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Bernoulli's principle and the Venturi effect

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Introduction

Bernoulli's principle and the Venturi effect are important theoretical and clinically applicable concepts in fluid mechanics. This article explores the physical principles and clinical application of fluid flow in anaesthetic practice with a particular focus on Bernoulli's principle and equation and the Venturi effect.

Bernoulli's principle

Bernoulli's principle governs the behaviour of fluids along the length of a tube.[1] The principle applies to fluids in either liquid or gaseous states.[2] The principle was published by Daniel Bernoulli (1700–1782), a Swiss physicist and mathematician.[3] Bernoulli's principle states that an increase in the flow velocity of a fluid is accompanied by a concomitant decrease in its pressure and vice versa.[4]

Numerous observations typifying the pressure drop experienced in rapidly moving fluids present themselves in our daily lives. When overtaking a truck with a car on the highway, the car tends to veer towards the truck and this phenomenon is explained by Bernoulli's principle. When a car overtakes a truck, a channel is created, and the velocity of airflow within that channel must increase causing the pressure within the channel to drop. Thus, the pressure on the outside of the two moving vehicles is greater than the pressure within the channel created by the two vehicles, and it is this pressure outside the two vehicles that pushes them together.

Bernoulli's equation

Quantitatively, Bernoulli's principle is expressed as Bernoulli's equation. Bernoulli's equation describes the relationship between the pressure, velocity, and elevation of a moving fluid. Bernoulli's equation states that for an ideal fluid, which is inviscid, incompressible, and flowing along a streamline, the following sum is constant:[5,6]

$$\mathrm{P} + \frac{1}{2}\,\rho v^2 + \rho g h = \text{constant (Equation 1)}$$

Where: P = pressure, *p* = density of the fluid, v = velocity of the fluid, g = acceleration due to gravity, h = height above a set reference point. The second and third terms in the above equation are the kinetic and potential energy respectively.

It is worth noting that Bernoulli's equation can either be derived from Newton's second law of motion or the work-energy theorem.[5] The derivation of Bernoulli's equation is beyond the scope of this article. However, Bernoulli's equation is the direct application of the law of conservation of energy to an ideal fluid.[5,6]

From Equation 1 it is important to note that if the kinetic energy of the fluid increases, there will be a concomitant fall in either its potential energy or pressure.[4] Bernoulli's equation is useful in determining the flow velocity of a fluid or its pressure along a streamline. If in the Bernoulli equation (Equation 2 expressed below) subscripts 1 and 2 refer to any two points along the streamlined path the fluid follows, the equation becomes:

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \text{ (Equation 2)}$$

If it is assumed that the height remains constant and the predominant fluid flow is horizontal, such that potential energy can be ignored, Bernoulli's equation then becomes Equation 3:

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 \text{ (Equation 3)}$$

The above terms can be rearranged as follows:

$$P_1 - P_2 = \frac{1}{2}\rho v_2^2 - \frac{1}{2}\rho v_1^2 \text{ (Equation 4)}$$
$$\therefore\ \Delta P = \frac{1}{2}\rho\,(v_2^2 - v_1^2) \text{ (Equation 5)}$$

Simplified Bernoulli's equation in echocardiography

In echocardiography, the simplified Bernoulli's equation (Equation 8) is routinely used to quantify pressure gradients across valves from measured Doppler velocities.[7] When using Bernoulli's equation in clinical practice, pressure is converted from Pascal to mmHg and the density of blood is assumed to be 1 060kg.m^{-3}.

$$\Delta P \approx \frac{1}{2} \times \frac{1060\ kg.m^{-3}}{133.3\ Pa}\,(v_2^2 - v_1^2) \text{ (Equation 6)}$$
$$\therefore\ \Delta P \approx 4\,(v_2^2 - v_1^2) \text{ (Equation 7)}$$

When measuring Doppler velocities across a valve, the distal velocity is greater than the proximal velocity , the difference becomes even greater after squaring the velocities. Consequently, in echocardiography, the second term is often omitted during calculations resulting in the commonly used and simplified Bernoulli's equation:[7]

$$\Delta P \approx 4\, v_2^2 \text{ (Equation 8)}$$

The Venturi effect

A Venturi is a tube with a section of narrowed diameter along its length.[1] The Venturi effect was described by Giovanni Battista Venturi (1746–1822) and it describes the fluid dynamics through a Venturi.[8] The Venturi effect arises because of Bernoulli's principle and thus it is an extension thereof. According to the Venturi effect, when fluid flows through the Venturi its velocity increases leading to a decrease in pressure. Fluid flow exiting the narrowed section and returning to the wider section will then have a decreased velocity with an increased pressure.[1] Figure 1 illustrates the Venturi effect with increasing fluid velocity (v_2) through the narrow constriction. Note the pressure drop at the level of the constriction and the gradual opening of the tube beyond the constriction to maintain streamlined flow (v_1).

Application in anaesthesia

In clinical practice, a Venturi can be applied to a number of devices used in daily anaesthetic practice. These devices with a Venturi design may be used to measure flow or enhance the entrainment of fluids. It is worth noting that the Venturi effect does not describe the entrainment of fluids.[4] Nonetheless, entrainment is a useful practical side effect of the Venturi effect.

The following list of equipment takes advantage of the physical principles of fluid mechanics described by Bernoulli's principle and the Venturi effect. These include pressure restriction valves, flow measurement devices, portable suction units, gas flow nebulisers, high air flow oxygen enrichment (HAFOE) devices, oxygen tents, jet ventilation with a Venturi injector device, carrier gas in an anaesthetic vaporiser, and as a driving gas in a ventilator.[1,9,10] In the section that follows, this article will expound on the applicability of the Venturi effect in HAFOE devices.

It is noteworthy that the mechanism of entrainment by the fixed orifice in a Venturi device and the final delivered fraction of inspired oxygen (F_iO_2) can also be explained by jet mixing.[11] The physical principles behind jet mixing are beyond the scope of this article and the particular focus is on the Venturi effect in explaining the mechanism of air entrainment.

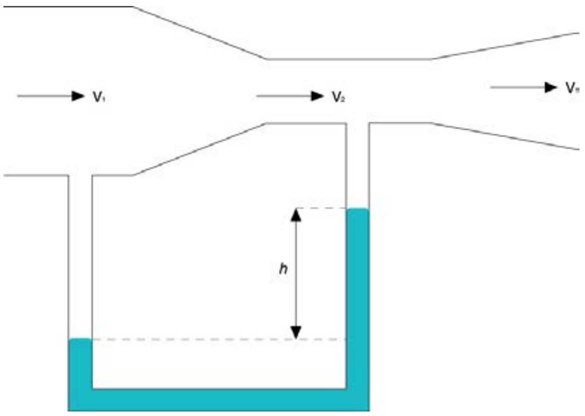

Figure 1: The Venturi effect

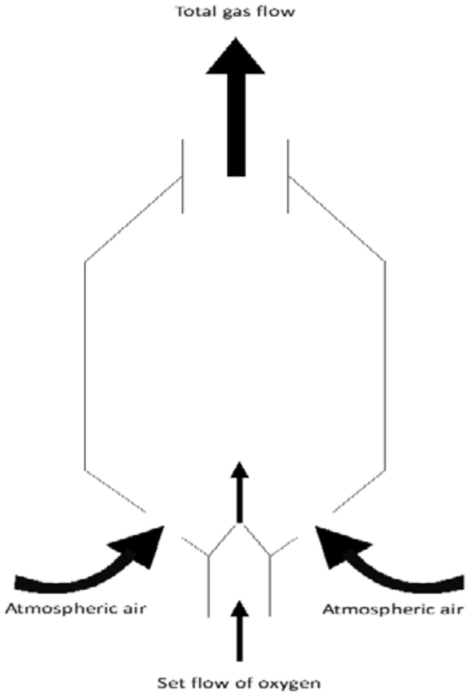

Figure 2: Fixed orifice Venturi device

HAFOE devices

HAFOE devices are air entrainment devices that deliver a constant F_iO_2.[12] HAFOE devices such as the Venturi mask are also known as fixed performance devices. The different fixed orifice Venturi devices are coloured-coded. Figure 2 illustrates a fixed orifice Venturi device. Each colour-coded fixed orifice Venturi device states the required oxygen flow to deliver the specified F_iO_2. On the sides of the fixed orifice Venturi device are apertures that allow the entrainment of atmospheric air.

A set flow of oxygen is delivered across the constriction, atmospheric air is entrained through the side apertures. This results in a higher total gas flow with a lower oxygen concentration.

The concentration of the final delivered F_iO_2 is independent of the flow rate and dependent on the entrainment ratio.[8] For example, a 40% fixed orifice Venturi device has an air-to-oxygen entrainment ratio of 3:1. Thus, a set flow of 8 l/min delivers a total flow of 24 l/min. However, more atmospheric air can be entrained if the patient's peak inspiratory flow rate exceeds the total gas flow supplied by the fixed orifice Venturi device, leading to a further dilution of the final delivered F_iO_2.[12]

To calculate the air-to-oxygen entrainment ratio, the following equation can be used:[8]

$$\mathit{Entrainment\ ratio} = \frac{\mathit{Entrained\ flow}}{\mathit{Driving\ flow}}$$

Conclusion

Bernoulli's principle and the Venturi effect are the cornerstone concepts that govern how fluids behave in a system. These concepts are leveraged in daily anaesthetic practices to provide optimal care to patients during the perioperative period.

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