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ABSTRACT

A new oil-free rarefied gas compressor (vacuum pump) of unusual design has been developed producing pressure ratios of 100,000:1. It is capable of maintaining inlet pressure of 1 pascal (absolute) while discharging to atmospheric pressure. It contains four reciprocal pistons with four stages of compression. The choice of reciprocal motion (instead of rotary) is primarily due to simplicity of air cooling for both, the piston and the cylinder. The pistons are lined with a low-friction composite material and they are of stepped design. The back side of each piston is connected to the inlet of the next stage to minimize leakage. There is a dual system of valves: one operates at the high mass flow rates, the other when a certain vacuum level is reached. A unit having a volumetric capacity of 1,000 lit/min. uses less than 600 watts power at low mass flows (including the power wasted by the electric motor). The device can be used for evacuation of clean systems without any possibility of contamination by lubricants. With some modifications, it can also be used for clean gas transfer applications.

INTRODUCTION

The Vacuum Products Division of Varian Associates in cooperation with the Commonwealth Scientific and Industrial Research Organization of Australia (CSIRO) has developed a somewhat unusual, entirely oil-free vacuum pump. Before the 20th century, vacuum pumps were called air pumps, or pneumatic machines. The use of the word "pump" is purely historic. If the reference to the atmospheric pressure is avoided, the action of the vacuum pump is indistinguishable from a compressor and so we think it is appropriate to bring the technology of the new device to the attention of the engineering and scientific community attending the Compressor Engineering Conference.

The conventional oil-sealed dual-stage vacuum pumps produce routinely pressure ratios for non-condensible gases exceeding one million. This is possible only by using oil not only for lubrication but also for sealing the narrow spaces separating the discharge and inlet areas of the pump. Equally important is the function of the oil in filling the "dead" space under the discharge valve. The oil is continuously introduced from an external reservoir into the pumping space near the end of the compression cycle. Thus, at the "zero" flow condition, mainly, oil containing small gas bubbles is discharged through the valve. The oil also serves as a medium for cooling the rotor.

There are two important disadvantages associated with the presence of the oil. At low absolute pressures, when molecular flow conditions are approached, the vapor of the oil and its fractions migrate into the vacuum chamber and contaminate it. On the other hand, some gases (for example, in semiconductor microelectronic device processing) react with and destroy the oil in an unacceptably short time. In recent years, the oil-sealed vacuum pumps have been replaced by multistaged Roots, claw, screw or turbine-type compressors. However, all of these still contain some possibility of contamination from the lubricated seals or drives partly exposed to the internal vacuum space in the pump.

During the initial work at CSIRO, which established the feasibility of the entirely oil-free vacuum pump, the reciprocal piston mechanism was chosen because of the simplicity of providing adequate air cooling for the piston, the cylinder and the atmospheric seals of the pump. The performance of the four-stage oil-free piston pump, in regard to the compression ratio at zero flow, is not equivalent to the dual-stage oil-sealed pumps but it is adequate for most applications. Using a different terminology, the ultimate pressure of one pascal (7 mTorr or 0.007 mmHg) produced by the oil-free pump is equivalent to 99.999% vacuum.

DESIGN FEATURES

The basic schematic arrangement of the device is shown in Fig. 1. For the simplicity of mechanical ballancing, the pistons are arranged in 180° opposition and driven by a more or less conventional connecting rod/eccentric bearing arrangement from a common shaft. We use a 1,200 rpm direct coupled motor and 2.54 cm (1.0 in.) piston stroke.

As can be seen, the piston is of stepped design. The primary reason for this is to minimize the atmospheric leakage through an oil-free lip seal mounted at the atmospheric end of the narrow section of the piston. The piston is lined by a low-friction, reinforced PTFE-type material. The liner is approximately 0.5 mm thick and is bonded to both cylindrical surfaces of the piston using a low-vapor-pressure epoxy resin. It is machined to the final dimension after bonding (and curing) using diamond tools. The cylinder is made of hard-coated aluminum. The radial distance between the piston and the cylinder is about 0.0025 cm (0.001 in.).

The atmospheric air leakage inward, across the dry lip seals, is of the order of 0.1 std. cm^3/sec. in the first three pistons. In the last piston, with the final discharge pressure being somewhat above atmospheric pressure, there is a small outward leakage. The back side of each piston, except the last, is connected to the next pumping stage. This prevents the leakage between the piston and the cylinder from reaching the inlet side of the particular piston.

The schematic in Fig. 1 is more complex than required for a simple connection of four pistons in series. This is due to the attempt to minimize the power required for the operation of the pump. The first two pistons are connected in parallel to double the pumping capacity, the last piston is double sided, i.e. includes two stages of compression. There are two overflow valves which are used to minimize the work of compression and avoid unnecessary production of heat. Overflow valves and the final discharge valve are placed together in a single discharge box for the convenience of connections whenever the pumped gas cannot be exhausted into the ambient air.

There are also two systems of valves, one functioning at the higher pressures as in any compressor, and the other at the lower pressures when the pneumatic forces are insufficient to open the spring-loaded valves. At the lower pressures, the inlets to the pumping space are through narrow slots in the cylinder (indicated in the drawing) which are uncovered by the piston at the end of the stroke. The exhaust occurs then by pushing the valve open with a piston when it reaches a bumper attached to the exhaust valve. The "dead" space between the piston and the valve plate (at the end of the forward stroke) is about 0.2 mm (0.007 in.). The entire drive mechanism with its grease lubricated bearings is in the atmosphere.

The pistons are hollow inside, and the smaller sections of the cylinders communicate with atmospheric air. Thus, it is easy to cool the friction surfaces in a reciprocating piston mechanism. The coefficient of friction of the PTFE material is near 0.1. The total power dissipated in the pump at the lower pressures is about 250 watts for the 500 lit/min. pump (inlet volume flow) and 300 watts for the 1,000 lit/min. pump. The motion of the pistons, connecting rods, and eccentric drive bearings produce adequate convection inside the crankcase and the crankcase is cooled by one or two small fans.

PERFORMANCE

The basic performance of two oil-free pumps is shown in Fig. 2 in terms commonly used in the high vacuum industry, i.e. the volumetric capacity at varying inlet pressures. The general pressure-flow characteristic is similar in kind to the basic performance of oil-sealed vacuum pumps. The larger pump has a lower ultimate pressure, i.e. the pressure at zero external flow (inlet valve closed) because the volumetric capacity is twice as high but the leakage at the atmospheric lip seals is the same.

The pressure-flow performance also has been obtained for gases other than air: nitrogen, argon, helium and hydrogen. For practical purposes, the performance remained unchanged. The flow rate was somewhat higher for gases of smaller molecule weight, the greatest difference not exceeding 15%. The overall pressure ratios were correspondingly lower, the greatest variation being about a factor of two.

Fig. 3 shows the power requirement at varying inlet pressure. It can be seen that, for continuous operation with the given motor, the inlet pressure should be kept below about 6 kilopascals (45 Torr or mmHg). If required, a larger motor could be used but then, at higher inlet pressures, the pump temperature would rise, eventually being limited by the temperature of the internal valves which utilizes bushings made of a material similar to the one used for piston liners.

The longevity of the pump, when pumping clean air in the absence of abrasive particles (which can be filtered), is one to two years of continuous operation depending on inlet pressure and the general temperature level. No maintenance is required for a period of one year of continuous operation, after which the pump should be cleaned and the atmospheric seals replaced. In non-continuous operation, several years of operation can be expected. A number of pumps used for the initial evacuation of vacuum chambers (which subsequently are pumped by other vacuum pumps) have been in operation for three and a half years without any maintenance.

The cleanliness achieved in the residual gas composition at the inlet of the pump (at zero flow) is remarkable. Mass spectrometer measurements show only constituents of air, including water vapor.

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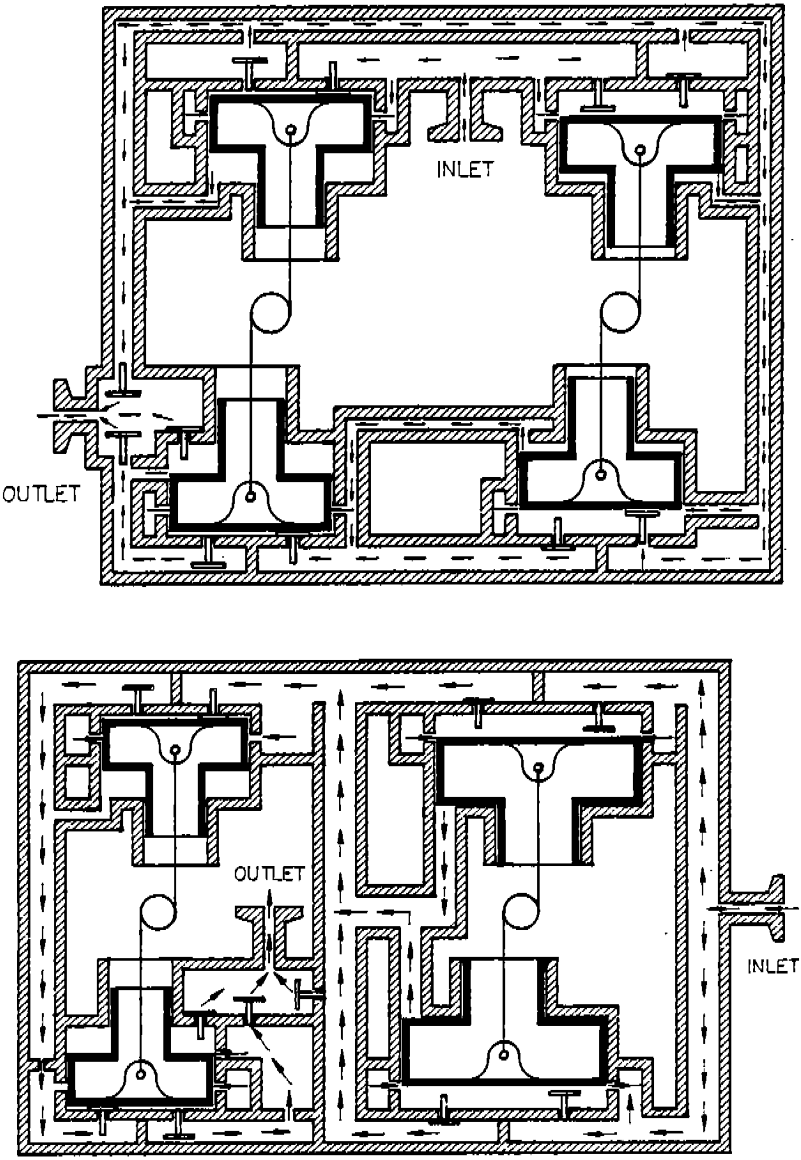

Fig. 1. Two alternate arrangements for a four-piston four-stage oil-free vacuum pump.

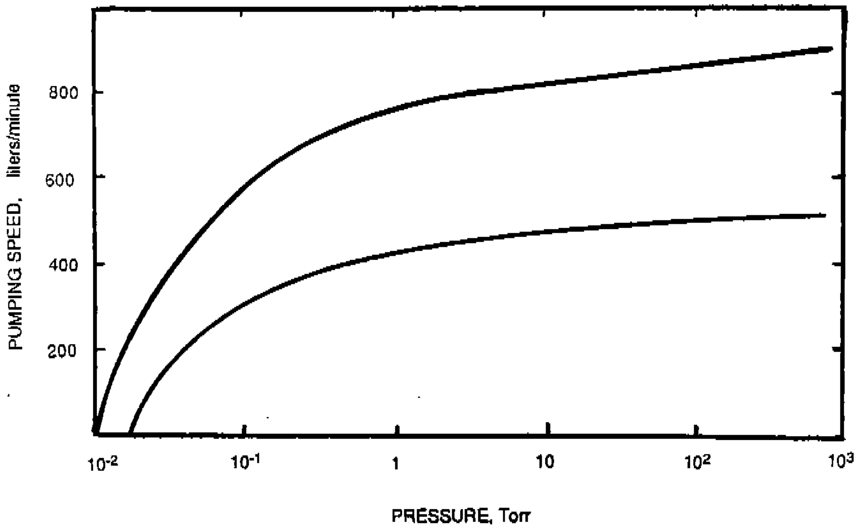

Fig. 2 Volume flow at various inlet pressures for two oil-free pumps.

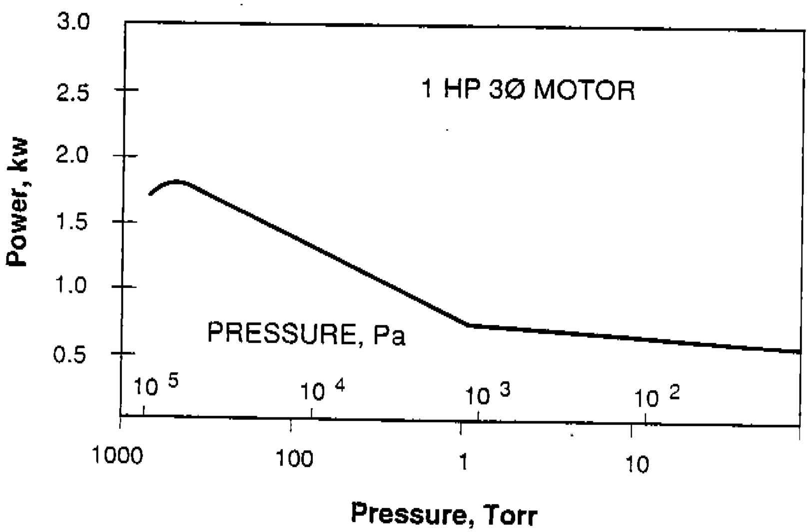

Fig. 3 Total power consumption for the 500 lit/min pump at various inlet pressures.