Helmut Bannwarth

Liquid Ring Vacuum Pumps, Compressors and Systems

Conventional and Hermetic Design

Translated by
Christine Ahner

WILEY-VCH Verlag GmbH & Co. KGaA

H. Bannwarth
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Author

Helmut Bannwarth
Emil-Gött-Strasse 7
D-79194 Gundelfingen
Germany

Translation

Christine Ahner
translate economy
Freiherr von Eichendorff-Str. 8/1
D-88239 Wangen/Allgäu
Germany

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Two-stage vacuum system with hermetic liquid ring vacuum pumps for recovery of aromatic compounds (Hermetic-Pumpen GmbH, Gundelfingen, Germany)

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Dedicated to my wife Karin

Foreword

Modern technology is based on both craftsmanship and scientific knowledge. The further development in technology depends decisively on how far scientific results are brought in purposefully in view of economical aspects. Here, physics is of great importance.

When trying to determine today's relation between physics and technology it can be assumed that physics is pure science while technology means designing on a scientific basis. Physics is one of the bases technology needs. Those who are capable of utilizing physical understanding for their developing and designing skills can avoid lengthy and costly experimenting.

In 1991, on the occasion of the 125th birthday of LEDERLE GmbH, the technical manual "Liquid ring vacuum pumps, compressors and plants, conventional and hermetic" was issued for the first time in German language.

The author succeeded in communicating physical and technical basics in a remarkable way. The book met with great interest both among planners and operators.

Vacuum technology has become indispensable for many branches of industry.

The demand for more protection of health, workplace and environment in modern process engineering didn't stop at the vacuum pump either. The product range of LEDERLE GmbH in the vacuum sector has been further developed according to these requirements and has been based on the experiences of the plant operators. As a result, nowadays liquid ring vacuum pumps and compressors in hermetic design are on the market.

The great success and the active interest the first issue of this reference book met with induced us to issue an edition in English. With this, an international clientele and interested circles will have a specialist book in their hands that deals with the design and application of pumps and plants in the vacuum range. The author, Helmut Bannwarth, once more substantiates his expert competence in an impressive way.

We cherish the hope that this book will find a wide and attentive readership, and that owing to the continuous cooperation between manufacturers, planners and operators ideas and suggestions for further progress will arise.

Dr. Roland Krämer
Managing Director – Engineering
Lederle-Hermetic GmbH

Wolfgang Krämer
Managing Director – Sales
Lederle-Hermetic GmbH

December 2004

Preface

In 1991, the first edition of the technical manual "Liquid ring vacuum pumps, compressors and plants" was published in German language by the publishing house VCH Verlag in D-69496 Weinheim, Germany. Three years later, in 1994, the second, revised edition came out and I took advantage of the opportunity to update and complete it according to the progressing technical developments.

With this first edition in English language, again updated, I could fulfil the request for a translated version of the book expressed by many interested students and practitioners of industry and engineering offices at home and abroad.

I express my thanks to the publishing house Wiley-VCH Verlag particularly for the again pleasant cooperation and the continuous support I enjoyed.

I would also like to express my gratitude to the managing directors of the company group Lederle GmbH and Hermetic-Pumpen GmbH, Mr. Wolfgang Krämer and Dr. Roland Krämer for their generous support. Many thanks to all companies and publishing houses not mentioned here for kindly providing me with the respective documents.

December 2004 *Helmut Bannwarth*

Preface of the first edition in German language in 1991

The Greek philosopher Democritus and other well-known scholars as well as the metaphysicians of the Middle Ages have already dealt with the subject vacuum.

In 1640, Otto von Guericke, the Mayor of Magdeburg, conducted the first experiments regarding the generation of vacuum. On the occasion of the Reichstag in Regensburg in 1654, he demonstrated the effect of air pressure on two evacuated hemispheres (known as Magdeburger Halbkugeln). Owing to his thorough knowledge in this field and the machines and plants he had designed, he is regarded as the founder of the entire vacuum technology.

In 1643, the Italian mathematician and physicist Evangelista Torricelli succeeded in inventing the barometer, the first device for the measurement of vacuum.

Today, neither modern physical-technical basic research nor industrial process engineering is conceivable without methods and appliances based on vacuum technology. There is hardly any field of technology offering so many possibilities of application as the field of vacuum technology does. Meanwhile, in this sector a lot of industrial companies developed components and vacuum systems that are partly available on the market as standard units. Due to the progressing development in the field of vacuum technology, project and design engineers will not find all the required equipment on the market, but will have to convert already existing plants for new experiments or will have to design new pilot plants or production plants by themselves.

The intention of this book is to design and manufacture a vacuum plant suitable for rough vacuum making use of the conventional components, the practical experience and standards valid in the vacuum sector.

At the beginning, we cast light on the field of gas physics in vacuum technology and provide an overview of the whole vacuum field. Thereby, all machines used in practice for the generation of vacuum will be taken into consideration. In particular, the liquid ring vacuum pumps and compressors are being elucidated, as well as components usually applied in industry and their combination to vacuum systems. Here, great importance is attached to the hermetic liquid ring machines and components nowadays used for closed and environment-friendly cycles. Furthermore, we will also report comprehensively on the practical layout of vacuum pumps, pipework and vacuum containers, on the assembly and control of machines and plants, the

surface quality in vacuum technology, vacuum hygiene, safety-at-work, explosion protection and explosion-proof electrical resources. Some chapters are completed with practical calculation examples.

As far as standards, recommendations and guidelines in vacuum technology and the adjacent fields exist they have been quoted to a large extent.

Physical values shall be SI-units, however, even tables and charts with old units that are still valid and in use, such as the former internationally introduced pressure unit "Torr", are taken into consideration.

The appendix contains an extensive compilation of the international SI-unit system, conversion tables and common constants, national and international standards as well as recommendations, pictograms, and material data of fluids often found.

This book is written from the engineer's practical point of view and is mainly addressed to students, technicians and engineers involved in designing and operating of machines and plants in the field of vacuum or to those keen on familiarizing themselves with this subject.

With this work, a supplementary reference book, practically oriented and reflecting the latest state of knowledge, will be available on the specialist book market.

I want to express my thanks to the management of the company Lederle GmbH, Pumpen- und Maschinenfabrik, D-79194 Gundelfingen for providing me with a large part of photos and drawings that actually made the publication of this book possible. My particular thanks go to Mr. Hermann Krämer, graduate engineer and General Manager of the company, for his generous support. I also thank the companies and publishing houses for providing me with pictures and charts and their permission to reproduce them.

January 1991 *Helmut Bannwarth*

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1
Gas Physics and Vacuum Technology

1.1
The term "vacuum"

In standard specification list DIN 28400, Part 1, the term "vacuum" is defined as follows:

Vacuum is the state of a gas, the particle density of which is lower than the one of the atmosphere on the earth's surface. As within certain limits the particle density depends on place and time, a general upper limit of vacuum cannot be determined.

In practice, the state of a gas can mostly be defined as vacuum in cases in which the pressure of the gas is lower than atmosphere pressure, i.e. lower than the air pressure in the respective place.

The correlation between pressure (p) and particle density (n) is

$$p = n \cdot K \cdot T \qquad (1\text{-}1)$$

k Boltzmann constant
T thermodynamic temperature

Strictly speaking, this formula is valid only for ideal gases.
The legal pressure unit is Pascal (Pa) as SI unit. The usual pressure unit in vacuum technology is millibar (mbar). This pressure unit is valid for the whole vacuum range from coarse vacuum to ultrahigh vacuum.

1.2
Application of vacuum technology

Vacuum is often used in chemical reactions. It serves to influence the affinity and therefore the reaction rate of the phase equilibrium gaseous – solid, gaseous – liquid and liquid – solid. The lowering of the pressure causes a decrease in the reaction density of a gas. This effect is used e. g. in the metallurgy for the bright-annealing of metals. There are several kilograms of metal for 1 liter annealing space, whereas less than 1/3 of the total volume is filled with gas; as a result, the oxygen content of

the residual air is less than 1 mg in the pressure range of 10 mbar. Compared to the metal mass, the oxygen content decreases to 10^{-5}. This leads to a retardation of the oxidation process, thus allowing higher process temperatures. It also causes an increase in the ductility of the products. When teeming melted materials, such as metals, apart from a retarded oxidation also degassing (desorption) takes place at the same time. The result is metal of particular purity. In the metal and sinter ceramics industry, sintering processes are based on the same principle. The impediment of fermentation caused by aerobe micro-organisms with the help of vacuum can also be called reactive retardation, an example of which is vacuum packaging. On the other hand, a reactive acceleration is reached, e. g. when after the evacuation of the materials to be treated, gases or liquids are discharged in order to increase the reaction density. The reaction density can also be controlled as required by means of a decrease in pressure, e.g. when chlorinating. In this case, diluting gases are not required.

The selection of the adequate technology for a chemical-physical process depends on pressure-related parameters and the specific characteristics of the material to be treated. This requires e.g.

- the determination of the optimal ranges of vacuum and temperature,
- the determination of the required equipment,
- the determination of all necessary auxiliary means, which vacuum pumps or vacuum devices belong to.

The dimensions of a vacuum plant are not only determined by the performance data of the process devices, but also by the operating range of the vacuum. In the range of high vacuum the sizes of the individual devices are not as important for the dimensions of the total plant as the required suction capacity and the sizes and dimensions of the vacuum pumps, i.e. the vacuum pump stations.

Generally, in vacuum process engineering of the chemical industry or related branches vacuum plants usually consist of the following main components:

- Vacuum devices for the execution of the process
- Condensation devices for the compression of the arising vapor
- vacuum pump or combination of pumps
- accessories, such as separators, heat exchangers, vacuum vessels, metering and control devices.

1.2.1 Basic operations in process engineering

In the industrial process engineering, basic operations are usually carried out in coarse vacuum, seldom in fine vacuum. The application of high vacuum is considered only in particular cases.

The machines used here are vacuum pumps and compressors. With lower vacuums and higher flow rates mostly extractor fans are used.

Regarding the use of waste heat and the careful heating of thermally sensitive material it is advantageous for the performing of the vacuum process to work at low temperatures. The most different processes are carried out through vaporizing, drying, condensing, degassing, filtering etc. under vacuum. Generally, it can be said that the total operating costs of vacuum plants increase with higher vacuum.

Mechanical vacuum pumps can be designed as dry or wet running pumps with pistons or rotating elements.

Dry running vacuum pumps are used for pumping dry and non-condensable gases. In case of existing condensable vapors, condensers have to be installed on the suction side in which the condensable particles are condensed through cooling. In the field of coarse vacuum, usually surface condensers or mixing condensers are used, while low-temperature condensers or absorption condensers are used in the fine vacuum range.

Wet running vacuum pumps are particularly suitable for the suction of condensable vapors or gases, as well as for mixtures of gases and liquids. In wet running vacuum pumps driven by an operating liquid (e.g. water or another liquid chosen according to the process), the process gas can be condensed. Owing to this fact, condensers installed on the suction side of the pumps are not required. The diagram of the basic layout of a vacuum device is shown in fig. 1-1.

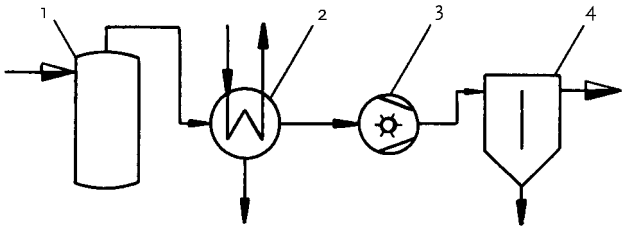


Figure 1-1. Basic scheme of a vacuum plant
1 vacuum vessel
2 condenser
3 liquid ring vacuum pump
4 liquid separator

1.2.2
Basic fields and worked-out examples for the application of vacuum technology

Vacuum technology is dominant in many fields of research and industry (Table 1-1) and is applied by using the most different process technologies (Table 1-2).

Table 1-1. Fields of application of vacuum technology [1.1]

Field of knowledge	Branch of industry/technology
Physics (mechanics, continuum mechanics, thermodynamics, electrodynamics, optics, nuclear physics, surface physics- and chemistry)	Scientific instrument production (precision mechanics) Mechanical engineering and heavy engineering industry Electronics (for measuring and control problems) Automation and controlling Cryogenic engineering
Biophysics	Chemical process engineering (oils, greases, waxes, resins etc.)
Physical chemistry Chemistry	Metallurgy
Material engineering	State-of-the-art technologies (glass, ceramics and metallic compounds)
Pharmacy Medicine	

Field of application	Examples
Nuclear technology	Crystal growing (scintillation detectors) Evaporation (solid-state detectors) Working with closed systems (hot laboratories, plutonium, etc.) Filtration Sintering under vacuum (nuclear metals, ceramics, carbide)
Optical industry	Vaporization technologies (interference layers, laser, maser, glass fiber optics, optoelectronics)
Electrical engineering/electronics	Drying (insulation oils, coolants) Impregnation (insulation material) Hermetic sealing (boosters) Evacuation and degassing (e.g. tubes, lamps) Evaporation and sputtering (e.g. condenser production, thin-film technology) Encapsulation (tubes, semiconductor elements) Welding and surface treatment (micro-circuits) Crystal growing (epitaxial growth) Surface reactions (transistors, circuits)
Scientific instrument production	Physical and chemical analyses Analyzing appliances (surface analysis, UV examination, electron and ion microscopes, X-ray analyzers, microwave devices) Lowest temperature analyses Particle accelerators, storage rings Fusion plants
Chemical industry	Distillation (fatty acids, oils, alcohol, etc.) Filtration Drying, dehydration vaporization, sublimation

Field of application	Examples
Food industry	Freeze-drying (fresh and cooked food)
	Preservation and conservation
	Dehydration and concentration (milk, coffee ...)
	Crystallization (e.g. sugar)
Pharmaceutical industry	Distillation (vitamin A, E, ...)
	Freeze-drying (blood, ...)
	Drying (antibiotics, hormones, ...)
	Sterilization (dressing materials, ...)
Metallurgy and semiconductor manufacturing	Distillation (Mg, Ca, Li, Se, Na, K, ...)
	Reduction (Ti, Mg, Zr, Fe,Cr, ...)
	Sintering (high-melting and reactive metals, carbides, ...)
	Melting and casting (Pb, Sn, Mn, Ge, alloys, high-melting and reactive metals)
	Drying (powder)
	Heat treatment
Production engineering	Impregnation (molds for casting)
	Injection molding (Mg alloy components without voids)
	Fastening (chucks)
	Welding and soldering (precision devices)
	Surface finish (hard material or anticorrosion coating)
Space engineering	Biological processes and developments
	Material development and control
	Development and control of devices (motors, gauges, ...)
Office machines industry	Welding and treatment
	Registration
	Heat insulation
Transportation in various industry branches	Lifting and transporting (paper, metal sheets, pavement plates, cathode ray tubes, ...)
Miscellaneous applications	Evaporation (paper, plastics, fabrics, ...)
	Thermal insulation (Dewar flasks, ...)
	Forming (plastics, vacuum casting)
	Concrete hardening

1.2.3 Overview of the most important vacuum processes

Tab. 1-2 contains processes preferably carried out under vacuum.

Table 1-2. Vacuum processes in process engineering [1.2]

Process	Important advantages through vacuum
Endothermic processes	
Vacuum vaporization	Low temperature of material and heating agent Increased heat efficiency
Vacuum distillation	Better separation effect, molecular distillation; Oxide-free and gas-free metal distillation
Vacuum sublimation	Under triple point (freeze-drying)
Vacuum drying	Quick and careful drying without shrinking; increased dissolving speed
Vacuum calcination	Shifting of phase equilibrium, decomposing temperature drops
Vacuum annealing and sintering	Bright annealed products are free from oxides, gases and scale
Vacuum melting	Gas-free melted product, high-purity metals, chemicals, plastics, sealing compounds
Vacuum casting	Non-porous cast products with high density
Vacuum soldering	Furnace soldering without flux, oxide-free hard soldering
Vacuum evaporation	Surface finish through vapor deposition of thin films of metals and non-metals
Vacuum reaction	Thermal conversion at low temperatures and decreased reaction density
Vacuum steam generation	Water vapor heating below 100 °C, rapid control
Processes without catalytic oxidation	
Vacuum degassing	Gas-free liquid, viscose, plastic masses
Vacuum gas injection	Fumigation, disinfection, sterilisation, sorption
Vacuum mixing	Modified sorption, improved wettability
Vacuum extraction	Higher dissolver speed, dissolver recovery
Vacuum filtration	Continuous residue decreasing
Vacuum impregnation	Complete impregnation of porous bodies, agglutination
Vacuum transport	Fluidized bed transport of bulk materials by means of induced draught
Vacuum insulation	Thermo-barochamber
Vacuum packaging	Improved shelf life, no aroma losses
Exothermic processes	
Vacuum condensation	Distillate recovery, higher energy yield
Vacuum cooling	Ice generation without coolants
Vacuum crystallization	Higher crystal yield through flash distillation of solvents
Vacuum reaction	Higher distribution rate, low reaction density
Vacuum presses	Non-porous agglomeration or agglutination of powders and laminates

1.2.4

Basic designs of apparatus for mass transfer and mass combination

The most important vacuum processes applied in process engineering are given in Table 1-3. They are subdivided according to thermal processes and grouped together according to the apparatus equipment.

Table 1-3. Basic symbols, apparatus and process technique in vacuum engineering [1.2]

Component	Basic symbol	Symbol range					
Vacuum apparatus							
		Mass transfer				Mass combination	
	Heat tone	endothermic	endothermic	exothermic	without	without	endothermic
	Process	evaporating distilling deodorising	drying subliming calcining	degassing cooling crystallising	filtering extracting	agglomerating shaping impregnating	sintering, soldering, melting, casting, coating
Condensers							
	Condenser	liquid	liquid and solid		solid	liquid	dissolved
	Cooling fluid	through pipes	around pipes	Condensation trap	rotat. cooler	Injection	Absorption
	Process	Surface condensation with condensate separation				Co-condensation	
Pumps							
		Piston	Rotor	Rotor	Rotor	Motive fluid	Motive fluid
	Process	Positive displacement vacuum pump oscillating	rotating	rotating	Kinetic vacuum pump rotating		
Separators							
	Fluid	liquid	solid	solid	solid	gaseous	
	Process	Droplet separation	Dust separation by Gravity	Filter	Submerged washing	Circulatory washing	
Vacuum vessels							
	Fluid	liquid	liquid	liquid or solid	liquid or solid	solid	solid
		Heating, cooling coil	Heating, cooling jacket	with cover opening	with stirrer	Bottom opening	Bottom opening with stirrer
Heat exchangers							
	Fluid	liquid	liquid	liquid or solid			
		Tube system	Tube coil	Double shell with stirrer			

1.2.5 Limits to the application of vacuum in process engineering

In the field of vacuum, the kind of gas flow depends on the respective prevailing vacuum.

According to the Hagen-Poisseuille law, laminar gas flow exists in coarse vacuum. In the range of high vacuum, the internal friction is no longer decisive, as the collision of the molecules and the tube wall occurs more often than the collision among the molecules themselves. This kind of flow is called Knudsen molecular flow, i.e. the average molecular speed and the mean particle path of the gas molecules determine the flow process. The range between coarse and high vacuum is called fine vacuum. The fine vacuum range is the transition zone between the Hagen-Poisseuille flow and the Knudsen flow. The range of vacuums higher than in high vacuum is called ultrahigh vacuum.

According to the Knudson equation

$$K = \frac{\bar{l}}{d} \tag{1-2}$$

the different types of flow are subdivided as shown in table 1-4.

Table 1-4. Flow types in vacuum [1.3]

K	< 0.5	0.5 – 3.0	> 3.0
Type of flow	Hagen-Poiseuille flow	Transition zone	Knudsen molecular flow

K Knudsen number
$\bar{l}$ mean free path [m]
d diameter of the flow channel [m]

Therefore, for the type of flow arising in tubes, the ratio of the mean free path (a gas molecule does on average until its collision with another molecule), which increases with decreasing pressure and the diameter of the flow channel is decisive.

Material transport. With the increasing vacuum, the transport of gases and vapors gets more and more difficult. This is a result of the fact that with decreasing pressures the available forces diminish and the volumes increase. With pressures lower than 0.1 kPa (= 1.0 mbar), in practice only insignificant quantities of gas and vapor are transported in pipes.

Heat transport. Only in the range of atmospheric pressure heat transfer through convection is technically applicable, whereas high vacuum is a good heat insulator. In vacuum processes, the heating-up of the material occurs practically only in direct contact with heating elements through radiation, rarely through dielectric heating or inductive heating.

1.3
Operating ranges and measuring ranges of vacuum

Vacuum ranges are ranges of pressures or particle densities according to which it is agreed to classify vacuum.

The rounded down limits of these ranges are listed as pressure values or equivalent particle density values in Tab. 1-5.

The particle density values given in the table apply to a temperature of $\delta = 20\,°C$.

1.3.1
Vacuum pressure ranges

Table 1-5. Vacuum ranges (acc. to DIN 28400, Part 1, July 1979)

Formula character	Unit	Coarse vacuum, CV	Fine vacuum, FV	High vacuum, HV	Ultrahigh vacuum, UHV
P	[Pa]	$1 \cdot 10^{15}$ to $1 \cdot 10^{2}$	$1 \cdot 10^{2}$ to $1 \cdot 10^{-1}$	$1 \cdot 10^{-1}$ to $1 \cdot 10^{-5}$	$< 1 \cdot 10^{-5}$
P	[mbar]	$1 \cdot 10^{3}$ to 1	1 to $1 \cdot 10^{-3}$	$1 \cdot 10^{-3}$ to $1 \cdot 10^{-7}$	$< 1 \cdot 10^{-7}$
n	[m^{-3}]	$2.5 \cdot 10^{25}$ to $2.5 \cdot 10^{22}$	$2.5 \cdot 10^{22}$ to $2.5 \cdot 10^{19}$	$2.5 \cdot 10^{19}$ to $2.5 \cdot 10^{15}$	$< 2.5 \cdot 10^{15}$

It seems to suggest itself to divide measuring ranges in decimal powers, as follows:

Millibar range	from 1000 to 1 mbar, essentially the normal and coarse vacuum range
Microbar range	from 1 to 10^{-3} mbar, the fine vacuum range
Nanobar range	the high vacuum range
Picobar range	and below, the ultrahigh vacuum range

1.3.2
Vapor pressure curve of water in vacuum

For vacuum process engineering with a prevailing thermal mass transfer, it is practical and clearer to divide into vacuum operating ranges following the thermometric fixed points of water as so-called fundamental material which the chemists, process engineers and technicians have to deal with every day (Fig 1-2). According to this, in the boiling range of pure water between 0 and 100 °C corresponding to 6.11 mbar to 1013mbar, the normal or basic vacuum range results, in which the boiling process always occurs as pure vaporization.

Processes with lower pressures at which vaporization takes place through sublimation from the solid phase (ice) below 0 °C are to be allocated to the fine or high vacuum range.

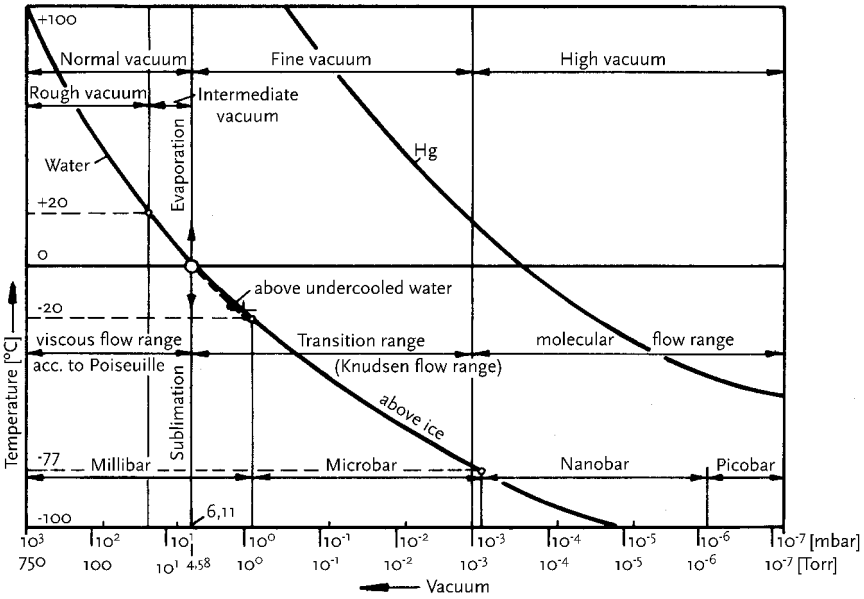


Figure 1-2. Vapor pressure curve of water in different vacuum ranges [1.2]

1.3.3
Vacuum operation ranges, temperature pressure table

In Tab. 1-6, vacuum operating and measuring ranges in millibar and Torr are compared to the specific boiling points of pure water (H_2O), mercury (Hg), methanol (CH_3OH) and ethyl alcohol (C_2H_5OH). From this, the difference between the vapor pressures of the individual fluids and the dependence on the pressure temperature are clearly deriving. In fine and high vacuum, the operating ranges coincide with the measuring ranges.

Table 1-6. Operating ranges and measuring ranges of vacuum [1.4]

		Measuring ranges				Boiling ranges in °C			
			mbar[1])		Torr[2])		H_2O	Hg	$C_2H_3 \cdot OH$	CH_3OH
Normal vacuum	Rough vacuum		1013		760		100	357	78,3	64,7
			1000		750		99,6	356,2	78	64,2
			800		600		93,5	344	71	56,5
			600		450		85,5	329	61,5	48
			400		300		75	309	54	40,5
			200		150		60,1	278	45	32
		↑	100	↑	75	Evaporation	45,7	251	29,5	16,5
			80		60		41	242	24	11
			60		45		36,4	232	17	5,5
			50		37,5		32,5	225	14	3
			40		30		29	218	11,5	0
			30		22,5		24	208	8	–3,5
	Intermediate vacuum	Millibar range	23,4	Torr range	17,53		20	201	5	–6
			20		15		17,2	196	3,5	8
			15		12		14	190	–1	–11,5
			12		9		9,7	181	–4	–15,5
			10		7,5		7	176	–9	–19,6
			8		6	↑	3,8	170	–12,5	–24
			6,11		4,58		0	162,5	–15,6	–25
Fine vacuum range			6		4,5	↓	–0,2[3])	162	–17	–20,5
			4		3		–5	152	–21,5	–32
		↓	2	↓	1,5		–13	135,5	–28	–38
			1		0,75		–20,3	119	–38,5	–47,5
		↑	1000	↑	750					
			800		600		–22,7	115,5	–42	–50,5
			600		450		–25,4	110	–45,5	–53
			400		300		–29,3	102	–48,5	–56,5
			200		150	Sublimation	–36	89	–53	–61
			100		75		–42	77,5	–60	–67,5
		Microbar	80	Millitorr	60		–43,7	73,5	–63	–70
			40		30		–50	63	–68	–74,5
			10		7,5		–60,5	42,5	–75	–83
			8		6		–62	39,8	–77	–85
		↓	4	↓	3		–67	31	–81	–88,5
			1		0,75					
High vacuum range		↑	1000	↑	750		–76,3	14,4	–87	–94
			800		600		–77,8	12	–88,5	–95
			400		300		–82	5	–91,5	–98
			100		75		–90	–9	–94	–100
		Nanobar	80	Microtorr	60		–91,5	–11		
			40		30		–96	–17		
			10		7,5		–101,5	–29		
			8		6		–103	–31		
		↓	4	↓	3		–106	–36		
			1		0,75		–112	–42		
Ultra vacuum range		↑	1000	↑	750					
			800		600		–113			
			400		300		–116			
			100		75		–121,5			
		Picobar	80	Nanotorr	60		–122			
			40		30		–124,5			
			10		7,5		–129,5			
			8		6		–130			
[1]) 10^3 N/m^2		↓	4	↓	3		–132,5			
			1		0,75		–137	–100		
[2]) mm Hg			1000		750					
			800	Picotorr	600		–137,5			
[3]) above ice			400		300		–139,5			
			100		75		–143,5			

1.3.4 Total pressure measuring

Pressure units. In vacuum technology, the Torr unit is used as the practical unit for pressure, which is tantamount to millimeter mercury column (mm Hg), the same applies to the unit millibar (mbar). In the international unit system (SI), Pascal (Pa) or Newton/square meter (N/m^2) are used as pressure units. There are still other customary pressure units which should no longer be used, however. When pressure values are quoted, usually negative decimal powers (e.g. 2×10^{-1} Torr) are employed. Table 1-7 may help in converting old units, no longer permitted in business and official communication since 31/12/1977, into new units.

Table 1-7. Conversion table for pressure units (acc. to DIN 28400, part 1 July 1979)

	Pa [$N \cdot m^{-2}$]	1 bar = 1000 mbar	Atm	Torr
1 Pa = 1 $N \cdot m^{-2}$ =	1	10^5	$0.986923 \cdot 10^{-5}$	$0.750062 \cdot 10^{-2}$
1 bar = 1000 mbar =	10^5	1	0.986923	$0.750062 \cdot 10^3$
1 atm =	$1.01325 \cdot 10^5$	1.01325	1	$0.760000 \cdot 10^3$
1 Torr =	$1.33322 \cdot 10^2$	$1.33322 \cdot 10^3$	$1.315789 \cdot 10^3$	1

Depression and vacuum. In technology, the terms overpressure (p_e), depression (p_u), and vacuum are used. The lowest pressure theoretically possible is 0 Pa = 0 $N \cdot m^{-2}$ = 0 mbar.

This would correspond to a 100 per cent vacuum (Fig. 1-3). Vacuum is a rarefied air or gas space. With 100 percent vacuum there is a total absence of air and gas.

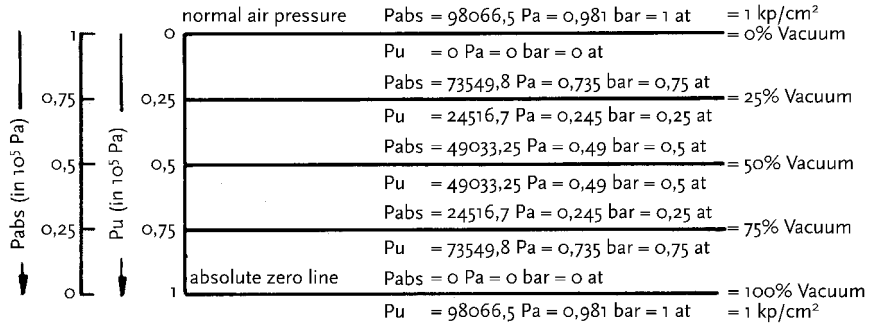


Figure 1-3. Underpressure and vacuum [1.5]

According to the following formula, vacuum can be calculated in percent:

$$\text{Vacuum} = \frac{P_u}{P_{air}} . 100\,[\%] \tag{1-3}$$

As this is a pressure ratio, any pressure unit can be used for calculation. However, for p_u and p_{air} the same pressure units have to be used in the formula.

Vacuum in percent can also be determined from barometer readings B in Pa and the readings of a vacuum gauge H in Pa using the following formula:

$$\text{Vacuum} = \frac{1.01325 \cdot 10^5\ \text{Pa} - (\text{B} - \text{H})}{1.01325 \cdot 10^5\ \text{Pa}} \cdot 100\ [\%] \tag{1-4}$$

Example 1.1:
How much underpressure is in a vessel with a vacuum of 80% and an air pressure of $0.98 \cdot 10^{-5}$ Pa?

Solution:
According to equation (1-3), the result is:

$p_u = \text{Vacuum in } \% \cdot p_{air}$
$p_u = 0.80 \cdot 98000\ \text{Pa} = 78\,400\ \text{Pa} = 784.0\ [\text{mbar}]$

Absolute pressure, overpressure and underpressure. A pressure higher than the outside air pressure is called overpressure p_e. A pressure below the outside air pressure is called underpressure p_u. (Fig. 1-4)

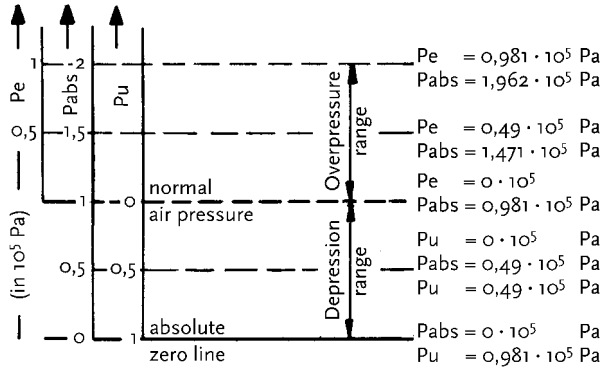


Figure 1-4. Absolute pressure, overpressure and underpressure [1.5]

In technology, the absolute pressure p_{abs} is used for calculations taking the currently prevailing air pressure into consideration.

The absolute pressure p_{abs} is the pressure calculated from the absolute zero line.

$$p_{abs} = p_e + p_{air} \quad \left[\text{Pa};\ \frac{\text{N}}{\text{m}^2};\ \text{mbar}\right] \tag{1-5}$$

$$p_{abs} = p_{air} - p_u \quad \left[\text{Pa};\ \frac{\text{N}}{\text{m}^2};\ \text{mbar}\right] \tag{1-6}$$

Example 1.2

In a condenser, an underpressure of 650.00 mbar prevails, with the barometer showing 980.00 mbar.

How much is the absolute pressure in mbar, in Pa and the vacuum in percent?

Solution:

Acc. to equation (1-6), the result is:

$$p_{abs} = p_{air} - p_u$$

$$p_{abs} = 980\ \text{mbar} - 650\ \text{mbar} = 330\,[\text{mbar}] = 3{,}30 \cdot 10^4\,[\text{Pa}]$$

and acc. to equation (1-3) the result is:

$$\text{Vacuum} = \frac{P_u}{P_{air}} \cdot 100\,[\%]$$

$$\text{Vacuum} = \frac{650\ \text{mbar}}{980\ \text{mbar}} \cdot 100\,[\%]$$

$$\text{Vacuum} = 66,32\,[\%]$$

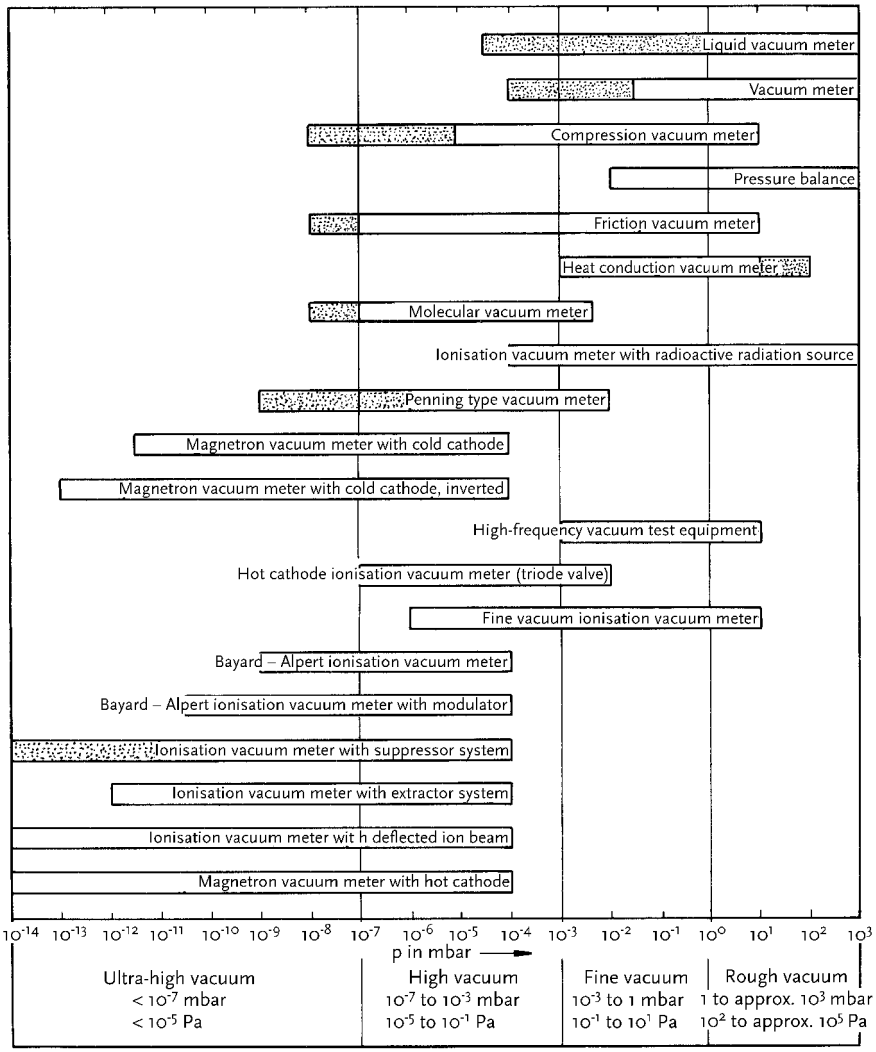
1.3.5 Pressure meters

In order to be able to record the pressure range from 10^5 to 10^{-11} Pa metrologically, various physical basic principles are employed according to which the pressure meters are subdivided.

There are

- mechanical gauges
- heat conduction vacuum manometers
- friction manometers
- radiometer manometers
- ionization manometers.

Up to pressures of 1 Torr, the direct measuring and display of the mechanical force acting upon a surface is carried out by means of mechanical manometers. Pressures below 1 Torr are determined by other measuring methods. Here, physical quantities such as friction, thermal conduction and ionization are measured. The measured quantities can be converted into electric currents or voltages, thus enabling the application of most modern electric and electronic methods of analysis.



The limits of the measuring ranges are without engagement. In the diagram are shown the usual limits.

Measuring range for special execution or for special operating data.

Figure 1-5. Measuring ranges of common vacuum gauges (acc. to DIN 28400, Part 3, October 1980)

Mechanical gauges

In the following, only the group of mechanic gauges will be described [1.1]. These devices utilize the action of forces of the pressure for pressure display. To this group includes:

- Bourdon pressure gauge
- Diaphragm gauge
- Modulation meter
- Liquid manometer

Bourdon pressure gauge. This gauge (Fig. 1-6a) is a bent tube made of elastic material with an oval cross section. One tube end is closed while the other one is connected to a vacuum vessel. Owing to different actions of forces onto the upper and lower broadside of the tube (Fig. 1-6b) the tube bends during evacuation. By means of a lever mechanism, the tube deformation is transferred to a pointer.

Features

- Pressure readings independent from kind of gas
- Measuring range: atmospheric pressure up to about 1000 Pa
- special versions for laboratories up to about 1 Pa, e.g. versions made of corrosion-resistant materials (glass or quartz) are known
- Accuracy of readings depends on design, usually relatively low

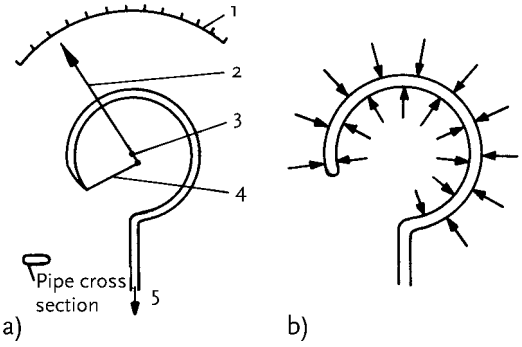


Figure 1-6. Bourdon tube
a) basic design b) force balance
1 scale, 2 pointer, 3 pointer's centre of motion, 4 lever, 5 vacuum vessel

Diaphragm gauge. This type of gauge uses the deformation of a diaphragm (or the changing of the length of a bellows) dividing two ranges of different pressures for pressure display. The deformation is displayed mechanically, optically or electrically (fig. 1-7). As the diaphragm deformation does not occur proportionally to the pressure, gauging devices with linearization appliances are partly used. The reference pressure is mostly selected in the lower pressure range, i.e. in fine and high vacuum, to be independent from altitude, fluctuating air pressure and weather. The readings are independent from temperature and outside air pressure, as the sensing element and the display are not in contact with the measured gas. In these devices, the clearance between the solid wall and the nesting ripple diaphragm, or the so-called pressure capsule in versions with two nesting ripple diaphragms, (acc. to [1.6]) is evacuated (fig. 1-8).

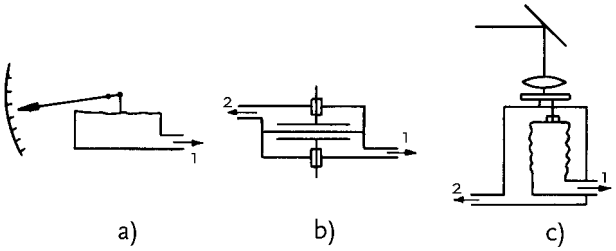


Figure 1-7. Diaphragm vacuum gauge with different kinds of display
a) mechanical display (pointer) b) electrical display c) optical display
1 to vacuum vessel, 2 to reference vacuum

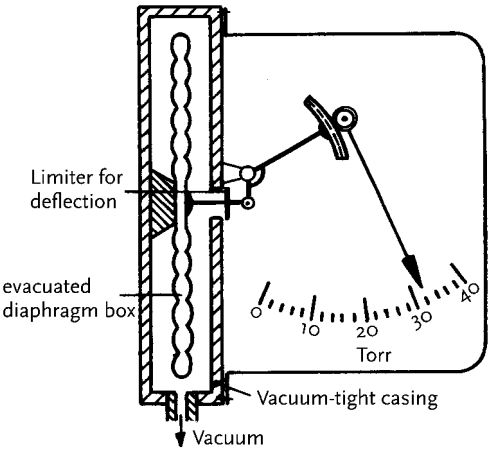


Figure 1-8. Diaphragm vacuum gauge with diaphragm box

Features

- Pressure readings independent from kind of gas
- Measuring range: depending on the versions, from 10^5 Pa to 10^{-2} Pa or for pressure differences of some hundreds of Pa up to 10^{-2} Pa, in laboratory versions up to some 10^{-3} Pa
- Accuracy: depending on the version, in some ranges up to several percent. Owing to the combination with switches, suitable for controlling; with electric display, remote readings and registration are possible.

Modulation manometer. The change of pressure according to the state equation for ideal gases arising from the periodical change of volume is used for the pressure measurement.

$$\Delta p = -p_o \frac{\Delta V}{V} \tag{1-7}$$

p_o average pressure
V_o average volume
$\Delta V = \Delta V_o \cdot \cos \omega \cdot t$
(constant gas mass being presupposed)

The periodic volume change can be produced e.g. with a piezo-ceramic measuring transmitter, the periodic pressure change can be detected by means of a sensitive microphone (fig. 1-9).

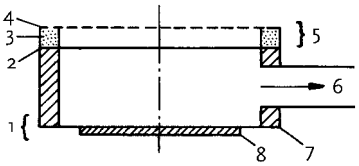


Figure 1-9. Modulation gauge according to Hartung and Jurgeit
1 – modulator, 2 – diaphragm, 3 – insulator, 4 – electrode, 5 – receiver, 6 – vacuum vessel, 7 – metal diaphragm, 8 – piezo-oscillator

Features

- In case of suitable design, pressure display independent from the kind of gas – at least in certain pressure ranges
- Measuring ranges: from atmospheric pressure up to about 10^{-4} Pa
- Accuracy: several percent
- Due to electronics, process control in vacuum, remote indication and registration of pressure are possible

U-tube gauge. The hydrostatic pressure of a liquid column compensating the pressure of the gas serves the pressure measurement.

$$p = \rho \cdot g \cdot h \tag{1-8}$$

ρ liquid density
h liquid column height
g acceleration of free fall
p hydrostatic pressure

The open, simplest type of U-tube gauge (fig. 1-10) is not really common in vacuum engineering, as for the measuring required for the determination of the gas pressure the air pressure has to be read as well. For technical purposes, a shortened closed U-tube gauge has become established (Fig.1-10b). In order to record the measuring range up to air pressure, a U-tube with a branch length of more than 760 mm