Accelerator Production of Tritium/Low Energy Demonstration Accelerator/Coupled-Cavity Drift Tube LINAC (APT/LEDA/CCDTL) Low Beta "Hot Model" Vacuum System

Installed at the Los Alamos National Laboratory

Federal Manufacturing & Technologies

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Contents

Section

Abstract

Summary

Discussion

Scope and Purpose

Activity

Design Preparations

Gas Load

Surface Area

Conductances

Outgassing

Permeation

Leaks

Total Estimated Gas Load

Pumping Speed

Design

Pumps

Gauging

Connectors

Valves

Plumbing

System Construction

Equipment Cabinet

Installation

Specifics

Operation

Pumping Speed

Outgassing

Vacuum Levels

RGA Indications

Accomplishments

Future Work

References

Appendices

A. Preliminary Conductance Calculations

B. Preliminary Gas Load Estimates

C. Equations

Illustrations

Figure

1 Side View of Hot Model Without Cooling System or Roughing System Depicted

2 Typical RGA Spectrum Without RF Applied

3 Hot Model With Vacuum System Attached

4 Turbo Pump and Ion Pump Underneath the Hot Model

5 Hot Model Gas Load Block Diagram With Original Proposed Manifold

Abstract

The vacuum system for the APT/LEDA/CCDTL (Accelerator Production of Tritium/Low Energy Demonstration Accelerator/ Coupled-Cavity Drift Tube LINAC) Low Beta "Hot Model" (LBHM) has been installed and is currently operating at Los Alamos National Laboratory (LANL). The Hot Model has been built to test a new concept in accelerator technology. The vacuum system was designed and partially assembled at the Kansas City Plant prior to being shipped to LANL where final assembly and installation on the APT/LEDA/CCDTL/LBHM occurred. The system was designed for both flexibility and low cost. Simple outgassing and conduction models were used to predict pumping needs. This design contains almost no custom parts, which allows for quick and inexpensive changes as needed. The system consists of three pumping stages: roughing, turbomolecular, and ion, and utilizes all four of the available ports on the Hot Model. This has allowed the system to reach a better level of vacuum than the originally anticipated need.

Summary

AlliedSignal Federal Manufacturing & Technologies (ASFM&T) was engaged to design and install a complete vacuum system for the Hot Model. This design included gas load calculations, ultimate pressure estimates, and controls. In addition, consideration was given to acquiring data on the operation of the system.

The initial design was completed at ASFM&T Kansas City in conjunction with the Los Alamos National Laboratory (LANL) personnel responsible for the project. This design was subjected to preliminary and final design reviews at LANL and incorporated additional requirements as needed.

The vacuum equipment was inspected and the controls mounted into a cabinet at ASFM&T Kansas City. These were then shipped via commercial carrier to LANL where they were assembled and mounted to the Hot Model. The equipment was then proved-in and tested. The Hot Model had RF applied to in June 1999.

Discussion

Scope and Purpose

This report details the design and installation of the Accelerator Production of Tritium/Low Energy Demonstration Accelerator/ Coupled-Cavity Drift Tube LINAC (APT/LEDA/CCDTL) Low Beta "Hot Model" Vacuum System. The system has been installed at Los Alamos National Laboratory (LANL).

Throughout this report the assumption will be made that the reader is either familiar with the APT/LEDA/CCDTL program or that such information is irrelevant for the purposes of this report. Any details of the program essential for a thorough understanding of

the vacuum system will be included here.

Activity

Design Preparations

Gas Load

In preparation of designing a vacuum system, a gas load analysis was performed. This analysis included estimates of surface area, conductances, outgassing rates, and leaks.

Surface Area

The estimate for the total surface area of the interior surfaces of the Hot Model was performed from drawings provided by Los Alamos National Laboratory (LANL). The complex surfaces were converted to simplified common geometrical shapes in order to facilitate the ease of the estimate calculations. While these simplifications probably did interject some error, it was felt that this discrepancy would be small. In addition, an attempt was made to make certain that all errors introduced by these surface model changes would be such as to overestimate the total gas load and thus lead to a more robust vacuum system capable of handling the actual gas load.

The total surface area calculated from these models yielded an estimate of 2876 square inches which was rounded up to 3000 square inches for the next level of calculations.

Conductances

The gas conductance calculations of the various sections of the Hot Model were performed in a manner similar to those used for the surface area. That is, the various openings and tubes were estimated to be of simple geometrical shapes such as circular and rectangular tubes of either long or short lengths. These shapes were then modeled utilizing standard conductance equations from A. A. Van Turnhout's comprehensive book, *Vacuum Technology*. (See Appendix A.)

Outgassing

Since the Hot Model is made of OFHC (oxygen free high conductivity) copper, a well-known material, it was decided to use the standard commercial numbers given for its outgassing. These somewhat optimistic numbers indicated, that unbaked, the outgassing rates were:

Initial vacuum 10^{-8} to 10^{-10} Torr-liters/sec-cm²

4 hours vacuum 10^{-10}

40 hours vacuum 10^{-11}

These numbers indicated an approximate gas load of 2×10^{-6} Torr-liters/sec after about four hours of pumping, assuming proper handling of the material after brazing. These numbers were deemed reasonable since there appeared little probability that the system would see RF with only four hours of pumping time. Events eventually dictated that there would be hundreds of hours of pumping time before the system saw RF.

Permeation

Since the original specifications for the system were on the order of 10^{-6} Torr, it was decided that gaseous permeation of the Hot Model would contribute an insignificant amount to the gas load and so was ignored. In retrospect, it might have been informative

to add an estimate of the total permeation of the system to the gas load analysis.

Leaks

Since all vacuum systems leak, it was deemed prudent to incorporate a figure into the total gas load for this. This estimate was calculated by taking the length of the various brazes and connections and then multiplying them by a leak rate. The rate of 10^{-9} Torr-liters/sec was chosen as a good representation of leak rates for these seals utilizing these joining techniques. This yielded a total leak rate of approximately 1.5×10^{-6} Torr-liter/sec. While this number is admittedly somewhat speculative, it was felt that it erred on the side of indicating a larger gas load than that which would actually be experienced by the vacuum pumps.

Total Estimated Gas Load

The combined gas load was determined by simply adding the estimated leak rate and the estimated outgassing rate. These numbers provided a total estimate of 3.5×10^{-6} Torr-liters/sec for the Hot Model. It should be emphasized here that this total is for the Hot Model only and does not include the gas load produced by the vacuum system and the associated additional plumbing. Also, at the time the estimates were performed the RF window specifications were not known and so were omitted from these calculations.

Pumping Speed

From the calculations of gas load and conductance it is possible to estimate a minimum pumping speed (see Appendix B). The originally anticipated vacuum system was envisioned as utilizing a pumping manifold such as that found in many modern accelerator vacuum systems. With this in mind, the estimate assumed a custom stainless steel system with large conductances and minimal outgassing and leakage. The system was also assumed to use only the bottom two ports available on the Hot Model. With these restrictions and the stated goal of a 10^{-6} Torr vacuum inside the Hot Model, a minimum pumping speed of 9 liters/sec was calculated. This number was arrived at by modeling the projected gas loads of the various sections and their respective conductances. To account for leakage the estimated leak rate was rather arbitrarily divided up into even parts and then added to the outgassing rates. This yielded a set of simultaneous equations which were then solved (see Appendix C) utilizing MathCad®, a commonly used mathematics program from MathSoft, Inc. The assumption was also made that the pressure could not be allowed to exceed 1×10^{-6} Torr anywhere in the interior parts of the Hot Model. This limiting requirement dictated that many sections of the system would necessarily be in the low 10^{-7} Torr range.

Design

The actual design of the vacuum system began after the initial calculations were concluded. The very low conductances of the installed ports on the Hot Model were the cause of great concern in the ability of the system to reach good vacuum levels in a reasonable amount of time. Another major consideration in the design was to incorporate great flexibility in the system since the Hot Model is an experimental setup and, as such, subject to many design changes. Among the other major factors was the time required to obtain necessary parts and equipment and, of course, the total cost of the system. With this in mind it was decided to try an innovative approach to the total system design in order to maximize pumping efficiency while minimizing cost. Crucial to the minimization of cost was the elimination of the use of as many custom-made parts as possible. It was felt that custom-made manifolds are inherently more expensive and less flexible.

Pumps

The decision was made early to utilize a combination of high vacuum pumps to achieve needed pressure levels. Ion pumps were chosen because of their proven abilities and long history in accelerator systems. Turbomolecular pumps were chosen for their excellent pump-down characteristics and as a complementary match for the ion pumps. Since a clean system was desired, a dry scroll pump was chosen for both the backing of the turbomolecular pumps and for roughing the system out.

Gauging

Hot cathode Bayard-Alpert ion gauges were chosen to provide measurement for the high vacuum range and thermocouple gauges

for the low vacuum range. Eventually four ion gauges and two thermocouple gauges were installed.

Connectors

Knife-edge type seals of the Conflat® seal type manufactured by Varian were decided upon for use throughout the high vacuum section. This style of connector is considered an industry standard for high vacuum applications and as such is easily available. KF (Klein Flange) type couplings, another industry standard, were decided upon for the roughing portion of the system for their good seal and ease of change properties.

Valves

Manually operated valves were chosen throughout the design in order to reduce the overall complexity of the system. It was felt that the added wiring and/or pneumatics would become a problem amidst the very extensive cooling system plumbing and wiring. Gate valves were chosen to control the turbomolecular pumps with right angle and in-line block valves for the rest of the system.

Hindsight has shown that while the use of manual valves saved expense in purchase and installation cost, there were several drawbacks to this decision. The manual valves became increasingly difficult to reach as the various parts of the plumbing and temperature measurement system were installed. In some cases it now requires a person with good flexibility and reach in order to adjust the valves. The lack of automatic gate valves on the turbomolecular pumps means that in the case of a catastrophic power failure the entire system could be exposed to atmosphere. This has necessitated some modifications in operating procedures. A third, but less important, limitation imposed by this choice is the difficulty in testing various vacuum pump effects. One benefit from utilizing the manual gate valves is the ability to slowly bring the turbomolecular pumps on-line with the ion pumps already operating at high vacuum. This helps to limit gas surges in the system resulting from the equalization of pressures initiated by this pumping configuration change.

Plumbing

With the decision to avoid the use of custom parts it became paramount to choose plumbing configurations with great flexibility. It was also decided to locate both the ion and turbomolecular pumps into as close a proximity to the Hot Model as practical. This close configuration has several advantages, among which are an increased pumping speed, decreased surface area, and fewer parts. The decrease in surface area is important because it lessens the total gas load faced by the pumps through the resultant decrease in outgassing. A solution in keeping with these parameters would be the use of four-way crosses on all four available ports on the Hot Model. Most of the high vacuum parts of the system could then mount directly onto these crosses. This design would thus lessen the total surface area and internal volume. This design also would allow the use of smaller vacuum pumps and fewer high vacuum components while shortening pump-down times.

It must be pointed out that had we decided to use a custom manifold, then many connectors would have been replaced with welds and subsequently probably would have lowered the chance for leaks. The main reason for not utilizing a welded manifold is that it is inherently less flexible and therefore very restrictive to future change.

The plumbing for the roughing system was allowed a great amount of leeway in lengths and construction as it was believed to have relatively little impact on ultimate vacuum levels or gas handling capabilities at high vacuum. Flexible tubes were used in conjunction with extenders and elbows to allow the greatest freedom of placement for the scroll pump. This design allowed for rapid and easy changes in design both of the high vacuum system and the roughing line.

Consideration was given to future needs of the system in the early design stages. A port was added in anticipation of the inclusion of a Residual Gas Analyzer (RGA) in addition to the vacuum pumps and gauges on the high vacuum side of the system. Also, on the high vacuum side, a provision for backfilling the entire Hot Model with a dry gas and an extra port for additional unknown needs were included. Extra ports were also included in the roughing lines for leak testing and possible reconfigurations.

System Construction

The first phase of system construction included the receiving and inspection of the various vacuum parts and their associated electronics. This took place at AlliedSignal FM&T (ASFM&T). The installation of the controllers and power supplies into an equipment cabinet also took place at AlliedSignal FM&T in the Test Equipment department. The cabinet and the parts were then packaged and shipped to Los Alamos National Laboratory where they were connected to the Hot Model.

Equipment Cabinet

The equipment controls were placed in an equipment cabinet salvaged by AlliedSignal FM&T's Test Equipment. The custom power supplies and safety interlocks were also salvaged from equipment destined for scrap. This salvage effort provided a large cost savings to the project while providing a high level of safety and reliability.

The equipment placed in the racks included the five ion pump controllers (one for the RF window), two turbomolecular pump controllers, one gauge controller, power switches for the scroll pump, and extra electrical outlets. Two 30-amp power supplies and cooling fans were also installed in the cabinet. Extra emphasis was placed on the cooling fans due to the unknown strength of the deleterious effects of the lower air pressure resulting from the high altitude of the final installation site.

Installation

Installation of the vacuum system on the Hot Model began as soon as the Hot Model was available in October 1998. Approximately two-thirds of the way through installation it was learned that the vacuum system would need to perform two orders of magnitude better than the original specifications called out. There was also an expressed need for a quick switching circuit from the RF window to control the input of RF to the system. This interlock was to protect the RF window from overheating due to reflected power. This switch would need to be designed to operate quickly off the analog output of a new high accuracy ion gauge. It was decided that a comparator circuit would be utilized for the interlock and that the new ion gauge controller would be installed in the equipment cabinet.

With these new requirements the importance of the earlier decision to use off-the-shelf parts became apparent. The system was able to adapt quite easily to these changes and also to routing problems of the plumbing system around the cooling system being installed concurrently.

To facilitate further testing of the vacuum system and to collect data it was decided to add two more ion gauges directly to the Hot Model for a total of four ion gauges reading high vacuum pressure.

Installation of the main parts of the vacuum system was completed in November 1998. The addition of the comparator circuit and the additional ion gauges occurred as the parts became available and schedules permitted. A residual gas analyzer (RGA) was also eventually added to one of the four-way crosses.

Specifics

The Hot Model ended up with five Varian VacIon Plus nominal 25 liter/second ion pumps connected. Four of them were mounted as depicted in Figure 1. The fifth ion pump was connected to the RF window on the other side of the Hot Model from that shown in the figure. The two turbomolecular pumps are both Varian V70LP nominal 70 liter/second pumps and are also located as shown. A Varian 300DS nominal 300 liter/second scroll pump was chosen to do both the backing and roughing chores. This dual use of the scroll pump was chosen for both economy and space considerations.

Figure 1. Side View of Hot Model Without Cooling System or Roughing System Depicted

All the pumps utilized are "dry" pumps in that they do not use oil in areas which will be exposed to the vacuum. This was an important consideration in the selection of the pumps. Oil-filled pumps could have potentially contaminated the system, which might have been disastrous for the system when RF was applied. The turbomolecular pumps are of the ceramic bearing type which have the bearing lubricant integral to the bearing. While there is always some material being worn away, and therefore into the pump, it was felt that in this case the amount was negligible. Ion pumps are inherently dry and as such required no special consideration. The scroll pump is a carbon type and will therefore produce some particles of carbon but, like the turbomolecular pump, it was believed not to be an important issue in such small quantities.

The valves utilized on the high vacuum side all contain viton main seals, as do the roughing line valves. Due to the small openings and expected poor conductance, gate valves were used on the turbomolecular pumps. No valves were placed on the ion pumps in

an effort to keep costs down and improve conductance. This decision was made based on the belief that the ion pumps would not be exposed to a deleterious environment.

Granville-Phillips ion gauge tubes were placed on cavity 24 and cavity 25 by Lawrence Livermore National Laboratory personnel in order to measure the vacuum levels at those points in conjunction with tests to be performed. A Granville-Phillips ion gauge was placed on the RF window in order to monitor the pressure there and to provide a signal which could be monitored and used to shut down the RF source if the pressure were to rise too high. This pressure trip point was used in the early conditioning of the Hot Model and worked well. In order to provide quick response times it was decided to use the analog output of the controller and thus avoid the relatively slow internal digital process inherent in the ion gauge controller. This signal was input into a custom comparator circuit, designed and built at ASFM&T Test Equipment, which in turn provided a signal for the RF generating equipment. These three ion gauge tubes were controlled by Granville-Phillips Stabil-Ion 360 and 370 controllers. The last ion gauge was a Varian gauge tube, which was placed on a drift tube and was used as an indicator of the general condition of the vacuum. This gauge tube was connected to a Varian senTorr controller.

The Varian thermocouple style gauges were placed on a drift tube and on the roughing line. The drift tube gauge is the roughing out indicator for the Hot Model and also controls the drift tube ion gauge. Once the ion gauge is triggered by the thermocouple gauge, then it can be determined whether or not to energize the remaining ion gauges. The roughing line gauge is for determining whether or not a suitable vacuum condition exists on the exhaust ports of the turbomolecular pumps.

Operation

Pumping Speed

A study was performed on the Hot Model in the pre-RF condition in order to get an estimate of pumping speeds and outgassing rates. This study concluded that the pumping speed was approximately 60 liters/second, both with and without the RF window connected. These measurements were performed at approximately 1×10^{-5} Torr and without utilizing the additional pumping speed afforded by the turbomolecular pumps.

Outgassing

The same study mentioned above concluded with some trepidation and caveats that the outgassing rate of the Hot Model, with the vacuum system in place, was in the neighborhood of 2×10^{-9} Torr-liters/second/cm². This was after the system had been under vacuum less than

18 hours and, as was pointed out in the study, the system was not always handled consistently with standard high vacuum techniques. As of this writing the conditioning is still going on and it is expected that the outgassing rate will drop significantly. It is also expected that a post-conditioning study of the outgassing rate will be performed.

Vacuum Levels

As expected for a system with small conductances, the pump-down times are relatively long. It was found that flushing the system with bursts of dry nitrogen helped lower the pump-down times but this was not quantitatively measured. Since a rapid pump-down was not a requirement for the system, the actual pump-down curves were not computed. The ultimate vacuum level the system is capable of reaching is not yet known. In its pre-RF conditioned state the system was consistently in the low 10^{-8} range and had even made some forays into the 10^{-9} Torr region while the Hot Model's temperature was lowered by the cooling system. Again, it is expected that these pressures will be lower after the conclusion of the conditioning phase.

There was a slight gradient indicated by the vacuum gauges in the steady state but this could easily have been due to variances in the measurement equipment or just due to noise. During conditioning a very large gradient developed with the RF window rising

to a high pressure and the cavities lagging behind. The cavities did not see the high peaks which the RF window experienced. This flattening of peaks would be expected as a direct consequence of the RF window having its own ion pump attached. For additional pumping speed and in an effort to keep pressures low, the turbomolecular pumps were run during the conditioning exercises. While there is no quantifiable data, it is assumed that the additional pumping speed provided by these pumps helps to bring the cavities back to high vacuum levels quickly.

RGA Indications

The residual gas analyzer (RGA) installed on the system was an Inficon Transpector. After several days of pumping, a spectrum such as one would expect to see in an unbaked vacuum system began to appear. The highest peak was that of hydrogen, with water and the nitrogen/carbon monoxide mix following behind. Both the oxygen and the argon peaks were greatly attenuated with respect to the hydrogen, water, and nitrogen/carbon monoxide peaks, indicating a well-sealed system with a small external leak rate and small virtual leaks.

With the application of RF the vacuum system experienced large spikes of most gases, but the ratios of the gas mixture stayed relatively unchanged with one striking exception. While the water peak did increase even in relation to the other gases, it was the carbon dioxide peak which experienced the largest percentage increase, moving from close to the noise levels to being the fourth largest constituent of the internal atmosphere.

Figure 2. Typical RGA Spectrum Without RF Applied

Accomplishments

The Hot Model vacuum system has proved itself to be of a very successful design. It easily achieved the initial pressure requirements and with minor modifications met the additional two orders of magnitude improvement necessitated by the experiment. This level of vacuum was provided at relatively low equipment cost and with a great deal of design flexibility. Future test chamber designs would probably do well to build on the knowledge acquired here.

Future Work

Further testing is required to learn the complete extent of the vacuum system's possibilities. One suggested test would be to close off different ion pumps and subsequently determine the internal gradients produced by the system. Another informative test would be to quantify the difference in the pumping speed between just the use of the ion pumps and the ion pumps in tandem with the turbomolecular pumps. A third useful test would be the pump-down curve for the system. As mentioned earlier in this report there are also some tests already expected to take place after RF conditioning has concluded.

Figure 3. Hot Model With Vacuum System Attached. (Note the vacuum controls in the cabinet to the right.)

Figure 4. Turbo Pump and Ion Pump Underneath the Hot Model

Hot Model Gas Load Block Diagram with
original proposed manifold

Figure 5. Hot Model Gas Load Block Diagram With Original Proposed Manifold

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2 Kishiyama, K., et al, Test Report: Accelerator Production of Tritium/Low Energy Demonstration Accelerator CCDTL Phase 3A Low-Beta Hot Model Pump Speed Tests, 1/19/99

Appendix A

Preliminary Conductance Calculations

Appendix A

Preliminary Conductance Calculations

C1 Long circular tube

$$d = 2 \text{ cm}$$

$$l = 15.2 \text{ cm}$$

$$C1 = 12.1 \text{ d}^3/l = 6.4 \text{ l/s}$$

C2 Long rectangular tube

$$A = \pi /3 (d/2)^2$$

$$d = 3.6$$

$$A = 22 \text{ cm}^2$$

$$a = 9.1 \text{ cm}$$

$$b = a/A = 2.4 = 9.1 \text{ l}$$

$$C2 = [(30.9)(a^2)(b^2)k]/[(a+b)/l] = 155 \text{ l/s}$$

$$C3 \text{ } C3 = C2 = 155 \text{ l/s}$$

C4 Slot

$$A = 15.2 \text{ cm}^2$$

$$a = 7.6$$

$$b = 2$$

$$l = 7.4$$

$$C4 = 30.9*[ab^2/lk] = 106 \text{ l/s}$$

$$C5 \text{ } C5 = C4 = 106 \text{ l/s}$$

C6 Long circular tube

$$d = 2.3$$

$$l = 6.9$$

$$C6 = 21 \text{ l/s}$$

C7 Slot

$$A = 22 \text{ cm}^2$$

$$a = 9.1$$

$$b = 2.4$$

$$l = 7.6$$

$$k = 1.2$$

$$C7 = 148 \text{ l/s}$$

C8 Long tube

$$d = 2$$

$$l = 17.8$$

$$C8 = 5.4 \text{ l/s}$$

$$C9 \ C9 = C7 = 148 \text{ l/s}$$

$$C10 \ C10 = C7 = 148 \text{ l/s}$$

C11 Long tube

$$d = 2$$

$$l = 11$$

$$C11 = 8.8 \text{ l/s}$$

$$C12 \ C12 = C10 = 148 \text{ l/s}$$

C13 Two short tubes

1st tube

$$l1 = 2 \text{ cm}$$

$$d1 = 3.3 \text{ cm}$$

2nd tube

$$l2 = 8.1 \text{ cm}$$

$$d2 = 5.1 \text{ cm}$$

$$C1^{\text{st}} = [12.1 * d^3] / [l + 1.33 * d] = 68 \text{ l/s}$$

$$C2^{\text{nd}} = 108 \text{ l/s}$$

$$1/C13 = 1/C1^{\text{st}} + 1/C2^{\text{nd}}$$

$$C13 = 42 \text{ l/s}$$

Assume 2" stainless steel pipe for manifold

$$C14 \ d = 5.1 \text{ cm}$$

$$l = 38 \text{ cm}$$

$$C14 = 42.2 \text{ l/s}$$

C15 Short tube

$$d = 5.1 \text{ cm}$$

$$l = 10.2 \text{ cm}$$

$$C15 = 94.5 \text{ l/s}$$

Appendix B

Preliminary Gas Load Estimates

Appendix B

Preliminary Gas Load Estimates

$$Q1 = Q_{\text{endwall23}} + 1/2 Q_{\text{ccav23}} + Q_{\text{ring23}} + 1/9 Q_{\text{leak}}$$

$$Q2 = Q_{\text{cap23}} + 1/9 Q_{\text{leak}}$$

$$Q3 = 1/2 Q_{\text{ccav23}} + 1/2 Q_{\text{ccav24}} + Q_{\text{ring24}} + 1/9 Q_{\text{leak}}$$

$$Q4 = Q_{\text{cap24}} + 1/9 Q_{\text{leak}}$$

$$Q5 = 1/2 Q_{\text{ccav24}} + 1/2 Q_{\text{ccav25}} + Q_{\text{ring25}} + 1/9 Q_{\text{leak}}$$

$$Q6 = Q_{\text{cap25}} + 1/9 Q_{\text{leak}}$$

$$Q7 = 1/2 Q_{\text{ccav25}} + 1/2 Q_{\text{ccav26}} + Q_{\text{iris}} + 1/9 Q_{\text{leak}}$$

$$Q_8 = Q_{cap26} + 1/9 Q_{leak}$$

$$Q_9 = 1/2 Q_{ccav26} + Q_{endwall27} + 1/9 Q_{leak}$$

$$1/9 Q_{leak} = 1.7 * 10^{-7}$$

$$Q_1 = 4.3 * 10^{-7}$$

$$Q_2 = 2.3 * 10^{-7}$$

$$Q_3 = 4.6 * 10^{-7}$$

$$Q_4 = 2.2 * 10^{-7}$$

$$Q_5 = 5.2 * 10^{-7}$$

$$Q_6 = 2.3 * 10^{-7}$$

$$Q_7 = 6.3 * 10^{-7}$$

$$Q_8 = 2.3 * 10^{-7}$$

$$Q_9 = 4.5 * 10^{-7}$$

Appendix C

Equations

Appendix C

Equations

1. $P_4 - P_3 = Q\alpha / C_4$
2. $P_4 - P_5 = Q\beta / C_5$
3. $P_3 - P_1 = Q\gamma / C_1$
4. $P_3 - P_2 = Q\delta / C_3$
5. $P_5 - P_3 = Q\epsilon / C_6$
6. $P_2 - P_P = Q\mu (1/C_{13} + 1/C_{14} + 1/C_{15})$
7. $P_8 - P_7 = Q\eta / C_{10}$
8. $P_8 - P_9 = Q\theta / C_{12}$
9. $P_7 - P_5 = Q\kappa / C_8$
10. $P_5 - P_6 = Q\lambda / C_7$
11. $P_9 - P_7 = Q\nu / C_{11}$
12. $P_7 - P_6 = Q\xi / C_9$
13. $P_6 - P_P = Q\sigma (1/C_{13} + 1/C_{14} + 1/C_{15})$
14. $P_1 - P_2 = Q\tau / C_2$
15. $Q\alpha + Q\beta = Q_4$
16. $Q\gamma + Q\delta = Q_3 + Q\alpha + Q\epsilon$
17. $Q_8 = Q\eta + Q\theta$
18. $Q\lambda + Q\epsilon = Q\kappa + Q\beta + Q_5$
19. $Q\nu = Q\theta + Q_9$
20. $Q\eta + Q\nu + Q_7 = Q\kappa + Q\xi$
21. $Q\sigma = Q\lambda + Q\xi + Q_6$
22. $Q\mu = Q\tau + Q\delta + Q_2$
23. $Q\tau = Q\gamma + Q_1$

Solutions

Assuming that P_8 is the highest pressure and that $P_8 = 5 * 10^{-7}$ we have:

$$P_1 = 4.807 * 10^{-7}$$

$$P_2 = 4.778 * 10^{-7}$$

$$P_3 = 4.838 * 10^{-7}$$

$$P_4 = 4.875 * 10^{-7}$$

$$P_5 = 4.891 * 10^{-7}$$

$$P_6 = 4.872 * 10^{-7}$$

$$P_7 = 4.958 * 10^{-7}$$

$$P_P = 3.837 * 10^{-7}$$

$$Q_\alpha = 3.885 * 10^{-7}$$

$$Q_\beta = 1.685 * 10^{-7}$$

$$Q_\gamma = 2.017 * 10^{-7}$$

$$Q_\delta = 9.387 * 10^{-7}$$

$$Q_\epsilon = 1.103 * 10^{-7}$$

$$Q_\eta = 6.2 * 10^{-7}$$

$$Q_\theta = 3.9 * 10^{-7}$$

$$Q_\lambda = 2.775 * 10^{-7}$$

$$Q_\nu = 6.005 * 10^{-7}$$

$$Q_\kappa = 3.635 * 10^{-7}$$

$$Q_\xi = 1.274 * 10^{-7}$$

$$Q_\tau = 4.502 * 10^{-7}$$

$$Q_\mu = 1.619 * 10^{-7}$$

$$Q_\sigma = 1.781 * 10^{-7}$$

Pressure at Pump

$$Q_{\text{tot}} = Q_{\text{1/4}} + Q_{\text{A}}$$

$$Q_{\text{tot}} = 3.4 * 10^{-6} \text{ torr*liters/sec (pretty good agreement with initial estimate)}$$

Pumping Speed

$$S = \text{pump speed}$$

$S = Q/P = 8.9$ which is approximately 9 liters/sec