OPTIMIZING GAS QUENCHING

Gas type and pressure, blower motor power, and furnace design features are among the important factors to consider when choosing a vacuum furnace gas quenching system.

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The need by heat treaters to boost productivity and improve metallurgical properties while minimizing environmental impact lead vacuum furnace manufacturers to place increased emphasis on enhancing gas quenching performance. To achieve this goal, a better understanding of gas cooling fundamentals was first acquired and then applied to such variables as gas type, pressure, and flow rate. The result: dramatic improvements in gas quenching over the past decade.

Historical perspective

Since the mid-1960s, vacuum gas quenching furnaces have emerged as a leading thermal processing technology. Rapid gas quenching in vacuum furnaces using argon, nitrogen, or helium media has replaced water, oil, and liquid salts in the heat treating of many stainless steels, high-temperature alloys, and tool steels. (In the process, the quenching gas is backfilled into the vacuum furnace and recirculated through a convection-dominated, water-cooled heat exchanger.)

Present vacuum furnace technology provides gas quench capability at pressures of 2 to 20 bar (15 to 285 psig). In the United States, pressures in the 2 to 10 bar (15 to 135 psig) range prevail. Gas velocities in use today are five to seven times greater than those common 10 to 15 years ago.

Benefits: Gas quenching in vacuum furnaces has several ad-

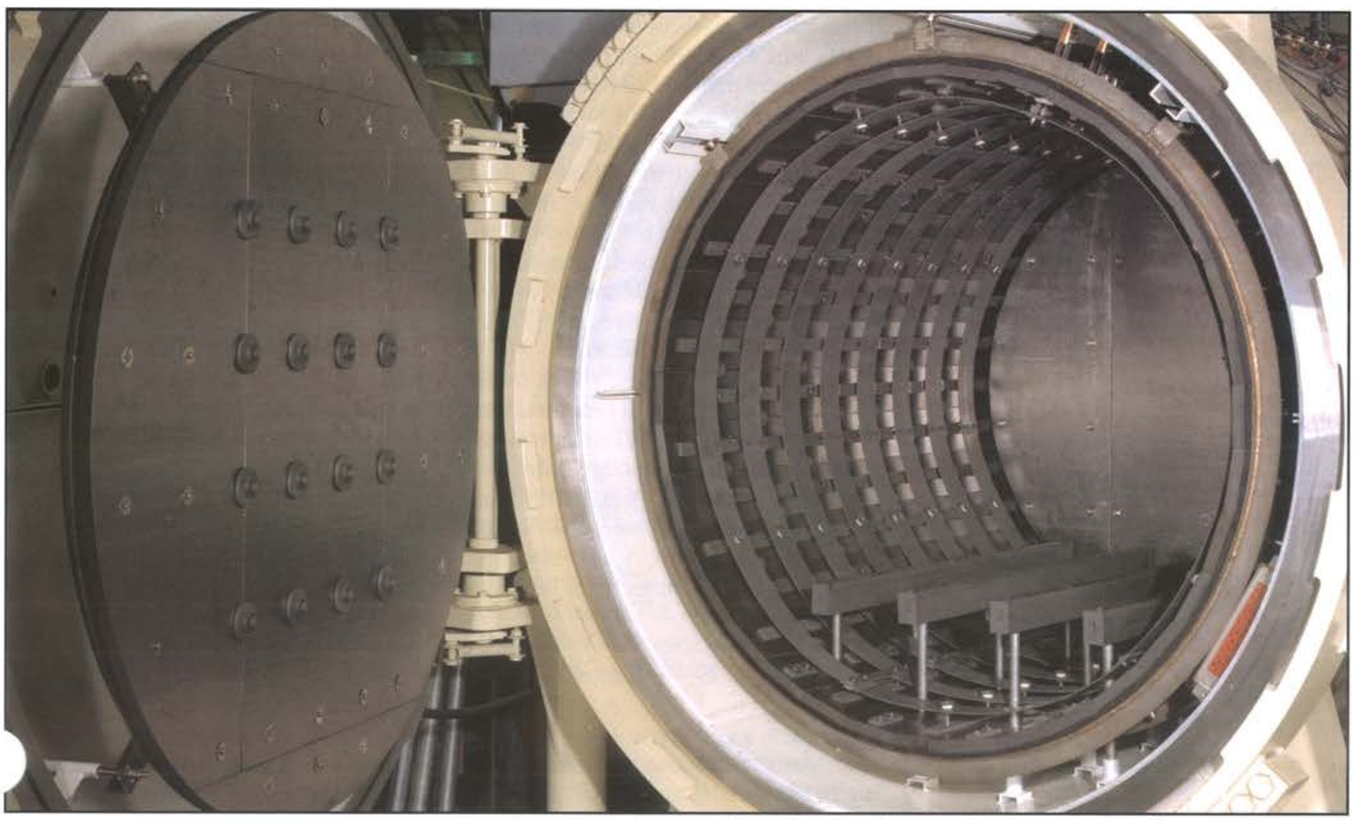

Fig. 1 — The interior of a VFS vacuum furnace. Furnace size, the efficiency of its water-cooled heat exchanger, and the ease of gas flow through furnace and workload can affect gas quenching performance. For example, cooling tends to be faster in smaller furnaces.

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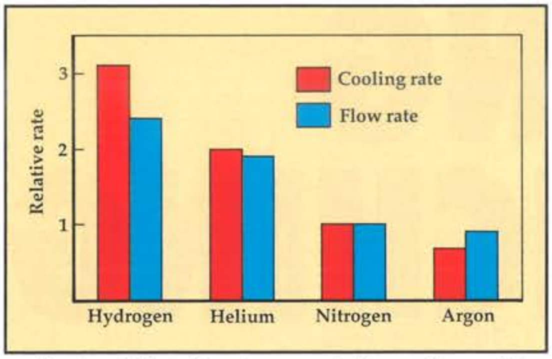

Fig. 2 — Effect of gas type on relative cooling and flow rates at constant gas pressure and blower motor power.

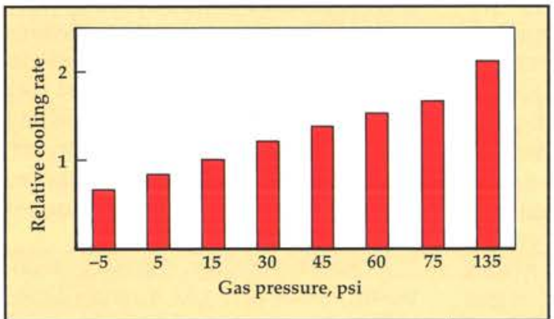

Fig. 3 — Effect of gas pressure on relative cooling rate at constant blower motor power. (Note: psi X 0.06895 = bar.)

Gas quenching in vacuum furnaces has replaced conventional liquid quenching in many applications.

vantages over conventional liquid quenching systems:

- Flexibility to change cooling rates easily, and even within a single cycle. Gas quenching can produce full hardness in many steels that were formerly oil quenched. In liquid quenching, where the cooling rate is fixed, multiple baths would be needed.
- Can use microprocessor-based controls and directed gas flows to maintain cooling uniformity.
- An ability to more precisely control heat-up and quench rates helps raise productivity and minimize distortion.
- Gas quenched parts are clean and scale-free.
- Processing in vacuum furnaces produces no toxic or combustible waste gases, which makes it safer and more environmentally friendly than many liquid quenching processes.

Role of cooling coefficient

There are three primary factors that govern heat transfer in vacuum furnaces: the cooling or heat transfer coefficient, H; the difference between the temperature of the load and the recirculated gas; and the surface area of the load exposed to the gas. Because the temperature difference and surface area factors remain constant (or almost constant) for a specific application and heat treating process, the only way to significantly affect cooling rate in gas quenching is to alter the cooling coefficient.

The cooling coefficient is a measure of the rate of heat removal per unit area per degree of temperature. It also is commonly used to compare the cooling characteristics of furnaces. For general comparisons of vacuum furnace gas cooling processes, the cooling coefficient can be expressed as:

$$H = kGS^{0.47}(HP)^{0.23}F,$$

where k = a constant, G = gas type coefficient, S = quench pressure, HP = gas blower horsepower, and F = furnace coefficient.

Quenching gas: The cooling coefficient is significantly influenced by the type of gas used for quenching. The relative cooling rates of hydrogen, helium, nitrogen, and argon are plotted in Fig. 2. The chart tells us, for example, that for a given furnace and blower and constant gas pressure, helium will cool a given workload twice as fast as nitrogen.

Blower horsepower: It is critical to note that a change from one cooling gas to another requires a change in the blower fan to maintain constant motor horsepower. For example, a furnace designed for nitrogen quenching at 6 bar will not cool twice as fast after a simple substitution of helium. The lighter helium gas will not "fully load" the fan motor that was sized originally for nitrogen. In this example, the furnace would be backfilled to 6 bar with helium, but the motor would run at only 14% of full current. The net effect: an improvement in cooling performance of only about 25%.

The effect of blower horsepower can be better appreciated by applying the cooling coefficient equation. Relative values of H for various gas blower powers (in horsepower) are:

Blower power, hp	Relative cooling coefficient, H
50	0.85
100	1.0
150	1.1
200	1.2
300	1.3

Thus, if all other factors for a given furnace are constant, doubling fan power will increase cooling performance by roughly 20%. Since fan size or displacement will increase to utilize the higher available power, actual gas flow or velocity also will rise. In this case, fan power can be viewed as another way to indirectly approximate gas velocity.

Furnace design: Cooling performance is also directly influenced by furnace design factors. Examples: the relative ease of gas flow through the furnace and the workload, the efficiency and effectiveness of the water-cooled heat exchanger, and the size of the furnace.

With all other variables held constant, relative cooling performance increases with decreasing furnace size. For example, our Model HL26 x28 cools roughly 55% faster than the larger HL36x38, while the even larger HL50x50 cools at only 65% of the HL36's rate. (Note: The numbers in the furnace model designations indicate the approximate heating element diameter and the depth of the hot zone, both in inches.)

Gas pressure: The strong influence of gas quench pressure on relative cooling rate is shown in Fig. 3. Higher pressures increase the rate. With all other factors remaining constant, a doubling of gas quench pressure will boost cooling performance by about 40%.

Assessing furnace performance

During a recent trial for a customer who processes tool and die materials, we came up with a meaningful test for comparing the gas quenching performance of different furnaces. Using readily available materials, we devised a 3000 lb (1360 kg) load that simulated a load of hot forging dies. This standard test load is illustrated in Fig. 4. (Note: This is not an ideal arrangement for production heat treating, because the larger, flat pieces on the bottom prevent the cooling gas from impinging on much of the load.)

The test load was heated and nitrogen-gas quenched at 6 bar in both a VFS and a competitor's vacuum furnace. The performance of our furnace was so disappointing that we made significant modifications to it at no cost to the customer. The result: a 25% improvement in cooling performance.

Figure 5 shows the cooling curves for tests run in our customer's VFS furnace before and after it was modified. Also plotted is an average cooling curve for a newer VFS furnace of the same size. The performance improvement is dramatic. The cooling curves in Fig. 6 show that the performance of this 6 bar furnace compares favorably with that of a competitor's 5 bar furnace.

Special test loads are used to compare the cooling performance of different furnaces.

Also plotted in Fig. 6 is the cooling curve for our newest 10 bar furnace. This furnace was equipped with a variable-speed drive system for the gas blower. During these tests, the drive was programmed for a very slow ramp-up of about 70 seconds to full speed. In production, the ramp-up time would be set at less than 10 seconds.

Another "standard" test load that we use for comparing furnace cooling performance is the 1500 lb (680 kg) bar load illustrated in Fig. 7. By following this "map" we can easily reproduce the load from test to test, enabling the direct comparison of results. Thermocouples 1,2,3,4, and 5 are inserted in 1 in. (25 mm) diameter steel heat sinks; Thermocouples 6 and 9 are inserted in 3 in. (75 mm) diameter steel bars; Thermocouple 7 is inserted in a 2 in. (50 mm) diameter steel bar; and Thermocouple 8 is left uncovered in the center of the bottom basket.

Cooling curves developed from Thermocouple 7 readings for loads nitrogen gas quenched in 10 and 6 bar furnaces are plotted in Fig. 8. Note the effect of the slow ramp-up rate for the variable-drive gas blower in the 10 bar furnace.

'Obstacles' to gas quenching

Plotted in Fig. 9 is a series of cooling curves for nitrogen gas quenching of a 1000 lb (455 kg) load of Schedule 40 steel pipe. The curve

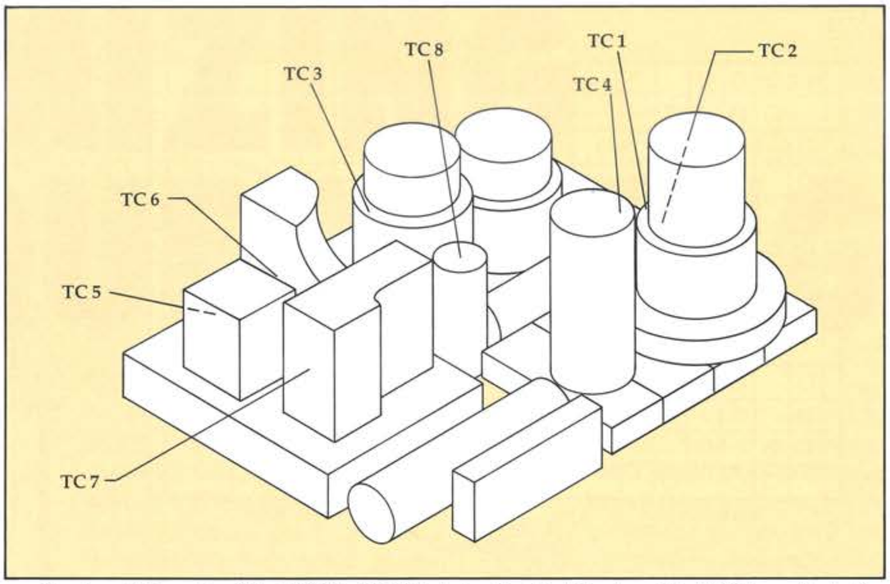

Fig. 4 — Schematic of the 3000 lb (1360 kg) standard test load used by VFS to evaluate the effectiveness of gas quenching systems. (TC = thermocouple.)

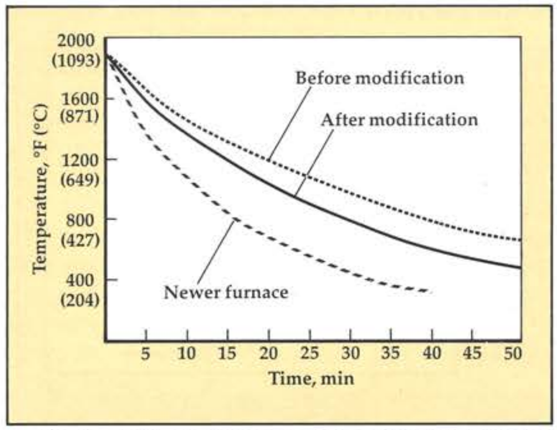

Fig. 5 — Data for 6-bar quenching of 3000 lb (1360 kg) test loads in a customer's VFS furnace before and after it was modified. An average cooling curve for a newer VFS furnace of the same size also is given.

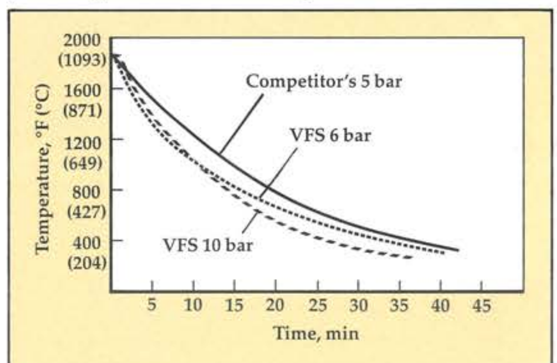

Fig. 6 — Cooling curves for a 6 bar VFS furnace ("newer furnace" in Fig. 5), a competitor's 5 bar furnace, and the most recent VFS 10 bar furnace. The data were developed using the 3000 lb (1360 kg) test load.

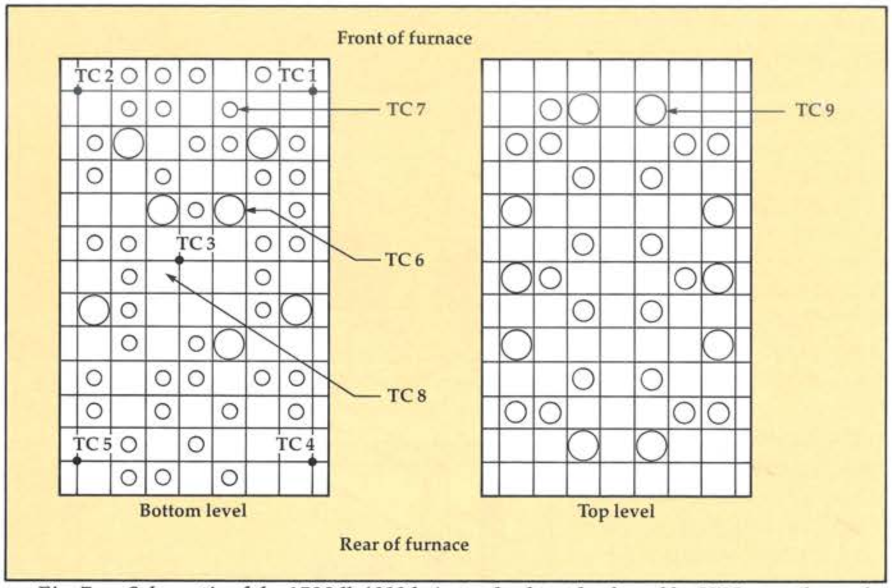

Fig. 7 — Schematic of the 1500 lb (680 kg) standard test load used by VFS to evaluate the effectiveness of gas quenching systems. Small and large open circles indicate locations of 2 in. (50 mm) and 3 in. (75 mm) diameter steel bars, respectively. (TC = thermocouple.)

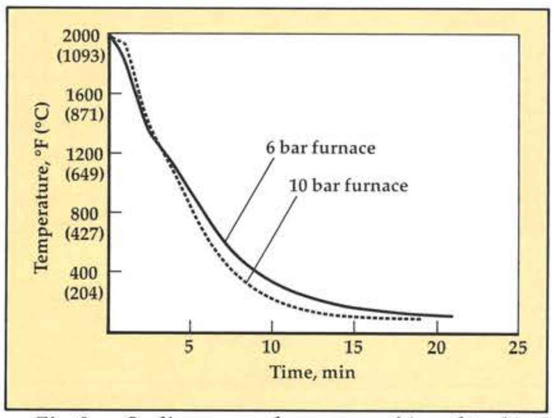

Fig. 8 — Cooling curves for gas quenching of steel in 6 and 10 bar furnaces, developed using the 1500 lb (680 kg) standard test load. The temperature profiles represent the center of a 2 in. (50 mm) diameter bar.

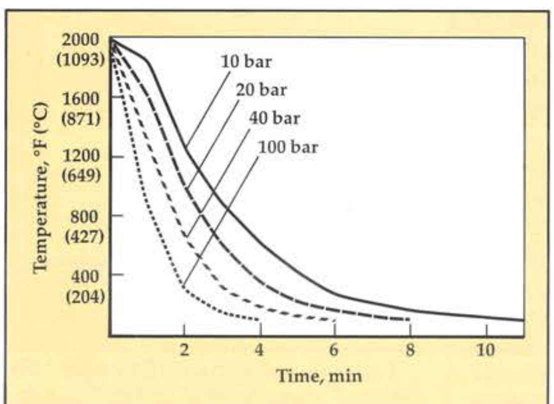

Fig. 9 — Quenching at various gas pressures of a 1000 lb (455 kg) load of Schedule 40 steel pipe. The cooling curve for the load quenched at 10 bar is actual; the other curves are calculated from it.

for 10 bar nitrogen gas is the average of nine thermocouples positioned throughout the load. The other curves were calculated from the 10 bar data assuming that everything remains constant except gas pressure. These curves dramatically show that higher gas pressure alone will not be enough to eliminate the need for oil quenching of certain alloys, for most operators will find it impractical to use equipment at sufficiently high pressures to match liquid quench rates.

This becomes especially evident when several of the "obstacles" to high-pressure gas quenching are considered. For example, to rapidly backfill the furnace, the heat treater requires a large volume of gas at a pressure substantially higher than the desired quenching pressure. The usual approach is to position one or more high-pressure gas storage vessels next to the furnace and use a compressor to boost the normal gas pressure up to the required storage pressure.

Some operators also have experienced erosion of hot zone materials with increasing gas pressure and turbulence. Furnace manufacturers have learned that high-pressure gas quenching requires careful selection of materials and design parameters to avoid or minimize this effect. To minimize premature wear and distortion (and associated maintenance and downtime) vacuum furnaces that have few or no moving parts in the hot zone are preferred.

What the future may hold

Better understanding and application of heat transfer fundamentals will lead to additional improvements in gas quenching technology. Theoretically, there is no limit to the increase in cooling rate that can be achieved by boosting gas velocity and pressure. However, the feasibility of constructing extremely high-pressure, high-velocity systems is constrained by economic considerations and the complexity of the technology involved. Gas quenching pressures in the United States are certain to exceed 10 bar, but there will be a practical limit.

Helium-argon or helium-nitrogen mixtures are routinely used by a growing number of heat treaters, and this trend is likely to continue. The development and commercialization of a relatively inexpensive helium recovery system would significantly increase the use of helium.

Increasing blower motor horsepower is not likely to play a significant role in achieving faster quenching, because most vacuum furnace manufacturers are already using very large systems. Size, cost, and energy consumption considerations also discourage the use of much larger drives.

Modifications to furnace design, however, offer possibilities for significant advances in gas quenching performance. Innovative ways to optimize gas flow and heat transfer, to provide both *uniform* and *rapid* quenching, are being studied. **HTP**

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