Single-Chamber HPGQ Vacuum Furnace with Quenching Efficiency Comparable to Oil

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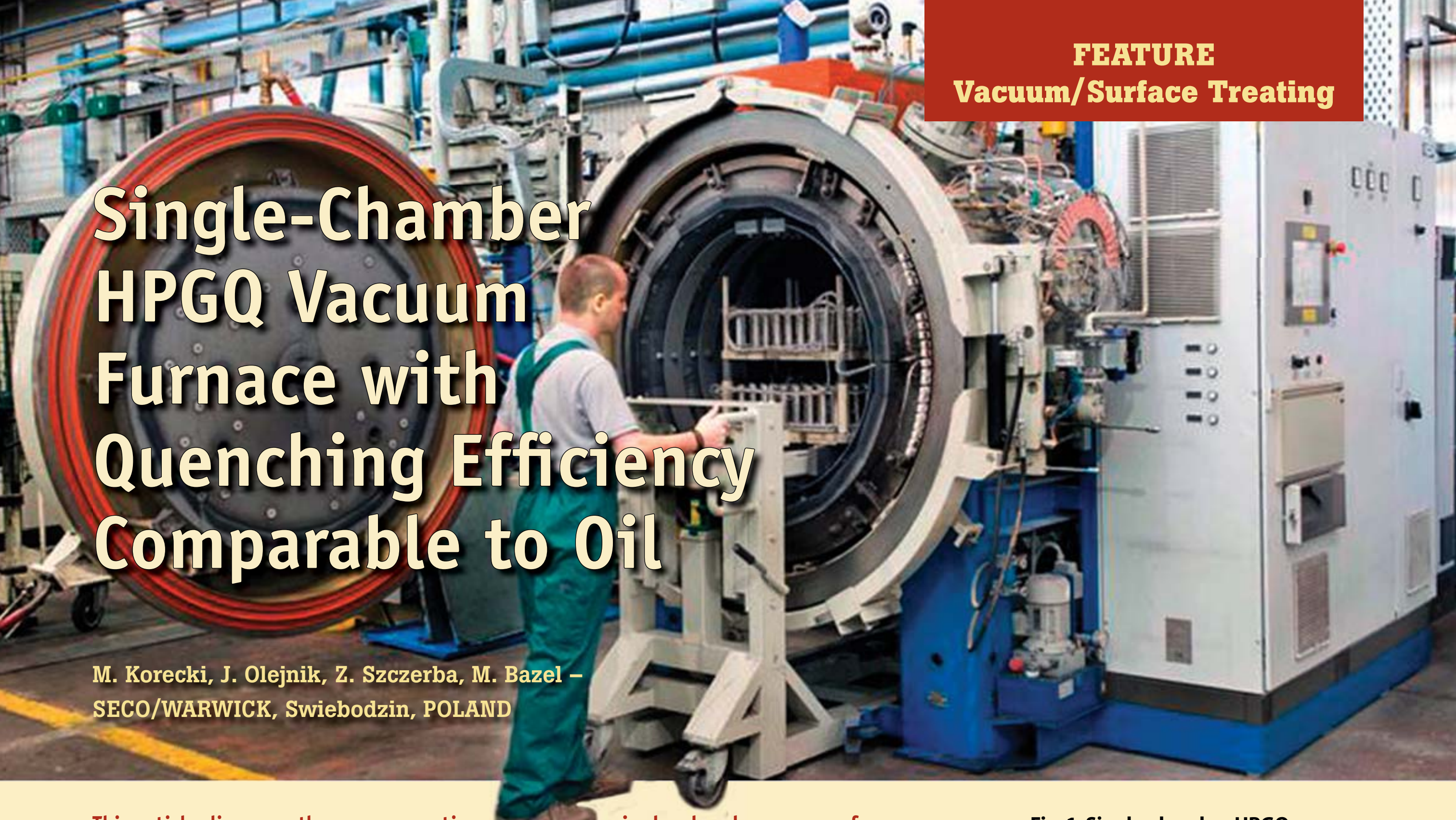

Fig. 1. Single-chamber HPGQ vacuum furnace type 25.0VPT-4035/36IQN

This article discusses the new generation, single-chamber vacuum furnace with a high-pressure gas-quenching system (HPGQ) able to quench with an efficiency better than that achieved in furnaces with a separate gas-quenching chamber (cold chamber) and comparable to the efficiency of oil systems. The performance of the furnace cooling system as it relates to the physical properties of quenching gas at ambient and process temperatures is presented and discussed. Finally, the efficiency and technological effect of quenching in gas is compared with results obtained in typical oil-quench systems.

Gas has been expanded as a quenchant with the application of vacuum heat-treatment technology. In the present decade, development of gas-quenching systems (HPGQ) progressed due to the commercialization of low-pressure carburizing (LPC), which has come into common use.

Low-pressure carburizing may gradually replace traditional atmosphere-carburizing technology and oil-quench hardening in two-chamber furnaces (sealed or integral quench). In order to achieve the same or better results, vacuum-furnace quenching-system designs must be improved to achieve the same cooling efficiency as oil using gas as a modern and more environmentally friendly medium. Gas-quenching systems outperform oil in almost every aspect. Nonetheless, current technology performance is not as strong as oil quenching given the limitations of carburized-case applications in some steel grades and/or the part dimensions.

For the purpose of measurement and comparison, many methods and coefficients help to determine the efficiency of a given system and quenching medium. These include: Grossmann's Number (H), cooling rate at given temperature (typically at 705°C), λ coefficient and heat-transfer coefficient (α) as the most objective. Quenching parameters of typical oil systems were determined with α coefficient within the range from 1,000-2,500 W/m^{2}K according to traditional division for slow- (1,000-1,500 W/m^{2}K), medium- (1,500-2,000 W/m^{2}K) and fast-speed oil (2,000-2,500 W/m^{2}K).[1]

HPGQ vacuum furnaces may be classified as two types depending on design. Single-chamber furnaces (heat treatment and quenching occurs in one chamber without dislocation of charge) have slower cooling due to construction and material limitations. The more efficient two- and multi-chamber furnaces utilize a separated, dedicated cold quenching chamber.

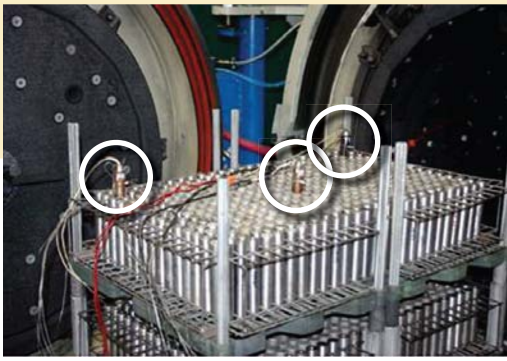

Fig. 2. Measurement of α coefficient for reference charge of 100% packing density with α probes located in the left corners and in the middle of top level (positions 1, 5 and 9).

At present with current technology, an average α coefficient of 600-800 W/m^{2}K can be obtained in HPGQ separated chambers for nitrogen under 20 bar and slightly above 1,000 W/m^{2}K for helium. Single-chamber furnaces with 15-bar nitrogen have α coefficient of 400-700 W/m^{2}K and below 1,000 W/m^{2}K for helium.[2,3,4,5] These parameters still differ from those available with oil.

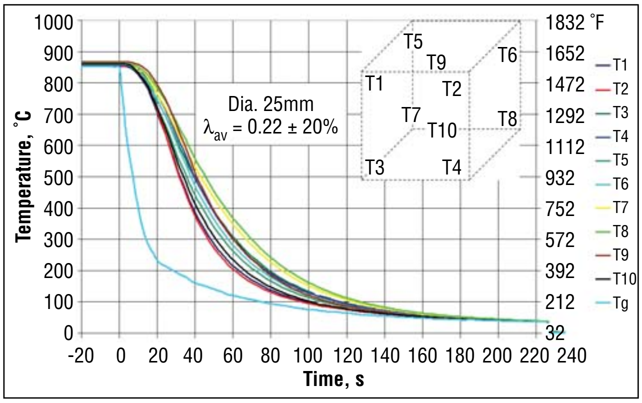

Fig. 3. Temperature trends during 24-bar helium quenching in austenitic specimen cores of 25 mm diameter for 50% charge packing density

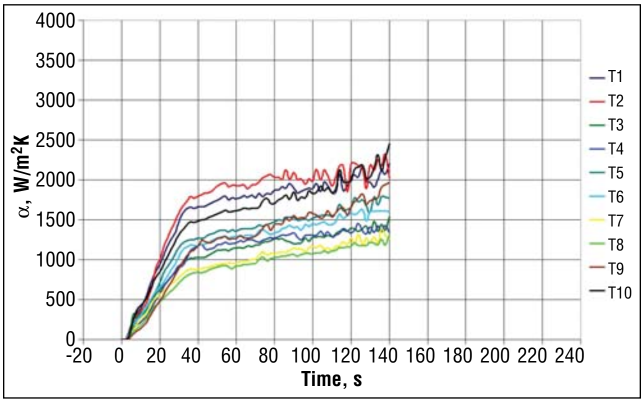

Fig. 4. α coefficient during 24-bar helium quenching in austenitic specimen cores of 25 mm diameter for 50% charge packing density

Single-chamber furnaces have more simple construction, are less expensive and find application for batch and flexible production. Multi-chamber systems are more complicated in construction, more expensive and are typically used for mass-production applications.

Taking this into consideration, SECO/WARWICK designed a single-chamber furnace providing parameters similar to those obtained in separated quenching chambers and even comparable to oil-quenching systems. It is appropriate for mostly small and medium companies but also has applications in heavy industry and mass production, especially in these challenging times.

Testing Furnace

Tests were carried out with an industrial furnace made by SECO/WARWICK S.A., type 25.0VPT-4035/36IQN. This is a universal, single-chamber vacuum furnace designed for LPC under FineCarb® and PreNitLPC® technology (intensive high-temperature carburizing with control of grain growth[6]), hardening with high-pressure gas and tempering within one cycle. The furnace allows for an advanced quenching technique with temperature control (marquenching, austempering) and gas heating (convection). The furnace has been equipped with an innovative power-management system that reduces the consumption of electrical energy.[7] The construction consists of a cylindrical heating chamber with graphite insulation and circular, flat heating elements. The furnace has been equipped with a closed-loop, nozzle-type gas-cooling system and has been adapted for operation with nitrogen and helium (future use, hydrogen) at a pressure of 24 bar (Fig. 1). The technical specification of the furnace is as follows:

• Working space (W/H/L)	600/600/900 mm (24/24/36 inches)
• Charge mass (gross)	800 kg (1,760 pounds)
• Rated temperature	1320°C (2400°F)
• Working vacuum	range 10^{-2} mbar (10^{-2} torr)
• Heating system power	150 kW
• Cooling pressure	24 bar, N_2, He, H_2
• Cooling blower motor power	220 kW

Cooling System

The furnace cooling system consists of the following: a blower located at the rear that forces gas flow into the charge area through a closed loop, cylindrical-nozzle-injected system located in the sidewalls and front of the heating chamber; a back hatch for the gas outlet; and a water heat exchanger. Cooling gas circulates in the following order: blower → nozzles → charge → back hatch → heat exchanger → blower. The nozzle cooling system is characterized with excellent evenness and penetration in a densely packed charge due to the proper location of the nozzles and high-acceleration gas flow. Gas velocity at the nozzle outlet is around 70 meters/second (230 feet/s) for nitrogen and can be increased to over 100 meters/second (330 feet/s) for helium.

Measurement of α Coefficient in Ambient Temperature

Tests were carried out with a 25 mm (1 inch) diameter heated α probe invented by SECO/WARWICK. Probes were located in 10 positions of the working zone on two levels – at the corners and center – of the reference charge for three load-density arrangements: 0%, 50% and 100%. The reference charge of 100% density was prepared with 25-mm steel cylinders and a 150 mm (6 inch) length located vertically on a two-level tray with 768 pieces and 500 kg (1,100 pounds) gross total mass, as shown in Figure 2.

Tests were conducted using various conditions of pressure and velocity of nitrogen and helium, and the obtained results are shown in Table 1. Results confirmed the impact of pressure (density) and gas velocity on α to 0.7 power and an increase of α by 30-35% when nitrogen is replaced with helium. In addition, the application of helium resulted in a blower motor loading decrease by about six times, which enabled acceleration of the fan (by 50%) and a proportional increase of gas velocity.

Under conditions of blower maximum power (220 kW), the average α coefficient for nitrogen (24 bar and 65% velocity) was 940 W/m^{2}K and at some locations over 1,000 W/m^{2}K. For helium (24 bar, 150% velocity), it resulted in 1,800 W/m^{2}K and

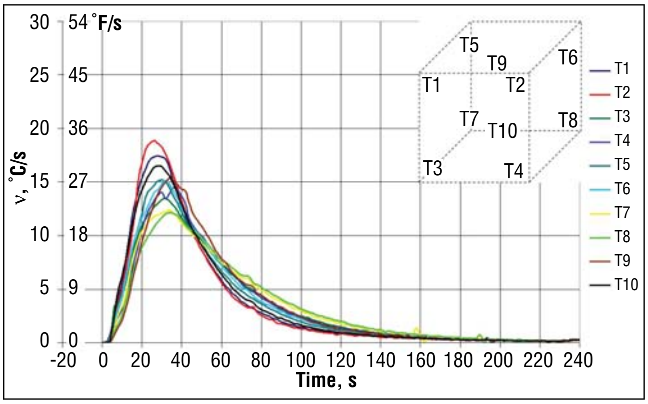

Fig. 5. Rate of temperature drop during 24-bar helium quenching in austenitic specimen cores of 25 mm diameter for 50% charge packing density

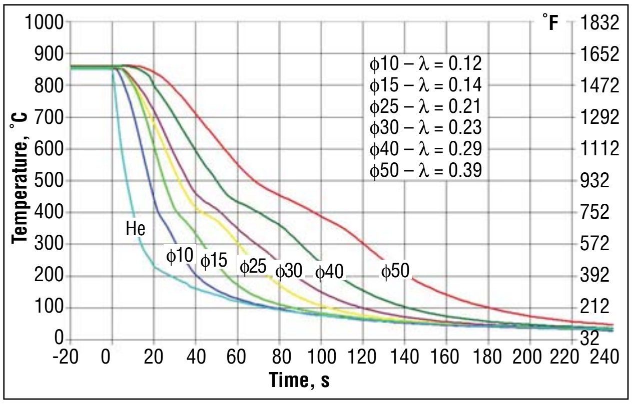

Fig. 6. Temperature trends during 24-bar helium quenching in cores of 16MnCr5 steel specimens of different diameters for 50% charge packing density

a maximum above 2,000 W/m^{2}K. Cooling uniformity within the working space was +/-15%. Charge packing density did not have a significant impact, but for nitrogen with loads of 50% and 100%, an increase of α coefficient occurred as compared to an empty chamber (0%). For helium, a decrease of α occurred with 50% charge packing. At 100%, α increased up to values obtained with the empty chamber.

Cooling Efficiency and Uniformity

The test was carried out for the charge of 50% packing density. Specimens made from austentic stainless steel of 25 mm diameter (1 inch) and 150 mm (6 inch) length were located at 10 standard points of the working zone. Thermocouples were placed in the center of the specimens to monitor the temperature during the actual cooling process. Tests were carried out for helium maximum cooling rate (24 bar, 150% gas velocity). Measurement results and different interpretations were determined for cooling curves (Fig. 3.), α coefficient (Fig. 4.) and cooling rate (Fig. 5.).

Cooling curves provided data for the calculation of λ coefficient that determined the cooling rate from 800°C (1472°F) to 500°C (932°F) in hundredths of seconds. The average λ was 0.22 (22 seconds) with a spread from 0.18 to 0.26 for the whole working zone. However, α coefficient increased from the beginning of cooling and stabilized after 40 seconds from the start of the process due to quenching-gas temperature changes. Its average value was around 1,600 W/m^{2}K after 80 seconds, which corresponded to results obtained at ambient temperature. On the other hand, the maximum cooling rate was achieved at 700°C (1292°F) after around 25 seconds at 12-18°C/s (22-32°F/s). Generally, considering the cooling uniformity of the whole working space determined with λ, α and cooling rate, it was in the range of +/-20%.

Steel Hardening Test

The next test related to technological properties of the furnace cooling system was as-quenched hardness. For this purpose, the 50% packing-density charge was prepared, and specimens of diameter 10, 15, 25, 30, 40 and 50 mm were evenly located. Samples were made from steel grades 16MnCr5, 20MnCr5 and 18CrNi8, and the chemical compositions are shown in Table 2. Steel thermocouples were installed inside the core of specimens made from 16MnCr5. Hardening followed at the austenitizing temperature of 860°C (1580°F) using a 24-bar helium quench with 150% gas velocity.

The diagram in Fig. 6 presents results of temperature measurement inside the specimens of different diameters. Specimens of diameters of a given range obtained λ coefficient from 0.12 to 0.39 with 0.21 for 25 mm (1.0 inch) diameter, which corresponded very well to results obtained during cooling efficiency and uniformity tests. Analysis of data indicated a maximum cooling rate of the core of 28°C/s (50°F/s) for the specimen of 10 mm (0.4 inch) diameter and approximately 9°C/s (16°F/s) for the specimen of 50 mm (2.0 inch) diameter.

Table 1. Values of α coefficient for gas type, pressure and velocity as well as charge packing density

Heat transfer coefficient α, W/m^{2}K	Load density		
Conditions	0%	50%	100%
N_2, 11 bar, 100% velocity	630	740	700
N_2, 24 bar, 65% velocity	830	980	920
He, 24 bar, 150% velocity	1790	1610	1810

Table 2. Chemical contents of essential alloy additives of steels selected for hardening tests

Steel		C,%	Mn, %	Cr, %	Ni, %
16MnCr5	Range	0.14-0.19	1.00-1.30	0.80-1.10	
	Real	0.16	1.17	0.97	
20MnCr5	Range	0.17-0.22	1.10-1.40	1.00-1.30	
	Real	0.17	1.18	1.05	
18CrNi8	Range	0.15-0.20	0.40-0.60	1.80-2.10	1.80-2.10
	Real	0.17	0.47	2.03	1.98

As the absolute hardness value obtained after quenching depends also on steel chemical composition within a given grade (Table 2), the comparison shall provide for more objective assessment with regard to efficiency of the cooling system. For this purpose, the same charge (as in case of helium) was subjected to hardening with a two-chamber vacuum furnace equipped with a tank filled with Vacu Quench B244 oil. After quenching with helium and oil, hardness measurements were taken on the surface and core of specimens and compared (Table 3).

Hardness results indicated some correlations for all examined grades of steel. For samples with larger diameters (25-50 mm), helium quenching was more intense than oil quenching (higher hardness). For specimens of 15 mm (0.6 inch) diameter, hardness results are similar. For specimens of 10 mm (0.4 inch) diameter, a higher hardness was obtained with oil than with helium.

For 16MnCr5 steel, the 50-mm-diameter specimen was 24 HRC after helium quenching, and after oil quenching it was 21 HRC. For the 15-mm sample, hardness values were quite similar for both quenches – 29 HRC. The 10-mm sample was 38 HRC after oil quenching and 30 HRC with a helium quench. Results for 20MnCr5 and 18CrNi8 steel were similar but less dramatic due to their better hardenability (less quench-rate sensitivity).

Our findings can be explained on the basis of the critical cooling rate that appears after 20 seconds of quenching for the small-diameter specimens (10 mm). At that time, the fastest oil-quenching phase (boiling phase) took a primary role, while helium quenching had not yet reached nominal parameters, mainly due to the high temperature of the cooling gas (220°C, 428°F). For larger-diameter specimens (over 15 mm) at the critical cooling rate of 30 seconds, the third, slower cooling phase of oil – convective cooling – was effective, while helium quenching exhibited its maximum cooling rate. This was confirmed by measuring α coefficient, which for helium was twice the 600 W/m^2K value found for the oil convective-cooling phase of the quench.

Summary

1. Tests were conducted with the single-chamber vacuum furnace equipped with a gas-quenching system for nitrogen and helium at 24 bar.
2. Tests and processes were carried out under industrial conditions with a charge of 300-500 kg (660-1,100 pounds) and working space of 600/600/900 mm (24/24/36 inch).
3. Helium quenching efficiency was found to be similar to medium oil with α coefficient equal to 1,600 W/m^2K.
4. The whole working zone indicated very good cooling uniformity (+/-20%) thanks to intensive gas penetration into the charge with the nozzle cooling system.
5. The hardening test confirmed very good gas cooling parameters. Hardness values exceeded values obtained from oil for samples above 15-mm (0.6-inch) diameter.
6. For small parts below 10 mm (0.4 inch), oil quenching provided higher hardness.

Table 3. Comparison of surface and core hardness obtained after 24-bar helium quenching with the single-chamber vacuum furnace and oil hardening with the two-chamber vacuum furnace

Steel grade	Dia., mm/inch	He (24 bar), HRC		Oil, HRC	
		Surface	Core	Surface	Core
16MnCr5	10/0.4	32.1	30.4	38.5	37.7
	15/0.6	31.0	29.5	31.9	29.3
	25/1.0	29.5	28.1	28.5	27.1
	30/1.2	28.6	27.2	27.1	25.7
	40/1.6	26.7	25.7	26.7	22.0
	50/2.0	24.8	24.3	24.0	21.1
20MnCr5	10/0.4	42.0	41.7	43.1	41.4
	15/0.6	37.0	37.2	38.1	37.8
	25/1.0	33.7	33.1	30.2	29.6
	30/1.2	32.7	32.4	30.4	30.1
	40/1.6	31.9	31.5	30.2	29.9
	50/2.0	30.6	29.7	28.3	28.6
18CrNi8	10/0.4	44.4	43.5	45.7	44.0
	15/0.6	43.5	43.4	43.2	42.8
	25/1.0	42.9	42.4	43.8	41.0
	30/1.2	43.0	41.4	43.0	41.0
	40/1.6	42.9	40.4	38.6	37.9
	50/2.0	42.2	39.4	36.6	36.7

Conclusion

The single-chamber vacuum furnace made by SECO/Warwick S.A. equipped with a high-pressure gas-quenching system (HPGQ) proved capable of hardening steel grades and sizes that previously were thought to be best suited for either oil quenching or separated gas-quenching chambers in dual- or multi-chamber furnaces.

The single-chamber furnace is a device of simple construction and operation that requires a smaller investment in capital cost and at the same time produces work reliability, taking advantage of the flexibility in the technology and all of the advantages inherent with gas quenching. **IH**

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Additional related information may be found by searching for these (and other) key words/terms via BNP Media SEARCH at www.industrialheating.com: high pressure gas quenching, oil quench, low-pressure carburizing, convective cooling, critical cooling, quench efficiency

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