Intro to Compressible Flows

Basics of Compressible Flows – Lesson 1

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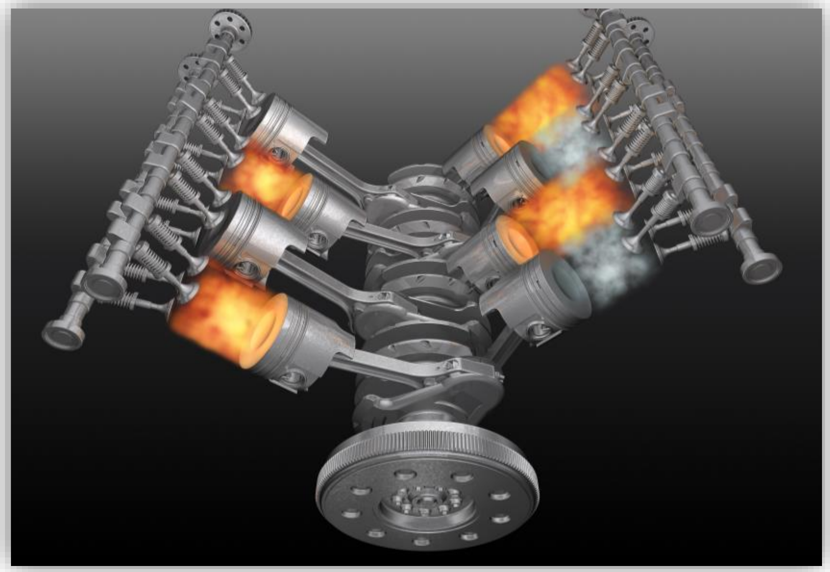
What Is Compressible Flow?

- Compressible Fluid Dynamics is a branch of fluid dynamics which studies fluid flows where density changes are relatively large. In other words, variations in density cannot be neglected to accurately describe fluid dynamics of the flow at hand.
- In general, if density variations in the flow are greater than 5%, then the flow is compressible.
- While all fluids are compressible, liquids can be assumed to be incompressible in most applications.
- Compressibility of gases, on the other hand, cannot be ignored in higher-speed flows (Mach number, $M > 0.3$).

Space Shuttle Launch



Components of Internal Combustion Engine

Compressible Flow Applications

- Compressible flows are ubiquitous, and are seen in applications ranging from simple acoustics, subsonic aircraft flight, high-speed flight vehicles and spacecraft, high-speed nozzle flows used in propulsion and power applications, and more!

High-speed Train

Steam Turbine

Supersonic Commercial Flight

Definition of Compressibility

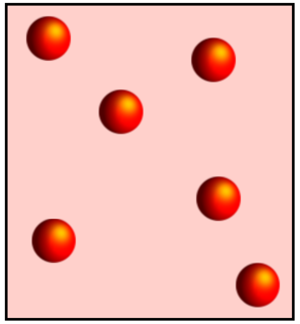
- Compressibility is the fractional change in the volume of a fluid or a solid in response to a unit change in pressure.
- Compressibility is a material property which depends on the molecular structure of matter and intermolecular forces which define the susceptibility of matter to compress under applied pressure.

Gases

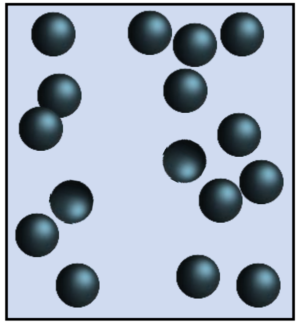
- Molecules widely separated
- Molecular kinetic energy ≫ attractive forces
- Expand to fill in the entire container
- Significant non-negligible compressibility

Liquids

- Molecules held close together by attractive forces
- Attractive forces are not strong enough to keep molecules in fixed positions
- Have a definite volume independent of the container
- Much less compressible than gases



Fluid dynamics of gases is referred to as Gas Dynamics. This will be our primary focus!

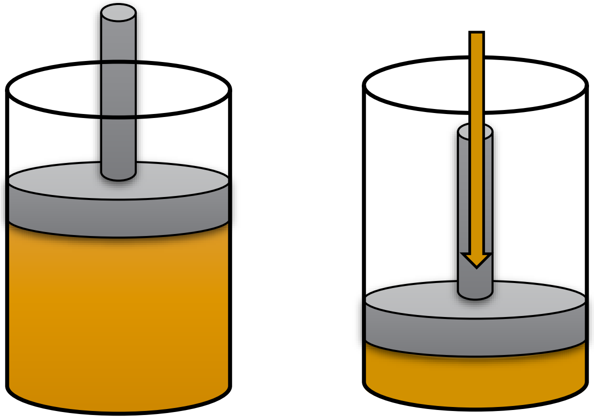


Definition of Compressibility (cont.)

- Compressibility (β) can be expressed as:

$$\beta = \frac{1}{K_s} = -\frac{1}{V}\frac{dV}{dp}$$

V – volume, p – pressure. Negative sign convention indicates reduction in volume with increase in pressure. Compressibility is an inverse of the bulk modulus K_s.



- Compressibility is a function on the thermodynamic state of the system. We know from experience that temperature in a gas container increases when the gas is compressed.

- This concept is directly applied in diesel engines, where the air is compressed to increase its temperature to a point that it will automatically ignite the fuel, without the need of a spark.

Definition of Compressibility (cont.)

- Let's quantify the differences in compressibilities between liquids and gases:

$$\beta_{water} = 5 \times 10^{-10}\ m^2/N \qquad \beta_{air} = 10^{-5}\ m^2/N \qquad \Longrightarrow \qquad \frac{\beta_{air}}{\beta_{water}} = 2 \times 10^4$$

Four orders of magnitude difference

- Expression for the compressibility can be rewritten in terms of specific volume, v, (or volume per unit mass):

$$v = \frac{V}{m} = \frac{1}{\rho}$$

which then leads to the relation between pressure, density and compressibility:

$$\beta = \frac{1}{\rho}\frac{d\rho}{dp} \qquad \Longrightarrow \qquad d\rho = \rho\beta dp$$

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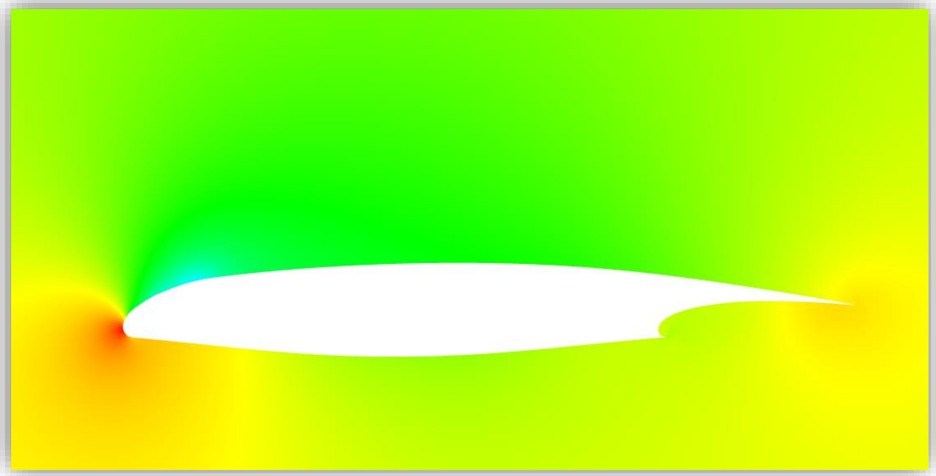
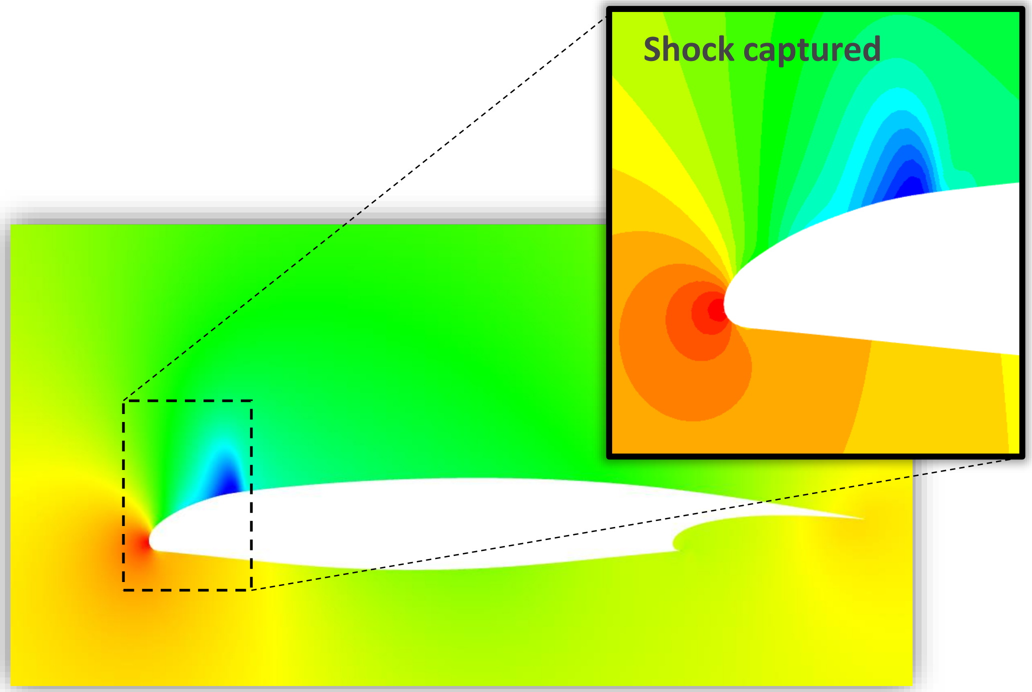
What if Compressibility Is Ignored?

- Ignoring compressibility in flows with large physical density variations has detrimental effects.
- In such flows, the constant density approximation does not accurately capture the flow physics.
  - Compressible waves (e.g., shocks, expansions, sound) will not be predicted.
  - Forces on the objects will be outright wrong.



Compressibility Effects Ignored
Flow over an Airfoil (Static Pressure Contours, M = 0.6)



Compressibility Effects Accounted
Flow over an Airfoil (Static Pressure Contours, M = 0.6)

Summary

- The inverse of bulk modulus is a measure of fluid compressibility. This value is large for gases compared to liquids, which makes gases more compressible.

- We will primarily focus on gas flows, and our main interest will be in Gas Dynamics.

- For flows where density variations are significant, ignoring these variations will lead to profoundly erroneous results.

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