Vacuum Technology

An introduction

L G Carpenter MA, BSc, FInstP

Second Edition

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Preface to the First Edition

The aim of this book is twofold: first, to provide for those who are about to use vacuum technology as a tool for the first time an introduction to its principles, before they consult more specialised works and the literature, and second, to present a broad view of the field to those who for professional reasons need a general knowledge of the subject.

This double aim has imposed omission of detail, brevity of style and, in some cases, over-generalisation, the evils of which I hope may be mitigated by the references given to more specialised books and papers.

Appendices I and II are intended for the convenience of those readers who may wish to be reminded of the physical formulae and terms used in the text.

I gratefully acknowledge my indebtedness to many friends and colleagues, including Mr G I Lewis, Mr W N Mair, Mr B D Power, Mr T W G Rowe, Mr P Ridgway Watt and particularly Dr G W Green, who read the whole of the first draft and made many constructive criticisms and suggestions. Mr M J Watts kindly read the proofs, but responsibility for remaining errors is entirely mine.

My thanks are due to Professor J P Roberts, whose invitation to lecture on vacuum technology in the Department of Ceramics at the University of Leeds led to this book, and to Professor D W Holder for stimulating discussions and for the hospitality of his laboratory.

To the publishers, and especially to Mr Neville Goodman, whose helpful patience has been unfailing, I am deeply grateful.

L G Carpenter

Department of Engineering Science
Oxford

June 1969

Preface to the Second Edition

The aim of this edition is the same as that of the first, namely to provide a brief introduction to vacuum technology and to supply literature references so that topics of special interest to the reader can be pursued in depth.

The framework of the book is unchanged, but additions, corrections and updatings have been made.

L G Carpenter

September 1982

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1 Vacua and Vacuum Technology

1.1 What is a Vacuum?

The term vacuum is generally used to denote a portion of space in which the pressure is significantly less than 1 bar†. The definition has been refined by the British Standards Institution as follows:

Coarse or rough vacuum	760–1 Torr
Medium vacuum	$1–10^{-3}$ Torr
High vacuum	$10^{-3}–10^{-6}$ Torr
Ultra-high vacuum	10^{-8} Torr and below.

From the physical point of view, a high vacuum exists where the mean free path (see Appendix I, § AI.9) of the molecules, as calculated from the pressure, is much greater than the linear dimensions of the vessel. The situation is then dominated by gas–wall (as opposed to gas–gas) collisions. Viscosity, as ordinarily defined, has little reference or meaning in these circumstances, the basic concept being one of random wandering from one gas–wall collision to another without 'memory' of the incident direction before collision. However, one aspect of vacuum technology which does not fall within this definition of a vacuum is the action of vapour-stream (diffusion) pumps whose action depends on gas–gas collisions. This is dealt with in § 3.3.

Formerly the torr was in common use as a unit of pressure. However, it is now (1982) more usual to employ the pascal or the millibar, the relation between these units being:

$$1 \text{ mbar} = 0.75 \text{ Torr}$$
$$1 \text{ Pa} = 7.5 \times 10^{-3} \text{ Torr}.$$

† 1 bar = 750 Torr, the torr being approximately the pressure due to a column of mercury 1 mm in height.

1.2 The Basic Topics of Vacuum Technology

The creation of a vacuum involves two processes, the first being the removal of the gas originally contained in the volume of the work chamber, and the second a competition between the capacity of the pump and the production of gas, not originally in the gas phase, but stemming from leaks—real or virtual—the latter being gas desorbed (see Appendix II, § AII.4) from the walls and contents. Hence the topics to be treated include the speed of pumps and the conductance of channels by which they are connected to the work chamber (Chapter 2); their construction and mode of operation (Chapter 3); means of determining the pressures achieved and the composition of the gases composing them (Chapter 4); the design and choice of materials to minimise leaks, both real and virtual (Chapter 5); and the rather special techniques needed for producing and measuring the highest vacua (Chapter 6). Some practical applications of vacuum technology are described in Chapter 7.

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2 Conductance and Pump Speed

2.1 The Concept of Conductance

Conductance (F) is concerned with the speed of gas flow through an aperture or channel under unit pressure difference. It is somewhat analogous to electrical conductance in that, as will become evident in § 2.2, the reciprocals of conductances in series (i.e. resistances) are additive. The definition is as follows:

$$F = \frac{\text{flux of gas molecules in } PV \text{ units}^{\dagger} \text{ per second}}{\text{pressure difference across the aperture or channel}}.$$

Thus, if $\dot{V}_1$ is the volume per second[‡] (measured at the pressure P_1) traversing the aperture or channel, across which a pressure difference $P_1 - P_2$ exists,

$$F = \frac{P_1 \dot{V}_1}{P_1 - P_2}. \tag{2.1}$$

For a perfect gas (see Appendix I, equation (AI.8))

$$P_1 \dot{V}_1 = n \dot{V}_1 kT \qquad P_1 - P_2 = (n_1 - n_2)kT \tag{2.2}$$

where n denotes the number of molecules per cm^3, k is Boltzmann's constant and T is the absolute temperature. Then

$$F = \frac{n_1 \dot{V}_1}{n_1 - n_2} \tag{2.3}$$

$$= \frac{\text{flux of molecules per second}}{\text{difference in molecular density}} \tag{2.4}$$

and has dimensions [Length]^3 [Time]$^{-1}$, i.e. volume per unit time.

† For meaning of PV units, see Appendix I, § AI.7.

‡ The notation $\dot{x}$ is used throughout for dx/dt.

2.2 Conductances in Series and Parallel

It is sometimes convenient in design calculations of gas flow through channels to work with the reciprocal of F, namely the impedance (W) and to write

$$\dot{Q} = P/W \tag{2.5}$$

where $\dot{Q}$ is the gas flow in PV units per unit time and P the pressure difference across the channel.

Equation (2.5) is analogous to Ohm's law, $\dot{Q}$, P and W being analogies of current, voltage and resistance in electrical circuits.

For an assembly of channels *in series* the resultant impedance (W_0) is

$$W_0 = \sum W_i \tag{2.6}$$

where W_i is the impedance of the ith channel.

For a number of channels *in parallel* the total flow is clearly equal to the sum of the individual flows, and

$$\dot{Q} = \sum P/W_i \tag{2.7}$$

which, since the pressure is the same across each channel, becomes

$$\dot{Q} = P \sum 1/W_i. \tag{2.8}$$

However, if W_0 is the resultant effective impedance of the whole assembly

$$\dot{Q} = P/W_0. \tag{2.9}$$

Hence, comparing (2.8) and (2.9)

$$1/W_0 = \sum 1/W_i. \tag{2.10}$$

The practical consequence of (2.6) is that the overall conductance of a number of conductances in series is dominated by the smallest conductance (largest impedance) of the assembly, in analogy with the dominance of the largest resistance in a chain of series resistances in the electrical case.

2.3 The Effect of Pressure on Flow Regime and Conductance

Three regimes of gas flow may be distinguished. At high pressure—where λ (the mean free path) is much less than d (a typical dimension of the vessel)—there is Poiseuille flow, which is dominated by viscosity, i.e. by inter-molecular collisions. At the other extreme ($\lambda \gg d$) there is free molecular flow, in which gas-molecule–wall collisions are dominant. The intermediate case is called transition flow, where both mechanisms are operative.

For molecular flow, F is independent of pressure, and dependent only on geometry and on the molecular weight and temperature of the gas; it is therefore a simple and most useful concept. Molecular flow alone will be dealt with here, because it is truly a vacuum phenomenon (in the sense of § 1.1), and because it is the conductance in the low-pressure molecular flow channels which, except in very large chambers or in pumping large continuous gas loads, usually determines the efficiency of the pumping system as a whole.

Conductance in the Poiseuille and transition regimes is a function of pressure as well as geometry and temperature. Values of conductance in the three regimes are given for example by Dennis and Heppell (1968) and by Lewin (1965, pp 14 ff).

2.4 The Conductance of an Aperture

Consider the case of molecular flow through an aperture of area A in a diaphragm of area large compared with A, separating two vessels at the same temperature in which the molecular densities are n_1 and n_2 molecules/cm^3 respectively, and the mean speeds (being determined by the temperature) have a common value $\bar{c}$ cm s^{-1}. From equation (AI.6), the numbers of molecules which 'hit' the aperture from the two sides† and pass through it are $\frac{1}{4}An_1\bar{c}$ and $\frac{1}{4}An_2\bar{c}$ respectively. Hence the net flux is $\frac{1}{4}A\bar{c}(n_1 - n_2)$ and from equation (2.4)

$$F = \frac{A\bar{c}}{4}\frac{(n_1 - n_2)}{(n_1 - n_2)}$$

$$= \tfrac{1}{4}A\bar{c}. \qquad (2.11)$$

Note that F is directly proportional to area and independent of shape.

† Assuming the Maxwellian speed distribution undisturbed by the flow.

The precise validity of the formula depends upon the edges of the aperture being infinitely thin, otherwise some of those molecules which hit the edge of the aperture fail to pass through it. The magnitude of this failure depends on the ratio of the thickness of the aperture walls to its linear dimensions.

At 25°C. $\bar{c}$ for N_2 is 4.745×10^4 cm s^{-1}, hence F for an aperture of 1 cm^2 is about 11.9 ls^{-1}. Equation (AI.3) shows that $\bar{c}$, and therefore F, is proportional to $(T/m)^{1/2}$ where m is the mass of the molecule.

2.5 The Conductance of a Channel

For molecular flow through a long channel, Dushman (1962, p 88) gives the conductance as

$$F = \frac{4}{3}\bar{c}\frac{1}{\int_0^l H/A^2\,dx} \tag{2.12}$$

where H is the perimeter, A the cross section area at any point x, and l is the total length.

For the particular (and common) case of a long tube of constant radius a, formula (2.12) becomes, if a and l are in cm,

$$F = \frac{2}{3}\frac{\pi a^3 \bar{c}}{l} = 30.48\frac{a^3}{l}\left(\frac{T}{M}\right)^{1/2} \text{ls}^{-1} \tag{2.13}$$

where T is the absolute temperature in Kelvins and M is the molecular weight. A useful approximation for air at 25°C is

$$F = 10^2 a^3/l \text{ ls}^{-1}. \tag{2.14}$$

Equation (2.13) gives the conductance of a long tube, and ignores the fact that, even if the tube were infinitely short (i.e. merely an aperture), it would still have (see equation (2.11)) a conductance of $\frac{1}{4}\pi a^2\bar{c}$. Remembering that the reciprocals of conductances are additive it may be shown that the total conductance is approximately obtained by adding a length $8a/3$ to the geometric length l of the tube. Thus for short tubes (a comparable with l), equation (2.13) overestimates the conductance. The end effect is shown by the curvature in the large diameter, small length region of figure 2.1, which gives curves for the conductance of circular tubes for air at 20°C. Right angle bends do not materially decrease the rate of molecular flow (see Lewin 1965, p 16).

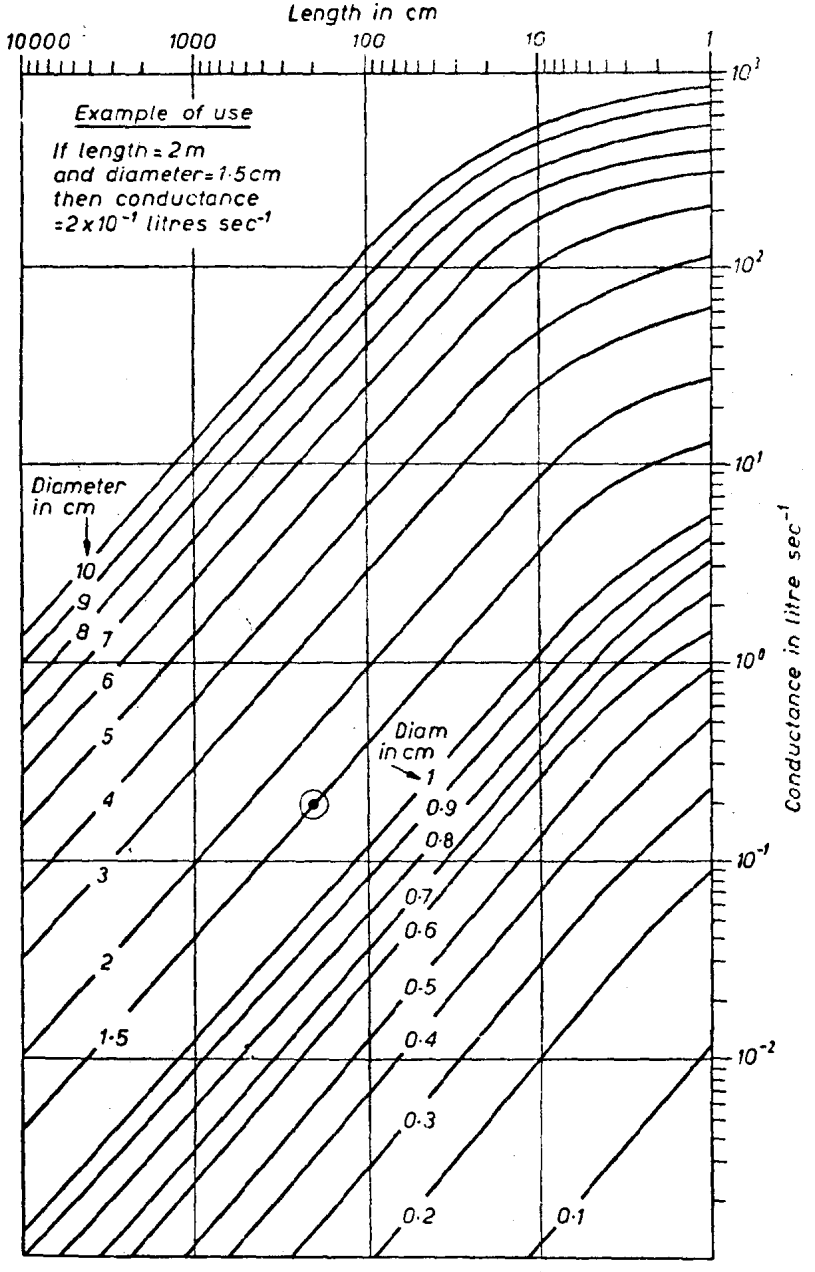

Figure 2.1 Conductance of cylindrical tubes for air at 20°C.

The mechanism of conductance is discussed from the molecular point of view in Pollard and Present (1948), and Steckelmacher (1966) has given an excellent critical review of work on molecular flow conductance for systems of tubes and components.

2.6 The Conductance of a Cold Trap

It is often desirable to interpose a tortuous cooled channel between a diffusion pump (see § 3.3) and the work chamber being pumped. Its purpose is to condense the working fluid of the pump at a temperature such that its saturated vapour pressure at this temperature is acceptably low in the work chamber. Such a channel is called a 'cold trap'.

To be effective, a cold trap must be at a sufficiently low temperature and of such geometry that a vapour molecule of pump fluid cannot get from the pump to the work chamber without hitting the wall of the trap and condensing upon it for a time that is long compared with the duration of use of the trap. Equally, a molecule of the gas to be pumped cannot traverse the trap from the work chamber to the pump without hitting the wall of the trap and being cooled thereby, i.e. its speed will be reduced. Thus both opacity and reduction of velocity impede the pumping of gas molecules, so in calculating the total conductance of the pumping system the conductance of the cold trap must be taken into account. The conductance has been computed in some simple cases (see e.g. Dushman 1962, p 101). In applying formulae valid for air at room temperature, allowance must be made for the effect on $\bar{c}$ of the trap temperature and also of the molecular weight of the gas, if it is other than air.

The conductance of traps may be approximately predicted by an optical analogue method (Carpenter and Watts 1972, 1976, 1982). This exploits the similarity between the scattering of molecules from a rough surface and the scattering of light from a diffusely reflecting surface.

2.7 The Speed of a Pump

A pump is a device with an inlet port having the property that a certain fraction of the molecules of the gas to be pumped which enter it do not

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