11th International DAAAM Baltic Conference
“INDUSTRIAL ENGINEERING”
20-22 April 2016, Tallinn, Estonia

ANALYSIS OF SELECTION CRITERIA FOR VACUUM GAUGES AND ITS ACCURACY

Stekleins A., Gerins E., Kromanis A.

Abstract: *Vacuum technological process can be performed using specific equipment and in order to reach desired result it is essential to focus on the pressure inside a vacuum chamber. Pressure can be measured using various types of vacuum gauges with different operating principles. During technological process a high level of vacuum should be reached, therefore it's essential to select proper gauge for reliable and correct vacuum measurements. One particular vacuum gauge cannot be selected for broad vacuum range because due to physical reasons it is impossible to construct vacuum gauge, which can be reliable and carry precise pressure measurements in the entire range of vacuum. Gauge operating principles and pressure measuring ranges are not the only factor that affects vacuum gauge selection process. Vacuum gauge operating conditions influence measurement accuracy due to high risk of contamination, vibrations, temperature, etc. Vacuum gauge mounting on the chamber is also one of the main factors for accurate pressure measurements.*

This paper is focused on analysis of selection criteria for vacuum gauges and its accuracy. The analysis of different type vacuum gauges is given, in order to understand operating principles, their main advantages and disadvantages. Accuracy and repeatability of several vacuum gauges are compared. As an example of the vacuum gauge accuracy problem one specific experiment is given. Diaphragm and ionization gauges were selected for experiment due to their pressure diapason, accuracy, repeatability and ionization gas correction options. Those vacuum gauges are most commonly used for vacuum technological processes. Main idea of the experiment is to show the consequences of unreliable and uncalibrated ionization gauge.

Keywords - vacuum gauge, selection, pressure, accuracy

1. PRIOR ART OF VACUUM GAUGES

The prior art mainly discloses three types of vacuum measurement gauges which are used to measure a pressure inside vacuum chamber...

In measurement of vacuum mainly two pressure units are frequently used: Torr and mbar. Pressure in vacuum chamber can vary starting from 10^3 Torr up to 10^{-7} Torr, it all depends on the technological process to be performed. Knowledge of vacuum amount within the chamber is main priority during technological process in order to achieve desired product quality.

Pressure range in nanotechnology can be very wide, therefore a vacuum gauge must be selected depending on conditions and requirements of the technological process.

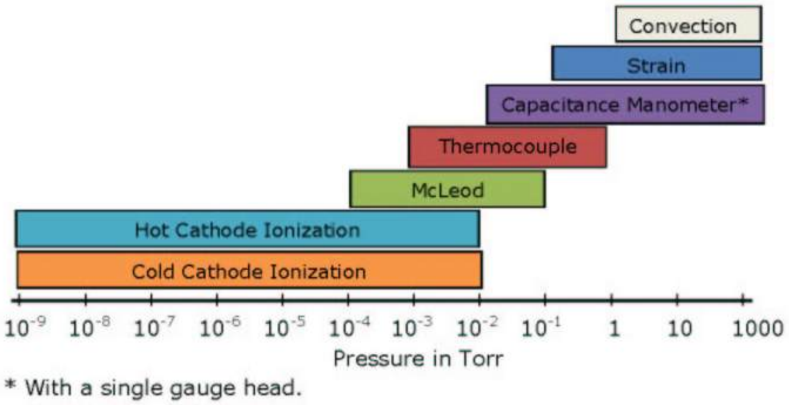

Fig. 1. Pressure ranges for several vacuum gauges [5]

To understand, which vacuum gauge can be selected in specific situation, we need to know their constraints and measuring range (Fig. 1.) [5].

1.1. Low vacuum gauges

To measure the low vacuum, vacuum gauges with mechanical operating principles are used, where a pressure affects a flexible component of the vacuum gauge. Such a flexible element can be a membrane or small tube, where it deforms upon applying pressure (Fig. 2.) [8].

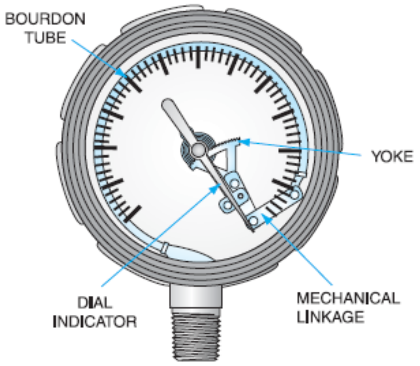

Fig. 2. Capacitance manometer [8]

An example on this principle is the capacitance manometer, and such gauge is effective from 10^{3} torr to 10^{-4} torr, and beyond. Akram (2012) discusses potential accuracy and stability of diaphragm vacuum gauge and possibility to use it as main gauge for low vacuum or at least it can be considered to be one of the first choices for low vacuum measurement and mainly due to the high membrane sensitivity [1]. Deformations of flexible element in mechanical gauges are measured with electrical or optical methods [2].

1.2. Medium vacuum gauges

Vacuum gauges for medium vacuum use different operating principle. It uses thermal conductivity as one of the gas characteristics. Therefore, mechanical low vacuum gauges are not an option, because molecular density differs and mechanical force cannot make an impact. Thermal conductivity is defined as the amount of heat transfer per unit time across the unit area of small plane located perpendicular to the direction of heat flow divided by the temperature gradient [1]. As an example for measuring medium vacuum Pirani vacuum gauge can be used. Pirani measuring gauge uses thermal conductivity principle where pressure and gas ability to transfer heat are bonded together.

Pirani gauge main principle is simple: vacuum gauge utilizes the thermal conductivity of gases at pressures than approx. 10 to 100 hPa. The surrounding gas dissipates the heat to the wall of the tube. In the molecular flow range, the thermal transfer is proportional to the molecular number density and thus to the pressure and when the temperature of the *wire is kept constant, its heat output will be a function of pressure.. However it will not be a linear function of pressure, as thermal conductivity via the suspension of the wire and thermal radiation will also influence the heat output.* [6].

In a gaseous environment the hot wire loses heat in four different ways such as: radiation, conduction along the wire to the end supports, heat conduction by the gas molecules and gas convection [8].

We have used Pirani vacuum gauges before, but we also have noticed that after some time the gauge accuracy starts to fail. We are of the opinion that it can be related to the fact that vapour condensates on gauge sensing wire during technological process and thermal conductivity changes.

Prior art discusses vacuum gauges with accuracy +/- 15%, which is not acceptable, because it is almost impossible to reach repeatability in technological process with this kind of instability in measurements.

1.3. High vacuum gauges

In high vacuum we cannot use thermal conductivity characteristics and the same refers to mechanical vacuum gauges with their operating principle due to molecular density changes when high vacuum is being reached.

In this vacuum diapason another physical principle is used, such as ionization of gas. The vacuum gauges with this operating principle are called ionization vacuum gauges. Ionization gauge consists of two gauges such as Pirani gauge for low vacuum measurement and Bayard-Alpert gauge for high vacuum measurement. In ionization gauges, the positively charged molecules are attracted by ion collector, indicating positive-ion current, which is ultimately calibrated in pressure [1].

Ionization gauges can be divided into several types: filament gauge (Bayard-Alpert), which use thermionic emission of electrons from a hot wire, while cold cathode gauges (Penning, Inverted Magnetron) use electrons from a glow discharge of plasma.

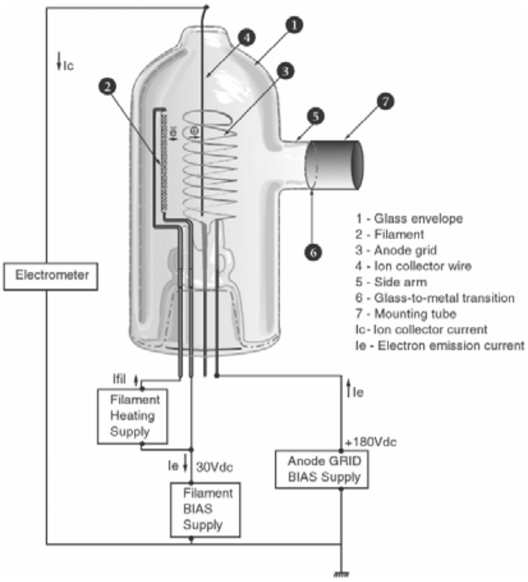

Fig. 3. Typical Bayard-Alpert vacuum gauge configuration [7]

Fig.3 illustrates Bayard-Alpert vacuum gauge and its operating principle, where *electrons boil from the hot filament and are accelerated towards the anode grid, besides that current of highly energetic electrons traverse the inner volume of the grid cage and ionize some of the gas molecules the encounter in their path, exit the grid and are immediately directed back into its inner volume by the electrostatic field, resulting in a multiple-pass ionization path that ultimately end by collision with a grid wire. The ions formed inside the anode grid are efficiently collected by the grounded collector wire that is located along the axis of the cylindrical grid and connected to the controller's electrometer also if the electron emission current and the temperature of the gas are constant, then the ion current is proportional to the number density and the pressure of the gas. In the result, the positive ion current provides an indirect measurement of the gas pressure.* [7]

Ionization vacuum gauge is commonly used to measure high vacuum. The gauge is configured to switch on gas correction if in a technological process a gas, such as argon or other gas, is used. This can be also a drawback of the device, because gas compositions can be different, which forces to work with respective gas correction. Correction coefficient difference can make a significant impact on pressure measuring accuracy. Vacuum gauge cannot measure pressure accurately if technological process is performed with one type of gas, but it has been calibrated with another gas. It becomes even more problematic when combination of several gases is used in the vacuum chamber.

2. VACUUM GAUGE ACCURACY

Vacuum gauge accuracy is one of the main factors and selection criteria when choosing a vacuum gauge. It's very important to maintain desired pressure in vacuum chamber during technological process, therefore a vacuum gauge with high accuracy must be selected.

Vacuum gauges has their own pressure measuring ranges and based on their operating principles have respective accuracy. For example, INFICON® company ionization vacuum gauge (model HPG 400) provides +/-15% of reading accuracy in pressure diapason from 10^{-5} to 1 mbar. Consequently, the gauge accuracy range is up to 30%, which is too high for vacuum technological processes. Main goal of all technological process is to provide repeatability of the process. For example, in applying different coatings in a vacuum chamber we need to operate in a very small pressure range, with respective gas flows and other parameters, but also we need to apply coating with same properties over and over again, but it can be problematic with a large deviations in a vacuum measurements. In order to be able to allocate the largest possible measuring range to the individual type of vacuum gauge, one has to accept the fact that the measurement uncertainly rises very rapidly, in some cases up to greater extent, particularly at the upper and lower range limits [1]. This behaviour of VISCOVAC® (Spinning Rotor Gauge-SRG) is shown in Fig.4 [1].

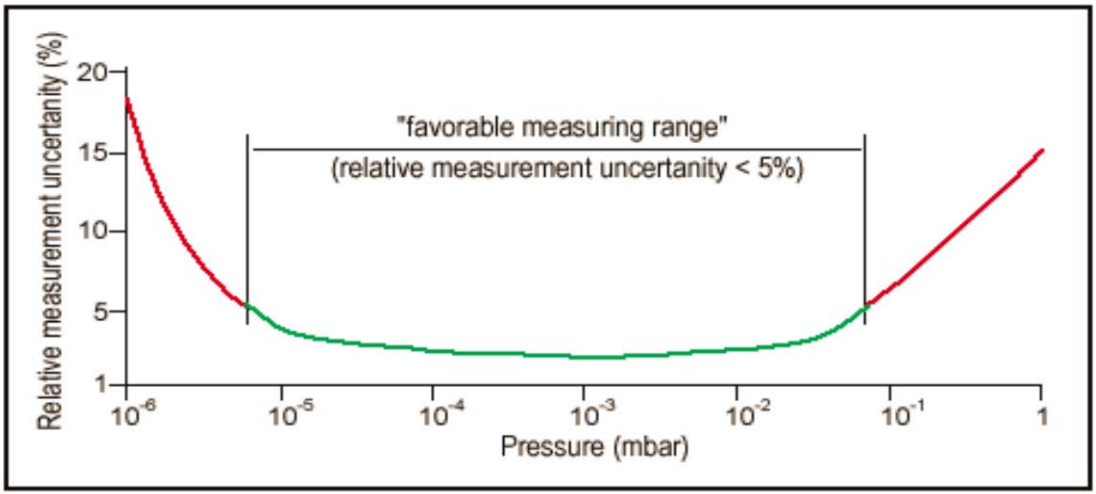

Fig. 4. Spinning rotor gauge measuring range and its accuracy [1]

Fig. 4 illustrates a difference between spinning rotor gauge measuring range and precise measurement range. Precise measurement range for this particular example is approximately from $8x10^{-5}$ to $2x10^{-1}$ mbar, accuracy remains in 5% boundary. Correct usage of vacuum gauge is based on the shown example and described analysis, which gives a theoretical conception of precise measurement range.

For most room temperature measurements the effects of ambient temperature variations on Bayard-Alpert gauge readings are insignificant. Determining the gas temperature is a difficult task in tabulated Bayard-Alpert gauge, because most molecules equilibrate with envelope, but the envelope temperature is not symmetric because of asymmetric location of the filament. [7]

Another, but not less important is magnetic field influence on vacuum gauge sensitivity, which has strong effect on charged molecules trajectories.

Vacuum technological process, its maintenance and control are the main aspects for research and below described experiments.

3. EXPERIMENTS

In research for vacuum gauge accuracy, the experiments were designed and conducted. During the technological process it is hard to rely on specific vacuum gauge especially if ionization gauge is taken as an example. Mainly two types of vacuum gauges were selected: INFICON® diaphragm vacuum gauge CDG 025D and ionization gauge HPG 400 [9, 10]. Diaphragm vacuum gauge is not affected by gas, therefore it is more reliable than ionization gauge. During experiment an inert gas (argon) was fed into the chamber. The deviations were identified between ionization gauge measurements with argon correction coefficient and without it. In Table 1 and Table 2 HPG ionization gauge is shown as second measuring device and diaphragm gauge as the third. In Table 1 an argon correction is turned off, respectively in Table 2 the argon correction is turned on.

Argon was fed into the chamber in volume 100 sccm or 14,4%. With argon correction turned on the gauge reaches satisfied level of the vacuum. In order to reach pressure measurement without correction and change it from 8.58 up to 6.88^{-4} torr, argon must be reduced to 11.2 % or 78 sccm.

No.	Gauge Pressure (Torr)
1	8,59E-4
2	8,58E-4
3	1,70E-3

Table 1. HPG 400 pressure measurement with argon in a chamber and without gas correction

This experiment illustrated pressure measurement difference and possible solution with special effect, which result in argon flow reduction.

Nr.	Gauge Pressure (Torr)
1	8,52E-4
2	6,88E-4 (cor)
3	1,70E-3

Table 2. HPG 400 pressure measurement with argon in a chamber and gas correction

After preliminary statistical analysis we concluded that the difference in measurements is equal to 22 sccm. The difference in measurements can be identified, where argon correction is directly related to the coating quality and product in common. In current experiment one of the technological waste factors such as argon was selected. From economical point of view we could reduce argon flow by 22 sccm if selected pressure measurement by ionization gauge is correct. In the result, significant amount of argon can be saved. The aim of the research is to understand why different gauges measurement results are not identical and how much it influences final product quality. In order to analyse vacuum gauges, their technical data and possibilities, advantages and disadvantages special vacuum chamber must be build, as well as device accuracy and sensitivity must be checked, and interconnection between accuracy and period of use must be found.

4. CONCLUSION

Prior art identifies basic knowledge of vacuum systems, their functions, elements and important stages during coating process. It was concluded that the gauge selection is based on several principles, but mainly it is essential to consider gauge pressure measuring range, its operating principles, sensitivity and accuracy. There are other factors, which also may influence vacuum gauge measurement accuracy and durability, such as contamination, vibration and environment.

Consequently, simple experiment with different vacuum gauges showed that main problem is deviation of measured pressure. Therefore, said deviations must be analysed more carefully to reach the desired results. Even small changes in pressure can significantly influence coating characteristics, which must be secured by producer to match certain quality criteria.

5. FURTHER RESEARCH

During technological process certain parameters correlate, for example voltage, dynamic coating speed and pressure. Reaching better vacuum will result in increase of dynamic coating speed. Therefore, it is essential to understand vacuum gauge behaviour in different environments, test it in different pressure measuring ranges, as well as check its sensitivity and obtain full picture of process and its accuracy, which influence coating process and final product quality. In order to reach stated aims it is necessary to develop an experimental vacuum chamber. The design of chamber in principle is similar to vacuum calibration chamber. The basic design is to have a small chamber in order to get high vacuum, with enough connection spots for vacuum gauges. Said chamber should be provided with two types of pumps: for low vacuum mechanical pump, and for high vacuum a turbo pump. Small chamber with powerful turbo pump and mechanical pump backing it up should provide interesting experiments for vacuum gauge accuracy, sensitivity and stability.

6. REFERENCES

1. H. M. Akram, A. Fasih, Selection of gauges for vacuum measurements of system with diverse ranges, Physics Procedia, **32**, 2012, 32, 503-512 (15.01.2016).
2. http://www.cfi.lu.lv/fileadmin/user_upload/lu_portal/projekti/cfi/Studentiem/laboratorijas_darbi/Vakuumpaarklaajumu_LD_2010.pdf (27.11.2015)
3. https://www.pfeiffer-vacuum.com/en/know-how/introduction-to-vacuum-technology/fundamentals/ (17.01.2016)
4. http://www.mtm-inc.com/av-20110418-measuring-pressure-in-a-vacuum-system.html (18.02.2016)
5. https://www.pfeiffer-vacuum.com/en/know-how/vacuum-measuring-equipment/fundamentals-of-total-pressure-measurement/indirect-gas-dependent-pressure-measurement/ (17.09.2015)
6. http://www.thinksrs.com/downloads/PDFs/ApplicationNotes/IG1BAGapp.pdf (21.10.2015)
7. http://www.thinksrs.com/downloads/PDFs/ApplicationNotes/IG1pg1052app.pdf (19.10.2015)
8. http://www.lesker.com/newweb/gauges/gauges_technicalnotes_1.cfm
9. http://products.inficon.com/GetAttachment.axd?attaName=63947B95-6133-4A34-B0B5-5E23373905CE

10. http://products.inficon.com/GetAttachment.axd?attaName=ABF1271B-9952-4891-9011-0FDCF13D14FF