Miniature peristaltic vacuum pump for use in portable instruments

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This article describes the development, construction, and performance characteristics of a small, low-mass, low-power-consumption vacuum pump for use at pressures down to 5×10^{-2} Torr. The pump is based on a peristaltic tubing pump modified to overcome rapid tubing deterioration problems normally encountered when peristaltic pumps are used for vacuum pumping. Typical uses of the pump are for portable scientific and engineering instruments requiring pressure and flow characteristics compatible with the pump. These include the backing of high-vacuum pumps, rough-pumping vacuum systems used with certain ion and cryosorption vacuum pumps, and interstage pumping of membrane separators.

I. INTRODUCTION

Many portable instruments used for scientific and engineering applications require a means of producing a vacuum with pressures under 1 Torr. Such instruments include mass spectrometers, cooled infrared sensing detectors, microwave spectrometers using Stark cells, instruments containing unsealed low-pressure lasers, trace gas concentration systems, leak detectors, etc. Often these applications require minimizing the size, mass, and power consumption of components in order to enhance the instrument's portability and utility. Unfortunately, commercially available vacuum pumps for use at pressures under 1 Torr that are capable of pumping directly to atmospheric pressure, and with throughputs up to 1 Torr ℓ min^{-1} (including He), have sizes, masses, and power consumptions that are not compatible with portable applications

The National Institute for Occupational Safety and Health (NIOSH) has had a continuing interest in bringing the benefits of laboratory gas chromatography/mass spectrometry (GC/MS) to industrial hygiene field studies. This has been difficult, partly due to the size and mass of currently available transportable GC/MS units, which is substantially due to the size and mass of vacuum system components. As part of downsizing existing GC/MS equipment, we initiated work on the development of a small, low-mass, low-power-consumption vacuum pump for backing a turbomolecular high vacuum pump. The pump was also suitable for use in interstage pumping of a multistage membrane separator on the MS inlet. It was desired that the pump provide a pressure under 1 Torr, at throughputs up to 1 Torr ℓ min^{-1}.

II. MATERIALS AND METHODS

We examined a number of possible pump designs that could be applied to this problem, including the following.

(1) Oil-sealed rotary vane pumps. This is likely the most common backing or roughing pump and has the advantages of a relatively simple design, moderate cost, and long lifetime. Problems with oil-sealed pumps include allowing some oil vapors to backstream into the high-vacuum pump and chamber, being subject to oil leakage during shipment and use, and allowing oil to migrate to high-vacuum areas during a power failure. They also periodically require a change of oil, an often messy operation done typically every 2000 h. Waste oil disposal can be a problem, possibly requiring disposal as hazardous waste. The pumps are usually manufactured as one- or two-stage pumps, having ultimate pressures as low as 10^{-2} and 10^{-4} Torr, respectively.[1,2] Our survey of commercially available pumps of this type indicated that the smallest had a mass of approximately 8 kg, consumed approximately 200 W power, and occupied approximately 7 ℓ volume. Most commercial pumps are not very energy efficient.

(2) Oil-sealed rotary piston pumps. This type of pump was more popular in the past, before improvements in vane materials made possible large rotary vane pumps. The rotary piston pump is still applied to very large flow applications and when substantial contaminants are present.[1,2] Oil problems common to the rotary vane pumps also apply here.

(3) Oil-less reciprocating piston pumps. A number of oil-less reciprocating piston pumps are being marketed for use where backstreaming of any pump-related contaminating vapors is not acceptable. These pumps generally use Teflon™ piston seals and multiple stages. They are usually large, heavy, and expensive when compared to a rotary vane pump. Lower pressure limits are typically 10^{-2} Torr. Our survey indicated that no small versions of these pumps were available.

(4) Diaphragm pumps. Miniature multiple-stage diaphragm pumps have been used successfully at pressures down to several Torr. By a careful selection of pump design, including multiple stages of pumping, one can achieve vacuums of <20 Torr. The lowest pressure obtainable using such a pump design appears to be limited by the minimum pump head dead volume and the gas pressure required to open the rubber leaf-type pump valves, which are common to most.

(5) Scroll pumps. While scroll pump designs have existed for some time, their application has been quite limited.[3] Sealing between scroll elements and their housings appears to limit the lower pressure of this design. Recently, some major vendors have offered pumps based on this principle. How-

ever, the pumps are quite large and not applicable to portable applications.

(6) Peristaltic pumps. Peristaltic pumps have been used for vacuum pumping at pressures >10 Torr. However, their pumping speeds are low, and their lowest operating pressure depends on the operating revolutions per minute (rpm) and the time the tubing has been in service. Tubing life and lower operating pressures are special concerns. The simple design, modest cost, small size and mass, and dry operation are positive features of this pump. The pumps are by nature valveless and have essentially zero dead volume, thus overcoming many difficulties in producing the low pressures associated with some other pump designs.

A. Pump selection

Oil-less piston pumps and scroll pumps, if economically miniaturized, could be quite useful. There appeared to be some possibility of utilizing a flexible scroll to improve their pumping characteristics and ease of manufacturing; however, producing adequate sealing in scroll pumps would be quite difficult. While the oil-sealed rotary vane pump and oil-sealed rotary piston pump may hold potential for miniaturization, their inherent disadvantages for portable instrumentation use and our estimation that they would be difficult and expensive to prototype eliminated them from further consideration. After consideration of the various pump design features, the attributes of diaphragm and peristaltic pumps became evident. Both diaphragm and peristaltic pumps were commercially available in the small size and mass needed, but they did not meet the low-pressure requirements. Both had a long history of service in higher-pressure applications and modest cost for existing apparatus. For portable instrument operation it appeared possible that service intervals could be more frequent than for a laboratory instrument; consequently, some pump designs not normally considered for a laboratory instrument could be applicable to a portable instrument. Particularly desirable would be a simple pump, which would be inexpensive to prototype and produce and would not require extensive research and development efforts to perfect. Consequently, both diaphragm and peristaltic pump designs were considered attractive, and some initial experimentation took place with both.

B. Testing of a miniature diaphragm pump

After the availability of miniature, low-power-consumption diaphragm pumps was reviewed, two Brailsford & Co., Rye, NY, model No. TD4×2N pumps (with a 4.5 mm stroke) were selected (two pump heads per unit, resulting in four pump heads in series). The pumps were selected based on their size, mass, power consumption, and the lower-pressure claims of the manufacturer. Each pump consumed <4 W and had a mass of 345 g, a size of 9×5×10 cm (9×10×10 cm for two pumps in series), and a free air pumping speed of approximately 4 ℓ min^{-1}. The pump stroke was selected based on what the manufacturer felt was the maximum stroke that could be produced with that design which would result in a minimum dead volume (minimum volume of cylinder in maximum stroke position). These pumps utilized rubber diaphragms and rubber leaf-type valves. The pumps were operated connected to a pressure gauge and gas flow controller on the vacuum inlet.

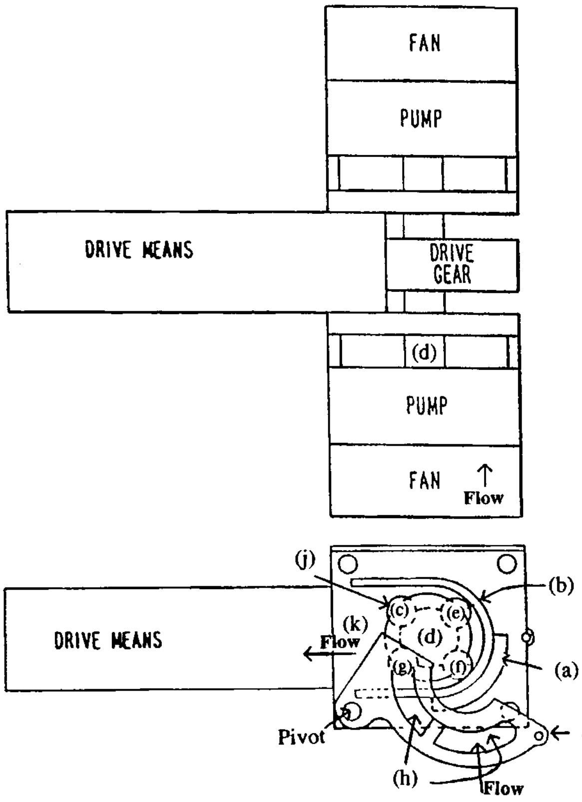

FIG. 1. Miniature peristaltic vacuum pump.

Pressure measurements were made using an MKS Instruments Inc., Andover, MA, type 122A Baratron pressure transducer (200 Torr full scale) with a model No. D-1 readout unit. Flow of air into the pump inlet was controlled and measured with a Cole–Parmer Instrument Co., Niles, IL, model No. H-03217-24 flow meter.

C. Testing of peristaltic pumps

Peristaltic pumps operate by pressing a piece of flexible tubing between a roller moving along the tubing and a flat surface (platen) behind the tubing. As the roller moves along the length of the tubing, it forces the tubing contents out in front of it, leaving the tubing empty behind it. This can be seen in Fig. 1, where (a) indicates an imaginary section of platen, with tubing section (b) between it and the roller (c). In practice, the platen is normally a portion of a circle (arc) and the roller, mounted on an arm from a driven center pivot [drive shaft (d)]. The roller has a motion described by a circle of radius slightly smaller than that of the arc describing the platen. Normally, a series of rollers (c), (e), (f), and (g) are mounted on the same drive shaft and at the same radius. The rollers and platen length are adjusted so that as one roller is leaving the platen, another has entered it; thus, the tubing section between two sequential rollers is sealed, and as one roller leaves the platen, the tubing section behind it is sealed by the next roller. The pumping speed can then be estimated using the following equation:

$$v=\pi r^2 l n \omega q a_t a_\omega,$$

where v is the pumping speed (cm^3/min), r the tubing inside radius (cm), l the tubing length between rollers, n the number of rollers, ω the pump rpm, q the volume correction factor for tubing pinch by rollers, a_t the tubing collapse factor resulting from aging, and a_ω the tubing collapse factor resulting from the pump rpm.

An example of the above is provided by a pump with three rollers, $l=5$ cm, $q=0.63$, $r=0.24$ cm, and $\omega=300$ rpm, which would result in a pumping speed of 0.51 ℓ/min. Some correction for a_t and a_ω would also be necessary.

Peristaltic pump volumetric flow as a function of pressure should be relatively constant throughout the viscous flow pressure range for the pump tubing selected (>0.1 Torr for 5 mm i.d. tubing and N_2 gas). Pumping efficiency should fall off rapidly through the transition to molecular flow.[3]

Several models of peristaltic pump head designs were examined before one was selected for detailed testing. Those included the Cole–Parmer series 900, series L/S standard, series 07518 "Easy Load," and series 07021 "Quick Load" pump heads. We also examined several types of tubing available for use in these pump heads.

After our initial examinations of pump vendors' literature,[4] it was immediately evident the best choice was likely to be the thick-walled Norprene™ tubing. This was due to its relatively long lifetime with wall thickness sufficient to withstand atmospheric pressure without significant collapse, an ability to pump to a relatively low pressure, and a low permeability to air. Initial tests showed that only heavier walled tubing would not collapse when evacuated. Other tubing considered included silicone rubber, Tygon™, and Viton™, in various sizes and wall thicknesses. Norprene™ and Tygon™ are trademarks of the Norton Performance Plastics Corporation, Akron, OH, and Viton™ is a trademark of the E. I. DuPont Co. It is our understanding that Norprene™ is a thermoplastic elastomer alloy of polypropylene and EPDM rubber, with a mineral oil plasticizer, and minor amounts of carbon black filler. We tried samples of thick-walled silicone tubing 4.8 mm i.d. and Norprene™ thick-walled tubing of 4.8 and 6.4 mm i.d. Tests were also made with a thin-walled Norprene™ 3.1 mm i.d. tubing, using a modified Cole–Parmer model No. 900 pump head, operating at 130 rpm.

A series of tests was conducted to determine the performance properties of Norprene™ thick-walled tubing. These included relative pumping capacity as a function of time with different tubing temperatures, tubing temperature as a function of pump rpm and time, and pumping speed as a function of rpm. The measurements were accomplished (see Fig. 2) using a Cole–Parmer model No. 7015-20 pump head driven by a Dayton 4Z528 permanent magnet dc motor with speed controller. Tubing temperature was monitored using a type K thermocouple located on the side of the tubing against the

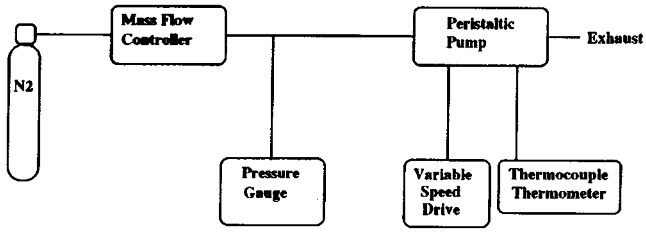

FIG. 2. Test apparatus for evaluating pump tubing.

platen. A Fluke model No. 52 thermocouple readout was used. A flow of N_2 was selected using a Unit Instrument Inc., Orange, CA, model No. UFC 1501A mass flow controller with a model No. 100-S readout. Pressure measurements were made using an MKS Instruments Inc., Andover, MA, type 122A Baratron pressure transducer (200 Torr full scale) with a model No. D-1 readout unit.

As will be shown in the data (Sec. III), problems were identified with the self-heating of the tubing. The heating led to short tubing lifetimes and elevated operating pressures. Consequently, changes in the design of the pump were made to facilitate cooling of the tubing and pump parts. This was demonstrated using the Cole–Parmer model No. H-07021-22 pump head, with 4.8 mm i.d., 10 mm o.d. Norprene™ tubing. The pump was a "quick load" type, using hinged platen assembly sections [see Fig. 1(i)]. The hinged design also allowed easy release of the tubing from compression, so that a "compression set" of the tubing did not take place when the pump was not in operation. The design also allowed rapid changing of the pump tubing. A photograph of the prototype pump is shown in Fig. 3. The open design of this pump head made it easy to modify for force air cooling of the tubing, as follows.

(1) Cooling ports were placed in the front covers that are integral with the hinged platen assembly [see Fig. 1(b)].

(2) A small fan, Papst Mechatronic Corp., Newport, RI, model No. 614 (24 V, 2.5 W, 24 ft^3 per minute with no flow resistance) was mounted on the face of a one-half-section of the front cover of the hinged platten assembly such that it also covered the surface of the other one-half-section of the

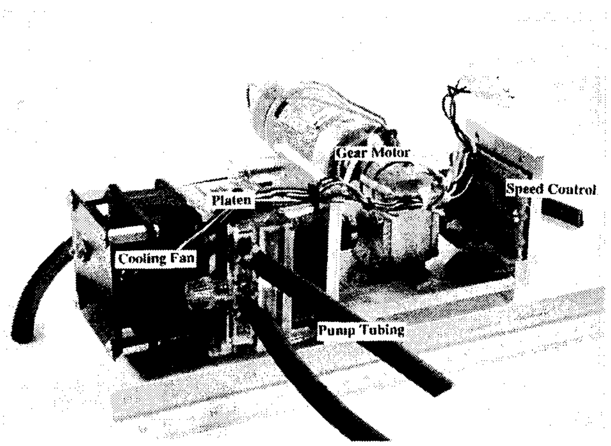

FIG. 3. Peristaltic vacuum pump assembly.

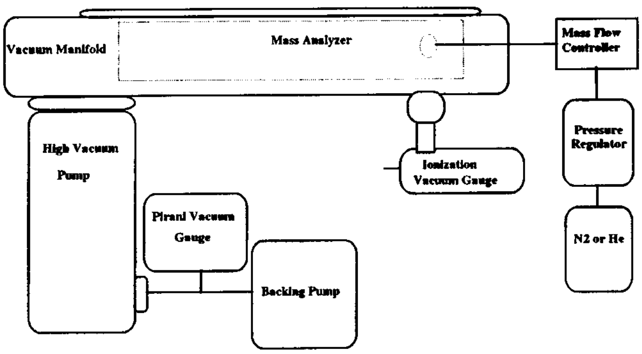

FIG. 4. Test apparatus for backing of high-vacuum pumps.

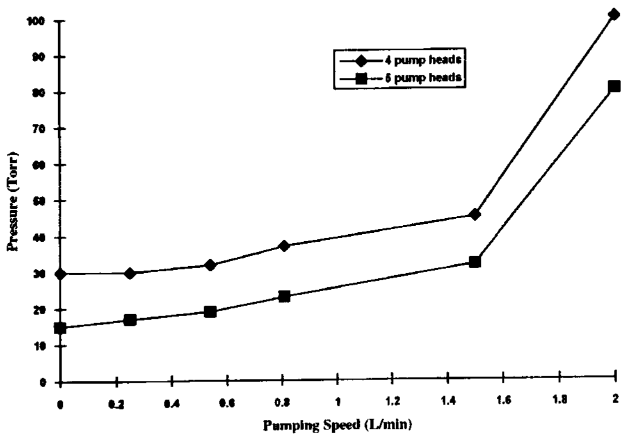

FIG. 5. Pumping characteristics of a diaphragm pump.

assembly when the assembly was closed [see Fig. 1(l)]. This allowed a flow of air through the cooling ports in the assembly.

(3) The rotor face [see Fig. 1(l)] was modified with airflow holes through it, such that air flowing through the hinged platen assembly could then flow through the rotor face and over pump's rubber tubing. The air then flowed out through the open top of the pump [see Fig. 1(k)].

In order to determine if the peristaltic pumps examined would have pumping pressures and speeds necessary to back typical high-vacuum pumps used in portable instruments, we examined the requirements of five high-vacuum pumps. They were an Alcatel Vacuum Products, Hingham, MA, model No. 5080 turbomolecular pump, a Varian Associates, Lexington, MA, model No. V60 turbomolecular pump, a Varian model V250 combination turbomolecular and molecular drag pump, an Alcatel model No. 5010 molecular drag pump, and an Edwards High Vacuum International, Wilmington, MA, model No. EQ 50/60 oil diffusion pump. In each case a hypothetical application was used for reference. This was to provide a high vacuum for a portable GC/MS, which required a pressure of 5×10^{-4} Torr at a throughput of 0.5 sccm He. For those conditions, the characteristics of each pump were taken from manufacturers' literature.

Laboratory tests were conducted using the miniature peristaltic vacuum pump with certain of the above-noted high-vacuum pumps, as follows: A vacuum manifold from a small mass spectrometer was used to attach the high-vacuum pump, as in Fig. 4. The miniature peristaltic vacuum pump (backing pump) was then attached to the exhaust of the high-vacuum pump, in conjunction with a HPS Corporation, Boulder, CO, model No. 10215001 Pirani gauge tube and a model No. 315 Pirani gauge readout, for monitoring backing pressure. A HPS model No. 919 hot cathode ionization vacuum gauge was used to monitor high vacuum. The flow rate of N_2 and He was selected by using a Unit Instrument Inc., Orange, CA, model No. UFC 1501A mass flow controller with a model No. 100-S readout.

D. Estimates of measurement error

Estimates of error for pressure measurements were based on the pressure gauge manufacturers claims. For the Pirani gauge, random error was estimated to be $\pm10\%$ ($\pm1\sigma$) and bias $<10\%$. For the ionization gauge, random error was estimated to be $\pm5\%$ ($\pm1\sigma$) and bias $<50\%$. For the Baratron gauge, random error was estimated to be $<\pm0.5\%$ ($\pm1\sigma$) and bias $<0.1\%$. Based on manufacturers' claims, temperature measurement errors at the thermocouple sensor were estimated to be $<\pm1.1$ °C ($\pm1\sigma$ random, plus bias). The temperature measurement should measure, within the cited accuracy, the temperature at the contact point with the pump tubing, which was located on the side of the tubing against the platen. It was felt that this would represent a higher temperature than that on the opposite side, which was exposed to air. Temperatures inside the tubing could be somewhat higher. Flow measurements, using the Unit Instruments mass flow controller, were claimed by the manufacturer to have an error of $\pm1\%$ of full-scale value (1 sccm) or ±0.01 sccm. Pumping speeds were then calculated using the throughput and pressure measurements.

III. RESULTS AND DISCUSSION

Figure 5 shows that using five miniature diaphragm pump heads of the type tested, pressures down to the 10–20 Torr range could be attained. The pumping speed of this pump was very high, even near the lower-pressure limit of the pump (up to 3 ℓ min^{-1} for a single-stage free flow at atmospheric pressure). This suggests that the pump would be excellent for rough pumping of large vessels, prior to the use of the miniature peristaltic vacuum pump. Producing pressures under 10 Torr did not appear to be practical using the types of diaphragm pumps we tested. Refinements of these pumps would be likely to reduce the lowest pressure attainable further; however, it did not seem likely that the limitations on dead volume and the operation of the rubber leaf valves would allow substantial gains. As pressures <1 Torr are desirable for backing most high-vacuum pumps, it appeared that diaphragm pumps were not ideal for that purpose.

By use of a modified Cole-Parmer model No. 900 pump head, operating at 130 rpm and having 3.1 mm i.d. Norprene™ tubing, a zero-throughput pressure of approximately 5×10^{-2} Torr was produced. The ability to produce this low

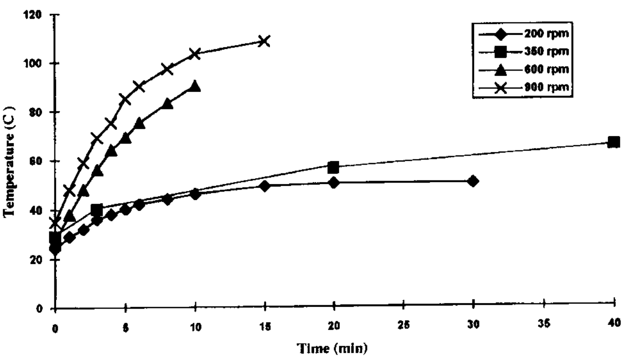

FIG. 6. Tubing temperature vs time.

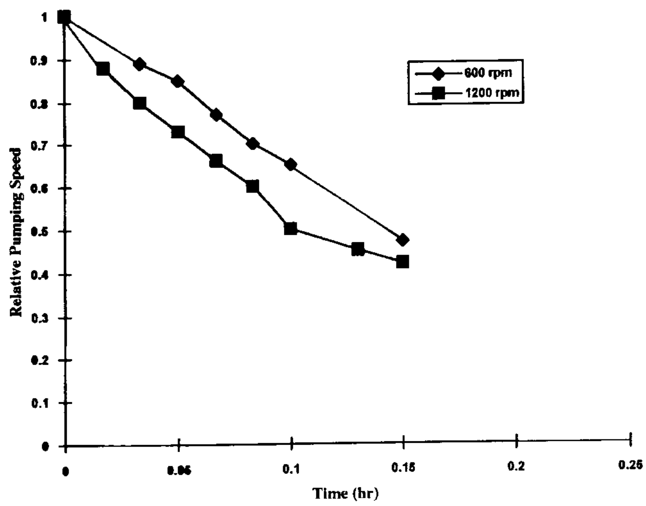

FIG. 8. Loss of pumping speed at 600 and 1200 rpm.

pressure encouraged our further investigation into this type of pump through assembling and testing of larger pumps.

Tests with 4.8 mm i.d. thick-walled silicone tubing resulted in initial zero-throughput pressures of approximately 9×10^{-2} Torr at 350 rpm. This was higher than the approximately 3×10^{-2} Torr produced using the same-dimensioned Norprene™ tubing. The silicone tubing failed, having less than 100 operating hours at 300 rpm. Attempts to use larger diameter (9.5 mm) thick-walled tubing were unsuccessful, as it appeared that the tubing did not seal itself adequately when compressed.

Figure 6 shows that the temperature of a peristaltic pump's tubing rises with operating time. This effect is particularly pronounced as the operating rpm increases. In all of these cases, no attempt was made to enhance the cooling of the pump tubing.

Figure 7 shows that when the pump is operated at 350 rpm and with tubing temperatures of 32 and 60 °C, the rate of loss of pumping capacity increases substantially as the operating temperature of the tubing increases. Figure 8 shows a similar effect when the operating temperatures of the tubing for the two pump rpm values are considered. It should be noted that the data presented in Fig. 8 are not for a constant tubing temperature. The tubing temperature versus operating time was as described in Fig. 6. The pronounced effect of increased tubing temperature on the deterioration of pump flow capacity led to a redesign of the pump, which incorporated forced air cooling of the tubing and pump parts. Cooling allowed the pump tubing to operate continuously at 350 rpm, at tubing temperatures of approximately 32 °C. Using the data in Fig. 7 and assuming that a capacity of 30% of the starting capacity would be sufficient for an intended application, the tubing could have a lifetime at 32 °C of approximately 170 h. If 20% of the starting capacity was acceptable, the lifetime could be >300 h.

Figure 9 shows that the rate of increase of pumping speed with pump rpm was nearly linear, up to approximately 900 rpm. After that, the pumping speed decreased as rpm increased. This is probably due to the time required for the tubing to relax back to its normal diameter, after a roller compressed it. The time available for that decreases as the pump rpm increases. Measurements were made at an indicated tubing temperature of approximately 40 °C; however, for higher rpm values, rapidly rising temperatures made it more difficult to monitor tubing temperature accurately. Figure 9 also shows that the no throughput or base pressure

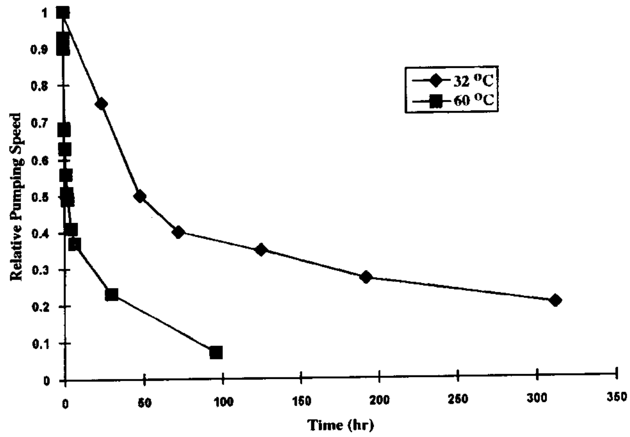

FIG. 7. Loss of pumping speed at 350 rpm.

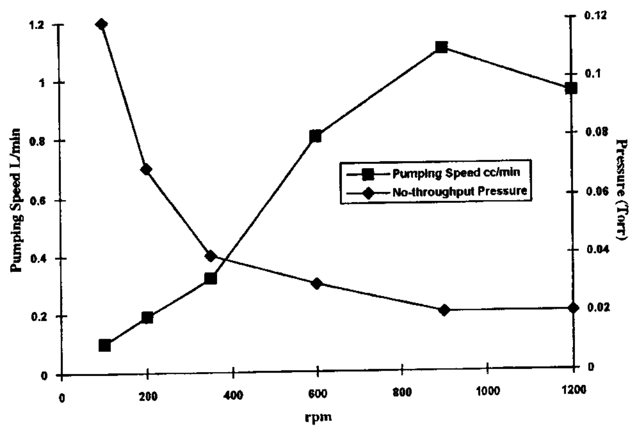

FIG. 9. Pumping speed and pressure vs rpm.

TABLE I. Possible applications for the miniature peristaltic vacuum pump.

Pump	Max. backing pressure (Torr)	Compression ratio (He)	Max. backing pressure for 5×10^{-4} Torr (Torr)	Pumping speed at max. backing pressure (ℓ min^{-1})
Alcatel 5080 turbo	5×10^{-2}	2.5×10^{3}	5×10^{-2}	10
Varian V60 turbo	8×10^{-1}	4×10^{3}	8×10^{-1}	0.625
Varian V250 turbo/mol. drag	20	1×10^{5}	20[a]	0.025[b]
Alcatel 5010 mol. drag	40	2×10^{4}	10[a]	0.05[c]
Edwards EO 50/60 oil diff.	0.9[d]			0.55
	0.45[e]			1.1

[a]For low operating power and temperature, keep under 1 Torr for continuous operation.
[b]0.5 ℓ min^{-1} at 1 Torr.
[c]Maximum pumping speed at 5×10^{-4} Torr limits flow to 0.25 sccm.
[d]Using DC702 silicone pump fluid.
[e]Using Santovac 5.

achieved by the pump is lower at high rpm's, with a value down to 0.02 Torr. The higher pressure at low rpm's may be due to some seal leakage in the tubing and the test system, producing a throughput somewhat greater than zero. As mentioned earlier, the low-pressure throughput of the pump appears to be substantially limited by the tubing-dimension-related transition from viscous to molecular flow, occurring at pressures between approximately 0.01 and 0.1 Torr.

A. Applicability of a miniature peristaltic vacuum pump as a roughing or backing pump for various high-vacuum pumps

Table I shows that the backing pressure requirements for the two turbomolecular pumps varied from 8×10^{-1} to 10^{-3} Torr. At the throughput cited, the miniature peristaltic vacuum pump would probably function well for the Varian V60 turbopump, but not for the Alcatel 5080. Both the Alcatel 5010 molecular drag pump and Varian V250 turbo/molecular drag pump allow high backing pressures and would work well with the miniature peristaltic vacuum pump. In order to keep their temperatures and power consumptions low when operated continuously, it would be advantageous to operate both of those pumps with a backing pressure under 1 Torr.

Table II shows that both the Alcatel 5010 molecular drag pump and the Varian V250 combination turbomolecular/molecular drag pump worked will with the miniature peristaltic pump as a backing pump. Backing the Alcatel 5080 turbomolecular pump was not as successful, due to the low backing pressure specified for that pump. This made its use impractical when using He as the flow gas. A turbomolecular pump, such as the Varian V60, should be more suitable for use with the peristaltic backing pump. Initial trials of the peristaltic backing pump with the Edwards EO 50/60 oil diffusion pump were not successful. This was due to the low backing pressure requirements of the pump using the Santovac 5 oil (used in trial), as well as to a possible incompatibility of the pump oil with the peristaltic pump tubing. This could probably be improved with the choice of a silicone pump fluid. Within certain limits, pumping speeds can be increased over those shown, by increasing the pump rpm,

TABLE II. Performance of miniature peristaltic vacuum pump in backing selected high-vacuum pumps.

Throughput (sccm)	Pressure (Torr): Alcatel 5010 mol. drag – High vacuum	Alcatel 5010 mol. drag – Backing[a]	Alcatel 5080 turbo – High vacuum	Alcatel 5080 turbo – Backing[a]	Varian V250 turbo./mol. – High vacuum	Varian V250 turbo./mol. – Backing[b]
0.00 (air)	1.5×10^{-5}	7.3×10^{-2}	4.4×10^{-6}	1.0×10^{-1}	1.6×10^{-6}	1.0×10^{-1}
0.1 (air)	8.0×10^{-5}	5.1×10^{-1}	8.4×10^{-5}	4.6×10^{-1}	c	c
0.2 (air)	1.6×10^{-4}	8.1×10^{-1}	5.0×10^{-4}	6.0×10^{-1}	5.5×10^{-5}	1.2
0.5 (air)	4.1×10^{-4}	1.6	d	d	1.2×10^{-4}	2.0
1.0 (air)	8.3×10^{-4}	3.2	d	d	2.4×10^{-4}	3.6
0.17 (He)	c	c	c	c	1.8×10^{-4}	8.0×10^{-1}
0.36 (He)	6.0×10^{-4}	4.8×10^{-1}	2.5×10^{-3}	4.5×10^{-1}	3.5×10^{-4}	1.5
0.72 (He)	1.1×10^{-3}	6.0×10^{-1}	d	d	8.3×10^{-4}	2.5
1.44 (He)	2.0×10^{-3}	1.0	d	d	c	c

[a]Two #15 pump tubes in parallel, at 350 rpm.
[b]One #15 pump tube, at 350 rpm.
[c]No data.
[d]Pump not operable under those conditions.

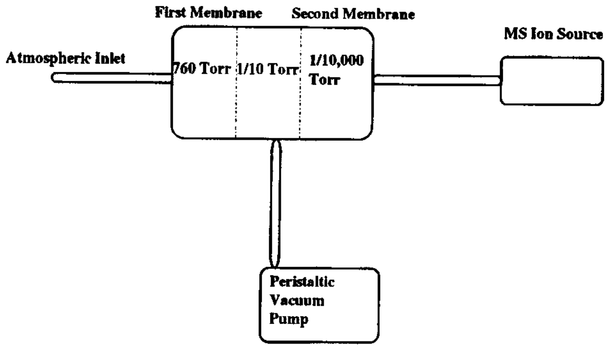

FIG. 10. Multistage membrane separator for MS inlet.

increasing the tubing i.d., or operating multiple tubing sections in parallel. An increase in power consumption and weight would result.

A peristaltic pump may be useful for rough pumping a vacuum chamber before starting an ion or cryosorption vacuum pump. Ion pumps should be started at the lowest possible pressure. It is possible to start most triode pumps at a pressure $\leq 5\times10^{-2}$ Torr, and under 10^{-3} Torr is required for most diode pumps; consequently the use of a peristaltic roughing pump would be possible only for triode pumps. Cryosorption pumps should be started at the lowest possible pressure to minimize the loss of pump capacity.

A peristaltic pump may be useful for interstage pumping of a membrane separator used to enrich sample concentrations at the inlet of a mass spectrometer. An example of such an application can be seen in Fig. 10.

B. Variable speed control for the pump

Many applications for vacuum pumps in portable instruments have varying flow requirements. An example of this is in a GC/MS, where flow gas (typically He at 0.5 sccm) is used only during a time interval immediately prior to, during, and immediately after a GC run. At other times, pump flow requirements are based on system leakage, which may be minimal. For a GC/MS application of the pump, we found it advantageous to operate the peristaltic pump at a very low rpm (typically 75) when flow requirements were low. This was done to extend greatly the lifetime of the peristaltic pump tubing and to reduce system power demands. The low rpm resulted in a lower tubing temperature as well as less mechanical flexing of the tubing. When flow requirements were higher, rpm was automatically increased. In that case, the automatic pump rpm increase was controlled by a pressure sensor sensing the high-vacuum pump backing pressure (located in the same position as the Pirani vacuum gauge in Fig. 4). An adjustable pressure setpoint allowed pump rpm switching over a range of 0.5–5 Torr. A reasonable pressure hysteresis was allowed (approximately 3 Torr) to avoid unnecessary cycling of pump rpm. The pressure sensor used was an HPS Division, MKS Instruments, Boulder, CO, series No. 325 Moducell, modified to allow for a wider hysteresis than normal. The vacuum sensor then controlled switching between two preselected operating voltages for the peristaltic vacuum pump motor.

C. Possible improvements in peristaltic vacuum pump design

It appears possible that some improvements in the pumping speed of a peristaltic vacuum pump could be made by using a larger i.d. tubing, with a thin wall. Tubing i.d. is presently limited by the wall thickness needed to prevent tubing collapse due to atmospheric pressure and the compression needed to seal the inside of the tubing completely. Thicker tubing walls and higher compressive forces lead to higher energy requirements for pump operation and lead to greater tubing heating problems. An idea as to how to overcome tubing wall collapse for larger i.d. thin-walled tubing was presented in a patent application, where the pump tubing was contained in a vacuum chamber.[5] This eliminated the effect of atmospheric pressure collapsing the tubing. Unfortunately, the pump described evacuated that vacuum chamber with the same tubing inlet as used for pumping from the application vacuum system. This would be very likely to limit lowest pressures it could produce, due to shaft seal and pump cover seal leakages, as well as tubing outgassing. These problems could be overcome by pumping the pump vacuum chamber with a second peristaltic pump tube, allowing the application vacuum system to be connected directly to the tubing inlet of the other peristaltic pump tube. While less frictional heat would be generated in a thin-walled tube, it is unclear what the tubing temperatures would be, as no air cooling of the tubing would take place. It is possible that partially filling the vacuum chamber with a low-vapor-pressure liquid (possibly a silicone or PTFE oil) could help solve any tubing cooling problems by carrying tubing heat to the pump housing. It is also possible that the chamber could be completely filled with a low-vapor-pressure, low viscosity liquid. This would allow a negative hydraulic pressure to be applied to the pump tubing, using a means such as a spring-loaded diaphragm in the chamber wall. This would eliminate the need for pumping a vacuum in the chamber. If this design provided the benefits of a substantially extended tubing life and greater pumping speed, the disadvantages of having a fluid-filled chamber might be acceptable.

IV. CONCLUSIONS

The data presented show that a practical miniature peristaltic vacuum pump can be used to produce pressures and pumping speeds that are likely to be compatible with many portable instrumentation needs. Limitations on the i.d. of pump tubing which will perform effectively, along with typical pumping speed requirements of applications such as a GC/MS, required at least periodic pump rpm values which produce undesirable tubing temperatures. Using forced-air tubing cooling methods, the pump tubing lifetime could be extended substantially, allowing for typical pump service intervals of over 100 h. Such service intervals could be compatible with many portable instrumentation applications. Servicing normally consisted of changing the pump tubing, which required only a few minutes of time and a small material's cost. The possible pumping speeds and lowest pressure produced (>1 ⁄ min^{-1}, and down to 2×10^{-2} Torr) are well suited to some applications. These could include backing a high vacuum pump (turbomolecular, molecular drag, or oil diffusion), use as a roughing pump with ion or cryosorption vacuum pumps in applications such as portable scientific instruments, and for interstage pumping of membrane separators. The pump's small size (<1 ⁄), low mass (<1.5 kg), low power consumption (<20 W), and relatively low cost further enhance its range of applications. The pump described in this article could reduce the pump mass and volume by >80% and its power consumption by >90% over the oil-sealed rotary pump alternatives we examined.

The miniature diaphragm pump evaluated was useful at pressures down to approximately 15 Torr. While this pressure would limit its usefulness as a backing pump for the high-vacuum pumps used in this study, its throughput, size, and low power requirements would make it very attractive for evacuating vacuum chambers and associated pumps and plumbing, prior to pumping with the peristaltic pump.

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