CONNECTION BETWEEN GLASS QUALITY AND THE CONVECTION FURNACE

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ABSTRACT

The manufacturers and users of tempering furnaces have met new requirements, when coated glass appeared into the market at the beginning of 90 s. Before heating of a clear glass was mainly based on radiation, but when low-emissivity products hit the market great difficulties in tempering were initially experienced.

Traditional heating methods very easily produce different types of faults which have been tried to remove with convection furnaces. In these furnaces heating rate of glass is controlled by forced convection. However, the control of the convection furnace is quite complicated, if high capacity and good quality are required.

In this paper the reasons for difficulties in tempering of coated glass is delt in view of basic heat transfer phenomena. The effect of different heat transfer mechanisms on glass heating and cooling are discussed. On the basis of theoretical observations the importance of different parameters and phenomena on heat transfer is shown. It can be concluded that the increase of convection during the heating period requires an advanced control system.

1. INTRODUCTION

The demand of coated low emissivity glass is expected to grow very quickly in the future. As such coated glass is not suitable for applications until it is tempered. In a tempering process glass is at first heated to the temperature of 610-650°C and rapidly cooled after that. The purpose during the cooling stage is obtain a compressive stress in the surface of the glass, so that in the middle region tensile stresses exist. This type of process is possible if the tempereture difference between the surface and the middle is sufficient. In the cold solidified surface region the rearrangement of glass molecules is prevented during the rapid cooling, while in the hot and soft middle region the rearrangement is still possible creating the decrease of density compared to the surface region. The density difference is responsible for creating compressive stress in the surface region and tensile stress in the centerline /1/.

The tempering process of coated glass is more difficult to control than in the case of clear glass. The main reason is that radiation properties of the upper and lower surface of coated glass are different. Because there always exists radiation, it leeds to a nonuniform and unsymmetrical temperature distribution during the heating period which causes the bending of glass due to thermal stresses. The curving of glass is the reason of typical faults such as white hazes, optical lenses, coating burn, large fragmentation, optical distortion and unstable bow /2/.

In order to obtain symmetric heating of coated glass forced convection has been added into the furnace to compensate unsymmetrical radiation heating. Different types of arrangements have been tried to keep glass flat during the heating. Manufacturers have developed furnaces, in which radiation and forced convection have been utilised in one or two stage furnaces. Also furnaces where only forced convection is used have been developed /2/.

2. HEAT TRANSFER IN TEMPERING

The toughening process currently in use for heating of glass is largely based on electrical heating. The glass is loaded on a conveyor for transfer into the heating furnace. After reaching the required temperature, it is quickly conveyed into the cooling section. In today’s technologies the most common method is based on horizontal oscillation, in which the glass supported by rollers moves slowly back and forth in the heating furnace.

A cold glass sheet to be heated in a furnace is affected by different types of heat transfer phenomena, which affect simultaneously. Traditionally, radiation from hot, electrically heated resistance elements in the ceiling of the furnace is used. However, this technique is not

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very suitable for coated glass because the coated surface absorbs radiation differently as clear glass resulting into an unsymmetrical temperature distribution and causing bending. A remedy to balance heating is the adoption of forced convection.

Fig. 1 shows different sources of heating when cold glass goes into the furnace. From the upper surface the glass sheet is heated by radiation and convection. If there does not exist any forced flow, natural convection is present. From the lower surface heat is exchanged by conduction from the rollers, radiation from rollers and the furnace beneath them and convection.

The heating should be controlled in such a way that the temperature distribution in glass is symmetrical. Because the prosess is time dependent, it is not easy to handle. In addition, even if the temperature distribution is symmetrical too large temperature gradients must be avoided.

Heat transfer mechanism mentioned above can be controlled to some extend. The temperature distribution of glass is governed by equation

$$\rho c \frac{T}{t} = \frac{}{x}\left(k\frac{T}{x}\right) + F \qquad (1)$$

where T is temperature of the glass, t and x stand for time and space. ρ, c and k and are material properties, density, specific heat and thermal conductivity, respectively. The last term F in Eq. 1 stands for radiation heat transfer in the glass. It is very difficult to include F in calculations because emission and absorption are dependent on the wavelength of radiation. For instance a soda-lime glass is opaque when the radiation wavelength l > 4 mm, but for smaller wavelengths there also exists radiation in the glass.

Eq. 1 has been solved including F for special boundary condition in the literature /3, 4/. In the case of a tempering furnace boundary conditions are everything but well defined. For that reason the effect of radiation inside the glass has been ignored in this paper.

In the furnace there also exists conduction heat transfer in rollers. The temperature distribution of the roller is governed by equation

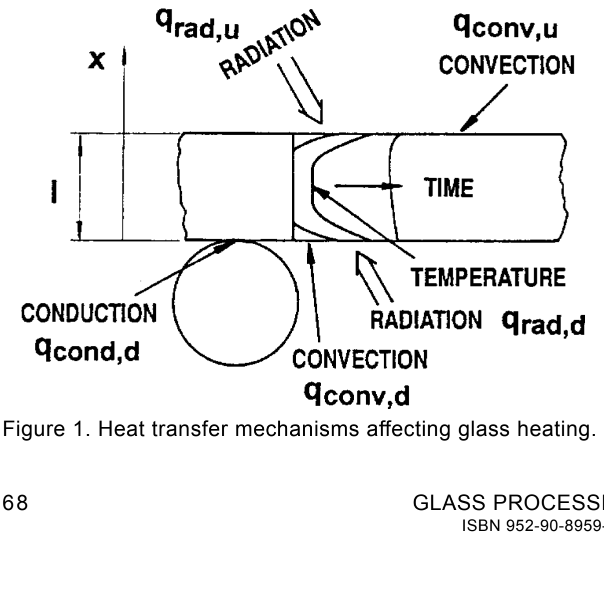

Figure 1. Heat transfer mechanisms affecting glass heating.

$$\rho_r c_r \frac{\partial T_r}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(k_r \frac{\partial T_r}{\partial r}\right) \qquad (2)$$

in which T_r is the roller temperature and r is the radius. ρ_r, c_r and k_r are the density, specific heat and thermal conductivity of the roller material, respectively.

Eq. 1 and 2 have to be solved simultaneously, because heat is exchanged between the rollers and the glass by contact heat transfer and radiation. With the notations in Fig. 1 the boundary conditions for Eq. 1, when a cold glass goes into a hot furnace, are

$$T(x,o) = T_o \qquad (3)$$

$$k\frac{\partial T(l,t)}{\partial x} = q_{rad,u} + q_{conv,u} \qquad (4)$$

$$-k\frac{\partial T(o,t)}{\partial x} = q_{rad,d} + q_{conv,d} + q_{cond,d} \qquad (5)$$

Similar types of boundary conditions are also needed to solve Eq. (2). Initially, the rollers are at the furnace temperature. During the heating period heat is transfered from the rollers by radiation and contact heat transfer to the glass. Both radiation and convection heat fluxes in equations (4) and (5) must have special equations. These are dealt in detail below.

2.1 NATURAL CONVECTION

Before the 1990's furnaces were mostly designed for tempering of clear glass. Heating could be arranged by radiation, but natural convection was always present. Even in that case heating was not uniform, because natural convection from a horizontal surface gives varying heat transfer coefficient. Natural convection is also present in the convection furnace, if there is no jets on the lower side of glass.

Natural convection from an upward or downward facing horizontal surface has been studied intensively, but there are only some works, in which simultaneous convection has been studied. Fig. 2 shows an essential fact concerning natural convection from a horizontal surface /5/. According to Fig. 2 heat transfer coefficient is almost two times larger in the edge compared to that in the center of the plate. Fig. 2 is the result for constant heat flux, when heat is transfered simultaneously from the upper and lower surface. A similar trend of heat transfer as in Fig. 2 has recently obtained also with the numerical

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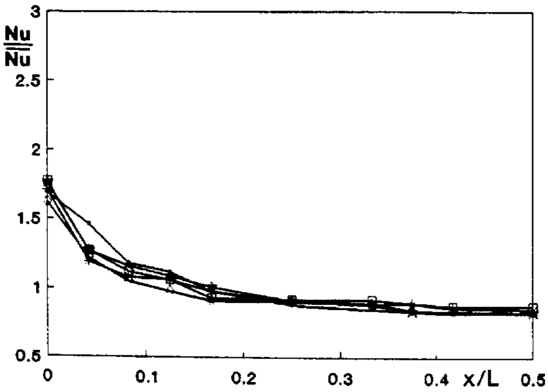

Figure 2. Local Nusselt number distribution of uniformly heated horizontal plate with simultaneous convection from upper and lower surfaces.

modelling /6/. The same kind of result is also obtained for a constant temperature boundary condition.

2.2 FORCED CONVECTION

When new low-emissivity glass products hit the market at the and of 1980's, great difficulties in the tempering of this kind of glass were initially experienced. Most of the problems resulted from unsymmetrical heating, because the coated side with low emissivity reflected radiation. Forced convection was adopted to balance heat transfer.

Forced convection is applied by arranging small jets, from which air is injected in order to create forced flow near the glass surface. A typical arrangement is shown in Fig. 3, in which the locations of jets are shown from 1 or 12. The jets are formed by blowing pressurized air through small holes of a horizontal tube above the glass plate. Heat transfer coefficient obtained with the arrangement of Fig. 3 is not easy to get. By using numerical modelling of fluid dynamics (CFD) some idea can be obtained how jet locations, nozzle diameter and air velocity affect heat transfer /7/. Heat transfer coefficient is not constant, but there are large variations as is seen in Fig. 4, which presents heat transfer coefficient of the area marked with lines in Fig. 3. However, when the glass plate is oscillating, it feels average heat transfer coefficient.

2.3 THERMAL CONTACT BETWEEN GLASS AND ROLLERS

Heat transfer between rollers and glass is based on contact heat transfer. It is dependent on thermal conductivities, hardness, emissivity and roughness of surfaces. In addition pressure is an important parameter. If surfaces are hard and pressure is low the contact surface is very small.

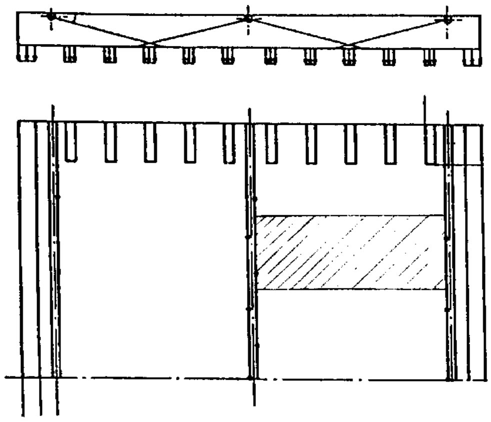

Figure 3. Principle of forced convection furnace.

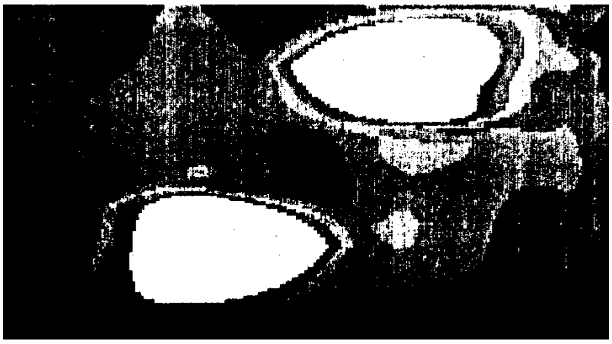

Figure 4. Typical distribution of calculated heat transfer coefficients (W/m^2K) with jet arrangement of Fig 3.

There exist many methods to evaluate contact heat transfer in the literature /8/. However, most of the studies are dealing with metals and materials used in electrical applications. In the tempering furnace the rollers are usually made of ceramic material. Thus we have ceramic material and glass, the properties of which totally different from those of metals.

When different types of methods presented in the literature are applied for the evaluation of contact heat exchange between the roller and glass, it was observed that its role is not dominating /8, 9/.

2.4 RADIATION

The effect of radiation must be taken into account always, even in the case of the forced convection furnace. In the lower surface heat exchange between the rollers and glass is mainly based on radiation. If ceramic rollers are used the emissivity is not a problem. Because the evaluation of view factors is straightforward /10/, radiation heat transfer is easily obtained. However, if metallic rollers are used, their emissivity changes during the operation and it gives uncertainties for calculations.

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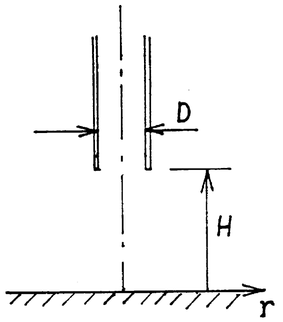

Figure 5. Dimensions of impinging jet.

The upper surface is problematic, when coated glass is heated. There are not available data of emissivity and absorptivity as a function of temperature for different types of coatings.

2.5 COOLING STAGE

In order to obtain such temperature gradients in glass that tempering is possible, very effective cooling of glass is needed. The thinner the glass plate the higher heat transfer is needed. Very high heat transfer coefficients are obtained by using impinging air jets. Even in the case of a single jet in Fig. 5, the heat transfer rate is a complex function of many parameters: Nusselt number (Nu), Reynolds number (Re), Prandtl number (Pr), the nozzle-to-plate spacing (H/D) and displacement from the stagnation point (r/D).

$$Nu = F(\mathrm{Re}, \mathrm{Pr}, H / D, r / D) \qquad (6)$$

In the chilling process the array of jets has to used. In that case the flow is also confined. Because air flow rates are quite high, also power consumption should be considered. In order to find an optimized solution both theoretical and experimental research is needed /11/.

3. SOME RESULTS

In order to show the difference between heat transfer of coated glass and clear glass Fig. 6 is presented. It shows the temperature distribution of a 1 cm thick glass 6 minutes after going into the furnace when only the emissivity of the upper surface is changed. For the clear glass emissivity of the upper surfaces was 0.8 and for the coated one 0.16. Other parameters were the same, namely convection heat transfer coefficient of the upper surface 18 W/m^{2}K, the length of the furnace 6 m, glass velocity 0,2 m/s and the loading of the furnace 1/3 /12/. It can be observed that with the same type of heating method the maximum temperature difference of coated glass is 18 K compared to 4 K for clear glass.

Some idea concerning the importance of different heat transfer phenomena can be obtained from Fig. 7. It shows how heat is transfered with different mechanisms during the heating period of coated glass in Fig. 6. It can be seen that at the upper surface forced convection and radiation are of equal importance. When looking at heat fluxes to the lower surface radiation has a dominating role, while natural convection and contact heat transfer from the rollers have only a marginal effect.

4. CONCLUSIONS

Systematic studies of heat transfer have increased the basic understanding concerning the behaviour of the tempering furnace. The importance of different types of heat transfer mechanisms have been discovered. For instance,

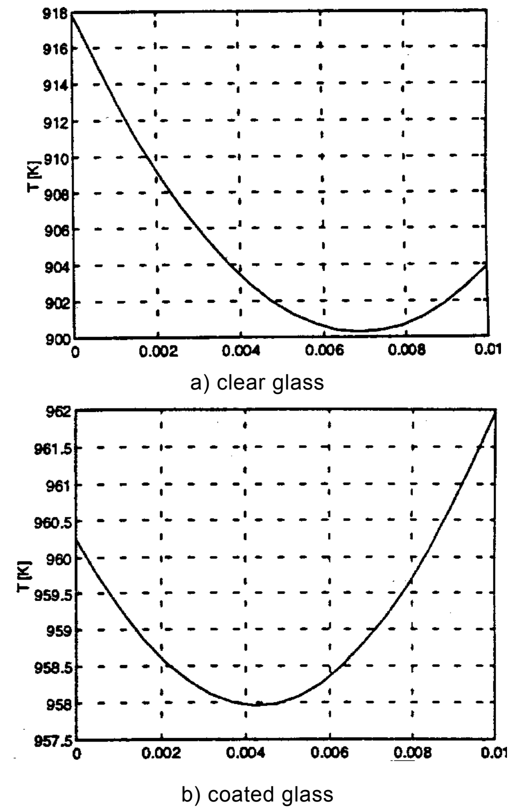

Figure 6. Temperature distributions of 1 cm thick clear glass (a) and coated glass (b) after 6 minutes, when furnace is operated in similar way.

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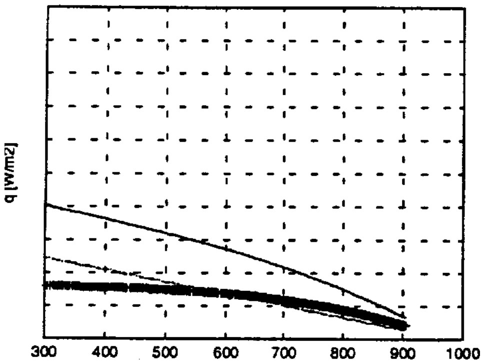
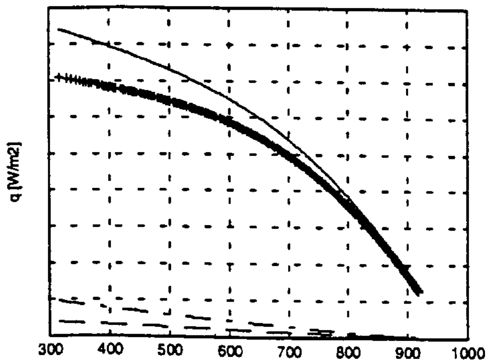


a) upper surface



b) lower surface

Figure 7. Heat fluxes to upper and lower surfaces of coated glass with different mechanisms as function of surface temperature.

—— total,	—·— natural convection
+++++++ radiation	- - - forced convection
	— — contact

it seems that contact heat transfer from the ceramic rollers has a minor role compared to radiation from them.

When forced convection is increased the importance of a process control system is of vital importance. In order to find the best operation parameters, the theoretical model, the basis of which is given above, shortens the trial period, when a new type of glass is tempered. Still the problem that the edges of glass experience different heat transfer rates exists. This tendency increases with glasses of larger dimensions.

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