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SUBMERSIBLE FANS AND PUMPS FOR CRYOGENIC FLUIDS*

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ABSTRACT

Three sizes of submersible electric motor driven fans have been designed, built and operated at 21 K at the Stanford Linear Accelerator Center. The largest is a 100 mm diameter, 2 stage vane-axial fan. Its nominal capacity is 6 liters per second at 2 meters head. It is driven by a 4 pole, 3 phase induction motor that runs at 1750 rpm. The next smaller one is an 85 mm diameter centrifugal pump. It pumps 3 liters per second at a head of 5 meters. The third one is a 75 mm single stage vane-axial fan. Its nominal capacity is 3 liters per second at a head of 2 meters. The 85 mm pump and the 75 mm fan are driven by 2 pole, 3 phase induction motors running at 3550 rpm. The motors were modified to operate submerged in the cryogenic fluid. The pumps operated in liquid hydrogen, liquid deuterium, and pressurized helium at 21 K. They can operate with denser fluids such as liquid nitrogen, but rotational speed, capacity, and head will be reduced. They have been operated in liquid helium.

INTRODUCTION

Various types of pumps and fans have been used to circulate liquid hydrogen in experimental apparatus at the Stanford Linear Accelerator Center since 1969. A submersible pump has no shaft seal so it can be incorporated in a device that has to be moved inside the vacuum tank that contains it. A static electrical feed thru is far less restrictive than an external drive motor. The fans used in previous targets were designed for circulating air, and adapted by the manufacturer for cryogenic service. Because liquid hydrogen is much denser than air, the motors had insufficient torque to run at near synchronous speed. The fans described in this report were designed to operate at near synchronous speed.

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DESIGN REQUIREMENTS

The electron beam heating of liquid hydrogen in a 650 mm Target[1] caused measurable density changes from inlet to outlet of the target even while it was circulated by a 76 mm fan.[2] In order to reduce density changes, a fan capable of higher heads and flow rates was needed. The calculated pressure drop through the existing target piping and heat exchanger is about 2.5 meters head when the fluid velocity is 3 m/s. That velocity corresponds to 5.5 L/s flow. The specific speed for a single stage pump or fan running at 1500 rpm is 56 $(\text{rpm})(\text{m}^3/\text{s})^{0.5}\text{m}^{-0.75}$.

Another target using 21K helium pressurized to 2500 kilopascals needed a means of rapidly circulating the helium through the target and heat exchanger. A flow velocity through the target of 3 meters per second was desired. The target cross section is about 11.3 square centimeters which makes the design flow rate 3.39 liters per second (54 gallons per minute). Estimated pressure drop through the complete loop is 9.5 meters of fluid being pumped. If one assumes a rotational speed of 3000 rpm, the specific speed for this pump is 32.3 $(\text{rpm})(\text{m}^3/\text{s})^{0.5}\text{m}^{-0.75}$.

A third target was equipped with a Globe VAX-3 fan that could run up to about 1000 rpm. Head and flow requirements were not calculated for this fan, but I wanted to improve its performance without major hardware substitutions.

SIX L/s, 2m HEAD, PUMP DESIGN

Since I had 3 Globe VAX 4.5 fans adapted for cryogenic service, and 10 years' experience using similar fans, I started with the intention of using them. New impellers and a new housing were required, so only the motors from the VAX 4.5 fan were used in the final design. The three phase-four pole motors have a synchronous speed of 1800 rpm when used with a 60 Hertz supply frequency.

At a specific speed of 56 $(\text{rpm})(\text{m}^3/\text{s})^{0.5}\text{m}^{-0.75}$, fans are inefficient. Using a 4 stage fan, or two 2 stage fans, the head per stage is only .625 m, changing the specific speed to 158 $(\text{rpm})(\text{m}^3/\text{s})^{0.5}\text{m}^{-0.75}$. If the motor runs at 1750 rpm, the specific speed is increased to 185 $(\text{rpm})(\text{m}^3/\text{s})^{0.5}\text{m}^{-0.75}$ which is in the region where fans are efficient. The next step was to calculate the horsepower and motor torque requirements assuming two 2 stage fans. To allow for fluid velocity head, I assumed a total head of 2 meters per fan of liquid hydrogen flowing at 5.5 liters per second. That is 0.009 horsepower (6.9 watts). With deuterium 0.018 horsepower (13.8 watts) would be required. I had no clues as to what efficiency to expect, so chose 50%. A $\frac{1}{25}$ horsepower motor with a rated torque of at least 0.18 N·m at 1500 rpm should work. A test of the motors revealed that the maximum torque that could be developed without burning out the windings was 0.14 N·m. Since the rotor was solid magnetic steel with no squirrel cage windings, slots were cut in the rotor, and copper squirrel cage windings were added. Torque and efficiency improved dramatically, making it possible to get up to 0.35 N·m torque with the new rotor. It was possible to operate warm or cold developing 0.18 N·m of torque without exceeding the current rating of the windings.

The housing is a 102 mm outside diameter tube with 1.65 mm wall thickness welded to standard 152mm (6 inch) outside diameter Conflat® vacuum flanges.

The flow area is inside the 102 mm tube, and outside the motor housing. The impeller was made 97 mm outside diameter on a 71 mm hub. 5.5 L/s flows through that annulus with a velocity of 1.6 m/s. An impeller made like a coarse screw turning at 1500 rpm would have a pitch of 64 mm per revolution. Since slippage is expected, the screw was made with 91 mm per revolution pitch. It was possible to use a 12.7 mm diameter cutter and still have a 6 bladed fan.

There are 12 straightening vanes between stages and after the second stage. The straightening vanes increase head by converting swirl to pressure by changing the direction of fluid flow. A conical plug was added beyond the straightening vanes to make a smooth transition from the flow annulus to the full area of the tube.

A tachometer generator was constructed by attaching a small horseshoe shaped permanent magnet to the motor shaft. The magnet rotates near a U shaped silicon steel laminated core wound with 2000 turns of fine wire. The resulting alternating voltage generator develops about 15 volts per thousand rpm. In the installation at SLAC, the voltage pulses are counted.

A hermetically sealed weld type connector made by the Connector Division of Gulton Industries, Inc. is used for the motor and tachometer wires. The one we use has a standard 6 pin plug making it easy to connect or disconnect the necessary wires.

The first few times these pumps were operated, they had differential pressure taps for the pumps connected in a way that read less than the total head developed by the pump. In the last installation, a pressure line is attached to the inlet side of the fan, and a bent tube acting like a pitot tube on the exhaust side of the fan. A Barton differential pressure transmitter is connected to these lines. The output is read in the control room.

These 100 mm fans were operated in series for one experiment. Motor voltage, current, and speed were logged. The flow was estimated by running one motor, and noting the speed of the other. The powered fan ran at slightly more than three times the driven fan at speeds from 300 to 1800 rpm. A log log plot of head vs flow was used for extrapolating the estimated flow with both fans running assuming the driven fan had no slip. Nominal flow was 4 L/s at 4 meters head with each fan drawing about 10 watts.

While testing the system with just one fan turning, it became evident that either fan running without the other was sufficient to prevent density changes within the target with the most intense beam the accelerator could deliver to it. For the experiment just completed in July 1985, the heat exchanger was connected so that half of it was used for cooling a hydrogen target, and the other half was used for a deuterium target. Each target used one 100 mm vane-axial fan. A flow transducer wasn't installed, but the motor voltage, current, speed, and developed head were recorded in Table 1. As expected, the deuterium target fan required more power than the hydrogen target fan. Since the heat exchanger and piping have less impedance to flow than the previous case, I estimate the flow to be at least 4 L/s when the fan is turning 1700 rpm or faster. The deuterium fan motor is loaded to its maximum at 2 amperes. At currents above 1.5 amperes, efficiency is reduced even though torque output increases at currents up to 4 amperes. Figure 1 shows a cross section of the fan.

TABLE 1
Individual 100 mm Vaneaxial Fans – Measured Parameters

HYDROGEN FAN DATA				DEUTERIUM FAN DATA			
Volts	Ampere	RPM	m Head	Volts	Amperes	RPM	m Head
4.00	0.54	516	0.11	10.0	0.74	900	0.15
5.00	0.70	720	0.27	11.0	0.82	978	0.26
6.10	0.83	942	0.52	12.0	0.91	1056	0.33
7.10	0.94	1134	0.70	14.0	1.07	1182	0.52
8.10	1.01	1308	0.97	16.0	1.22	1332	0.64
9.00	0.93	1548	1.29	17.0	1.28	1404	0.85
10.0	0.82	1662	1.51	18.0	1.33	1464	0.95
11.0	0.78	1710	1.61	19.0	1.40	1500	1.00
12.0	0.78	1734	1.61	20.0	1.50	1536	1.08
13.0	0.80	1746	1.67	22.1	1.71	1596	1.18
14.1	0.83	1758	1.67	23.5	1.91	1626	1.26
15.0	0.88	1764	1.67	24.8	2.12	1638	1.26

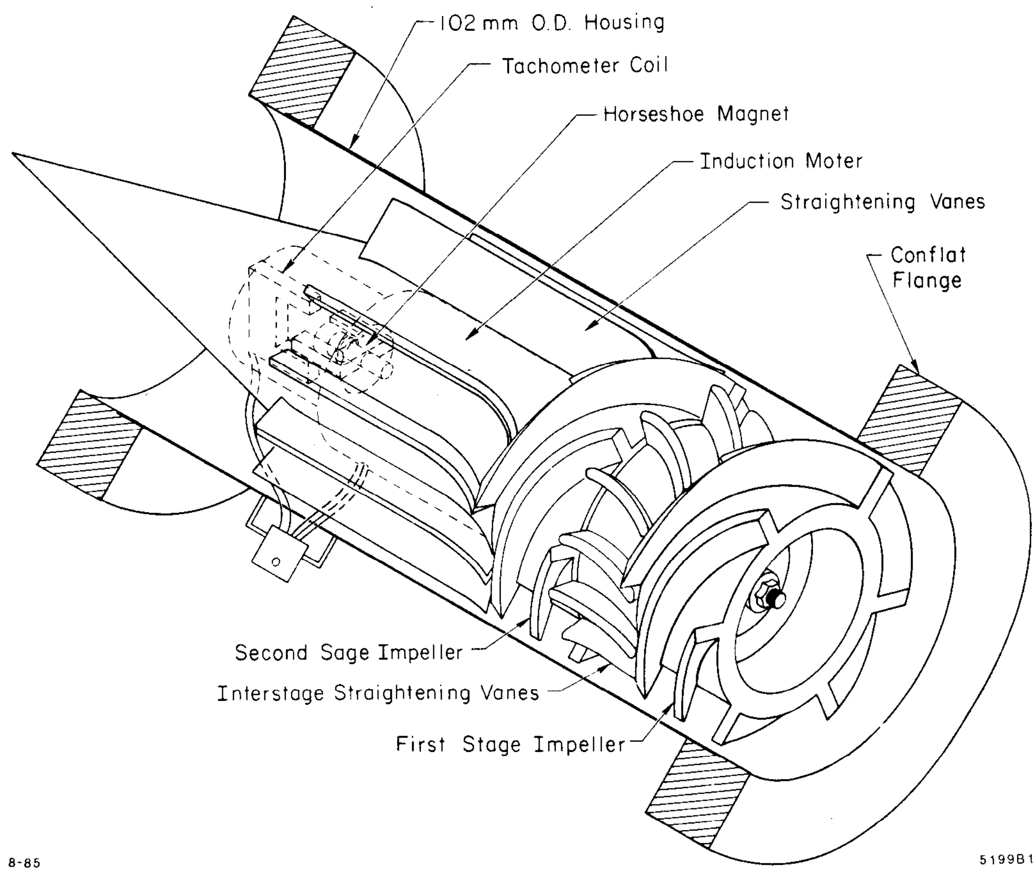

Figure 1. A 100 mm Dia. 2 Stage Vane-Axial Fan.

The target that needed this pump existed. The circulating fans on it had insufficient capacity for the beam heating planned for the experimental program. The space and location were fixed unless extensive rebuilding was undertaken, so I chose to design a pump to fit the space available. A single stage centrifugal pump works well at a specific speed of 1690 (rpm)$(m^3/s)^{0.5}m^{-0.75}$. Some fan motors are rated at 3000 rpm which I used for a design number. At 3000 rpm, the maximum head that can be developed by an 89 mm diameter impeller is 9.95 meters. At 3450 rpm that increases to 13.1 meters. Some commercial water pumps are available for these head and flow requirements, but they are not adaptable for use in liquid hydrogen. I did confirm that some of them had impellers about 89 mm in diameter. I tapered the face width to minimize changes in radial velocity. The vanes are radial primarily to allow the pump to operate the same in either clockwise or counterclockwise rotation. It is also less costly to machine radial vanes than spiral vanes.

The space available and existing piping layout had a strong influence on the housing design. I wanted the inlet on the side, and the discharge at the top, so the housing has a radial inlet and axial discharge. The inlet pipe connects to a standard 70 mm (2.75 inch) Conflat® flange. The 102 mm outside diameter tubing housing is welded to a 152 mm (6 inch) Conflat® flange.

In order to reduce flow direction changes, the impeller has a conical shape rather than straight radial. The conical design forces the flow to be a combination of axial and radial flows. The flow area through the pump is approximately the area of the inlet pipe. A cross section view of the pump is shown in Figure 2.

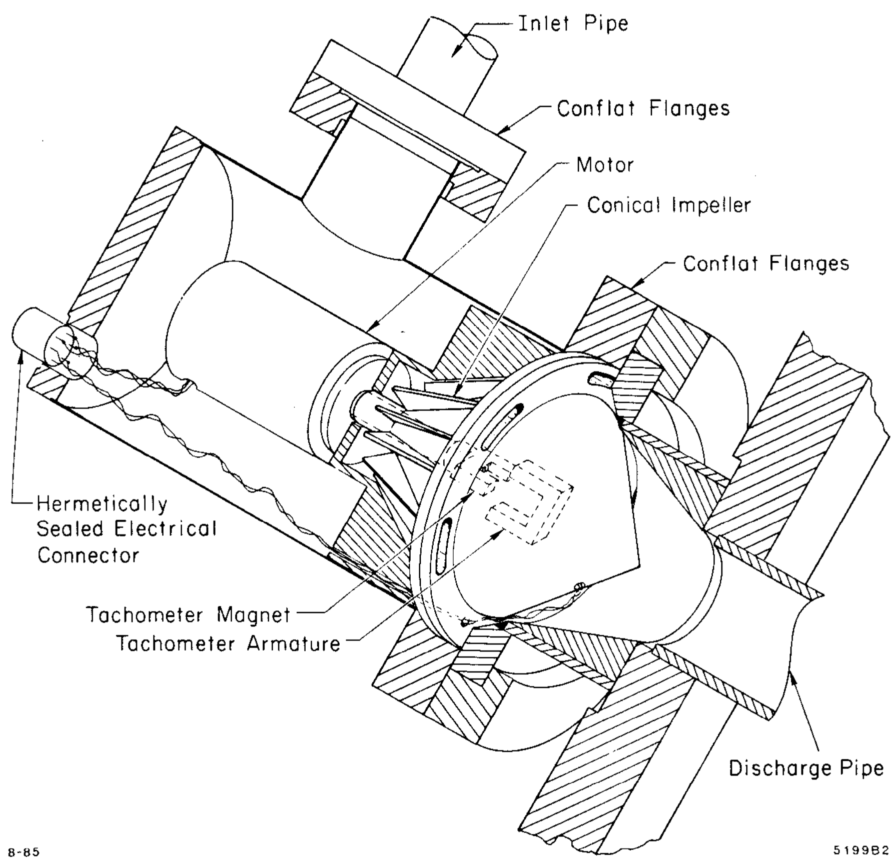

Figure 2. An 89 mm Dia Centrifugal Pump.

The hydraulic power equivalent of 185 gms/sec$\times$9.5meters is 0.023 horsepower (17.2 watts). For a 3000 rpm operating speed, the torque rating should be at least 0.042 N·m. I attempted to find a small commercial motor of that rating that I could adapt for cryogenic service. I found catalog information about several that should have been able to work, but discovered that none were stocked items. I chose to not wait for a motor to be manufactured, and looked for something of the right physical size to test. TRW Globe had a motor rated for 400 Hz at 115 volts, 0.042 N·m torque, and 65 watts. (PN 75A1004-1) I tested it with a variable voltage 60 Hz power supply. Static torque at approximately 1 amp (21.6 volts) was 0.042 N·m. It increased to 0.127 N·m at 2 amp (42.2 volts). Since the motor will operate at 21K, it appeared to be a good match for the pump. The only change necessary to operate this motor cold was to replace the lubricated ball bearings with some made for cryogenic service, and adjust the end play so that the bearings wouldn't bind when the motor case cooled, shrinking more than the shaft. The radial clearance between the rotor and the stationary parts of the motor didn't need changing. The winding insulation was not adversely affected by the low temperature.

The tachometer design is the same as the vane-axial fan tachometer.

The motor ran easily at nearly 3600 rpm drawing about 0.4 ampere at a voltage of 8 to 12 volts circulating pressurized helium gas. The differential pressure taps did not measure the total head. I estimate the total head to be about twice the measured head of 134 mm of water which is 2.5 meters of the helium pumped. If the developed head in that run was 5 meters, and the power used about 0.009 horsepower (7 watts), the flow rate would be no more than 2.6 liters per second. Either the impedance of the circuit is much less than estimated, or pump performance is much less than hoped for. The easiest way to increase the pump performance is to run it faster. A power supply of higher frequency is necessary to accomplish that. Fluids that are up to 4 times more dense than the pressurized helium will not overload the motor. In a test in an open dewar of liquid nitrogen, it was able to turn up to 2220 rpm while drawing 3.75 amperes at 35.0 volts. The total running time of 44 days was completed without any change in performance or measurable change in bearing behavior.

MODIFICATION OF THE VAX-3-FC FAN

The Globe TRW VAX-3-FC fans that we have been using for many years were equipped with 2 pole, 3 phase windings and solid rotors they use in their hysteresis synchronous motors. The propeller pitch is about 150 mm per revolution. Since the motor did not have enough torque to spin the propeller faster than 1100 rpm in liquid hydrogen, and about 900 rpm in deuterium, I made new impellers like a double pitch screw. The outside diameter is 68 mm with a 44.5 mm hub. The pitch is 25.4 mm per revolution. The maximum displacement then is 55.4 cm^3 per revolution. At 3500 rpm displacement is 3.2 L/s. I replaced the solid rotor with an induction motor rotor identical to the one supplied for the motor of the centrifugal pump. Torque and efficiency improved dramatically as in the case of the two stage fan motor. With this combination of propeller and motor the fan ran easily at 3600 rpm pumping liquid hydrogen through a 50 mm diameter target and its heat exchanger. The motor current was 0.90 ampere at 12.0 volts. The pressure head was 1.8 meters of liquid hydrogen, at an unknown flow rate, presumably a large fraction of the 3.2 L/s displacement. (10 watts is the power required for pumping 8 L/s against a 1.8 meter head.) Deuterium requires just twice the power of hydrogen, but otherwise should be the same. It appears that the motor could handle a coarser pitch propeller or operate at higher speeds with a higher frequency power supply.

SUMMARY

With minor modifications, some electric motors can operate very well in liquid cryogens. The advantages of avoiding a long shaft and shaft seal with a warm prime mover more than offset the disadvantage of the heat generated by a submerged electric motor in the applications at SLAC. Typical electrical inputs are 10 to 15 volt-amperes for the motors discussed in this report. I have not used a watt meter to measure power consumed. Since these motors are used to stir the cryogen being heated by the accelerator electrons which deposit up to 300 watts in the cryogen, heat generated by the motor is not of major concern.

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