Gas, tubes and flow

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Abstract

Optimizing the flow of both liquids and gases is crucial to many areas of anaesthetic and critical care practice. In this article, we describe the physical principles which govern the flow of gases and present scenarios from clinical practice to illustrate these concepts. The difference between laminar and turbulent flow is explained along with the factors which determine the nature of the fluid flow. The Venturi Effect, Bernoulli Principle and Coanda Effect are also described with reference to their clinical applications and their relevance to medical devices.

Keywords Anaesthetic gases; flowmeters; fluid dynamics; Hagen–Poiseuille; helium; laminar; turbulent; xenon

Royal College of Anaesthetists CPD Matrix: 1A03, 3A02

Learning objectives

After reading this article, you should be able to:

- explain the properties of gases
- describe the relationships between gas volume, temperature and pressure
- understand the differences between laminar and turbulent flow
- understand the Venturi Effect and the principles of air entrainment devices

Optimization of fluid flow is essential to many areas of anaesthetic and critical care practice. As such, it has direct applications to airway management, mechanical ventilation, resuscitation, clinical measurement and to organ support involving extracorporeal circuits.

Fluid dynamics

Fluid dynamics is the discipline concerned with the study of fluids in motion.[1] The term 'fluid' can be precisely defined mathematically but simply denotes states of matter that conform to take the shape of their container – both liquids and gases.[1] Gas dynamics (the study of gases in motion) and hydrodynamics (the study of liquids in motion) each have clinical applications.

Properties of gases

Gases and vapours consist of molecules with sufficient kinetic energy to overcome their internal forces of intermolecular attraction.[2] A solid or liquid may become a gas if it is heated to a temperature at or above its boiling point. The addition of this thermal energy overcomes the intermolecular forces causing the gas molecules to move freely, colliding with each other and with the walls of their container. These collisions against the container walls exert a force, which when accounting for the surface area of the container, can be measured as pressure (*pressure* = *force*/*area*).[2] The relationships between gas volume, temperature and pressure are interconnected and are described by Boyle's Law, Charles' Law and the Third Gas Law in Box 1. For this reason, gas properties are normally described with reference to standard temperature and pressure (STP), which is taken as 0 °C (273.15 Kelvin) and 101.3 kPa.[2] These gas laws refer to absolute temperature and absolute pressure, measured in Kelvin and kilopascals respectively. For example, according to Charles' Law, assuming a constant absolute pressure, the volume of a gas will double if the absolute temperature doubles. However, examination candidates should note that this only remains true if the units for temperature are given in Kelvin not Celsius (i.e. representing absolute temperature).

Flow in tubes

'Flow' is defined as the volume of fluid that moves past a fixed point per unit time. A fluid will be caused to flow through a tube under the influence of a pressure gradient and will move from a region of high pressure to a region of low pressure.[2]

$$\text{Flow } (Q) = \frac{\text{volume}}{\text{time}}$$

Reynolds number

The flow of fluids through a tube can be described as either laminar or turbulent which can be predicted by the Reynold's number (Re).[1]

$$\text{Re} = \frac{\text{density} \times \text{velocity} \times \text{diameter}}{\text{viscosity}}$$

The Reynolds number is a dimensionless concept. Its magnitude is determined by the density, mean velocity and viscosity of the moving fluid as well as the diameter of the tube through which it flows. When the Reynolds number is <2000 the flow is likely to be laminar.[2] When the Reynolds number is >4000 the flow is likely to be turbulent.[3] The main determinant is fluid viscosity as a more viscous fluid promotes a smaller Re and, therefore, laminar flow.

Both viscosity and density must be defined in order to fully understand the Reynolds number. Density describes the relationship between a substance's mass and volume (density = mass/volume) and is denoted by the units kg/m^3 or g/cm^3. Viscosity is measured in poise (derived from the name of the French physicist Jean Léonard Marie Poiseuille) and refers to the

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The gas laws

- **Boyle's Law** — in a closed system at a constant temperature the volume of a fixed mass of gas is inversely proportional to its absolute pressure

  $V \propto 1/P$

- **Charles' Law** — in a closed system at a constant absolute pressure the volume of a fixed mass of gas is directly proportional to its absolute temperature

  $V \propto T$

- **Third Gas Law** — in a closed system of a constant volume the absolute pressure of a fixed mass of gas is directly proportional to its absolute temperature

  $P \propto T$

- **The Combined Gas Law**

  $PV = nRT$

P, absolute pressure; T, absolute temperature; V, volume
R, absolute gas constant (8.32 Joules C^{-1} at STP)[3]
n, moles of gas present

Box 1

'thickness' or 'stickiness' of a fluid. Viscosity arises from a fluid's own internal forces of intermolecular attraction and presents a resistance to fluid flow.[3]

Laminar flow

When flow through a tube is laminar each fluid molecule moves in a predictable and stable trajectory.[1] The bulk flow of the fluid is smooth with fluid molecules moving in concentric channels, parallel to each other and in parallel with the sides of the tube. These channels are termed 'laminae', giving rise to the designation of 'laminar flow'.[1] Although the molecules travel in the same trajectory they move at different velocities with molecules in the centre of the tube travelling at the highest velocity of approximately twice that of the mean. In contrast, the molecules closest to the sides of the tube are motionless.[1] When viewed schematically in cross section, laminar flow appears parabolic as in Figure 1.[1,4]

The velocity of laminar flow is determined by the variables in the Hagen—Poiseuille equation. The flow rate is directly proportional to the magnitude of the pressure gradient. However, the tube radius is the largest determinant of the rate of laminar flow. The flow rate is proportional to the fourth power of the radius (r^4). Therefore, if the radius doubles the flow rate will increase by a factor of 16. The rate of flow is inversely proportional to the length of the tube and the viscosity of the fluid.[2] The fluid property with the largest effect on flow is the fluid viscosity (an inversely proportional relationship).

$$Q = \frac{\Delta P \pi r^4}{8 \eta l}$$

Q = flow rate, ΔP = pressure gradient, r = tube radius, η = fluid viscosity, l = length of tube.

Turbulent flow

Fluid molecules that experience turbulent flow travel in an apparently chaotic manner. Instead of predictable laminae there are internal vortex motions and eddies. Although not truly chaotic, these movements are a complex area of physical study and require time-averaging and statistical correlations in order to model accurately.[1] Turbulent flow is promoted by high flow rates, dense fluids and tubes that are of a wide or uneven calibre.[3] Its velocity profile is flatter than in laminar flow when viewed in cross section as illustrated in Figure 1.[1]

Resistance to laminar and turbulent flow

Figure 2 illustrates the differences in resistance to laminar and turbulent flow. With laminar flow, the flow rate is directly proportional to the magnitude of the pressure gradient. As such, the

Profiles of laminar and turbulent flow

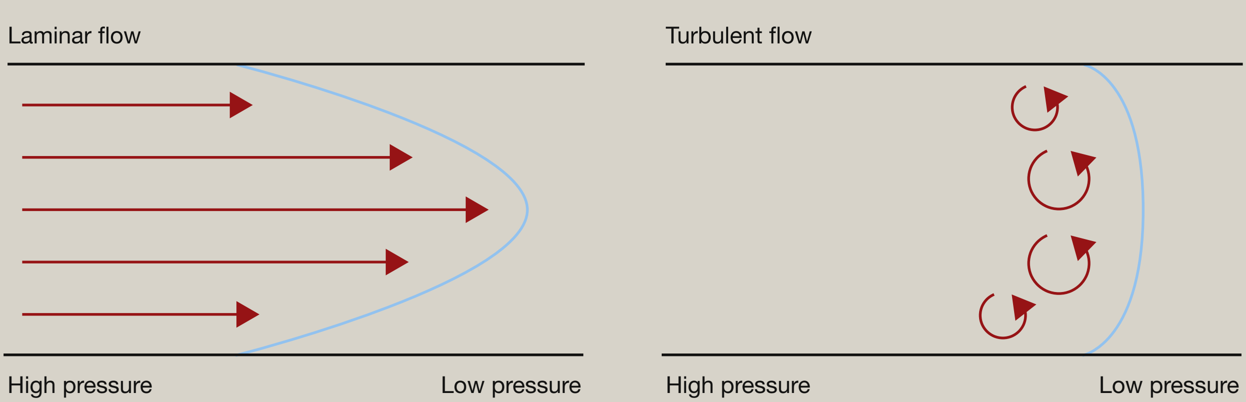

Figure 1

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