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Flow of gases through tubes and orifices

3.1 INTRODUCTION

Evacuation of a vacuum vessel by pumping requires the vessel to be somehow connected to the pump. This connection, usually consisting of valves and pipelines, will always result in some resistance for the gas on its way from vessel to pump. Obviously, for an unobstructed gas flow it will be important to keep this resistance as low as possible. A good understanding of the various gas flow types is essential to be able to determine the correct dimensions of the different necessary system components. In some cases, the proper operation of a vacuum system is undermined by a mismatch between successive vacuum components.

In the discussions in chapter 1 it already became clear that different transport properties of a gas, such as the viscosity and thermal conductivity, are to a large extent determined by the mean free path length relative to the dimensions of the considered vacuum volume. The ratio between these two quantities is introduced in § 1.16 as the *Knudsen number*:

$$Kn = \frac{\lambda}{d} \tag{1.66bis}$$

With the help of this number, the different properties of a gas may explicitly be characterized as a function of the pressure.

At a sufficiently **high pressure** such that the mean free path is small compared to the characteristic dimension d of the system component in question ($Kn \ll 1$), mutual particle collisions dominate over collisions with the wall. The characteristic properties of a gas flow will therefore be determined by intensive gas-gas interactions in these circumstances. The gas is called ‘dense’ and behaves as a cohesive medium. We speak in this case of a *viscous* flow.

Normally, in a gas flow at high pressure two kinds of forces may play a role: pressure forces and frictional forces. There are flows where frictional forces are negligible compared to pressure forces; in this case we have to deal with an (almost) frictionless flow. Such flows may occur through short length orifices (apertures, nozzles, short tubes). In this case, the pressure force causes acceleration (or deceleration) of the gas. For sufficiently high pressure differences across the orifice, the macroscopic gas velocity can become greater than the prevailing speed of sound; such flows are therefore known as *supersonic*. For flows through long channels or tubes, friction can not be neglected. In this situation, the flow strives to cancel out pressure forces by friction forces. The flow velocity is usually much lower than the speed of sound. The actual flow type is dependent on the magnitude of this flow velocity. At relatively low flow rates a so-called *laminar* flow is established, where the flow velocity anywhere points in the direction of the pressure drop and gas flows in layers over each other. The flow velocity is lowest at the channel wall and increases towards the channel centre. Above a critical flow velocity, the laminar flow becomes unstable in the sense that the gas starts to reveal small and more or less isolated elements moving according to an irregular and 'flighty' pattern. These are what we call swirls or turbulences: chaotic movements in the gas that occur and disappear spontaneously, and thus lead to an intensive mixing between different parts of the gas. The pressure, flow velocity and direction of flow in each point continuously change with time. In this case we are dealing with a so-called *turbulent* flow. The critical velocity above which turbulences appear is lower for rough channel walls.

At sufficiently **low pressure**, the mean free path is large compared with the dimensions of the orifice or tubulation ($Kn \gg 1$). The gas particles are no longer 'aware' of each other and mutual collisions are nearly absent. Now, the gas flow is essentially controlled by the limiting influence of the channel walls on the free movement of the gas particles. Such flows are therefore called free-molecular, or simply *molecular* flow.

In the **transition range** between the viscous and molecular regimes neither mutual collisions nor collisions with the wall may completely be neglected. The flow behaviour in this intermediate range is therefore best characterized as a 'mix' of both flow types. Unfortunately, there are no derivations of accurate analytical flow equations in this pressure range available; we can therefore only describe the flow by semi-empirical expressions. Gas flows in the transition range are usually denoted as '*Knudsen*' flow.

In the above discussion, we have specified the Knudsen number Kn only qualitatively as 'large' or 'small'. However, in order to be able to use it as a decisive parameter in answering the question in what flow regime we are and what flow model is applicable, we first need to specify limiting values to Kn for each flow range. Although these limiting values will somewhat depend on the geometry of the vacuum duct in question, the values for cylindrical tubes seem to possess a fairly general validity. More or less obvious, the characteristic dimension '*d*' of a cylindrical tube is its diameter. In practice, the flow through such a tube appears to be viscous for $Kn < 10^{-2}$ and molecular for $Kn > 1$, while the transition range applies for $10^{-2} < Kn < 1$. Using the relationship between λ and the prevailing pressure p, as derived in § 1.12, we may convert these limits to the product $p \cdot d$. For air at room temperature we calculate with expression (1.33) the flow to be viscous for $p \cdot d > 0.6$ Pa m and molecular for $p \cdot d < 10^{-2}$ Pa m. The Knudsen flow holds for $10^{-2} < p \cdot d <$ 0.6 Pa m.

Table 3.1 shows an overview of the different flow types and their validity range in terms of the Knudsen number Kn and the product $p \cdot d$ (air). In addition, for each flow type an indication is given of the extent to which flow rates are analytically quantifiable.

Table 3.1 Overview of flow types

Flow type	Kn range	$p \cdot d$ range	Quantifiability
Turbulent	$Kn < 10^{-2}$	$p \cdot d > 0.6$ Pa m	difficult
Laminar	$Kn < 10^{-2}$	$p \cdot d > 0.6$ Pa m	good
Supersonic	$Kn < 10^{-2}$	$p \cdot d > 0.6$ Pa m	reasonable
Knudsen	$10^{-2} < Kn < 1$	$10^{-2} < p \cdot d < 0.6$ Pa m	bad
Molecular	$Kn > 1$	$p \cdot d < 10^{-2}$ Pa m	good

In the following sections we will first focus on the supersonic flow. Understanding of this flow type is of particular importance in relation to the operation of diffusion pumps. In addition, in case of (unwanted) air break we are often dealing with a supersonic inflow. As an introduction to supersonic flow theory, a short summary is presented of the required thermodynamics and flow laws.

Subsequently, the laminar and molecular flow types are discussed. The laminar flow theory provides us with knowledge on the flow resistances of vacuum lines under viscous conditions. Understanding molecular gas flows is essential for pumping speed calculations in high vacuum.

Whether we are under viscous conditions dealing with either a laminar or turbulent flow in a vacuum line, can be deduced from the so-called *Reynolds number* (see § 3.6). From estimates of this Reynolds number we conclude that under vacuum conditions turbulent gas flows are of minor importance. In fact, turbulences in vacuum lines are only observed during the first few moments of evacuation from atmospheric pressure and upon backfilling a vacuum system to atmospheric pressure. In view of this limited importance, no further attention is given to the turbulent flow.

At the end of the chapter, attention is paid to important key terms as ‘conductance’ and ‘pumping speed’. Furthermore, with the help of the preceding theory, expressions are issued for the conductance of a few simple geometries at laminar and molecular flow.