Experimental Design of a High Vacuum System for PUPR-MC Plasma Machine

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ABSTRACT

In vacuum technology it is customary to divide a large pressure region (as of today, covering 16 orders of magnitude) into single, smaller regions. These divisions are somewhat arbitrary. Thus, the chemists frequently refer to the region between 100 and 1 mbar as an intermediate vacuum, while many technicians refers to the same region as the total pressure (below atmospheric). The pressure regions presented in this work are clearly distinguished from the point of view of the kinetic theory of gases as well as according to the kind of gas flow. Moreover, the practical technology in the different regions is distinguishable. A positive displacement pump is a mechanical vacuum pump, which transports the gas with the aid of pistons, rotors, vanes, valves and other devices, compresses it and expels it. Mechanical pumps are used when attaining a pre-vacuum or rough vacuum region, diffusion pumps (among others) should be used in order to obtain lower levels of vacuum. A suitable gauge must be selected for each vacuum region. Each region of vacuum calls for a different kind of vacuum measurement.

The vacuum system of PUPR-MC plasma machine was not working properly. This work report the design considerations and implementation of changes performed on PUPR-MC in order to attain the levels of vacuum needed for proper operation of this plasma device. After the modifications performed on the vacuum system the pressure in the plasma chamber of the device has been measured in the order of 10^{-5} *to* 10^{-6} *range, the normal range of operation for this machine.*

INTRODUCTION

In vacuum technology it is customary to divide a large pressure region (as of today, covering 16 orders of magnitude) into single, smaller regions. In general, the subdivisions are:

1. Rough Vacuum (RV) 1,000 to 1 mbar
2. Medium Vacuum (MV) 1 to 10^{-3} mbar
3. High Vacuum (HV) 10^{-3} to 10^{-7} mbar
4. Ultra-High Vacuum (UHV) below 10^{-7} mbar

These divisions are somewhat arbitrary. Thus, the chemist frequently refers to the region between 100 and 1 mbar, in which he (she) is chiefly interested, as an intermediate vacuum, and many technicians refer to that same region as the total pressure (below atmospheric). The pressure regions presented above are clearly distinguished from the point of view of the relationship in the kinetic theory of gases, the kind of gas flow, and the practical technology used to achieve them. There are essentially three types of flows present in vacuum.

Viscous flow: a type of fluid movement in which all particles flow in parallel to the axis of a containing pipe or channel with little or no mixing or turbidity.

Molecular flow: dominant in high and ultra-high vacuum. In these regions, the particles can move freely, virtually without mutual hindrance. The criterion is the mean free path of a particle is greater than the diameter of the conducting tube.

Knudsen flow: a transition from viscous flow to molecular flow. It predominates above all the other types of flow in the medium vacuum region.

VACUUM PUMPS

A fundamental distinction can be made between two groups of vacuum pumps:

1. Those that remove the gas particles from the pumped volume and convey them to the atmosphere in one or more stages of compression.
2. Vacuum pumps which condense or in some other manner bind the particles to be removed at a solid wall, which is often a part of the boundary of the volume being pumped.

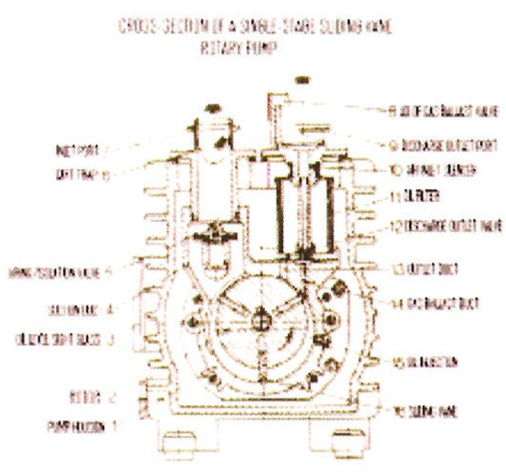


Figure 1: *Cross Section of a Single Stage Sliding Vane Rotary Pump*

A positive displacement pumps is a mechanical vacuum pump which transports the gas with the aid of pistons, rotors, vanes, valves and other devices, compresses it and expels it. There are so called oil-sealed and dry rotary pump.

ROTARY VANE PUMPS

Consist of a cylindrical housing in which rotates, in the direction of the arrow, an eccentrically mounted, slotted rotor. The rotor contains vanes, which are forced apart usually by centrifugal force and in some models by springs. These vanes slide along the stator walls and thereby push forward the air drawn in at the inlet to eject it finally through the oil above the outlet discharge valve.

The oil in the rotary vane pump, and other types of oil-sealed positive displacement pumps, serves as lubrication and sealing medium, fills the dead space and any gaps, and adds to the cooling of the pump by conducting the compression heat.

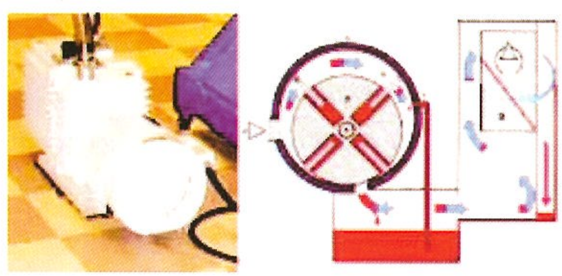


Figure 2: *Vane Mechanical Pumps used in PUPR-MC Plasma Machine*

Two-stage rotary vane pumps, instead of single-stage pumps, produce lower working and ultimate pressures. The reason is that in the single-stage oil sealed pump the oil is bound to come in contact with the outer atmosphere, where it absorbs gas; which in the course of the oil circulation partly escapes into the vacuum side of the pump, and thus limits the obtainable ultimate pressure. In the two-stage oil sealed displacement pumps, already pre-degassed oil arrives at the vacuum stage of the pump. Consequently, the ultimate pressure is already in the high vacuum pressure range, while the lowest working pressure is about at the lower limit of the medium vacuum pressure range.

The oil filling has to fulfill various functions:

1. To lubricate the moving parts.
2. To seal the moving parts against atmospheric pressure.
3. To seal the valve.
4. To fill the dead space under the valves.
5. To seal the workspaces in the pump against each other.

Above all, during long-term operation it must be ensured that the oil filling does not sink below the minimum value. During a pumping process, oil sealed rotary pumps expel oil vapors from their discharge ports because of their high working temperature. This leads to a loss of oil, which is dependent on the amount of pumped gas or vapor.

Diffusion Pumps

Once the mechanical pumps had done the job for the pre-vacuum, (as this stage of operation is called) diffusion pumps are used to obtain high vacuum. These consist basically of a pump body with cooled wall and a three or four stage nozzle system. The oil serving as pump fluid is in the boiler and is vaporized by electrical heating. The pump fluid vapor streams through the chimneys and emerges with supersonic speed from the ring-shaped nozzles. The so formed jet widens thereafter like an umbrella, reaches the wall where condensation of the pump fluid takes place. The liquid condensate flows as a thin film along the wall downwards and returns finally into the boiler.

Due to this spreading of the jet, the vapor density is relatively low. The diffusion of air or any pumped gases (or vapors) into the jet is so fast that the jet in spite of its high velocity becomes almost completely saturated with the pumped medium. Therefore, diffusion pumps have a high pumping speed over a wide pressure range, practically constant over the whole working region of the diffusion pump (10^{-3} mbar). The air at these low pressures cannot influence the jet, so that its course remains undisturbed. At higher inlet pressures, the jet course may be altered, resulting in a pumping speed decrease until, at about 10^{-1} mbar, it becomes immeasurably small.

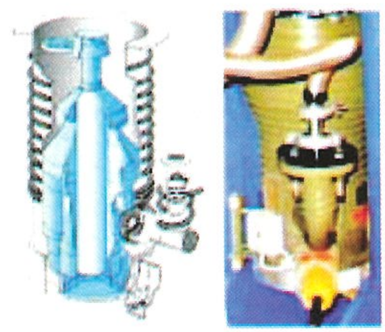


Figure 3: *Diffusion Pumps*

In oil diffusion pumps, it is necessary for the pump fluid to be degassed before it is return to the boiler. On heating of the pump oil, decomposition products can arise in the pump; contamination from the vessel can get into the pump or be contained in the pump in the first place. These constituents of the pump fluid can significantly worsen the ultimate pressure attainable by a diffusion pump, if they are not kept away from the vessel. The pump fluid must therefore be freed from these impurities and from absorbed gasses.

Figure 4: Diffusion Pumps on the Machine

VACUUM GAUGES

A suitable gauge must be selected for each vacuum region. Each region of vacuum calls for a different kind of vacuum measurement. The pressures measured in vacuum cover a range from 10^{13} mbar to 10^{-13} mbar, thus over 16 order of magnitude. Since it is impossible on fundamental physical grounds to build a vacuum gauge that can give quantitative measurements of the whole vacuum region, a series of vacuum gauges are used accordingly with the pressure region to measure. In several cases, the pressure indication depends on the nature of the gas.

IONIZATION VACUUM GAUGES

Ionization vacuum gauges measure, like all electrical vacuum gauges, the pressure in terms of the number density of molecules. In them a portion of the molecules or atoms within the gas space are ionized by electron impact. The ions produced give up their positive charge to a measuring electrode of the system. The resulting ion current is a measure of the pressure. The formation of the ions is a consequence of either a discharge at high electric field strengths (so called cold or self-sustaining discharge) or the impact of electrons, which are emitted from a hot cathode.

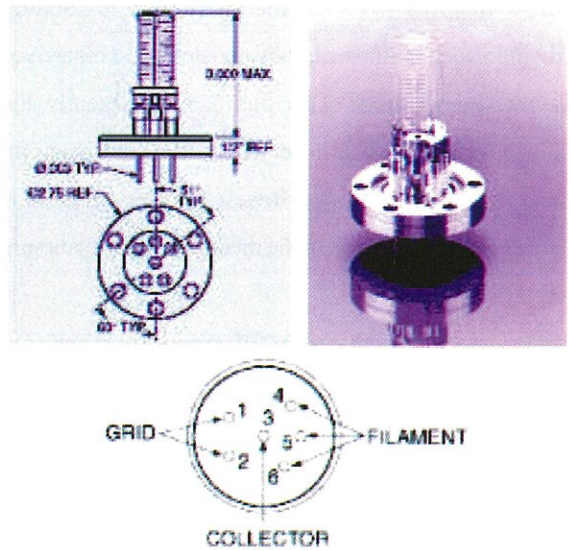


Figure 5: Ionization Vacuum Gauge

Glass ion gauge tubes evolved from triode radio tubes. In early configurations, a filament was in the center with a grid surrounding the filament and a collector surrounding the grid. Electrons were emitted from the hot filament and attracted by a positive electrical potential toward the grid. Electrons collided with gas molecules, forming positive ions. The positive ions were attracted to the collector with an appropriate negative potential. The ion current was proportional to pressure over a large range of pressures.

In order to extend the lifetime of the ion gauge tubes, scientists looked for a material that would provide a non-burnout filament. They discovered that iridium was a good alternative. Iridium could be operated at full temperature in air at atmospheric pressure with no bad effects. However, the iridium filaments had to be operated at very high temperatures in order to emit sufficient electrons for the ionization process. This took too much power and led to overheating of the gauge envelope.

***Figure 6:** Ionization Gauge on the Machine*

Electrons emitted from a hot filament at constant rate are accelerated towards a positively charged electron collector. In the space between the filamentary electron emitter and the ion collector these electrons collide with gas molecules, ionizing them. The positive ions thus formed are collected on the ion collector. The number of gas molecules ionized at a fixed electron flux is proportional to the gas density and, hence, to the gas pressure. We can define proportionality constant S such that:

$$S(sensitivity) = \frac{I_{ioncollector}}{I_{electroncollector} \bullet P}$$

where P=Pressure in Torr.

The sensitivity defined in this manner is independent, over a wide range, of the electron current and dependent only to the gauge geometry and the gas species. Thus, if you know the sensitivity (from the manufacturer's data) and the ion current at a known electron current, the pressure can be computed. Ionization gauges have different relative sensitivities for different gases and, thus, will only give true pressure measurements if the gas composition is known.

The relationship of the decreasing density of molecules and the decreasing pressure (and so increasing mean free path of a gas and its thermal conductivity) is exploited especially for pressure measurement in the medium vacuum region (1 to 10^{-3} mbar). The classical measuring instrument of this kind is the **thermo conductivity vacuum gauges**.

A sensing filament of radius r_1, which carries a current, has heat produced in it which is given off by radiation and thermal transfer to the gas surrounding the filament (also to the supports at the filament ends). In rough vacuum the thermal transfer due to convection is almost independent of the pressure. If however at few mbar, the mean free path of the gas is of the same order of magnitude as the filament diameter, heat transfer through the gas surrounding the filament becomes dependent of pressure. This continues to be so until at still lower pressures of about 10^{-3} mbar the mean free path becomes comparable with the inner diameter of the gauge head. Now heat transfer through the gas by conductance virtually ceases.

The voltage for the THERMOVAC applied to the Wheatstone bridge is regulated so the resistance of the filament remains constant independent of the heat loss. This means that the bridge is always balanced. This mode of regulation has a time constant of a few milliseconds, so the apparatus reacts very quickly to pressure changes. Since the heat transfer from the filament to the gas increases with increasing pressure, the voltage for the THERMOVAC applied to the bridge is thus a measure of pressure. The voltage measurement is corrected by electronic methods such that an approximately logarithmic scale is obtained over the whole measuring range. Whereas the thermal conductivity gauge of variable resistance will only cope with pressures between 10^{-3} and 10 mbar, the thermal conductivity gauges of constant resistance have a large measuring range.

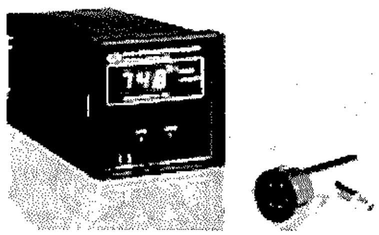


Figure 7: Thermovac

Convectron gauges provide useful pressure measurement over 6 decades from 1 millitorr to 1000 Torr, or from $1x10^{-3}$ mbar to 1000 mbar. This innovation in the art of vacuum measurement is accomplished with a single gauge tube and controller. The gauge tube contains a temperature compensated heat loss sensor, which utilizes conduction cooling to sense pressure at lower pressures. At higher pressures, it utilizes convection cooling in which gas molecules are circulated through the gauge tube by gravitational force. Their wide useful range, highly predictable performance and low prices make convectron gauges an excellent replacement for conventional thermocouple and Pirani gauges. They also are the measurement systems to consider in applications where conventional thermocouple and Pirani gauges have not been suitable because of limited range, or drift, or slow response. Convectron gauges offer the following advantages relative to thermocouple gauges:

1. System performance can be monitored continuously from atmosphere down without pressure blind spots.
2. Purchase of additional controller and gauge tube models is not necessary if your needs change to different segments of the range.
3. A much wider range can be covered with one Convectron gauge than with thermocouple gauges.
4. There is no chance of error that might be caused by using the wrong gauge tube-controller combination. One gauge tube fits all controller models.

VACUUM LEAK DETECTION

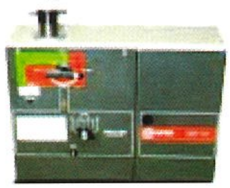
Anything that contains a liquid or a gas can leak – it could be a tire, a bathtub, or even a helium balloon. With these items, a leak would become obvious fairly quickly, as you'd be able to detect these leaks with one or all of your five senses. With some gases and liquids, however, a leak can be much more subtle and hard to detect, and can also have very damaging or even deadly consequences. In this case, one would need to use a leak detector to be alerted to the presence of leaking material. In our machine a leak could be the cause of not having plasma.

Leak Detectors

A leak detector is any device that is designed to detect a leak. Specific leak detectors for specific gasses, liquids and chemicals are used throughout the world of industry, ranging in types from very simple to highly sophisticated. An example of a very simple form of leak detection is the soap bubble method. In this case, a special type of soap solution is applied or brushed onto the area where a leak is suspected. If the pipe does have a leak, the escaping gas or material will cause a soap bubble to form. One drawback of this method is that it can only be performed when a leak is already suspected; more advanced technology is necessary to catch leaks that nobody is yet aware of.

There are leak detectors for identifying leaks in natural gas pipes and systems. Professional workers, who are trained to work with and around natural gas, generally use these. The two main types of detectors they use are combustible gas indicators, and flame ionization (FI) detectors. There are also leak detectors used to locate water leaks, whether in homes or in commercial buildings.

Water leak detectors are designated either passive or active. A passive detector has an audio component, such as a beep, to alert of a leak. An active detector not only sounds an alarm, but can also stop the leak, sometimes with the use of an automatic shut-off valve. Water leak detectors can either be installed on an individual appliance, or used with the plumbing system of the entire building.



Just as there are numerous liquids and gasses used in businesses and homes, there are many kinds of leak detectors to tell when these materials leak. There are also leak detectors for combustible gasses, methane gas, and refrigerant gasses used in air conditioning systems. Leak detection saves lives, saves money, and is frequently good for the environment as well, when used to stop chemical and gas leaks. Helium Leak Testing is typically performed in house using a Varian 936-40 Helium Mass Spectrometer Leak Detector. By using a "Calibrated Leak Standard" the equipment can be tuned to a sensitivity of 1E -11 Torr std. cc/sec. He.

METHODOLOGY

The following procedure was followed in the setup of the vacuum system of PUPR-MC plasma machine.

1. A new diffusion pump was installed.
2. All flanges were dismounted in order to clean the o-rings and surfaces. High vacuum silicon grease was applied in order to achieve better seal.
3. All joints were sprayed with helium and a Varian 936-40 helium leak detector was used in order to detect any leaks in the pre-vacuum stage.
4. Once a leak was detected it was fixed by either doing a re-coil, repositioning the o-rings, tightening the lose screws, and/or changing any valves or flanges. In this case three threads re-coiling were performed.
5. A quadruple mass spectrometer was used to detect leaks in the high vacuum and any leak detected was fixed by applying the same procedure mentioned above. Only a gate valve required to be replaced.

RESULTS

The methodology allowed the pre-vacuum stage pressure to decline from 10^{-2} to 10^{-3} Torr, which matches the optimal operation pressure range of the diffusion pumps. Such an improvement permitted to detect a larger leak that affected the high-pressure stage. The new high vacuum pressure decreased from 10^{-4} to 10^{-7} Torr. A higher vacuum produces *denser plasma*. This high vacuum plasma creates the appropriate conditions for plasma production and new research programs at PUPR-MC plasma machine, among them:

1. Plasma characteristics data acquisition using single, double, and emissive probes.
2. Measurement of plasma parameters and data acquisition systems using Single Langmuir probes, Double Langmuir probes, and Emissive

Probes.

3. Ion Implantation to several materials, such as: Stainless Steel, Copper, Aluminum and others using PUPR-MC plasma machine.
4. Bio-medical material sterilization using PUPR-MC plasma device.
5. Bio-medical material sterilization
6. Ion propulsion studies for spacecraft design.
7. Magnetic confinement studies to fusion research.

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