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SCIENCE IN THE GLASS INDUSTRY

OPTIMIZATION OF HEATING OF GLASS DURING QUENCHING

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Heating glass is one of the most important technological operations in the production of quenched glass. It determines the characteristics of the technological process as a whole and has a major effect on the quality of the production.

To ensure high output from quenching equipment and uniform quenching of glass, the time taken to heat the glass to the quenching temperature must be a minimum and the temperature gradient over the area and along the thickness of the glass must be below a given value. The heating time can be shortened by increasing the heating rate, but in this case the temperature gradient along the thickness of the glass increases, and as a result, the quenching may be uneven and the glass product may even fracture [1].

The most acceptable is the radiation method of heating (by means of electromagnetic radiation with a wavelength of 0.35-3.5 μm), since it makes it possible to even out the heating rate of the surface and internal layers of glass, hence lowering the temperature gradient along the thickness [2].

It has been determined experimentally that in industrial furnaces the glass heating is much slower than the process which corresponds to the absolute black-body model and is described more accurately by a model from the class of linear dynamic systems

$$\left.\begin{aligned}\frac{d\nu_1}{d\nu} &= \frac{\nu_S - \nu_1}{\tau_1};\\ \frac{d\nu_2}{d\nu} &= \frac{\nu_1 - \nu_2}{\tau_2},\end{aligned}\right\} \quad (1)$$

where ν_s is the temperature of the radiation source, ν_1 is the temperature of the surface layer, ν_2 is the temperature of the middle layer, and τ_1 and τ_2 are time constants.

In accordance with the indicated requirements we formulate the problem of optimization of glass heating.

It is necessary to find the law governing the radiation-source temperature so that a glass plate with an initial temperature equal to the ambient temperature

$$\nu_1(0) = \nu_2(0) = \nu_0, \quad (2)$$

heats up to the quenching temperature

$$\nu_1(t_3) = \nu_3 \quad (3)$$

in the minimum time

$$(t_3) \to \min. \quad (4)$$

The following constraints should be met:

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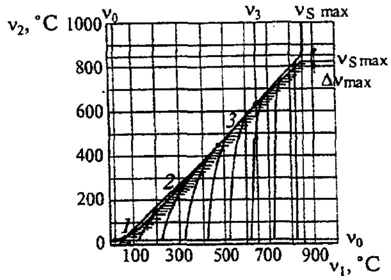

Fig. 1. Phase trajectories of glass heating.

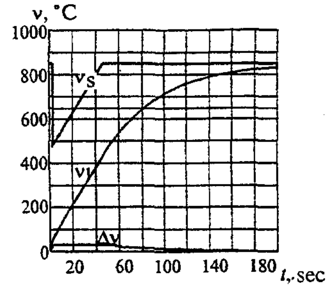

Fig. 2. Time diagrams of the optimal glass-heating process.

$$\nu_1(t) - \nu_2(t) \leq \Delta\nu_{max}; \quad (5)$$

$$\nu_S(t) \leq \nu_{S\,max}. \quad (6)$$

Constraint (6) is due to the fact that the radiation-source temperature in a real technological process is limited from above by the thermal shock resistance of the furnace equipment.

The formulated problem is known in the theory of optimal control as the problem of maximum speed with limitation of the phase coordinates [4]. In accordance with the Pontryagin maximum principle, the optimal principle in regard to speed is the law of radiation-source temperature

$$\nu_S(t) = \sup \nu_S, \quad (7)$$

where $\nu_S \in \Omega(t)$; $\Omega(t)$ is the set of values of the radiation-source temperature for which the constraints (5), (6) are satisfied.

The expression obtained has a clear physical meaning. To heat a glass plate to the quenching temperature in the minimum time while observing the given constraints it is necessary that at each instant during the heating the radiation-source temperature has the maximum value allowed by the constraints.

We construct the optimal law of variation of the radiation-source temperature by using the phase-plane method [5]. An expression to describe the phase trajectories for the system (1) is obtained by dividing the first equation of the system by the second,

$$\frac{d\nu_1}{d\nu_2} = \frac{\tau_1(\nu_1 - \nu_2)}{\tau_2(\nu_S - \nu_1)}.$$

We construct a family of phase trajectories (Fig. 1) for the boundary value of the inequality (6). For this purpose we assign numerical values of the variables in Eqs. (1)-(7). As an example we have chosen the heating of 6-mm-thick sheet glass in a PN-900 furnace: $\tau_1 = 49$ sec, $\tau_2 = 3.6$ sec, $\nu_0 = 20$°C, $\nu_3 = 650$°C, $\Delta\nu_{max} = 30$°C, and $\nu_{s\,max} = 850$°C.

According to Eq. (7), the optimal phase trajectory consists of segments that lie on the boundary of the region (5), and also segments that coincide with parts of the phase trajectories for the boundary value of the inequality (6). By the condition of the problem the system, (1) should be taken from the initial state (2) to the state (3). From the segments we construct the optimal phase trajectory, which begins at the point 2 and ends on the straight line 3 of the phase plane (see Fig. 1). The law of variation of the radiation-source temperature, which corresponds to the optimal phase trajectory, is the solution of formulated problem of optimization of glass heating (Fig. 2).

If the time taken to heat glass to the quenching temperature, with constraints imposed on the temperature gradient along the thickness of the glass and on the radiation-source temperature, is to be minimized, the heating process should include the following stages:

— heating at the maximum radiation-source temperature until the temperature gradient along the thickness of the glass reaches the limit;

— stabilization of the temperature gradient along the thickness of the glass at the limiting value because of variation of the radiation-source temperature from the minimum to the maximum at a constant rate; and

— heating of the glass to the quenching temperature with the radiation source at its maximum temperature.

In order to implement these stages of the heating it is sufficient to vary the speed of the glass and the thermal conditions in the sections. With this method the glass heating time is decreased to 80 sec from the 105 sec for the method used in practice, i.e., decreased by approximately 20%. The temperature drop between the surface layer and the middle layer remains equal to 30°C.

In summary, variation of the parameters of the technological process makes it possible to increase the output from the heating furnace of the quenching line, without violating the constraints on the temperature gradient along the thickness of the glass and reduces the waste by increasing the speed at which the sheets travel in the softened state.

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