High Gas Velocity: A New Frontier of Cooling Performance in Vacuum Furnaces

Robert Hill Jr., Solar Atmospheres of Western Pennsylvania, Hermitage, Pa.

Because there are diminishing returns in cooling capacity by simply increasing quench-gas pressure, increasing gas velocity might be the answer to the problem.

The popularity of vacuum processing various materials continues to grow every day. The vacuum furnace is no longer a piece of equipment located in some remote corner of a shop, operating only when the need arises. As vacuum furnace suppliers continue to improve their gas cooling designs, metallurgists are afforded the opportunity to process a greater variety of materials in a vacuum furnace that might never have been envisioned even five years ago.

As the gas cooling parameters are increased, better martensitic microstructures are obtained. In addition, materials traditionally "liquid quenched" are being added to the "gas quenching capability" list. Therefore, bright, clean, environmentally safe shops are now within all of our futures, replacing the old smoke-filled, oil-laden, flame-shooting and soot-producing facilities.

Pressure vs. velocity

The "bar war," or "pressure war," continues to be the main battle fought by many furnace manufacturers. For increased cooling, some furnace companies are promoting 20-bar, 40-bar and even 100-bar furnaces. As we continue to search for an increase in cooling rates, increasing pressure is only a partial answer. Figure 1 shows that the increase of pressure is not a linear function, so there is a point of diminishing return. So where does the design engineer look next? Increased gas velocity is one answer to this question.

To increase gas velocity, we must overspeed our blower motors. With many gases, particularly argon, the motor current due to the heat of compression of the heavy gas are immediately at the maximum amperage. Therefore, the majority of the blower motors on most vacuum furnaces operate at 3,450 rpm. Using a very light gas (helium) together with a variable frequency drive arrangement enables driving motors at 5,000 rpm. The gas speed exiting the cooling nozzles now exceeds 100 mph (160 kph).

A look at the physical properties of gases used for quenching in the table below illustrates why this is possible.

	Density, kg/m³	Spec. heat cap., J/kg · K	Therm. Cond., W/m · K
Argon	1.669	0.0173	523
Nitrogen	1.17	0.0255	1,040
Helium	0.167	0.1536	5,790
Hydrogen	0.084	0.175	14,300

Properties at 15°C, 1 bar

The properties of helium enable high velocity quenching. The low density of the helium molecule produces a high heat capacity and a high thermal conductivity—six times higher than that of nitrogen. The worst quench gas is argon, and the best quench gas is hydrogen. However, there are many critical safety issues to overcome with the use of hydrogen as a quench gas.

Solar Atmospheres has conducted experiments with respect to the explosivity of hydrogen (see Sidebar) at subatmospheric pressures. At the time of this writing, Solar is convinced that the safety issues concerning hydrogen can be resolved with further study. Hydrogen may be an answer to the problem of declining helium resources in the U.S.

Clean plant environment typical of shop with vacuum furnace equipment

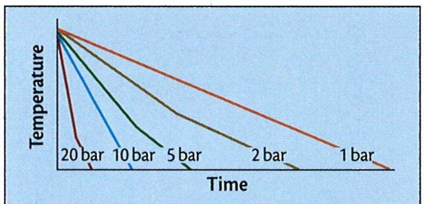

***Fig 1** The benefits of increased cooling capacity with increasing quench gas pressure follow the rule of diminishing returns.*

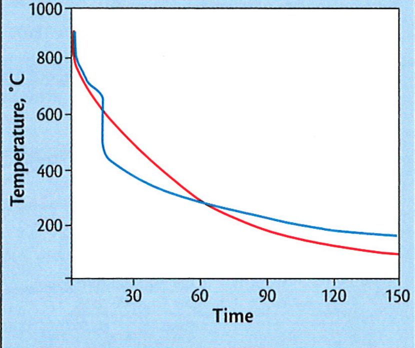

***Fig 2** Typical cooling curves for gas and oil quenching*

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Gas quenching offers minimal distortion

The main reason metallurgists would rather gas quench versus liquid quench is to minimize distortion. Figure 2 shows the typical cooling curves for gas and oil quenching. The oil-quenching curve exhibits the three distinct phases of liquid quenching; vapor phase, vapor transport phase, followed by convective cooling. The gas-cooling curve, on the other hand, is one continuous convective cooling curve. Therefore, minimal distortion and the elimination of cracking occur with the gas quenching process.

Performance vs. cost

While helium is more expensive than other gases used in vacuum heat treating (four times more than argon), it offers benefits that can often offset its higher cost, such as in power consumption, as shown below:

N/Ar mix - draws full motor current
300-hp motor = 300 kW
= $30/h @ $0.10/KWH
He - draws ~1/3 motor current
300-hp motor = 100 kW
= $10/h @ $0.10/KWH

Helium draws approximately one third of the power of nitrogen or argon at full motor current. The payoff occurs when using helium for cooling cycles with very large and heavy loads (Fig. 3). Electric power savings coupled with the improvement in production time and freeing the furnaces for higher revenue generation makes helium a very attractive process gas.

	Cost to backfill	Cost of electric per hour	Total cost
2 Bar argon	$220.00	$60.00	$1,300.00
2 Bar nitrogen	$20.00	$60.00	$620.00
2 Bar helium	$369.00	$24.00	$489.00

Fig 3 Cooling time using 2, 300-hp blower motors: 18 hr (Ar), 10 hr (N), 5 hr (He)

Cooling tests

Solar performed different tests to determine the exact cooling improvements achieved using increased gas velocities. A test was performed in each furnace at 10-bar nitrogen at nominal motor speeds (4,200 rpm). Another cooling test was performed to compare the improvement in cooling using helium at the same motor speed. Finally, a designed experimental test was performed, which consisted of over-speeding the motor at 5,000 rpm using helium at 10-bar pressure. The test load (Fig. 4) consisted of 18 bars 3 in. OD × 12 in. long (76 × 305 mm), each weighing 25 lb (11 kg) for a total weight of 450 lb (205 kg).

Thermocouple holes were drilled to a depth of 3 in. (76 mm) at three locations within the load; front, middle and rear. The identical load was processed in a 10-bar HL24 100-hp blower motor vacuum furnace (Fig. 5a) and a 10-bar HL36 200-hp blower motor vacuum furnace (Fig. 5b).

Results

The smaller chambers produced faster cooling rates (Figs. 6a and 6b). Cooling data from 2000 to 1000°F (1095 to

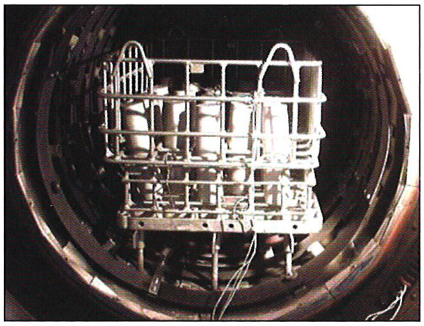

Fig 4 Test loads used to determine improvements of quenching using higher gas velocities

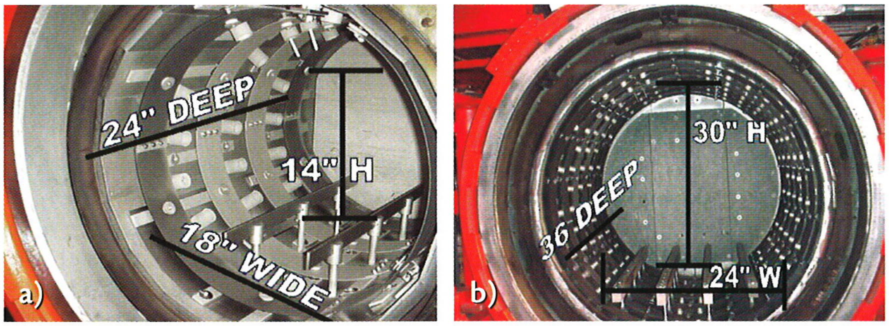

Fig 5 Vacuum furnaces used for cooling tests: 10-bar, 100-hp blower motor (a) and 10-bar, 200-hp blower motor (b)

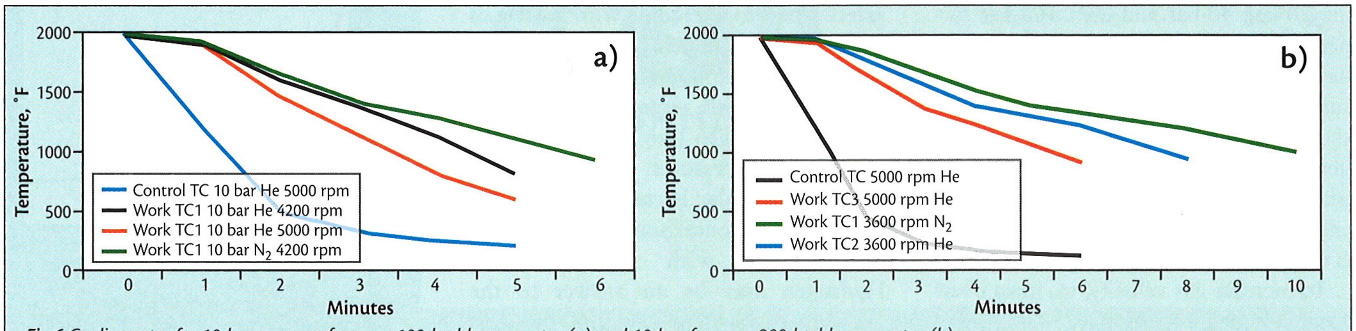

Fig 6 Cooling rates for 10-bar vacuum furnace, 100-hp blower motor (a) and 10-bar furnace, 200-hp blower motor (b)

540°C) at nominal motor speeds show there is an approximately 25% increase in cooling using helium compared with nitrogen. When over-speeding the furnace (5,000 rpm) at 10-bar helium, a 40% improvement is realized compared with 10-bar nitrogen.

Using helium cooling gas at high velocities, and operating at 10-bar overpressure paves the way for the metallurgist to process a greater variety of materials. This technology has taken the vacuum furnace to the forefront and the centerpiece of a modern technologically advanced commercial heat-treating facility. **IH**

For more information: *Robert Hill Jr., president, Solar Atmospheres of Western Pennsylvania, 30 Industrial Rd., Hermitage, PA 16148; tel: 866-982-0660; fax: 724-982-0593; e-mail: rab@solaratm.com*

HYDROGEN REACTION EXPERIMENTS

Experiments have been conducted by Trevor Jones at Solar to determine the explosive properties of hydrogen and air under near vacuum conditions, and also to determine what levels of energy are needed to ignite the mixtures.

Hydrogen by itself is a relatively safe gas. However, hydrogen can become very unstable when air is introduced. Of concern is what could occur if an air-hydrogen mixture is put into a vacuum. Hydrogen flammability properties at atmospheric conditions are well known, but not under a vacuum. Therefore, it is important to know the flammability limits of hydrogen/air ratios in vacuum processing applications using hydrogen for safety reasons. Such information can be helpful in designing a vacuum furnace with the necessary safeguards to preclude a severe hydrogen reaction.

The test chamber used to conduct hydrogen reaction experiments is shown in Fig. A. It consists of a 9 in. high by 4.75 in. diameter (~230 by 120 mm) chamber with four spring-loaded strip bolts to relieve the force of the explosion. Attached to the chamber are a vacuum pump, electronic digital vacuum gage, temperature gage, air inlet, spark plug (with ignition transformer) and a hydrogen tank. A heating element wire and a spark with a 1/4 in. (6 mm) gap also were used to obtain additional results. A sight glass allowed observing the reaction inside the chamber.

Four types of tests conducted to study the hydrogen reaction included 5,000-V spark plug test (using both a 1/16 and 1/4 in. gap) to determine the explosive ranges for various hydrogen-air mixtures, a heated wire test to determine the explosive ranges for various hydrogen-air mixtures and a heated wire element test to determine the explosive ranges for air ingress into a hydrogen filled chamber.

The spark plug test and the heated element wire test results showed that the chamber ignites deeper in vacuum then previously thought to be possible. With the 1/16-in. (1.5 mm) gap spark plug, the chamber will ignite in a 20% backfill of a stoichiometric mixture (30% hydrogen, 70% air). The heated element wire tests showed the chamber ignites at 15% backfill of the stoichiometric mixture. The 1/4-in. gap spark test results show that the chamber can ignite in richer concentrations of hydrogen in air than for the 1/16 in. spark. For the 1/16 in. spark, the chamber will not react above 60% hydrogen in air. By comparison, with the 1/4 in. gap spark, the chamber was able to ignite up to 80% hydrogen in air. This shows that the larger the arc (higher power) used to ignite the chamber, the easier it is to detonate the mixture. This is even more apparent if a rich amount of hydrogen is being used.

In the test involving air burning at the point of ingress, results show it is possible to burn off the air before it has a chance to accumulate. This could be a huge advance in the safety aspect of using hydrogen in heat-treating processes.

Fig B contains data from all tests to show the difference in reaction points for the different methods of ignition. The 1/4-in. spark has the highest energy, and, therefore, ignites the mixture in a wider range of ratios. The heated element wire and the 1/16-in. gap spark have nearly the same ignition points. The three tests produced similar results at the point of the stoichiometric mixture, a point where the reaction has high probability of ignition. As the mixture skews from that point, the air-hydrogen mixture has a less likely chance of igniting.

Further tests involving modeling of an actual vacuum furnace are needed to increase the understanding of how to design a vacuum furnace that would have the necessary safeguards to prevent a devastating hydrogen-air reaction.

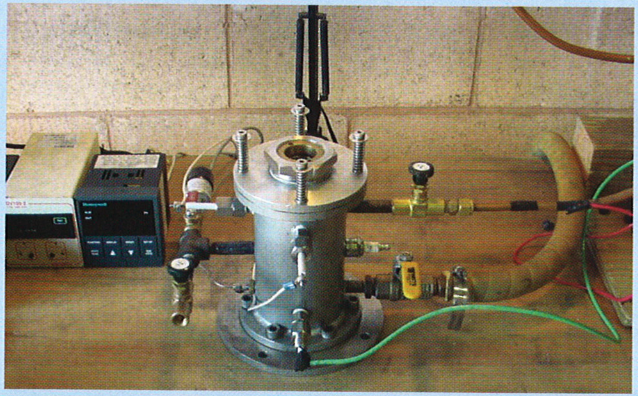

Fig A *Experimental hydrogen-reaction test chamber*

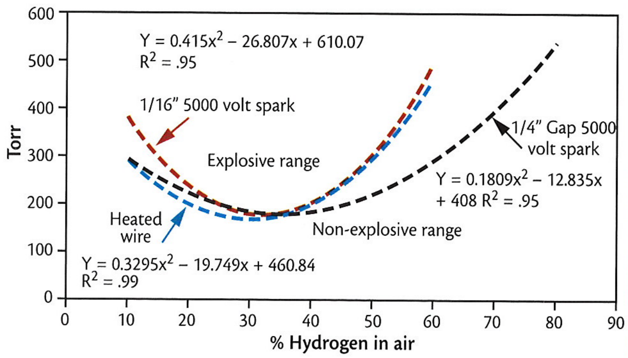

Fig B *Minimum hydrogen-air mixture ignition points for different ignition methods*