The single-chamber HPGQ vacuum furnace with hardening power of oil quench systems

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This article discusses how an advanced single-chamber vacuum furnace equipped with a high pressure gas quenching system (HPGQ) can exceed all current parameters achieved by separated gas quenching chambers (cold chambers) and is comparable to oil systems. In this article, the results of the measurements obtained from the furnace cooling system are reported in relation to gas physical properties obtained during the test in both ambient and at process temperature conditions. A comparison follows regarding quenching parameters and actual hardening results from both gas and typical oil conditions.

Gas has been expanded as a quenchant with application of vacuum technology in heat treatment. 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 technology based on atmospheric carburizing and oil hardening in two-chamber furnaces (sealed or integral quench). In order to achieve the same or better results, vacuum furnace quenching system designs had to be improved to achieve the same cooling efficiency of 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 case applications in some steel grades and/or dimensions.

For the purpose of measurement and comparison, many methods and coefficients find application with regard to the determination of efficiency of a given system and quenching medium. Such as e.g.: Grossmann's Number - H, cooling rate at given temperature (typically at 705°C), λ coefficient, and first of all - α heat transfer coefficient as the most objective. Quenching parameters of typical oil systems were determined with α coefficient within the range from 1,000 to 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 typical vacuum furnaces may be classified as two types depending on their construction: single-chamber furnaces (quenching and heat treatment follows in one chamber without dislocation of charge) with slower cooling due to construction and material limitations, and more efficient two and multi-chamber furnaces with a separated, dedicated cold quenching chamber.

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, while in the case of helium it is below 1,000 W/m^{2}K. [2,3,4,5]. These parameters still differ from those provided with oil.

Single-chamber furnaces have a more simple construction, are less expensive, and find application for short series and versatile production, while multi-chambers systems are more complicated in construction and expensive for mass production purposes.

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 cooling systems, appropriate for mostly small and medium companies, but also has applications in heavy industry and mass production, especially in these difficult times.

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

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 low pressure carburizing under FineCarb® and PreNitLPC® technology (intensive high temperature carburizing with control of grains 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 design). 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 with 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) under 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")
- Charge mass (Gross)
  800 kg (1,760 lb)
- Rated temperature
  1320°C (2,400°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

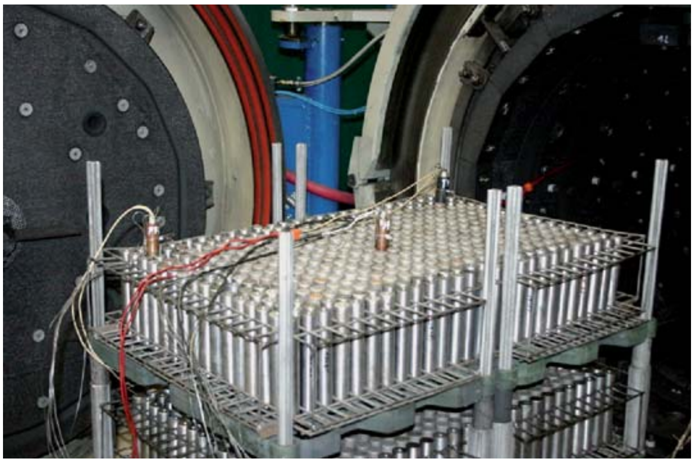

Fig. 2: Measurement of α coefficient for reference charge of 100% packing density. α probes located in the left corners and in the middle of top level (position No 1, 5 and 9)

Table 1: Values of α coefficient in respect of 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

Cooling system

The furnace cooling system consists of a blower located at the rear that forces gas flow through a closed loop, cylindrical nozzle-injected system into the charge area located in the sidewalls and front of the heating chamber, a back hatch for gas outlet and water heat exchanger. Cooling gas circulates within 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, as a result of proper location of the nozzles and high acceleration gas flow. Gas velocity at the nozzle outlet is around 70 m/s (230 ft/s) for nitrogen and can be increased to over 100 m/s (330 ft/s) for helium.

Measurement of α coefficient in ambient temperature

Tests were carried out with 25 mm (1") diameter α heated probe invented by Seco/Warwick. The probe was located in 10 positions of a working zone on two levels, one by one, at corners and in the middle, around the reference charge, for three load density arrangements: 0%, 50% and 100%. The reference charge of 100% density was prepared with steel cylinders of 25 mm (1") diameter and 150 mm (6") length located vertically on a two levels tray at number of 2x16x24 = 768 pcs, and 500 kg (1,100 lb) gross total mass as shown in **Fig. 2**. Tests were conducted using various conditions of pressure and velocity of nitrogen and helium, and the obtained results were as shown in **Table 1**. Results confirmed the impact of pressure (density) and gas velocity on α coefficient to 0.7 power and an increase of α coefficient by 30-35% in case of replacement of nitrogen with helium. In addition, the application of helium resulted in a blower motor loading decrease by about 6 times what enabled acceleration of a fan (by 50%) and an increase of gas velocity proportionally.

Under conditions of blower maximum power (220 kW) average α coefficient in case of nitrogen (24 bar and 65% velocity) was 940 W/m^{2}K, and at some locations over 1,000 W/m^{2}K. In case of helium (24 bar, 150% velocity) it resulted with 1,800 W/m^{2}K, and maximum above 2,000 W/m^{2}K. Cooling uniformity within the working space was within +/- 15%. Charge packing density had not much impact, although it was evident; in case of nitrogen at 50% and 100% an increase of α coefficient followed in comparison to an empty chamber (0%), and in case of helium a decrease of α followed in case of 50% charge packing, and at 100% an increase followed up to values obtained at 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") and 150 mm (6") length were located at 10 standard points of working zone. In the center of specimens, thermocouples were placed for the purpose of monitoring of temperature during real cooling process. Tests were carried out at conditions of helium maximum cooling rate (24 bar, 150% gas velocity). Measurement results and different interpretation were determined on graphs: **Fig. 3** - Cooling curves, **Fig. 4** - α coefficient, **Fig. 5** - Cooling rate.

Cooling curves provided data for the calculation of λ coefficient that determined temperature decrease rate from 800°C (1,472°F) to 500°C (932°F) in hundredth of seconds. The average λ was 0.22 (22 s) with spread from 0.18 to 0.26 for the whole working zone. However, α coefficient increasing from the beginning of cooling and stabilized after 40 s from the start of the process, which results from quenching gas temperature changes. Its average value was around 1,600 W/m^{2}K after 80 s which corresponded to results obtained at ambient temperature. On the other hand, the cooling rate got maximum value at 700°C (1,292°F) after around 25 s on the level 12-18°C/s (22-32°F/s). Generally, considering uniformity of cooling of the whole working space determined with λ, α and cooling rate it was in the band of +/- 20%.

Steel hardening test

The next test related to technical properties of the furnace cooling system, hardness obtained after quenching. For this purpose, the charge was prepared of 50% packing density, where specimens of diameter 10, 15, 25, 30, 40 and 50 mm (0.4, 0.6, 1.0, 1.2, 1.6 and 2.0”) were evenly located, respectively made from steel of three grades: 16MnCr5, 20MnCr5 and 18CrNi8. The chemical composition of the selected steel was presented in **Table 2**. Inside the core of specimens made from 16MnCr5 steel thermocouples were installed. Hardening followed from austenining temperature of 860°C (1,580°F) under pressure of 24 bar helium with 150% gas velocity.

The diagram in **Fig. 6** presents results regarding temperature measurement inside the specimens of different diameters. Specimens of diameters of given range obtained λ coefficient from 0.12 to 0.39 and 0.21 for 25 mm (1.0”) diameter respectively, which corresponded very well to results obtained during the cooling efficiency and uniformity test. An analysis of the data indi-

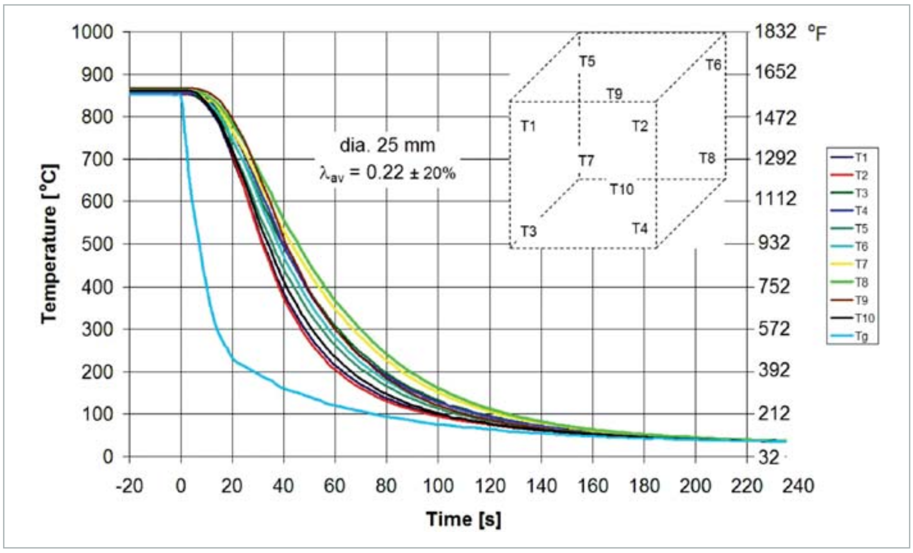

Fig. 3: Temperature trends during 24 bar helium quenching in austenitic specimen cores of 25 mm (1”) diameter for 50% charge packing density

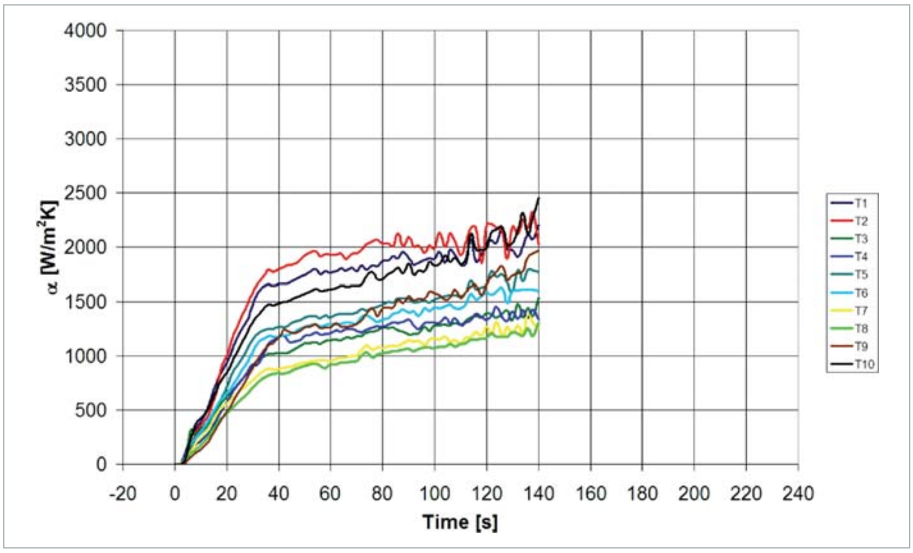

Fig. 4: α coefficient during 24 bar helium quenching in austenitic specimen cores of 25 mm (1”) diameter for 50% charge packing density

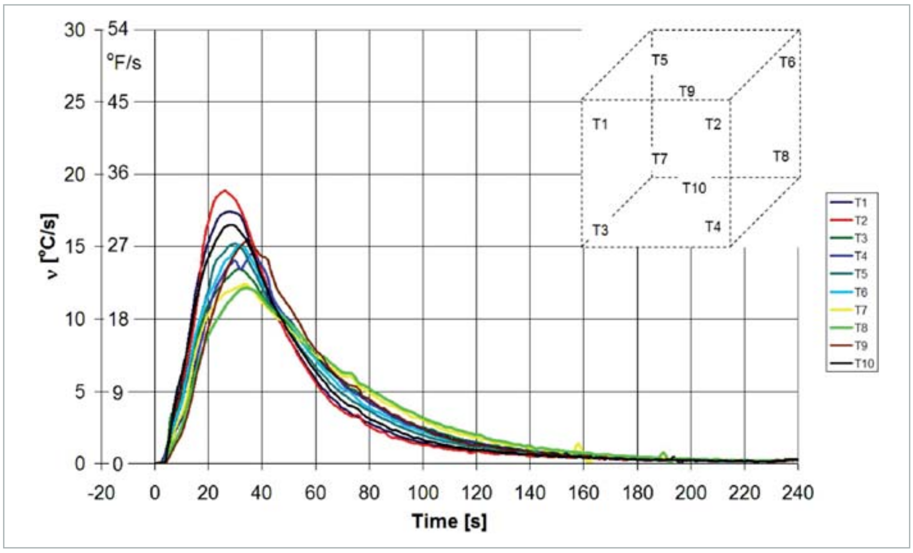

Fig. 5: Rate of temperature drop during 24 bar helium quenching in austenitic specimen cores of 25 mm (1”) diameter for 50% charge packing density

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	0.20	1.29	1.09	
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

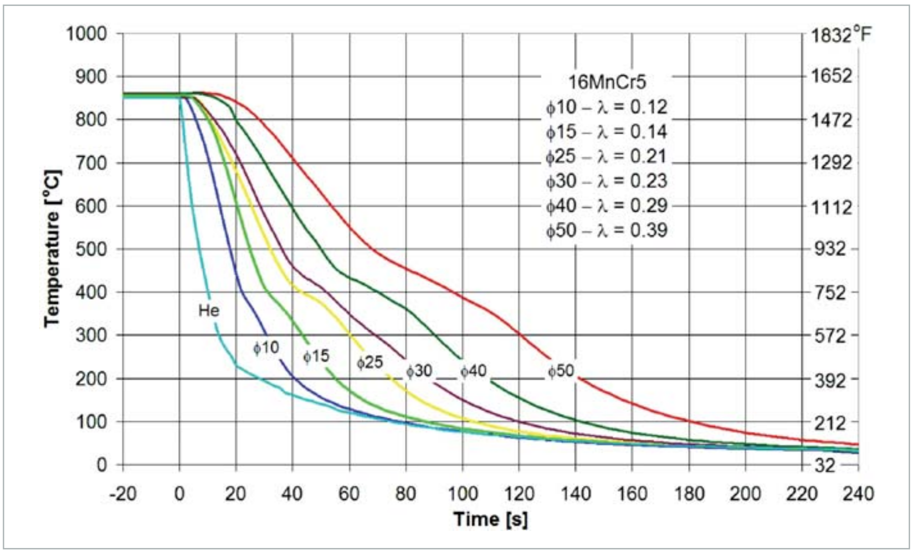

Fig. 6: Temperature trends during 24 bar helium quenching in cores of 16MnCr5 steel specimens of different diameters for 50% charge packing density

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]	
		Surf.	Core	Surf.	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

cated maximum cooling rate of the core 28°C/s (50°F/s) for the specimen of 10 mm (0.4") diameter and around. 9°C/s (16°F/s) for the specimen of 50 mm (2.0") diameter.

As an absolute hardness value obtained after quenching also depends on the steel chemical composition within given grade (Table 2) the comparison shall provide for a more objective assessment with regard to efficiency of the cooling system. For this purpose the same charge (as in the 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 measurements in respect of hardness on the surface and core of specimens were done and compared as presented in **Table 3**.

The results regarding hardness indicated some correlations for all examined particular grades of steel. In the case of elements of bigger diameters (50-25 mm, 2.0-1.0") helium quenching was more intense than oil quenching (higher hardness). This dependence did not apply to specimens of 15 mm (0.6") diameter of which the results are similar, and next the relation was quite reverse for specimens of 10 mm (0.4") diameter that obtained higher hardness with oil than with helium. The above correlation confirmed very well 16MnCr5 steel; for the specimen of 50 mm (2.0") diameter following helium hardening received hardness was around 24 HRC, and after oil hardening - 21 HRC; for the diameter of 15 mm (0.6") hardness values were quite similar and around 29 HRC, while in case of specimens of 10 mm (0.4") diameter hardness after oil treatment exceeded helium parameters and was 38 HRC to 30 HRC respectively. It was quite similar for 20MnCr5 and 18CrNi8 steel, however, less intensive due to better their hardenability (less sensitivity). Explanation of above phenomenon is the critical cooling rate that appears after 20 s of quenching in case of specimens of small diameter, e.g. 10 mm (0.4"). At that time, the fastest for oil quenching, the boiling phase took a main role, while helium quenching did not obtain nominal parameters yet, mainly due to the high temperature of the cooling gas (220°C, 428°F). In case of quenching with respect to specimens of bigger diameter, over 15 mm (0.6") at the critical moment (following over 30 s) the third, slower cooling phase of oil was to begin, namely convective cooling, while helium quenching obtained already maximum cooling rate. This was confirmed with measurement of α coefficient during oil convective cooling phase, which indicated around 600 W/m2K, which was twice less than in case of helium.

Conclusions

1. Tests were conducted with the single-chamber vacuum furnace equipped with gas quenching system for nitrogen and helium under pressure of 24 bar.
2. Tests and processes were carried out under industrial conditions, with charge of 300-500 kg (660-1,100 lb) and working space of 600/600/900 mm (24/24/36") size.
3. Results regarding measurement of helium quenching efficiency were similar to results obtained with medium oil, with α coefficient equal to 1600 W/m^2K.
4. The whole working zone indicated very good cooling uniformity (+/-20%), thanks to intensive gas penetration into charge with the nozzle cooling system.
5. Very good parameters of gas cooling system were confirmed with the hardening test, with hardness values exceeding values obtained from oil for elements above 15 mm (0.6") diameter of the cross section.
6. For small parts, below 10 mm (0.4") oil quenching provided higher hardness.

The single-chamber vacuum furnace made by Seco/Warwick S.A. equipped with 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 does not require 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.

Literature

[1] Kula, P.: Surface engineering. Technical University of Lodz, Poland, 2000.

[2] Lubben T.; Hoffmann, F.; Mayr, P.; Laumen, C.: Scattering of heat transfer coefficient in high pressure gas quench. AGA A.B. Sweden, 2000

[3] Edenhofer, B.; Bless, F.; Oimann, L.: The use of CFD modeling for the development of a New high-performance gas-quench chamber …, Heat Treatment of Metals, 3/2004, p. 59-63

[4] Loser K.: Auswahl geeigneter bschreckparameter fur die Gasabschreckung, Härterei Technische Mitteillungen, 4/2005, p.248-253

[5] Kula, P.; Pietrasik, R.; Siniarski, D.; Korecki M.: Flexible vacuum carburizing and gas quenching for automotive application, 2nd IFHTSE International Conference, Riva del Garda, Italy, 20 - 22.06.2005

[6] Korecki, M.; Kula, P.; Pietrasik, R.; Dybowski, K.; Krasowski, M.: Reducing carburizing time by PreNitLPC® technology, ASM 25th Heat Treating Society Conference, Indianapolis USA, 14-17 September, 2009

[7] Korecki, M.: Temperature control system for controlling heat treatment of metals, that is heating, soaking and cooling by a single frequency converter, US Patent 7,193,188, 2007 ■

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