The Venturi mask: more than moulded plastic

Introduction

Supplemental oxygen therapy is central to the management of most acutely ill patients and many patients with chronic disease. Oxygen should be regarded as a drug and therefore be prescribed and administered with consideration. Fixed performance devices such as the Venturi masks and humidifier systems deliver a fixed fraction of inspired oxygen (FiO_2) for a given oxygen flow rate. The indications, contraindications and hazards of oxygen therapy have been described by Booth (2006). This article aims to provide ammunition for the next ward round or clinical viva, by exploring both the physical principles behind these devices and celebrating the physicists whose names we use every day.

Fluid dynamics

Fixed performance oxygen devices exploit the fluid properties described by Bernoulli's principle and the Venturi effect. Fluid dynamics is the study of the behaviour of liquids and gases under flow conditions. These principles are applied in medicine in a myriad of situations; the rate of flow through intravenous cannulae, blood along arteries, inspired air through bronchioles or air and gases through external breathing circuits or oxygen delivery systems.

We know from the work of Hagen and Poiseuille that resistance to flow through a tube is governed by the radius to the power four, and inversely related to its length and the viscosity of the 'fluid'.

Bernoulli's principle

Bernoulli's principle states that, in fluid flow, an increase in flow velocity must be paired with a decrease in pressure, a concept which was built upon Boyle's understanding of gases and Newton's concepts of the conservation of energy.

Assume the flow of a fluid through the tubing illustrated in *Figure 1*. The flow rate (volume of fluid per unit time) will be constant at every point along the tubing, for example 10 litres per minute. The flow rate is calculated by multiplying the cross-sectional area by the velocity of flow (distance travelled per unit time, e.g. 10 metres per second). As illustrated by Mitchell (2003), the velocity of the fluid at the constriction must increase as the cross-sectional area decreases in order to maintain a constant flow rate. Bernoulli's principle states that the total energy within such a system must remain constant (Davis and Kenny, 2003; Miller, 2005); assuming that gravity, pressure gradient, fluid viscosity and other variables remain constant, as the kinetic energy (flow velocity) increases, the potential energy (pressure) decreases.

The Venturi effect

The Venturi effect exploits the drop in pressure induced by the rise in flow velocity at a constriction. The addition of a side port (Venturi valve) in the vessel allows another fluid to be entrained in (*Figure 2*). This effect is used in the eponymous fixed performance oxygen delivery systems, Bunsen burners and in car engines.

The Venturi valve and mask

In a Venturi mask, 100% oxygen flows through tubing at a specified flow rate. At the Venturi valve it flows through a narrow orifice forming a high velocity jet stream of oxygen. Atmospheric air is entrained via the side aperture, diluting the flow of 100% oxygen (*Figure 3*).

There are a series of preformed Venturi valves, the performance of which deliver a 'fixed' FiO_2, ranging between 24 and

Figure 1. Bernoulli's principle. The total amount of 'energy' at point A must equal that at point B. As flow velocity increases at point B, the pressure in the system at that point must fall.

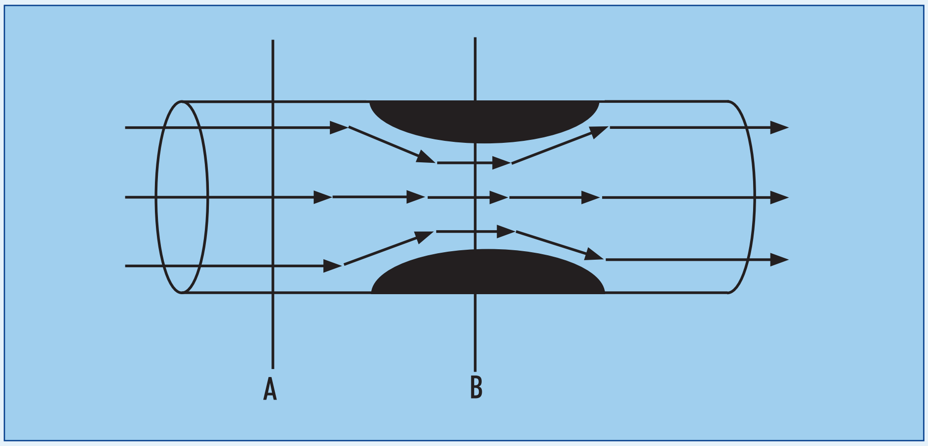
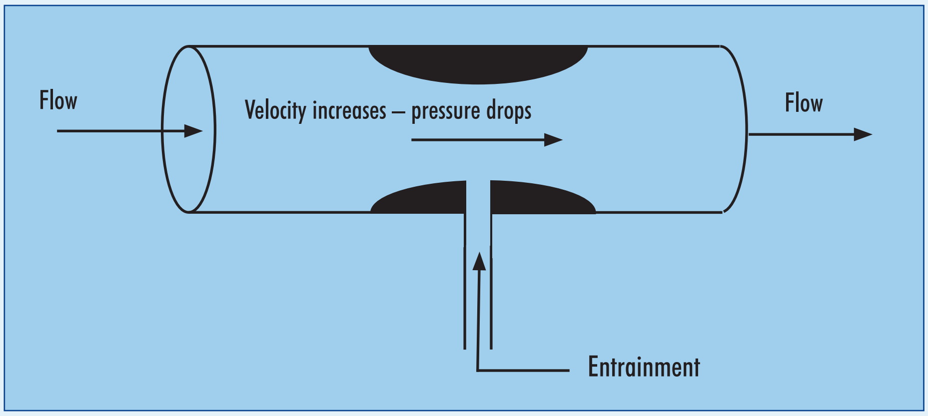


Figure 2. The Venturi effect. As flow velocity increases through a constriction in the vessel wall, an accompanying fall in pressure allows entrainment of a further fluid through a side port, known as the Venturi valve.



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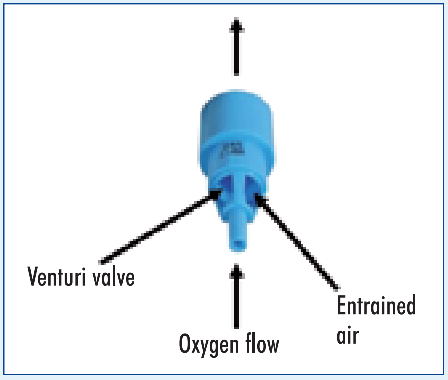
60%. These differ in the size of the oxygen inlet port and the side apertures, thereby varying the velocity of the oxygen jet stream (oxygen flow rate and orifice size) and the amount of air that can be entrained (valve aperture) to deliver the fixed FiO_2.

There is debate, however, that Venturi masks are not an application of the Venturi effect at all. Scacci (1979) and Miller (2005) argue that the air entrainment in a Venturi mask can be more accurately described as 'viscous drag' or constant-pressure jet mixing; viscous shearing forces between oxygen jet and the relatively static atmospheric air are believed to cause air entrainment rather than a Venturi effect. Nevertheless fluid dynamics and the work of Venturi and Bernoulli remain clinically relevant and deserving of recognition within the medical community.

The physicists

Daniel Bernoulli (1700–82) was born in the Netherlands where his father was a prominent academic in mathematics at the University of Groningen, although the family was originally from Basel in Switzerland. Bernoulli started formal academic studies at the age of 13 years at the University of Basel, obtained his baccalaureate examinations aged 15 years, his masters degree at 16 years of age, and had completed his doctorate of medicine by the time he was 20 years old.

Figure 3. The Venturi valve for oxygen delivery system.



Despite discouragement from his father, Bernoulli was fascinated by mathematics and in particular fluid mechanics. His work gave rise to many concepts, including Bernoulli's principle. His influence does not end there – he won prizes and awards for essays on tides and ocean currents, magnetism, a method for telling the time while at sea, the properties of vibrations in the strings of muscial instruments and the oscillation of air in organ pipes, to name a few (Quinney, 1997; Fye, 2001).

Several principles and equations used today still bear Bernoulli's name, and together with his lifelong friend and colleague Leonhard Euler, their names remain famous in academic institutions across the globe. Bernoulli died in Basel aged 82 years.

Much less is known and documented about Giovanni Battista Venturi (1746–1822). Born near Reggio in northern Italy his early education and influences are not recorded. At the age of 23 years he was ordained a priest, and 4 years later was professor of geometry and philosophy at the University of Modena in northern Italy; later he was appointed professor of physics (Biblioteca Nazionale Centrale, 1999; Davies, 2006).

Venturi followed the work on fluid mechanics of Bernoulli, and his own research gave rise to the Venturi effect, which today has far-reaching applications in medicine, the automobile industry, and in apparatus used to measure fluid flow. Like Bernoulli, Venturi outlived the life expectancy of the time, and passed away at the age of 76 years. BJHM

Conflict of interest: none.

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KEY POINTS

- Fluid dynamics may seem abstract and theoretical, but we rely on its application in many walks of life.
- Fixed performance oxygen devices are invaluable in the care of many groups of patients in both acute and chronic health care.
- Bernoulli's principle states that as the flow velocity increases at a narrowing, the pressure at that point must fall.
- The Venturi effect exploits the Bernoulli principle, and a side valve at this points allows a second 'fluid' to be entrained.