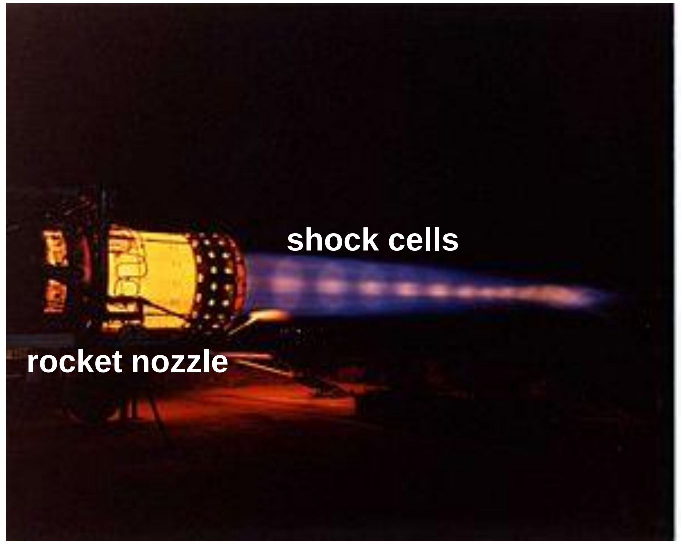


A generic missile body with Mach 5 embeds many flow structures occurring simultaneously; **oblique shock wave at the tip of the body**, **expansion fan at the shoulder**, **a dead air region at the compression corner** due to shockwave- boundary layer interaction **(SWBLI).**

Some examples of Compressible Flow



Shock wave structure inside a supersonic nozzle (C-D nozzle)
(off-design operation)



Test of a rocket nozzle

F-16 Fighter plane

Exhaust shock diamond

Compressible flows

There are many flows in aerospace and aeronautics where the **density** (ρ) variations must be accounted for. Some examples are the airflows around **commercial and military aircraft**, air flows through **jet engines**, through **propulsive nozzles** (C-D nozzle) and the flow of a gas in **compressors and turbines**.

In case of high-speed flows, the flowing gas/air can experience considerable **density changes as a result of externally applied pressures**. Thus the density can not remain constant all through the flow field. The **effect of compressibility** of the gas should be considered.

The branch of fluid mechanics which deals with this effect is known as "***Gas Dynamics***"

However, the **flow of liquid can be treated as incompressible** since the liquid density remains essentially constant under the action of externally applied pressures. For example, a pressure of 200 atm exerted on water raises its density by less than 1% of that at 1 atm.

Flow variables

Fluid Flows

Incompressible flow

Governing Equations

- Continuity equation
- Momentum equation (N-S equations, Bernoulli Eq.)

Flow Variables

p and *V* (2 Variables)

Compressible flow

Governing Equations

- Continuity equation
- Momentum equation (N-S equations, Bernoulli Eq.)
- Energy equation (1st law of Thermodynamics)
- Equation of state (Ideal gas law)

Flow Variables

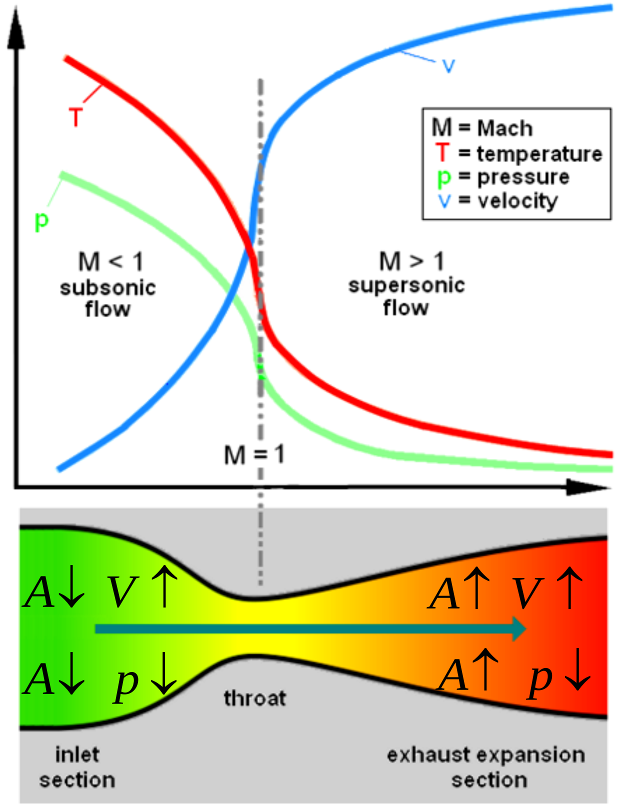
p, ρ, T and V (4 Variables)

Compressible flows

Many curious phenomena can occur with compressible flows. For example, *with compressible flows we can have fluid acceleration in diverging duct (and vice versa), fluid temperature decrease with heating, and the formation of abrupt discontinuities in flows across which fluid properties change appreciably (shock waves and others.)*

In this introductory study of compressible flow, we mainly consider the steady, 1-D, zero viscosity (inviscid, μ = 0), compressible flow of an ideal gas.

$$Q = A \times V \qquad \text{m}^3/\text{s (Incompressible flows)}$$
$$\dot{m} = \rho \times A \times V \qquad \text{kg/s (Compressible flows)}$$



Supersonic nozzle expansion
(design operation)

Mach Number, *M*

In fluid mechanics, the effect of compressibility in the flow field can be assessed by a number called the “**Mach number**”. This dimensionless number is defined as

$$\boxed{M = \frac{V}{a}} \qquad \text{or} \qquad \boxed{Ma = \frac{V}{c}}$$

where

V **is the flow velocity (/object velocity) and** ***a*** **is the local speed of sound in the fluid**.

Why speed of sound ? ? ?

This is the speed at which “signal” (disturbance) can travel through the medium. In case when an object moves through a fluid, it generates disturbances (infinitesimal pressure waves, which are sound waves) that emanate from the object in all direction.

When the speed of object becomes comparable or higher than the speed of sound, then the propagation and interaction of disturbance (signal) become complicated and different compared to low speed cases.

Flow classification

In aerodynamics (applied fluid mechanics), the following flow classes are classified roughly depending on the Mach number (external high-speed aerodynamics) -

$M < 0.3$: ***Incompressible flow*** (density effects are negligible).

$0.3 < M < 0.8$: ***Subsonic flow***, where density effects are important but no appearance of shock waves.

$0.8 < M < 1.2$: ***Transonic flow***, where shock waved first appear, dividing the subsonic and supersonic flows.

$1.2 < M < 3.0$: ***Supersonic flow***, where shock waves are present but there are no subsonic regions.

$M > 3.0$: ***Hypersonic flow***, where shock waves and other flow changes are especially strong. (Surface Chemistry, *Plasma dynamics*)

Speed of Sound

For a sound wave, by definition we have an infinitesimal pressure change (i.e. it is ***reversible***) and it occurs so quickly that there is no time for any heat transfer to occur (i.e. it is ***adiabatic***). Thus, sound wave propagates ***isentropically* (constant entropy, Δs = 0)** through a medium.

For an **ideal gas**, the speed of sound in gaseous medium can be expressed as-

$$\boxed{a = \sqrt{kRT}} \quad \text{or} \quad \boxed{a = \sqrt{\gamma RT}}$$

$$\boxed{a = \sqrt{\left(\frac{\partial p}{\partial \rho}\right)_s} = \sqrt{\frac{kp}{\rho}}}$$

where

→ $k \equiv \gamma = \text{ratio of specific heats} = \dfrac{c_p}{c_v} = 1.40 \text{ (for air)}$

→ $R = \text{gas constant} = 287 \text{ J/kgK} \quad (\text{for air, } M_{air} = 29 \text{ kg/kmol})$

$T = \text{absolute temperature (K)}$

$$p = \rho RT$$

$$R = c_p - c_v$$

$$c_p = \frac{kR}{k-1}$$

$$c_v = \frac{R}{k-1}$$

Speed of sound is a function of *Temperature, T* only for a particular media of gaseous fluid.