1

Basic concepts

1.1 INTRODUCTION

In Latin, vacuum means ‘void of air’. However, when we speak about 'vacuum' we usually do not mean ‘void of air’ in this strict sense. If the total pressure of a gas or a mixture of gases in an enclosed chamber is lower than the 1 atmosphere air pressure surrounding us, we say 'there is vacuum in the chamber'.

Even though it is not usual to speak of 'vacuum' in situations where the pressure is only a little less than 1 atmosphere (e.g. in the high mountains), this natural limit of 1 atmosphere has been chosen in order to clearly demarcate the vacuum range at the high-pressure end. The other extreme of vacuum, the complete absence of gas particles, will in practice never be attained. The closest one can get to this condition is in the low pressure regions of intergalactic space , where the gas density is estimated to be in the order of 10^4 hydrogen atoms per m^3. If based on astrophysical grounds a 'temperature' of 10^4 K is assumed for this hydrogen gas, this density corresponds to a pressure of approximately 10^{-20} (!) atmospheres. In enclosed volumes on Earth gas densities down to 10^9 particles per m^3 are achievable nowadays, corresponding to a room temperature pressure of about 5×10^{-17} atmosphere.

The term 'vacuum technique' refers to methods and techniques used to obtain and measure pressures below 1 atmosphere. Vacuum technique plays a crucial role in today's science and industry; we only need to think of examples like vacuum packaging, light bulbs, degassing, freeze drying, TV and computer monitors, the manufacture of thin films, pure metals, semiconductors, and closely related to this the research on solid state surfaces. It’s not too much to say that without the ability to evacuate large and small volumes, our society would remain at the technological level of the early 20th century.

After a brief historical review, we will discuss in the following paragraphs the fundamental physical laws which govern the behaviour of vacuum and play a role in the technique of evacuation. To this end, it is necessary to have some insight in the characteristics and structure of gases, but also of liquids and solids. The properties of rarefied gases at different pressures and temperatures are quite well explained by the kinetic theory of gases. The basic principles of this theory will be discussed, including topics such as the thermal motion of gas particles, the mean free path, rate of incidence, vapour pressure, evaporation rate etc. Also the empirical gas laws of Boyle/Gay-Lussac, Avogadro and Dalton have their formal basis in the kinetic gas hypothesis. Finally, we will focus on some non-equilibrium properties of gases at high and low pressures (thermal conductivity, viscosity, diffusion). The reasonably good agreement between the kinetic transport laws and experimental practice evidences the validity and usefulness of the kinetic gas theory.

1.2 HISTORICAL OVERVIEW

For the first ideas around the concept of 'vacuum' we must go back to the time of the Greek philosophers. Even before our era, in particular, Aristotle (382-322 BC) dealt with the question of whether a vacuum could exist. He argued that nature would abhor vacuum and therefore not allow the existence of empty space. This view, known as the 'Horror Vacui', lasted for twenty centuries.

Renaissance brought a change of views on many subjects. Through experimental observations, Copernicus, Kepler and Galilei discovered the earth to revolve around the Sun. This put a new trend in thinking. The philosophical approach was increasingly abandoned to make way for more rationalism, the search for an explanation of physical phenomena by conducting experiments.

The immediate reason for research on 'vacuum' came from the inability to pump water out of deep wells. Initially it was assumed that the applied pumps simply were not 'good enough'. One didn't yet recognise that the actual cause was a 'lack of air pressure'. Nevertheless, based on these and other observations, Baliani built in 1639 an instrument that today would be termed as a 'water barometer'. Then, Torricelli in 1644 filled a long glass tube with mercury and placed it upside down in a container with mercury. The mercury inside the tube dropped to a height of about 76 cm above the mercury level in the container. While he believed, above the mercury column an 'empty space' had been created, a clear explanation was not forthcoming. Through an extensive correspondence with other scientists this new knowledge spread all over Europe.

In this way also Blaise Pascal was informed about 'Torricelli's experiment' and repeated the test several times. To prove that the mercury column in the tube was held up by the prevailing atmospheric pressure, he asked his brother-in-law Perier in 1648 to repeat the experiment on the Puy de Dome, a 1465 m high mountain near ClermontFerrand. On top of the mountain the mercury column only came to a height of 65 cm! 'Horror vacui' anyway seemed to be different on top of the mountain. In honour of this 'evidence' today's standard unit of pressure is named 'Pascal'.

More or less parallel to these facts, Otto von Guericke in Magdeburg designed a pump by which a beer barrel, first filled with water and then sealed, could be evacuated. Shortly thereafter he replaced the leaky wooden beer barrel by two copper hemispheres placed against each other to form a single enclosed sphere, which could withstand the outside air pressure. To demonstrate the force of this air pressure, he did an experiment in which he evacuated the sphere and subsequently tried to pull both hemispheres from each other with two teams of eight horses. This ‘Test of the Magdeburg hemispheres’ drew a lot of attention during the Reichstag in Regensburg (1657). The Jesuit Father Caspar Schott repeated these experiments and described them in detail. In this way the new knowledge about this ‘vacuum set-up’ quickly spread. In The Netherlands, the phenomenon drew the attention of scientists like Christiaan Huygens, ‘s Gravensande and Peter van Musschenbroek; in England Robert Boyle and Robert Hooke were involved. The experiments of Boyle eventually led to the famous ‘law of Boyle’.

After this period, the phenomenon of ‘vacuum’ remained for some time in the ambiance of ‘Physique Amusante', until in the mid-19th century a new phase down to much lower pressures was initiated by the invention of mercury-filled pumps by Geiβler (1857), Töpler (1862) and Sprengel (1865). At the same time pressure measurement also became possible. The measuring range of the meanwhile well-known U-tube mercury manometer was expanded with the compression manometer of McLeod (1874). Edison’s invention of the light bulb in 1879 was possible thanks to the low pressure he could achieve with a Sprengel pump.

A common disadvantage of the aforementioned pumps was their low pumping speed. However, a breakthrough took place in 1905 with the invention of the mercury filled rotary pump by Gaede. Using Bunsen’s water jet pump (1870) as a roughing pump, Gaede achieved a pressure of about 10^{-3} Torr in a short pump time. In 1908 Gaede came up with an improved design for an oil-lubricated rotary pump, developed some years before by the Siemens employee Hoffman (1904). From that moment on, this improved version became known world-wide as the ‘Gaede pump’ and in fact can be considered as the forerunner of the current rotary-vane pump.

In 1911 Gaede designed the molecular pump: a fast-moving wall transfers momentum to gas particles colliding with it. This gives the gas particles an extra velocity component in the direction in which they should be discharged. Unfortunately however, the mechanical industry at the beginning of the 20th century was not yet sufficiently advanced for mass-production of this pump with the required accuracy.

In 1913 Gaede invented the mercury diffusion pump, improved by Langmuir in 1916 and later made to run on oil by Burch. These inventions came precisely at a time when the rapidly emerging light bulb and radio tube industry felt the need for well-functioning high vacuum pumps. Parallel to these developments in the field of hardware, researchers like

Knudsen, Langmuir and also Gaede progressed with the implementation of the kinetic theory of gases, while Clausing and Knudsen came up with a more detailed description of how gas flows under high vacuum conditions (molecular flow).

Although through all these developments vacuum in the period after 1910 found more and more application in such areas as the chemical industry, the pumping of vapours remained a problem associated with the condensation that occurs during compression. Only when Gaede conceived the gas ballast principle in 1935, did the problem come to the end.

The disadvantage of the intermittent pressure measurement with the McLeod compression manometer was overcome in 1906 by Pirani's thermal conductivity gauge, followed in 1916 by Buckley's ionization gauge, derived from the triode radio tube. In 1937 the Philips employee Penning invented the cold cathode ionization gauge. Although it became readily clear that this co-called 'Penning gauge' possessed a pumping action, it would take until 1958 before this principle was used in the so-called sputter-ion pump. The low-pressure range of the conventional hot cathode ionization gauge was improved in 1950 by the American researchers Bayard and Alpert. Today their 'Bayard-Alpert (B&A) ionization gauge' is still the most widely used high vacuum gauge.

In 1954 the arsenal of vacuum pumps expanded with the Roots pump: a dry rotary pump based on the principle of the air blower, developed by the Roots brothers already in 1868 to evenly boost a forge!

Between 1956 and 1959 Gifford and MacMahon developed a new method to achieve low temperatures: by compression and expansion of helium it appeared possible to cool a solid surface down to 10-20 K. It then took until 1974 before the first cryo pump based on this principle became commercially available.

A well-known disadvantage of the diffusion pump - the backflow of oil vapour to the high vacuum side - received new interest with the rise of surface science in the fifties. The predominant adsorption of oil vapour molecules flowing back to high vacuum rendered measurement on really clean surfaces an impossible goal. In 1958 Becker made an attempt to eliminate this problem by mounting a rotating baffle in the form of a fan on top of a diffusion pump. This turned out to be an effective tool, especially when a multiple stage fan was used. Since the baffle not only reduced the back-streaming of oil vapour, but also gave a considerable increase in pumping speed, Becker decided to further refine this 'rotating baffle' and build it as a stand-alone unit: the turbomolecular pump was born. The extensive mechanical and electronic developments since the beginning of the 20th century made this pump, unlike the former molecular pump of Gaede, become a successful design. Currently, the turbomolecular pump is considered as the 'workhorse' in high vacuum technology.

The same trends made it possible in 1977 to turn a theory of Knudsen dating from 1920 into a new manometer based on the phenomenon of gas friction: the spinning rotor gauge.