Pumping and the vacuum furnace

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The second installment of our series on practical aspects of vacuum heat treating focuses on the critical subject of pumping, highlighting the relationship between efficiency and vacuum pressure.

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It's not widely known that a mechanical vacuum pump operating at a pressure 100 times greater than its blank-off pressure is, in fact, pumping only a fraction of its rated capacity, usually stated at atmospheric pressure. This is an exact relationship to the Ideal Gas Law, pv = RT*.

For example, a common vacuum pump in the industry, a Stokes Model 412 vacuum pump, has a nominal rating of 300 cfm at atmospheric pressure. **Fig. 1** is a pumping speed curve from the company's catalog. Data from this curve indicates pumping speed, cfm rating, at a specific pressure and not at standard conditions or atmospheric pressure. All vacuum pump manufacturers, including Roots blower and diffusion pump manufacturers, publish their data in a similar manner.

What is assumed is that the standard gas laws are applied, and one corrects the data back to atmospheric conditions to realize cfm rating at standard conditions. **Fig. 2** is such a curve, and **Table I** is a list of points as an example of actual pumping capacity in terms of atmospheric conditions.

Fig. 1: Stokes Model 412 pumping speed curve

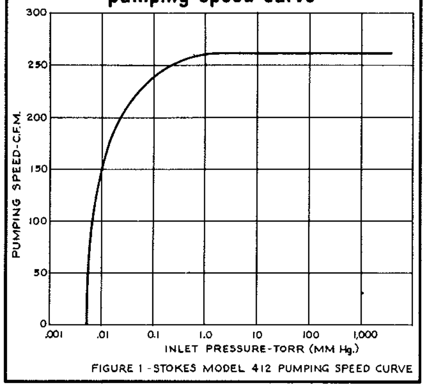
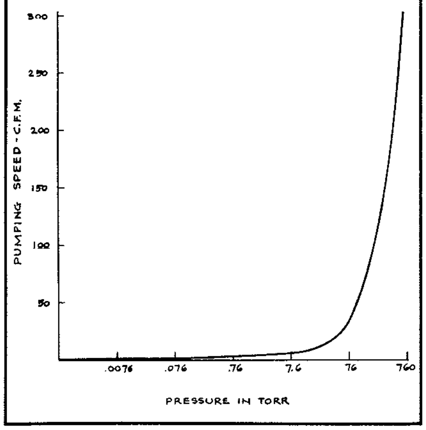


Fig. 2: Pumping speed in terms of atmospheric pressure



Blank-off condition, or that pressure below which the vacuum pump will no longer pump and is in equalibrium condition with the vacuum pump fluid and its mechanical tolerances, is about 10 microns Hg for this particular vacuum pump. Going up 100 times in pressure to 1,000 microns Hg, or 1 Torr (a poor pressure level for the vacuum furnace unless operating in the partial pressure mode), the vacuum pump operates at 1/1,000 of its atmospheric pressure rating, or a gas flow of 0.3 cfm/(18 cfh)—a very small gas flow indeed, considering the size of this vacuum pump.

A way to improve the pumping speed of the vacuum pumping system is to add a Roots-type vacuum booster (blower) that operates as a supercharger to the vacuum pump (as in a full blown blower in a race car). **Table II** shows the improvement with the addition of a 1,600-cfm rated (standard conditions) Roots blower in front of, and in series with, the 300-cfm mechanical vacuum pump **(Fig. 3)**.

Table I
Mechanical vacuum pump rated at 300 cfm

	Flow (standard conditions)	
Pressure	**cfm**	**cfh**
760 Torr (atm.)	300	18,000
76 Torr (.1 atm.)	30	1,800
7.6 Torr (0.1 atm.)	3	180
0.76 Torr (.001 atm.) or 760 microns Hg	0.3	18
0.076 Torr (.0001 atm.) or 76 microns Hg	0.03	1.8
0.0076 Torr (.00001 atm.) or 7.6 microns Hg	0.003	0.18

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*Ideal Gas Law: At low pressures and high enough temperatures, in the absence of chemical reaction, all gases approach a condition such that their P-V-T properties may be expressed by the simple relation

$$pv = RT$$

If v is expressed as volume per unit weight, the value of the constant R will be different for different gases. If v is expressed as the volume of one molecular weight of gas, then R_u is the same for all gases in any chosen system of units. Hence $R = R_u/M$. *Mark's Standard Handbook for Mechanical Engineers, 8th Edition*

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Table II
300-cfm mechanical vacuum pump supercharged with 1600-cfm Roots vacuum blower

	Pressure	Flow (standard conditions) cfm	 cfh
	760 Torr (atm.)	300	18,000
	76 Torr (.1 atm.)	30	1,800
	7.6 Torr (.01 atm.)	16	960
Roots Blower On	0.76 Torr (.001 atm.) or 760 microns Hg	1.6	96
	0.076 Torr (.0001 atm.) or 76 microns Hg	0.16	9.6
	0.0076 Torr (.00001 atm.) or 7.6 microns Hg	0.016	0.96

Fig. 3: Booster pump in-line with vacuum equipment

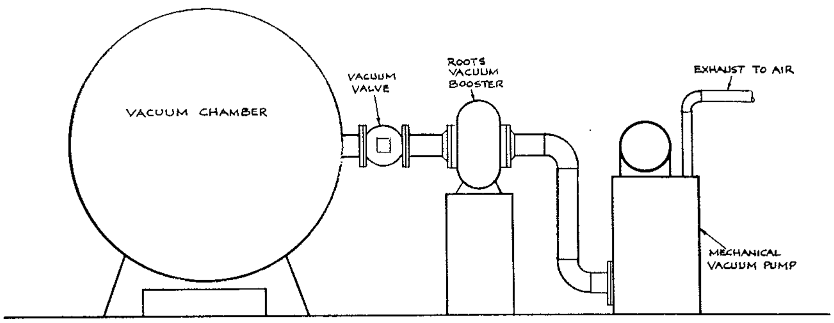


Fig. 4: Booster pump in-line with diffusion pump

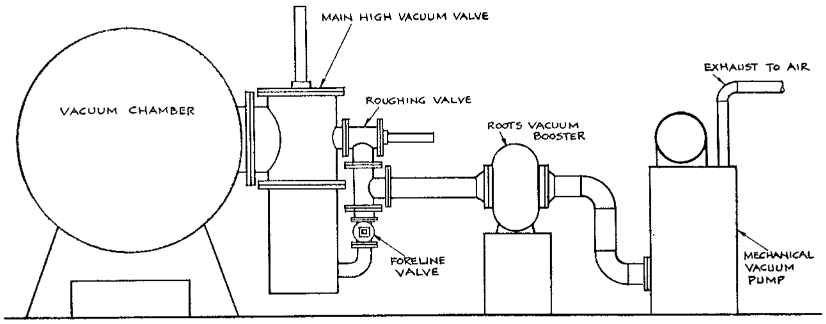


Table III
16-inch diffusion pump rated 10,000 liters/second

Pressure, Torr	Flow at atmospheric pressure Ltr/Sec	 Ltr/Hr	 cfh
1×10^{-3} Torr (1 micron Hg)	.01	36	1.27
1×10^{-4} Torr (.1 micron Hg)	.001	3.6	0.127
1×10^{-5} (.01 micron Hg)	.0001	0.36	0.0127
1×10^{-6} (.001 micron Hg)	.00001	0.036	0.00127

The Roots blower cannot be turned on at atmospheric pressure or an overload condition will occur; thus, the vacuum blower is started at a pressure below 10 Torr. In a design preferred by VFS, a second Roots vacuum blower is added to further supercharge and improve the overall system pumping speed.

When pumping into the high vacuum range (below one micron Hg) with a diffusion pump, the same is true (see **Fig. 4**).

A Varian 16-inch diffusion pump (common to the industry) is rated at 10,000 liters per second from the catalog (see **Fig. 5**, p. 38). Converting back to a rating similar to the ones shown in the other tables and to standard conditions gives the data shown in **Table III.**

The obvious is often overlooked. That is, as the pressure goes down, the vacuum pumps are pumping an ever rarified gas, making vacuum pumping a very inefficient and difficult job. To emphasize this point, the above data for the diffusion pump was purposely presented in the decimal system rather than in standard scientific notation (i.e., powers of 10). For the purpose of this presentation, pumping speeds have not been corrected for vacuum pump efficiency at reduced pressure, vacuum conductance losses for pumping lines, valves and traps, which all unfortunately further reduce the net pumping speed of the vacuum system.

This data is not at all new or startling to the vacuum engineer, but can be easily overlooked by one new to the field of vacuum heat treating, and can be sobering even for one with years of experience in the field.

However, what is dramatic is the poor net pumping speed of the system, resulting in the need for an absolutely leak-tight vacuum chamber, doors, power seals, and shaft feed-throughs. Even a slight air or water leak will overpower the vacuum pumps and cause the vacuum level to rise decades in pressure. Therefore, proper attention to details of seal design, types of vacuum valves, vacuum pump sizing, and welding technology is of absolute importance. Leak detection of all joints, welds, seals, valves, pumps, the vessel and the total system must be carried out with a sensitive and calibrated helium mass spectrometer and with an experienced technician. Further, leak detection is tricky at best and an art at the least.

After a system is assembled and leak tested, the final test is a pressure rise or leak rate check. That is, after complete vacuum pumpdown and outgassing, the vacuum pumps are valved off and the furnace allowed to leak back toward atmospheric pressure and the pressure logged against time (see **Fig. 6**, p. 38).

For processing critical superalloy work, a leak rate of less than 5 microns Hg per hour may be specified. For less critical work such as heat treating tools and dies, a leak

Fig. 5: Varian 16" diffusion pump speed curve

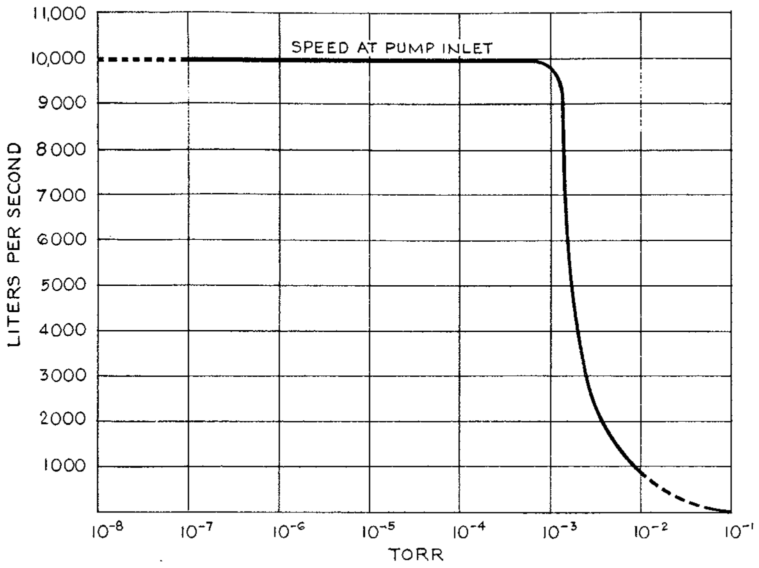
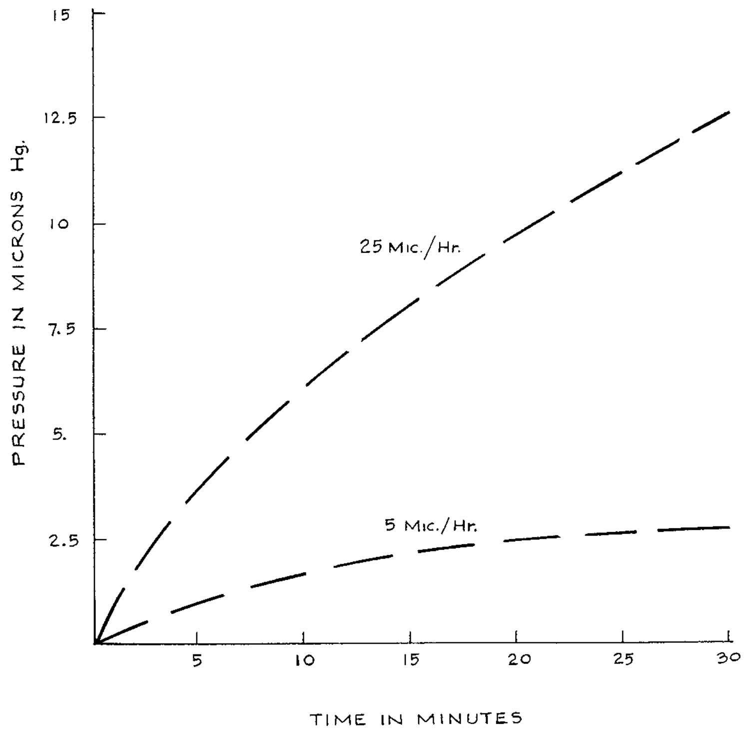


Fig. 6: Typical leak rate curves



rate of 25 microns Hg per hour would be an upper limit. However, the final test is the leak-rate, or pressure-rise, test; failure to detect leakage with other tests simply means the *leak has not been found.* For example, water leaking from a double wall vessel, heat exchanger, or power terminal will often elude a helium leak detector and different techniques must be utilized to isolate and locate this water in-leakage. Vacuum leaks that occur only when the furnace is at elevated temperature, causing expansion of cracks and allowing water or air to enter the vacuum, present another challenge to the vacuum technician. Fortunately, with today's modern vacuum furnaces and with the experience of the industry these situations are becoming rare.

Since the vacuum pumping system has limited pumping speed, the design of the furnace hot zone must compensate. The use of undue quantities of hygroscopic materials, such as alumina felt, that absorb moisture on exposure to air, and then on vacuum pumpdown and heating release water vapor to the vacuum environment, is to be avoided. A classic example is an overinsulated furnace whose vacuum performance is destroyed, particularly performance at temperatures in excess of 1200°F, where outgassing of hygroscopic materials occurs. Residual gas analyzer data indicates that water vapor is the predominant gas load even when operating at high vacuum conditions and temperatures above 2000°F. The preferred design is one that compromises between furnace energy losses and vacuum integrity.

It should be well noted that every time the vacuum furnace is opened for unloading or reloading of work, the hot zone and the vacuum chamber are exposed to air and the humidity of the atmosphere. Water vapor is poison to the vacuum furnace and contaminates the hot zone even with a one-minute exposure to our normal workaday environment. This happens every time the furnace is loaded and unloaded in production operations and even in a laboratory environment; even in a lab, there is *no such thing* as "clean, dry, and empty." (Standing open for long periods further aggravates contamination; therefore, the vacuum furnace always should remain at least pumped down to a partial vacuum in the micron Hg range.)

So the performance of a vacuum furnace must take into consideration everyday production operation, not a one-time acceptance test preceded by hours of full vacuum conditioning, back-filled with dry nitrogen to atmospheric pressure, and repumped-down and timed to satisfy an inspecting engineer. **HT**

Editor's note: The next article in this series will discuss the use of purging gas to sweep the stagnant gas remaining in the hot zone after a cycle.