NEXT-GENERATION HPQ VACUUM FURNACE

Application of the practical experience gained in the development of single-chamber HPQ furnaces having radial gas quenching systems to double- and multi-chamber systems enables significant improvement in gas cooling rate and uniformity, as well as the design of heating chambers.

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Vacuum furnaces with high pressure gas quenching (HPQ, or high-pressure quench) have been used for more than 25 years for heat treatment of tool steels, HSLA steels, and other metal alloys. Today, standard HPQ furnaces are designed with cooling pressures of 6, 10, 15 and 25 bar. HPQ furnaces have been integrated as an industry standard because of ease of operation, cycle automation, reduction of part distortion, and the development of new processes such as low-pressure (vacuum) carburizing (LPC). This paper discusses 20 years of global experience with radial design furnaces and new process applications.

Typical HPQ furnace with 16-bar gas quenching.

Selective Quenching

With the development of the HPQ process, metallurgists have been interested in quenching uniformity, particularly for densely packed charges and large-size parts such as molds and dies made of hot-work tool steels. HPQ furnaces are designed with two alternative methods of cooling gas flow: radial (with gas inflow from the circumference of cylindrical heating chamber wall) and axial (along the horizontal or vertical heating chamber axis).

Vacuum furnaces with radial nozzle type quenching have been successfully used worldwide for more than 30 years, while those having axial type quenching with reversible gas inflow are a standard design in common use in Europe. The axial type design has heating chamber size limitations because of poor cooling temperature uniformity and a slower cooling rate. There have been various attempts to improve the axial design, however, it has limitations that cannot be overcome. The radial design, on the other hand, can be configured to increase the speed and uniformity of quenching, especially for furnaces with larger heating chambers. As early as 20 years ago, radial type furnaces with larger heating chambers were used for hardening of large dies.

The first radial design was developed and patented in Europe in 1988.

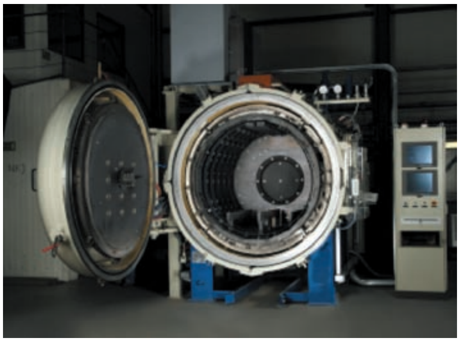

Fig. 1 —- HPQ furnace with axial/radial quenching system.

(Patent PL 156044). According to the patent, the cooling is divided into six control zones within the single chamber furnace. A manifold encircling the heating chamber is divided into six inflow zones, with three controllers built into the inlet pipe. The inlet was controlled by thermocouples distributed over the charge in these six zones. The system was an excellent solution for furnaces with a 2-bar quenching system. Other furnace manufacturers now have similar arrangements, providing a controlled supply of gas to separate zones (four, for example) via the divided manifold supplied from external pipelines.

The design becomes impractical in a HPQ class furnace with quenching pressure of 10 to 16 bar (Fig. 1). A significant increase of the cooling rate can be achieved by increasing the gas pressure during cooling and proper design of the cooling gas flow. Such a design should also provide for uniform quenching and/or its controlled run, which now becomes more important.

Design Solutions

Two successful furnace configurations are the horizontal VPT furnaces (Fig.1) and elevator hearth VVPT(EH) furnaces. The proprietary furnace design, in use since 1995, uses the concept of assisted convection heating by closing the cooling nozzles of the convection heating system. This design has a proven track record in more than 200 furnace installations (2 to 20 bar) with cylindrical radial heating chambers, including applications in "dirty" processes where metal sublimation deposits appear in nozzles and other cool sections of the hot zone.

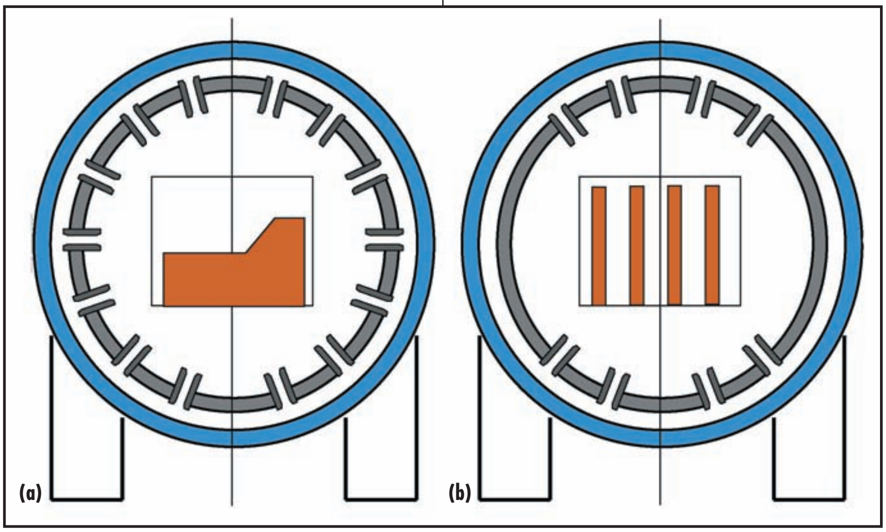

Fig. 2 — Radial gas flow (a), and axial gas flow (b).

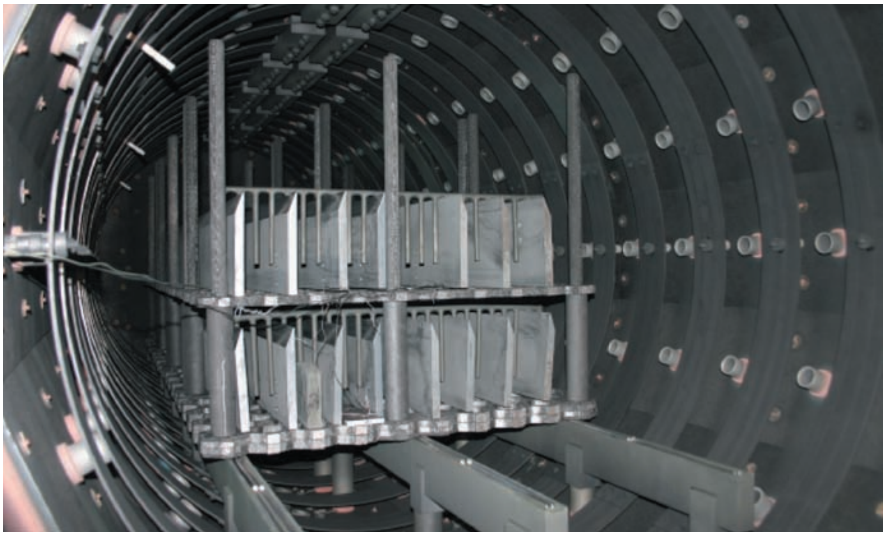

Fig. 3 — HPQ furnace with 36 × 32 × 140 in. work chamber designed for thermal treatment of knives (cutters) made of AISI S5 steel.

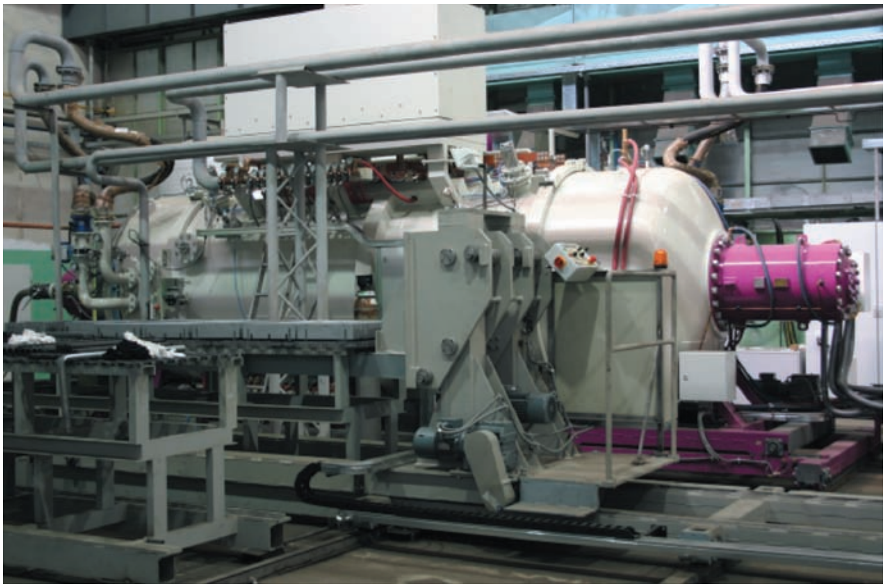

Fig. 4 — View of the 36 × 32 × 140 in. HPQ furnace

In the horizontal VPT furnace with radial gas flow (Fig. 2a), one operating system is used for closing nozzles arranged 360 degrees around the load in the cylindrical heating chamber. This design is very effective for heat treating densely packed and solid loads like molds and dies in general-purpose vacuum furnaces. However, to ensure optimum heat treatment of flat, long workpieces, (plates, for example), dual nozzle operating systems are applied where the user closes the side nozzles (Fig. 2b). By applying this method, the axial quenching effect is obtained in the heating chamber with radial gas flow. The heating chamber of a HPQ 900 × 800 × 1,500 mm (36 × 32 × 60 in.) furnace with 16-bar quenching shown in Fig. 1b is equipped with a dual nozzle closing operating system.

Figure 3 shows a HPQ furnace with a 900 × 800 × 3,600 mm (36 × 32 × 140 in.) heating chamber designed for heat treating cutters made of AISI S5 steel. The furnace is designed with a 16-bar radial/axial gas quenching system. Figure 4 shows a furnace installation with a quenching system equipped with two blowers (installed axially) with 350-kW rated motors.

The gas inlet system design is also in use in elevator hearth furnaces. The user can program inflow of cooling gas onto the load either in radial mode or from the hearth (bottom) plane with a gas outlet through top plane, which is a typical feature of the axial quenching system. Furthermore, in this application, volumetric gas flow in axial mode through nozzles arranged in the hearth is comparable with volumetric gas flow through the nozzles arranged in the cylindrical wall and in the hearth as used in the radial mode. Figure 5 shows diagram of the system and the 72 in. × 72 in. furnace. The furnace was provided with a 20-bar gas quenching system with a 400-kW blower motor.

Quenching Rate

The heat transfer coefficient (α), a basic parameter on which the quench rate depends, is dependent to an equal extent on the pressure (ρ 0.7) and on the linear velocity of gas (ω 0.7) flowing along the charge surface. This is illustrated by the equation:

$$\alpha \approx C \cdot \omega^{0.7} \cdot \rho^{0.7} (W/m^2 {}^\circ K)$$

The equation shows that to achieve a high quenching gas rate other than the relatively easy increase of quenching gas pressure, careful design of the furnace system is equally important. In practice, this involves a number of design steps including:

- Selecting the appropriate power rating of the blower motor
- Designing a furnace with low resistance of gas circulation
- Designing a suitable distribution of the quenching gas inlet nozzles using the radial quenching system
- Determining correct positioning of the hot gas outlet orifice from the heating chamber into the heat exchanger zone

In this design, the hot gas outlet zone in the form of a large-size hole positioned in the charge center line (Fig.1b) allows axial gas flow over the entire load length, thus ensuring high linear velocities in each part of a load. These are the most optimized design conditions to reach the highest quenching rates and to ensure high quenching uniformity within entire load volume.

These furnaces are particularly suitable for quenching loads containing HSLA steels, low-alloy cold-work tool steels, and molds and dies made of H13 steel according to the requirements of NADCA/GM DC-9999-1, as well as for hardening of steels after vacuum carburizing. The furnaces are designed with 10-, 12- 16-and 25-bar gas quenching systems.

Quenching rate parameters in such furnaces are defined by the heat transfer coefficient (α) or more frequently by the λ coefficient defined for testing loads consisting of steel bars, for example. Quenching tests of a very densely packed load consisting of steel bars with gross weight 450 kg (990 lb) in a standard 24 × 24 × 36 in. furnace under 10 bar N_2 pressure shows that λ= 0.7, while for a densely packed load of 300 kg (660 lb) gross weight, λ = 0.6. Test results also show that for parts with larger cross sections, differences in packing density have less of an effect on quenching rates (Fig. 6). Furthermore, in furnaces with larger heating chambers, achieving the parameters mentioned above is more difficult, while in furnaces with smaller heating chambers (e.g., 16 × 16 × 24 in.), more dynamic quenching conditions can be achieved. Quenching rates measured in the core of test bars achieved in a 24 × 24 × 36 in. furnace at 700°C (1290°F), which are suitable for hardening of certain grades of carburizing steels, are shown below

Bar diameter, mm	Quench rate, °C/s
25	5.6
50	4.0
100	2.3

The heat transfer coefficient (α) measured in these tests is in the range of 600 W/m^2 K. This value is suitable for hardening a number of HSLA steels and cold-work tool steels (e.g., O1, S1). However, it is too low to use single-chamber furnaces for hardening of common industrial carburizing steel grades after vacuum carburizing due to nonuniform hardenability.

Grossman quenching intensity factor H for gas quenching in standard Seco/Warwick HPQ furnaces is in the range of 0.10 to 0.15, while for quenching oils used in typical sealed quench furnaces, the range is 0.25 to 0.35. Therefore, single-chamber furnaces are already used for hardening of certain materials with limited cross sections with lower requirements as to core hardness (DIN 3990 – ML range). For more restrictive requirements (e.g., MQ1/MQ2), such furnaces are not used. In certain applications, furnaces with separate 20-bar quenching chambers where an H

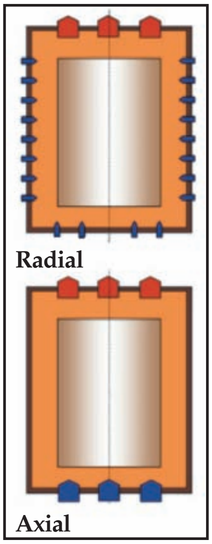

Fig. 5 — Elevator furnace (72 in. diam. × 72 in. high) with axial/radial quenching.

Fig. 6 — Quenching test results for densely packed loads of different size bars.

Fig. 7 — HPQ furnace with 16 × 16 × 24 in. work chamber.

Fig. 8 - Pumping system for 25 bar hydrogen.

factor of 0.2 is obtained are used instead of oil quenching furnaces. Such a cooling system enables successful hardening of above-mentioned steels with limited cross sections.

New Generation HPQ Furnaces for Vacuum Carburizing

Seco/Warwick developed a new-generation of single-chamber vacuum furnaces for applications where vacuum furnaces with separate quenching chambers have been used previously. The family of furnaces includes single-chamber furnaces with sizes 16 × 16 × 24 in., 24 × 24 × 36 in., and 36 × 32 × 48 in., with 25-bar helium or hydrogen quenching. They also provide for operation under 12 to 16 bar nitrogen pressure. Tests were performed in furnaces with 16 × 16 × 24 in. (Fig. 7) and 24 × 24 × 36 in. work zones. Heat transfer coefficients measured for oil, nitrogen, helium, and hydrogen are shown in Table 1. Figure 8 presents the pumping system of the 24 × 24 × 36 in. furnace adapted for quenching under 25 bar hydrogen .

With these results, single-chamber furnaces can be competitive with double-chamber designs, as well as with quenching in oil. The advantage of a single-chamber furnace is the capacity to apply intermittent hardening at the M_s (martensite start) temperature to equalize the temperature over the workpiece cross sections and charge (patent pending) before entering the area of martensite transformation.

The result is minimization of distortion. The method has been documented for oil (stop at 250°C) and gas quenching. For this purpose, the ConFlap (convection-assisted heating system) in Seco/Warwick furnaces is used where cooling nozzles are closed with flaps immediately after the required temperature is reached on the load surface, and opened after the core and surface temperatures reach an acceptable level within the martensite transformation area. This system reduces the distortion of heat treated parts significantly.

Double- and Multi-Chamber Furnace Systems

Figure 9 shows an installation of a double-chamber furnace used for vacuum carburizing and gas quenching at pressures up to 20 bar. Quenching in a separate ColdKam chamber allows for higher quenching rates compared with standard single-chamber furnaces, where during cooling stage, the heating chamber walls and internal furnace equipment is cooled together with the load.

Such furnaces are mainly used for heat treating HSLA steels, low-alloy cold-work steels, and vacuum carburizing with subsequent gas hardening. The furnace allows for hardening at cooling rates up to 15°C/s measured in core of 25-mm diameter bars making up the test load. The system shown in Fig. 9 is designed with two powerful gas blowers that force the axial type inflow of gas to the load space from the top with a linear velocity of about 15 m/s (for nitrogen).

Just as in case of single-chamber

Table 1 — Quenchant heat transfer coefficients for different furnace sizes

		Heat-transfer coefficient, W/m^{2}K		
Furnace size	**Oil**	**15-bar nitrogen**	**25-bar helium**	**25-bar hydrogen**
Oil bath	1,200 - 1,500			
16 × 16 × 24		650	1,500	2,000
24 × 14 × 36		550	1,250	1,650
36 × 32 × 48		500	1,150	1,500

furnaces with axial gas flow design, the separate gas cooling chambers with axial gas flow are better suited to uniform quenching of loads consisting of rods, other long workpieces having complex cross sections, and pinions. However, the experience of Seco/Warwick and others shows that similar hardening-distortion results (but better quenching rates) can be achieved in furnaces (quenching chambers) with radial gas flow provided that suitable volumetric exchange of the circulating quenching gas and careful distribution of cooling gas nozzles is considered.

For a nozzle cooling system, the same gas volume flows through smaller load cross section in a radial system than in an axial system (Fig. 10) resulting in higher linear flow rates. Seco/Warwick used this expe-

Fig. 9 - Double-chamber 24 × 24 × 36 in. furnace with 20-bar quenching.

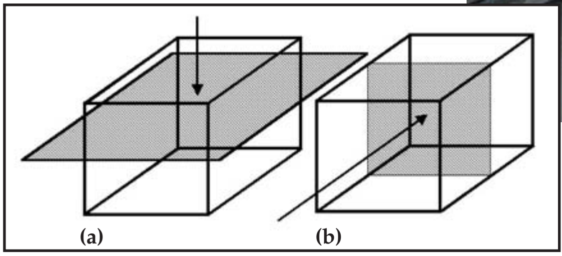

Fig. 10 - Flow area through useful space (a) axial, (b) radial.

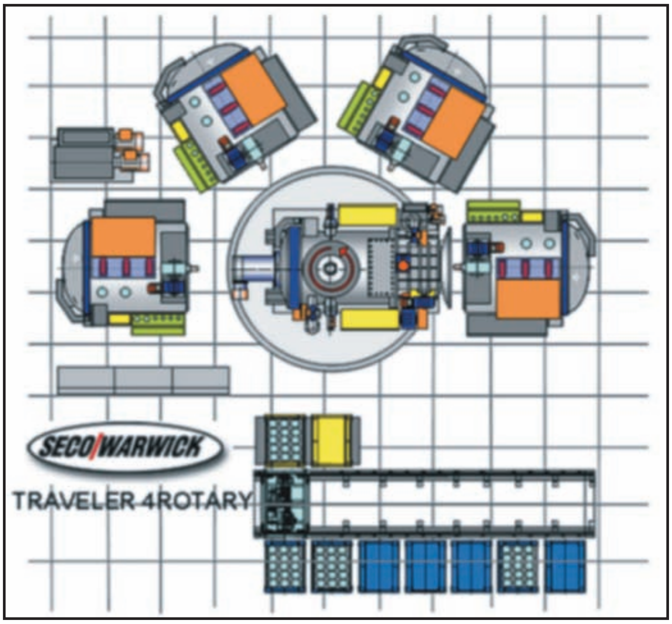

Fig. 11 — Seco/Warwick multi-chamber system (Traveler Rotary).

Fig. 12 — Double-chamber oil-quench furnaces 18 × 20 × 24 in. (top) and 30 × 24 × 48 in. (right) work chambers.

rience in the development of a new generation of separate ColdKam quenching chambers, achieving higher cooling rates, extending process capabilities, and improving quenching uniformity. This design is used in double-chamber furnaces and multi-chamber systems.

Another improvement (patent pending) enhances performance using a rotary pulsing system incorporating a 1/4 gas inlet surface. It facilitates penetrating the charge volume during quenching and supports uniform and rapid quenching even with a high-density packed charge.

The new chamber design enables higher linear gas velocities to over 20 m/s for nitrogen, thus yielding new process applications. Additionally, this design allows for constructing of multi-chamber systems with much longer heating chambers, such as 36 × 30 × 48 in. This new option provides higher efficiencies in vacuum carburizing systems. Because of the problems discussed above with gas flow uniformity, there are no axial-type chambers with sizes over 24 × 36 in. available in industrial practice. Figure 11 shows a typical design of Seco/Warwick multi-chamber system with four process chambers 24 × 24 × 36 in.

Double-Chamber Oil Quench Vacuum Furnaces

The implementation of a new generation of single- and multi-chamber systems with separate quenching chambers have not eliminated the limitations in workpiece cross sections, mainly in the case of standard carburizing steel grades. Such limitations defined by various standards (e.g., BAC 5617) still exist also for HSLA steels. For these applications, a new series of double-chamber oil quench vacuum furnaces, including vacuum carburizing furnaces, are available with a range of work-space dimensions including 18 × 20 × 24 in. and 30 × 24 × 48 in. (400 × 500 × 600 and 760 × 600 × 1,200 mm) as shown in Fig. 12. **HTP**

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