INTENSIVE AND DRASTIC QUENCHING: EQUIPMENT AND EQUIPMENT DESIGN[1]

N.I. Kobasko[2]
Lauralice de Campos Franceschini Canale[3]
George Edward Totten[4]

Abstract

Until recently, relatively little information has been available detailing commercial agitation designs that have been reported for either drastic or intensive quenching processes. The objective of this paper is to provide an overview of various agitation system designs that have been reported to date and to outline the necessary design criteria for both batch and continuous designs.

Key-words: Heat treatment, Intensive quenching, Drastic quenching, Equipaments

[1] *61º CONGRESSO ANUAL DA ABM-de 24 a 27 de julho de 2065, Rio de Janeiro, RJ, Brazil.*
[2] *IQ Technologies, Inc. Kiev, Ukraine*
[3] *Profa. Dra. Depto de Eng. Materiais, Aeronáutica e Automobilística, EESC-USP, Brazil.Email: lfcanale@sc.usp.br*
[4] *Prof Dr. Department of Mechanical and Materials Engineering, Portland State University, OH, USA. Email: totten@cecs.pdx.edu*

INTRODUCTION

So-called drastic quenching processes refer to quenching processes that are conducted with agitation rates sufficient to eliminate film-boiling during the cooling process. Intensive quenching refers to quenching process with sufficient agitation rates to prevent both film-boiling and nucleate boiling during a selected portion of the cooling process and this process is conducted in such a way as to produce maximum surface compressive stresses.

DISCUSSION

Continuous conveyor lines and design of the quenching processes

Let us consider how to apply the technique of Ref.[1-4] to various conveyor lines. In particular, we will calculate the speed of movement of conveyors depending on the shape and sizes of parts to be quenched and cooling capacity of quenchants. The most widespread conveyor line is presented in Fig. 1 [5].

At the top of Fig. 1 there is a principal scheme of a quench tank with a quenchant and devices for intensive agitation of the quenchant at the time of immersing a part to be quenched (see Submerged spray jets), as well as while the part lies on the moving conveyor (see Additional agitation on belt by pump or propeller). Intensive agitations by jets at the initial moment of immersing is necessary for avoiding or minimizing film boiling. Additional agitation of the quenchant during movement of parts on the conveyor is necessary for providing the uniformity of cooling of a part and raising the heat transfer coefficient at the convection, and also regulation of the duration of non-stationary nucleate boiling. Now we assume that quenchants are aqueous polymer solutions, the aqueous solutions of corrosion-preventing salts or pure cold water. Let the length L of conveyor immersed in the quenchant is equal to 1.5 m. It is required to determine the speed of movement of the conveyor which would provide temperature 650ºF (343ºC) at the core of the part when it should be delivered from the quenchant. To make these calculations we use formulas presented in Ref.[1, 2]:

$$w = \frac{L}{\tau} = \frac{\bar{a}\, L\, Kn}{\left(\Omega + b \ln \dfrac{T_0 - T_m}{T - T_m}\right) K}; \qquad (1)$$

where $\bar{a}$ is average thermal diffusivity of the material for the range of temperatures $T_0 - T_m$; Kn is Kondratjev number (dimensionless value); Ω =0.48 for cylinder-shaped bodies; b=1 if the core's temperature is determined; T_0 is austenitizing temperature or temperature at the time of immersing the part into the quenchant; T_m is temperature of the medium, if convection prevails, or temperature of boiling if nucleate boiling prevails.

The average thermal diffusivity $\bar{a}$ of the overcooled austenite within the temperature range of 1550ºF - 200ºF (840ºC - 100ºC) is equal to $5.36 \cdot 10^{-6}$ m^2/s.

Having all above-stated facts we calculate what speed of the conveyor should be to provide the core's temperature 650ºF (343ºC) for a cylindrical part made of AISI 4140 steel and having diameter of 25 mm and height of 50 mm. At the time of immersion the part has the same temperature of 1550ºF through all cross-sections. To answer this question, it is necessary just to determine Kondratjev number Kn. For the determination of Kn there must be available an experimental database. A lot of work in this area were made in Ref. [2, 3, 4].

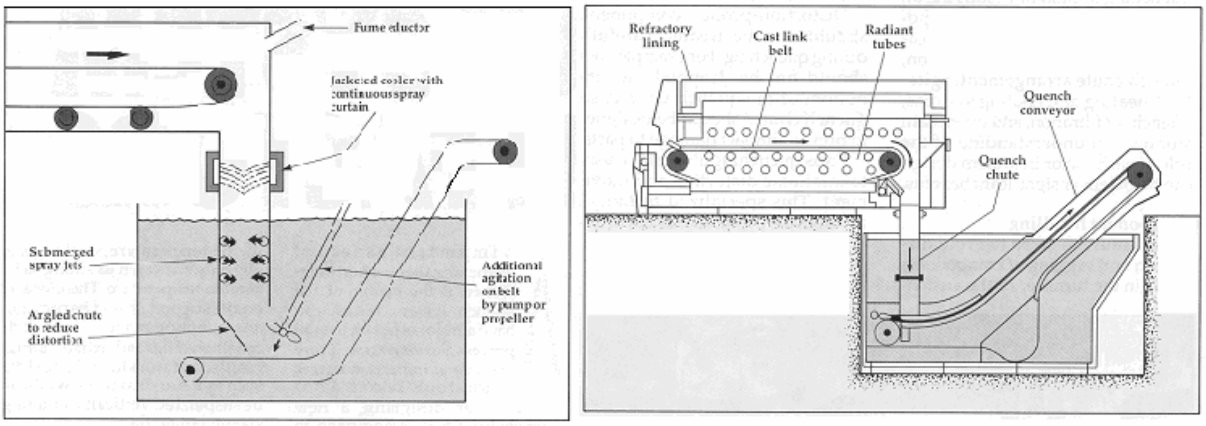

Figure 1- Typical line for continuous quenching.

Calculation of the speed of a conveyor in a quench tank

Let parts be of the cylindrical shape, diameter of 1" (25.4 mm) and length of 2" (50.8 mm), made of AISI 4140 steel, cooled from 1550ºF in 10% aqueous PAG-polymer solution. The speed of the solution's agitation is 80 fpm (0.4 m/s). Temperature of the solution is 90ºF. It is necessary to establish the speed of the conveyor so that upon delivery from the quenchant, the core of the part has temperature of 650ºF (343ºC). In this case there will be self-tempering of a part and no possibility of the quench crack formation at the raised cooling rates.

Substituting the found values in formula (1), we obtain:

$$W = \frac{5.36 \cdot 10^{-6} m^2/s \cdot 1.5m \cdot 0.512}{\left[0.48 + \ln\left(\frac{1550^0 F - 212^0 F}{650^0 F - 212^0 F}\right) \cdot 25.2 \cdot 10^{-6} m^2\right]} = 0.1 \, m/s$$ or 360 m/hr,

where $K = \frac{1}{\frac{5.783}{R^2} + \frac{9.87}{Z^2}} = 25.2 \cdot 10^{-6} m^2$.

Calculation of the speed of rotation of usual and screw drums

Besides continuous conveyor lines, rotating apparatus are often used, such as screw drums for longitudinal motion of parts to be quenched. In some cases quench tanks are used with devices rotating inside such as shafts on which supports for parts are fixed. When a part to be quenched is put on the support, the latter moves by semicircle in a quench tank and throws out a part into a basket or conveyor. Such devices can be easily automated and mechanized. In this case the speed of rotation of screw systems and drums depends on the shape and sizes of parts, thermophysical properties of material and cooling capacity of the quenchant. Such operations are often met in practice, because when the core achieves the martensite start temperature M_s, usual or intensive cooling must be interrupted immediately to prevent quench crack formation and provide self-tempering of the part.

Having the generalized dependences [1-4] for calculation of cooling time in a quenchant, one can receive simple formulas necessary at designing drum-type and screw systems.

Now we draw a simple formula for the determination of the speed of rotation of the screw drum. Let us denote the length of the screw drum along the circle as L and the quantity of the coils forming the screw conveyor as N. Then, during one rotation of a drum the longitudinal motion of a part to be quenched is L/N, and to pass all the way, it is necessary to make N rotations of the drum.

If process of cooling lasts, for example, for 1 minute, it is necessary for the screw conveyor to make N rotations per minute till the part is pushed out from the quenchant. If the process of cooling lasts, for example, 3 minutes, the quantity of rotations per minute must decrease by 3 times. If time of cooling of a part is equal to 5 minutes, the speed of the screw conveyor's rotation must decrease by 5 times. Because the frequency of the screw's rotation is directly proportional to quantity of coils and inversely proportional to necessary time of cooling, therefore, the formula for the determination of frequency n of the screw's rotation is as follows:

$$n = \frac{N}{\tau} = \frac{N\bar{a}\,Kn}{\left[\Omega + \ln\frac{T_0 - T_m}{T - T_m}\right]K} \qquad (2)$$

For better illustration we consider a specific example presented in Fig. 2. Fig. 2 presents the furnace and quench system consisting of a screw drum and rotating shaft with 8 coils forming the screw mechanism. The length of the screw in the quench system is 1.2 m. The quenchant used is 10% aqueous solution of Na_2CO_3 at temperature of 20ºC. Kn for this solution is 0.6, i.e., Kn=0.6. In the system presented in Fig. 2 balls of diameter of 2" (50.8 mm) made of AISI 52100 steel are quenched. The austenitizing temperature is 860ºC. It is necessary to calculate the frequency of the screw's rotation so that upon the part's delivery from the quenchant the temperature at the core of a ball must be 350ºC. We determine Kondratjev form coefficient K for a ball of diameter of 50.8 mm by formula:

$$K = \frac{R^2}{9.87} = \frac{(0.0254m)^2}{9.87} = 65.37 \cdot 10^{-6} m^2$$

Average thermal diffusivity of material is $\bar{a} = 5.36 \cdot 10^{-6} m/s$; $\Omega = 0.24 \cdot 3 = 0.72$ [11]. Substituting the found values in formula (2), we obtain

$$n = \frac{8 \cdot 5.36 \cdot 10^{-6} m^2/s \cdot 0.6}{\left[0.72 + \ln\frac{860^0C - 20^0C}{350^0C - 20^0C}\right] \cdot 65.37 \cdot 10^{-6} m^2} \approx 0.25\ rps\ or\ 15rpm$$

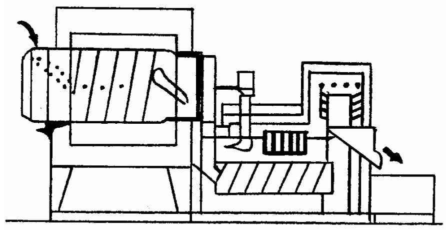

Figure 2- Screw furnace and quenching device for continuous quenching.

These calculations are also necessary at automation of processes of quench cooling. Designing of quench systems becomes complicated because it is necessary to create intensive agitation of a quenchant at the time of immersing a part to be quenched in a quench tank. Besides, it is necessary to prevent the penetration of vapor into the oven space. To solve these two problems special devices have been developed, which are presented in Fig. 3a, b, c, d, e. These devices allow to create intensive agitation of a quenchant at the time of immersing parts into a quenchant and to prevent the penetration of vapors into the oven space. More particulars on solving these problems are presented in Ref. [6, 7].

Aqueous solutions of polymers and salts of optimal concentration can be mainly used at the implementation of IQ-2 process. For implementation of IQ-3 process, usual water may be used, because very intensive streams or jets are applied here, which prevent the possibility of the formation of vapor films and even suppress the process of nucleate boiling.

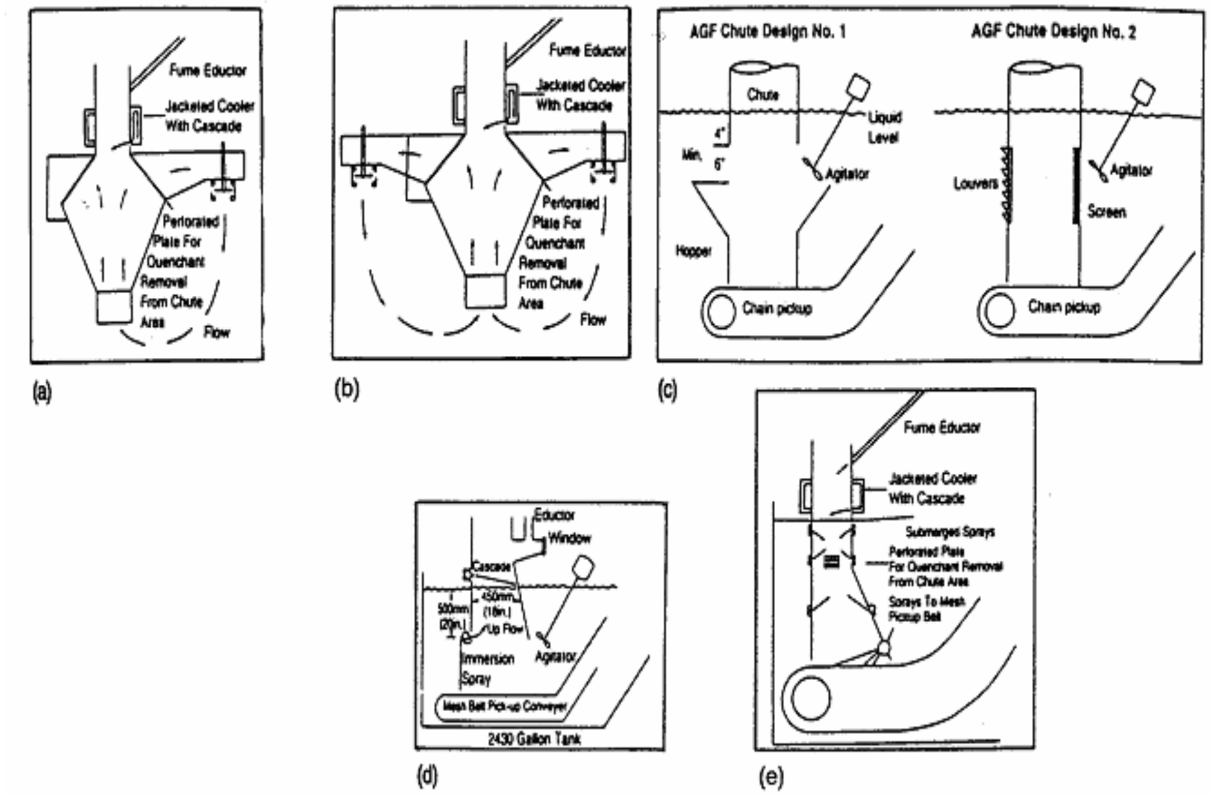

Figure 3- Devices for intensive quenching

Batch Quenching

A common view of a quench tank with a propeller for Batch Quenching is presented in Fig. 4. Rotating propellers drive water through directing pipes to a part to be quenched, as is shown in Fig. 5.

The speed of a stream of a quenchant in such systems can achieve 2-3 m/s. Designing similar systems is described in detail in Ref. [6, 7]. The most common view of system with rotating propellers in a pipe is presented in Fig. 4.

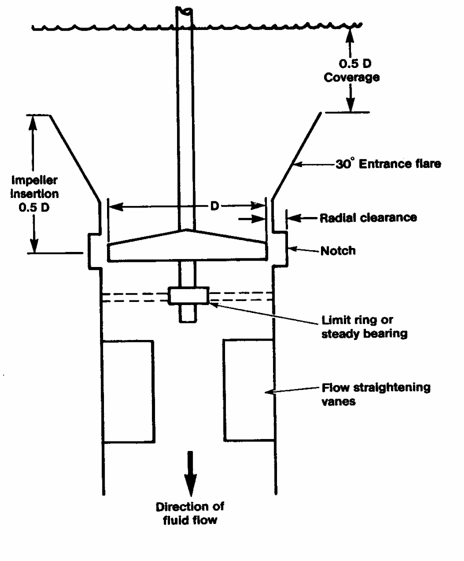

Figure 4 -Schematic of placing a propeller in a quench tank

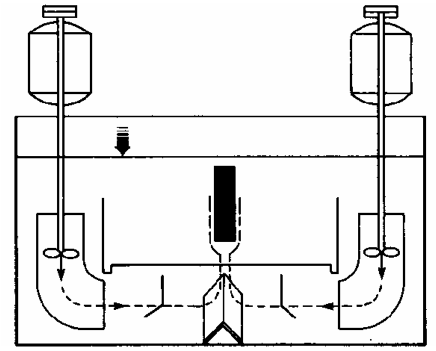

Figure 5 -Common view of a quench tank with impellers for batch quenching

Calculation of Kondratjev numbers Kn for various quenchants.

Having cooling rates at the core of cylindrical samples at temperatures 1300ºF; 650ºF and 400ºF [6], it is easy to count Kondratjev numbers for the quenchants studied. There exists interrelation between the cooling rate and Kondratjev number Kn as follows [8]:

$$V = \frac{\bar{a}\, Kn}{K}(T - T_m), \qquad (2)$$

where V is cooling rate $(\circ F/s)$;
$\bar{a}$ is average thermal diffusivity (m^2/s);
K is Kondratjev form coefficient (m^2);
For the infinite cylinder

$$K = \frac{R^2}{5.783}.$$

Therefore, Eq.(2) follows that

$$Kn = \frac{V \cdot K}{\bar{a}\,(T - T_m)} \qquad (3) \qquad \text{or} \qquad Kn = \frac{V \cdot R^2}{5.783 \cdot \bar{a}(T - T_m)}. \qquad (4)$$

Now we calculate Kn for polymer quenchants exhibiting inverse solubility based on Polyalkyleneglycol (PAG), such as UCON A, UCON E and others.

Average values $\bar{a}$ at the core's temperature of 1300ºF is equal to 5.19·10^{-6} m^2/s.

Proceeding from all stated above, the formula (4) for the determination of Kn at temperature 1300ºF for cylindrical samples of diameter of 0.5" (12.7 mm), 1" (25.4 mm) and 1.5" (38.1 mm) gets the following values:

$$Kn = 1.235 \cdot 10^{-3} V; \quad Kn = 4.94 \cdot 10^{-3} V; \quad Kn = 11.13 \cdot 10^{-3} V.$$

Table 1- Kondratjev number Kn for 10% aqueous solutions of UCON A and UCON E at temperature of 90ºF (~32ºC) and speed of the stream of 80 fpm (~0.4 m/s). Temperature of the core of probes is 1300ºF (704ºC).

Probe diameter in inches (mm)	UCON A	UCON E	$\overline{Kn}$
0.5 (12.7)	0.424 0.417	0.412 0.408	0.415
1 (25.4)	0.546 0.526	0.488 0.488	0.512
1.5 (38.1)	0.578 0.556	0.523 0.514	0.543

Table 2- Kondratjev numbers Kn for Houghton K oil at temperature of 110ºF (43,3ºC), no agitation, depending on sizes of cylindrical probes made of AISI 4140 steel

Probe diameter, inches (mm)	Kn at			$\overline{Kn}$
	1300ºF (704°C)	650ºF (343°C)	400ºF (204°C)	
0.5 (12.7)	0.230 0.206	0.073 0.073	0.026 0.026	0.106
1 (25.4)	0.142 0.139	0.120 0.121	0.046 0.046	0.102
1.5 (38.1)	0.392 0.407	0.136 0.139	0.071 0.071	0.213
2 (50.8)	0.420 0.414	0.158 0.150	0.084 0.084	0.218

The summary Table 1 presents values of Kn for 10%aqueous solutions of UCON A and UCON E at temperature of 90ºF (~32ºC), the agitation is at the speed of 80 fpm (~0.4 m/s). It is seen from this table that Kn practically does not change with change of the sizes of specimens, which agrees well with the theory presented Ref.[2-4]. Kn characterizes the cooling capacity of a quenchant, which depends on temperature and concentration of the solution. Besides, Tables 2 and 3 confirm this fact. With increase in temperature and concentration of a solution the cooling capacity of a quenchant reduces (see. Tables 2 and 3).

The maximal value of Kn, which can be achieved in practice, is equal to 1, i.e., Kn=1. Aqueous solutions of salts of optimal concentration are used for intensive and uniform cooling, and Kn for aqueous solutions of salts and alkalis in water is equal to 0.6, i.e., Kn=0.6.

It follows that aqueous polymer solutions exhibiting inverse solubility at their optimal concentration cool so uniformly and intensively as aqueous solutions of salts do. It is connected with the formation of polymer film at the metal surface to be cooled, which reduces the heat flux density and so it does not allow the development of film boiling, i.e., in this case $q < q_{cr1}$.

The way of putting heat-insulated films to the surface of metal with the purpose of the intensification of processes of quench cooling is copyrighted by the inventor's certificate [9]. When cooling in usual water, because of the formation of vapor films, Kn drops and changes within significant range.

To confirm the stated above, Fig. 6 presents the distribution of hardness on cross-section of a part quenched in oil, polymer quenchant and cooled by intensive sprays [6]. The polymer quenchants and intensive sprays yield the highest hardness on cross-sections and provide good hardenability. During quenching in oil the hardenability of a part sharply drops (see Fig. 6) [6].

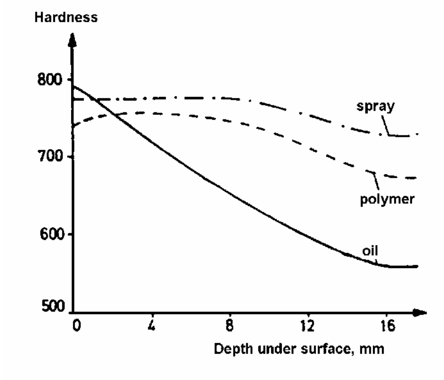

Figure 6 - Hardness distribution at the cross section of a cylindrical probe when quenched by sprayer and also in polymer quenchants and oils.

Cooling properties of oils Houghton K, Amolite 22 and Beacon 70

It is obvious from Table 2, Houghton K oil cools relatively faster, when the temperature of the core is equal 1300ºF and slowly when the temperature of the core is equal 650ºF and 400ºF. This is especially typical for still oil (see. Table 2).

With increase in circulation of oil up to 100 fpm (0.508 m/s), its cooling capacity is equalized a little with respect to both variation of temperature and variation of the sizes of probes (see Table 3).

When the sizes of parts increase, a great volume of the oil surrounding a massive part is warmed up to higher temperature. Small parts or probes give smaller quantity of heat to the medium, therefore, oil is warmed up less.

As is known, with increase in temperature of oils its cooling properties at first grow, and then fall [10, 11, 12].

There is an optimal temperature of oil at which cooling properties are maximal [10]. Thus, with increase in the sizes Kn grows due to the improvement of cooling properties of oil surrounding the part.

Kn decreases with decrease in temperature because the viscosity of oil sharply increases and cooling is slowed down, especially in the area of convection. The circulation of oil improves this situation a little. Similar regularities are observed for oils Amolite 22 (see. Tables 3 - 4) and Beacon 70 (see. Tables 5 - 6).

Calculated numbers Kn for various grades of oils may be used for not only the evaluation of their cooling capacity, but also calculations of cooling time for parts to be quenched. They can be also used at designing industrial lines and quenching equipment of any kind.

Table 7 presents Kn for 35% aqueous solutions of UCON A. These tables follow that high-concentration aqueous PAG solutions provide about the same conditions of cooling, as well as oil does. With decrease in concentration of solutions to 5 % - 10%, Kn is completely stabilized and practically does not depend on the sizes of cylinders (see. Table 1). During cooling in aqueous polymer solutions more uniform cooling at the whole surface is reached. During cooling in water local vapor films are observed, which results in cracking and distortion. Cooling capacity of 5-10 % PAG is higher than of water.

Table 3 - Kondratjev numbers Kn for Amolite 22 oil at temperature of 110ºF (43,3ºC), no agitation, depending on sizes of cylindrical probes made of AISI 4140 steel

Probe diameter, inches (mm)	Kn at			$\overline{Kn}$
	1300ºF (704ºC)	650ºF (343ºC)	400ºF (204ºC)	
0.5 (12.7)	0.065 0.056	0.035 0.036	0.026 0.026	0.041
1 (25.4)	0.088 0.084	0.063 0.063	0.046 0.048	0.065
1.5 (38.1)	0.134 0.165	0.092 0.089	0.071 0.071	0.104
2 (50.8)	0.306 0.288	0.106 0.106	0.04 0.04	-

Table 4- Kondratjev numbers Kn for Amolite 22 oil at temperature of 110ºF (43,3ºC), agitation of 100 fpm (0.508 m/s), depending on sizes of cylindrical probes made of AISI 4140 steel

Probe diameter, inches (mm)	Kn at			$\overline{Kn}$
	1300ºF (704ºC)	650ºF (343ºC)	400ºF (204ºC)	
0.5 (12.7)	0.136 0.128	0.169 0.165	0.163 0.143	0.15
1 (25.4)	0.184 0.185	0.225 0.233	0.197 0.206	0.205
1.5 (38.1)	0.275 0.311	0.280 0.273	0.254 0.240	0.27
2 (50.8)	0.342 0.319	0.273 0.251	0.251 0.226	0.28

Table 5 - Kondratjev numbers Kn for Beacon 70 oil at temperature of 110ºF (43,3ºC), no agitation, depending on sizes of cylindrical probes made of AISI 4140 steel

Probe diameter, inches (mm)	1300ºF (704ºC)	Kn at 650ºF (343ºC)	400ºF (204ºC)	$\overline{Kn}$
0.5 (12.7)	0.049 0.065	0.057 0.060	0.026 0.027	0.047
1 (25.4)	0.085 0.084	0.090 0.090	0.048 0.048	0.074
1.5 (38.1)	0.154 0.196	0.108 0.108	0.071 0.071	0.118
2 (50.8)	0.364 0.297	0.172 0.167	0.084 0.084	0.195

Table 6- Kondratjev numbers Kn for Beacon 70 oil at temperature of 110ºF (43,3ºC), agitation of 100 fpm (0.508 m/s), depending on sizes of cylindrical probes made of AISI 4140 steel

Probe diameter, inches (mm)	Kn at			$\overline{Kn}$
	1300ºF (704ºC)	650ºF (343ºC)	400ºF (204ºC)	
0.5 (12.7)	0.144 0.129	0.199 0.195	0.167 0.161	0.166
1 (25.4)	0.188 0.191	0.255 0.261	0.221 0.227	0.224
1.5 (38.1)	0.342 0.367	0.310 0.305	0.268 0.259	0.308
2 (50.8)	0.391 0.382	0.290 0.295	0.251 0.251	0.31

Aqueous solutions of PAG (5-10 %) can be used at the implementation of IQ-2 process.

Cooling time for the cylinder of diameter of 1.5 inches (38.1 mm) made of AISI 4140 steel in various quenchants is presented in Table 20. Time is calculated for the temperature range of 1550ºF - 400ºF, i.e., it is duration of cooling from austentizing temperature till the temperature at the center of the cylinder reaches 400ºF.

It is seen from Table 8 that the time of cooling of cylinders in water and 5%UCON differs very little. However, polymer solutions cool more uniformly at high temperatures and slow down a little the process of cooling of parts in the area of convection.

New ways of the intensification of processes of heat transfer during quenching

The optimal concentration of aqueous solutions of polymers and salts can be used for the implementation of intensive quenching methods. This section describes new ways of the intensification of processes of heat transfer during quenching. We may believe that some of them are the use of rotating magnetic fields and use of a principle of discrete-impulse energy input.

Table 7 Kondratjev numbers Kn for 35% aqueous UCON A solution at temperature of 110ºF (43,3ºC), agitation of 50 fpm (0.254 m/s), depending on sizes of cylindrical probes made of AISI 4140 steel.

Probe diameter, inches (mm)	Kn at			$\overline{Kn}$
	1300°F (704°C)	650°F (343°C)	400°F (204°C)	
0.5 (12.7)	0.046 0.054	0.197 0.190	0.135 0.145	0.128
1 (25.4)	0.075 0.074	0.330 0.311	0.218 0.212	0.203
1.5 (38.1)	0.099 0.120	0.365 0.365	0.377 0.301	0.271
2 (50.8)	0.157 0.220	0.546 0.581	0.444 0.478	0.404

Table 8 Time of cooling of the cylinder of diameter of 1.5" (38.1 mm) from 1550ºF (843ºC) to 400ºF (204ºC) depending on the quenchant applied. Steel is AISI 4140.

Quenchant	Cooling time, sec	
	No agitation	Agitation of 100 fpm (0.508 m/s)
Houghton K, 110°F	107	75
Amolite 22, 110°F	219	84
Beacon 70, 190°F	202	80
35% UCON A, 110°F	-	84
20% UCON E, 90°F	-	63
5% UCON E, 90°F	-	50
Water, 70°F	55	-

Use of rotating magnetic fields

Fig. 7 presents a principal scheme of the installation for the use of rotating magnetic field. The rotating magnetic field is formed due to using a stator of a usual electric engine, in which, instead of a rotor, parts to be quenched are moved along a circle of a cylindrical tank inserted into the stator. Parts to be quenched so may be bearing balls or balls of spherical mills.

Installation can carry out quenching process, namely: IQ-2.

At the first stage, balls are quenched in aqueous solution of salts of optimal concentration, for example, 6-8% Na_2CO_3. Balls are rotated in the magnetic field until the end of nucleate boiling and are periodically pushed out on the conveyor which delivers the parts from the quenchant. The parts are self-tempered in air. At the second stage the parts are washed and at the same time process of intensive cooling within the martensite range continues until they are completely cooled down. At the third stage the parts are dried and tempered by means of induction heating. Heating to the austentite temperature can be performed also by induction. This scheme is principal and it should be noted that there may be different ways of the implementation of the above-mentioned process. The advantage of the described technology consists in the following:

- magnetic fields improve the mechanical properties of material;
- alternating magnetic fields result in the destruction of vapor films;
- the process becomes controlled and easily automated.

More particulars on this technology are described in the inventor's certificate [15].

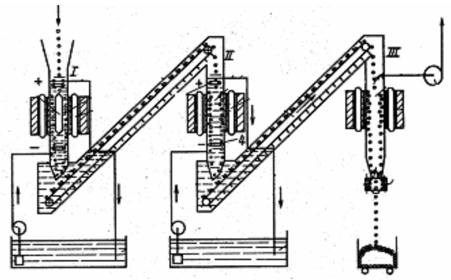

Figure 7- Line for quenching balls of bearing rings with the application of electromagnetic fields

Conclusions

1. The method has been developed for designing the movement of continuous conveyer lines with regard to the shape and sizes of parts to be quenched, as well as thermophysical properties of material and cooling capacity of the quenchant with the purpose of automatic control and creation of high-strength of materials.
2. It is shown that cooling capacity of quenchants is characterized by the main parameter of quenching, Kondratjev number Kn.
3. Tables of numbers Kn for various quenchants, which form database of initial data for specific calculations related to quench cooling are presented.

Results of calculations may be used by heat treating engineers and designers dealing with industrial lines.

References

1. N.I.Kobasko, Ukraine Patents No. 27059 and 56189
2. N.I.Kobasko, Theory and Technology of Quenching, Springer-Verlag, Berlin, 1992, pp. 367-389
3. N.I.Kobasko, Thermal Processes During Steel Quenching, MiTOM, 1968, No.3, p 2-6
4. N.I.Kobasko, Steel Quenching in Liquid Media Under Pressure, Kiev, Naukova Dumka, 1980, 206 p
5. Jack Hasson, Quench System Design Factors, Advanced Materials & Processes, 148 (No. 3), Sep. 1995, p 42S-42U
6. G.E.Totten, C.E.Bates, and N.A.Clinton, Handbook of Quenchants and Quenching Technology, ASM International, Materials Park, 1993, 507 p
7. G.E.Totten, M.A.H.Howes, Steel Heat Treatment Handbook, Marcel Dekker, 1997, 1192 p
8. J.M.Kondratjev, Heat Measurements, Moscow – Leningrad, Mashgiz, 1957, 244 p
9. G.V.Kovalenko, N.I.Kobasko, A.A.Khalatov, Method of Steel Quenching, Inventor's Certificate 1355634, USSR, published on 30.11.1987, Inf. Bull. No. 44
10. N.I.Kobasko, E.D.Nikolaev, Study of Cooling Capacity of Oils MS-20 and I-50. Technology and Organization of Production, 1977, No. 2, p 78
11. T.I.Tkachuk, N.Ya.Rudakova, B.K.Sheremeta, and M.A.Al'tshuler, MiTOM, No. 10, 1986, p 45-47
12. T.I.Tkachuk, N.Ya.Rudakova, B.K.Sheremeta, and R.D.Novoded, MiTOM, No. 10, 1986, p 42-45
13. M.Daming, Intense Quenching Method for Preventing Quench Cracking, Proc. Seventh Int. Congress on Heat Treatment and Technology of Surface Coating, Vol. 2, 11-14 Dec. 1990, Vneshtorgizdat, Moscow, p 62-71
14. N.I.Kobasko, US Patent 6,364,974 BI, April 2, 2002
15. A.L.Satanovskiy, N.I.Kobasko, A.A.Khalatov, Steel Quenching Method and Setup for its Implementation, Appl. No. 4608270/31-02 dd. 23.11.1988, Certificate No. 1627574, Bulletin of the Invention, 1991, No. 6