“Innovative Vacuum Pumps to Support Mass Spectrometry in Harsh Environments”

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Need for Customized Vacuum Pumps

While great strides have been made in the miniaturization and ruggedization of mass spectrometers intended for portable use and for use in harsh environments, considerably less attention has been devoted to their vacuum systems. These systems are often built from off-the-shelf commercial pumps not designed for such applications. For this reason, the vacuum pumps may severely limit the overall capabilities of the instruments they support. Specifically, in many applications commercially available pumps are too massive, too large, require excessive electric power for battery use, or are intolerant of vibration and shock. Under NASA/JPL and KSC funding, Creare is developing three innovative vacuum pumps specifically to address these shortcomings.

The Technical Challenges

Creare’s efforts have focussed on developing turbomolecular pumps (TMP), molecular drag pumps (MDP), and hybrid pumps containing both types (TMP/MDP). These types of pumps deliver clean vacuum at relatively high pumping speeds for all gas species, including noble gasses. For reasonable performance, TMPs must achieve rotor tip speeds that are a reasonably large fraction of the molecular velocity of the gasses being pumped; for a small diameter pump, this can require a very high rotational speed. Also, both types require that the clearances between the rotating and stationary parts of the pumps be small compared to the area through which the gas is intended to flow. For a small pump, this necessitates tight controls on machining and rotor motion during operation. Thus, building either miniaturized pumps or pumps tolerant of high external vibration levels presents significant challenges. Innovative approaches have been developed to meet these challenges.

An Ultra-Miniaturized Hybrid Turbomolecular/Molecular Drag Pump

Figure 1 shows a photograph of a prototype, ultra-miniaturized TMP/MDP. To provide good performance in a small envelope (3.4 cm diameter x 8 cm long), the pump motor spins at 200,000 rpm. The total pump mass is 130 grams. This pump has a measured ultimate pressure near 10^{-8} Torr and supports foreline pressures in excess of 10 Torr. The relatively high foreline pressure allows the pump to be used in a standalone fashion on the Martian surface and also in terrestrial applications employing small, commercially-available diaphragm rough pumps. The pumping speed for air is 4 L/s. The motor employs permanently greased, hybrid ceramic ball bearings originally developed for dental drills. The design bearing life is several months, and experiments to characterize the actual lifetime are currently underway.

A complementary prototype pump controller has also been developed, Figure 2, for use with this pump and, in slightly modified form, with the ruggedized pumps described below. This controller provides closed loop control and monitoring of pump operation under the direction of external commands received via a RS-232 port. This provides easy interfacing to the overall system controller for applications where a mass spectrometer is functioning autonomously in a remote location.

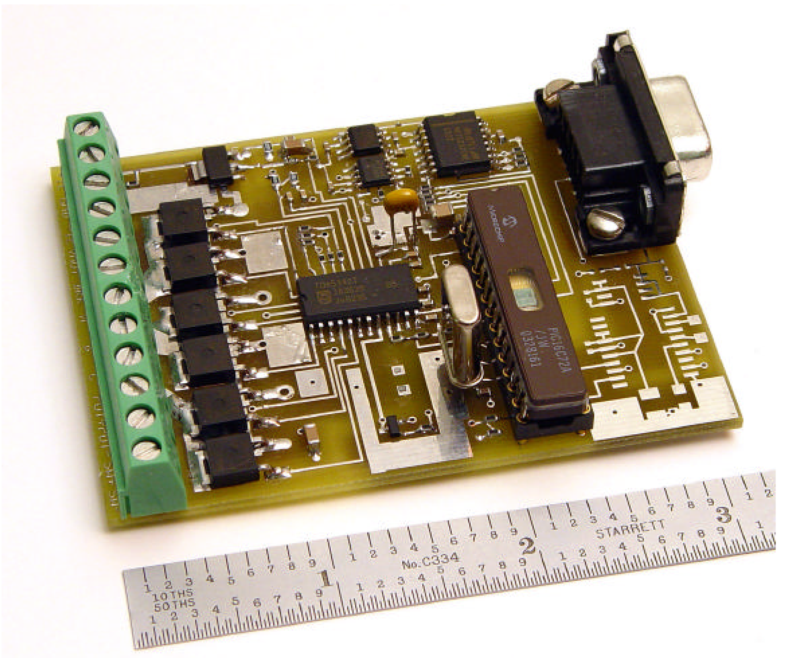


Figure 1: Prototype ultra-miniaturized TMP/MDP Figure 2: Pump controller for both series of pumps

The single most difficult design goal for this pump was low power consumption. This is essential for many remote operations with limited electrical resources. No commercial motor was available that provided the required rotational speeds with adequate bearing life and reasonable power consumption, so an extensive motor development program was conducted. The motor development effort consisted of a number of finite element electromagnetic analyses coupled with the construction and testing of a series of prototype motors. The eventual design achieved a nine-fold reduction in power loss compared to the only available off-the-shelf motor by minimizing eddy current heating in the motor shell, core losses in the stator substrate, ohmic losses in the coils, and bearing drag. In parallel, an extensive program of analytical model development and bench-scale testing was used to design the molecular drag stage to provide optimal pumping capability while minimizing viscous drag.

The effectiveness of these efforts can be judged by the measured power consumption of the complete pump, which is less than 2 Watts at low foreline pressures (below 1 Torr) and only 7 Watts at a discharge pressure of 10 Torr. At high foreline pressures the bulk of the power consumption is caused by viscous drag in the MDP section.

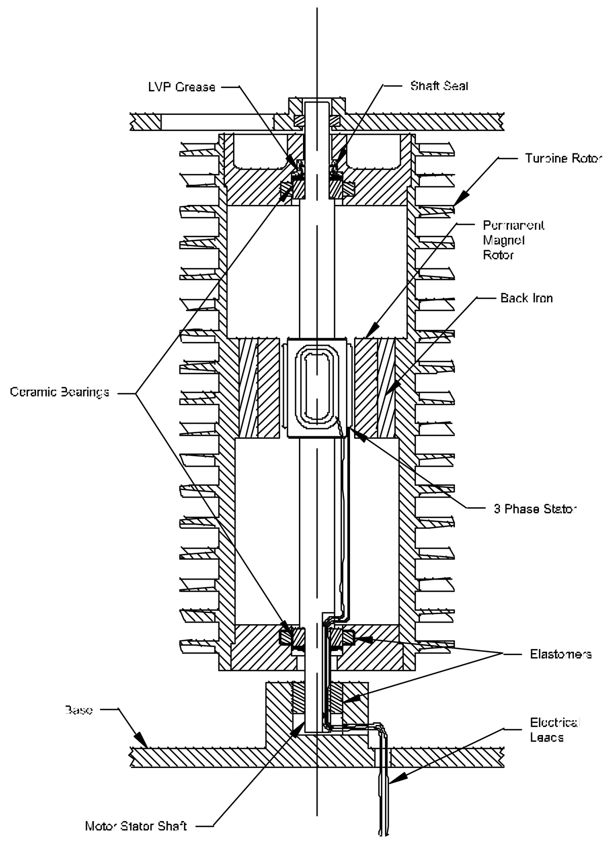
A Highly Ruggedized Vacuum System

The other two vacuum pumps currently under development at Creare are intended for a quite different use, a hazardous gas leak detection system for Space Shuttle launches. The current system in use at KSC utilizes commercial vacuum pumps that must be remotely situated because of high vibration levels around the launch pad. This results in the use of long sample lines which adversely slows response times.

To address this problem, Creare is developing a pair of highly ruggedized pumps based on an innovative “inside-out” electric motor. In this motor, the shaft is stationary while the outside “case” of the motor turns. As shown in Figure 3, the inside-out motor allows both the top and bottom of the pump rotor to be secured by bearings. Compared to the cantilevered rotor design normally employed by TMPs, this greatly reduces the side-to-side motion of the pump rotor that occurs in response to external vibration. An early prototype of this motor has withstood the standard vibration spectrum used to qualify equipment to fly on the Shuttle.

While the “inside-out” motor possesses great advantages in ruggedness, it too presents significant design challenges. One key design objective is achieving high motor efficiency while minimizing the mass and moment of inertia of the magnet and other rotating parts. Achieving high efficiency is important in this case, not because of limitations on available electrical power, but because of the difficulty of removing heat from the motor stator under vacuum conditions. Another design issue is sealing the pump to prevent axial leakage through the bearings.

The inside-out motor is intended for use in two pumps, a pure TMP and a companion MDP, in the vacuum system shown schematically in Figure 4. Optimization of the motor design is on-going, and completion of the project is scheduled for September, 2004.



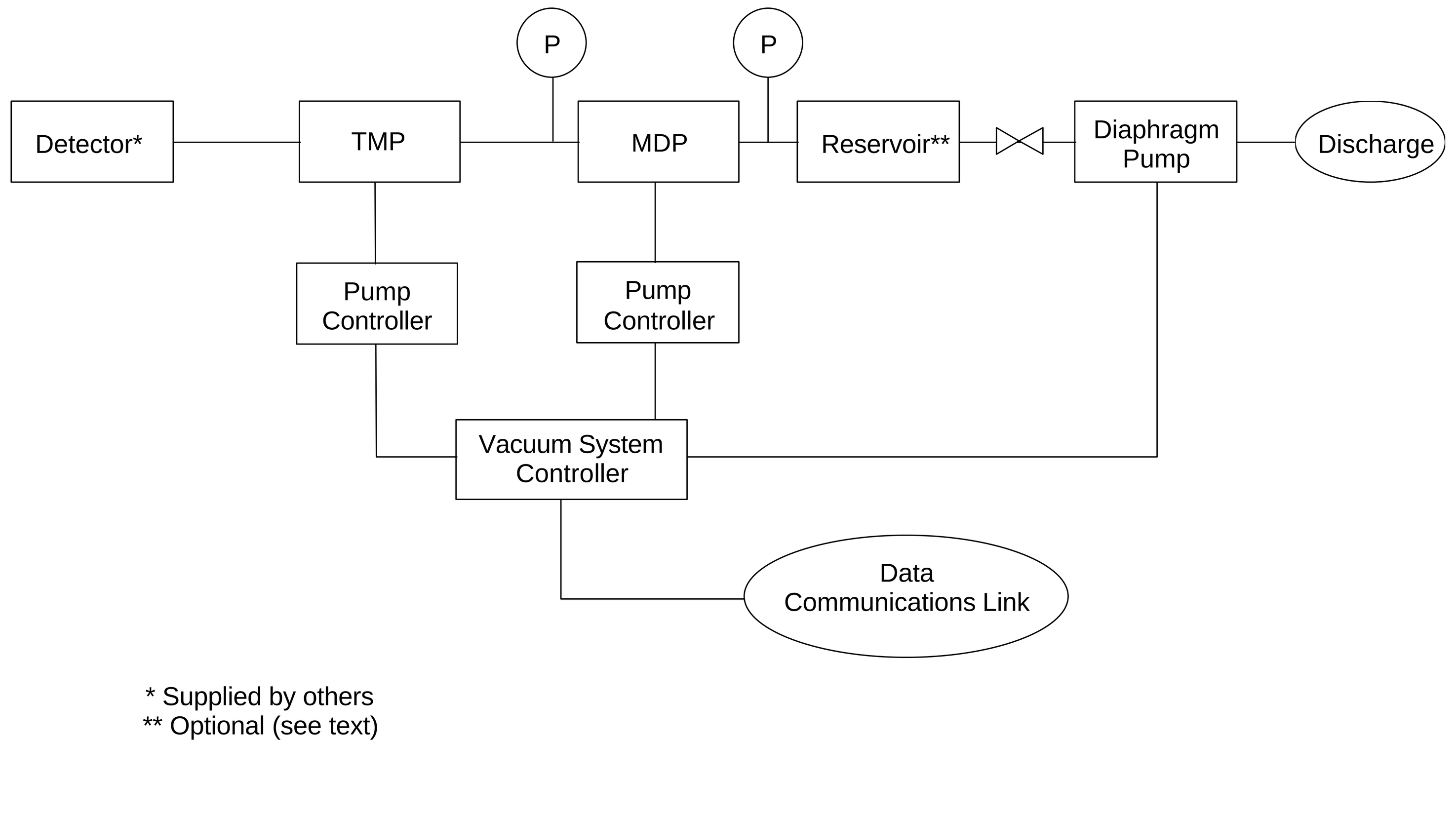


Figure 3: Ruggedized TMP concept Figure 4: Vacuum system for high vibration environment

Conclusions

To develop TMPs and MDPs that can perform effectively in harsh environments, a developer must negotiate a complex set of conflicting requirements. To be successful, a design effort must include analysis and laboratory experiments to understand electromagnetic interactions, mechanical design options, vibration and stress behavior, heat transfer, and free molecular and continuum fluid flow.

Three vacuum pumps are currently being developed at Creare using such techniques. These pumps are expected to offer small size, low power consumption, and ruggedness previously unavailable to builders of portable mass spectrometers or systems intended for harsh environments.

Acknowledgements

This research has been supported by the NASA Small Business Innovation Research (SBIR) Program through the Jet Propulsion Laboratory (Dean Wiberg) and the Kennedy Space Center (Duke Follistein). Their support is gratefully acknowledged.