

How to Temper Low-E Glass

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ABSTRACT

This paper presents the factors which must be taken into account when tempering glass with a low-emissivity coating or glass for subsequent off-line coating. Heat is transferred to the glass by convection, radiation and conduction. The key factor in the successful tempering of coated glass is the heating of the glass to an even temperature while preserving the quality and integrity of the coating.

At Tamglass we have found that forced convection and heat focussing are the solutions to tempering Low-E glass. It is important to find the optimum balance among convection, radiation and conduction during the tempering process. To achieve the best possible quality tempered product, glass movement and accurate position control are also important. The uneven heat absorption of Low-E glass can cause tempering problems, such as the excessive heat decrease in the rollers' surface temperature. This effect can, however, be controlled by sophisticated movement and heating control systems.

This presentation focuses on the technology currently in use. The latest spear-head technology for tempering Low-E glass makes use of, the so-called "high-convection furnaces". A detailed presentation of these will, however, have to wait until the technology is ready for full-scale commercial utilization. The object here is to cover the technology in industrial use today and it is based on our experience from more than 300 tempering furnaces delivered.

INTRODUCTION

In the first stage of tempering, the glass is heated to a temperature of 610-650° centigrade. Cooling follows the heating stage. The extent to which cooling is applied depends on the thickness of the glass. During the cooling process, a difference in temperature is created between the surface and the midplate of the glass. The rapidly cooling surface solidi-

fies and prevents the glass molecules from rearranging themselves, thus forming permanent bonds. In the hot and soft midplate the rearranging of molecules is still possible, and thus the molecules pack closer to each other while the surface is already solidifying./1/

The density and temperature distribution are shown schematically in Figure 1.

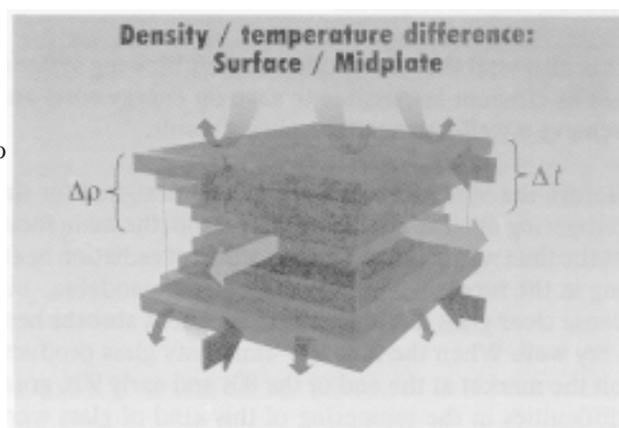


Figure 1: Density and temperature difference during the cooling stage

To create these tempering stresses, it is very important to generate a sufficiently large temperature difference between the surface and the midplate during the cooling stage. The density differences, and thus also the tempering stresses depend upon the magnitude of the temperature difference.

Due to the greater density of the midplate, a strong compressive strength is directed towards the surface, which generates an opposite tensile stress in the midplate of the glass. The compressive and opposite tensile stresses are of equal force.

The forces affecting the glass are displayed in Figure 2.

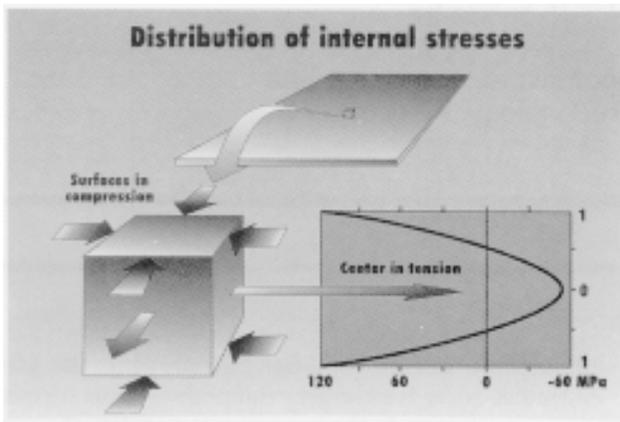


Figure 2: Distribution of internal stresses

For a quality result, the glass pane has to be heated up to an even temperature. To successfully and quickly raise the temperature of the glass to the adequate tempering level, precise control of the application of heat in the heating stage is required.

It is also vital that the cooling and air blowing systems are as efficient as possible to save on energy costs and achieve a well-balanced tempering result.

Before the 90s, furnaces were mostly designed for the tempering of clear glass. For this reason, the main focus at the time was on an even application of radiation heating in the furnace. This was quite understandable, because clear glass has high emissivity and it absorbs heat very well. When the new low-emissivity glass products hit the market at the end of the 80s and early 90s, great difficulties in the tempering of this kind of glass were initially experienced.

Most of the problems resulted from the unsymmetrical emissivity of the coated glass. This results in a strong bending of the glass as shown in Figure 3. The bottom side of the glass displayed high emissivity and absorbed heat effectively, the coated side with low emissivity, reflected heat radiation.

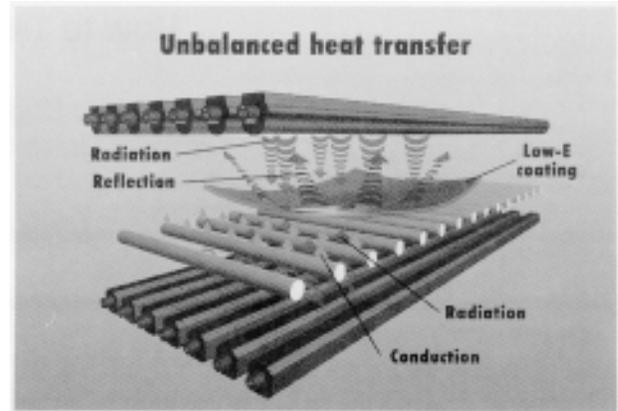


Figure 3: Bending as a result of unbalanced heating

This unsymmetrical behavior led to the bending of the glass in the furnace, as the uncoated bottom side of the glass heated up more quickly. The situation could have been helped by placing the coated side against the rollers, which would have resulted in less curving. This method has not, however, been used in Europe, because it may cause defects in the coating.

When the coating is on the top side of the glass the curving causes the following typical problems as displayed in Figure 4.

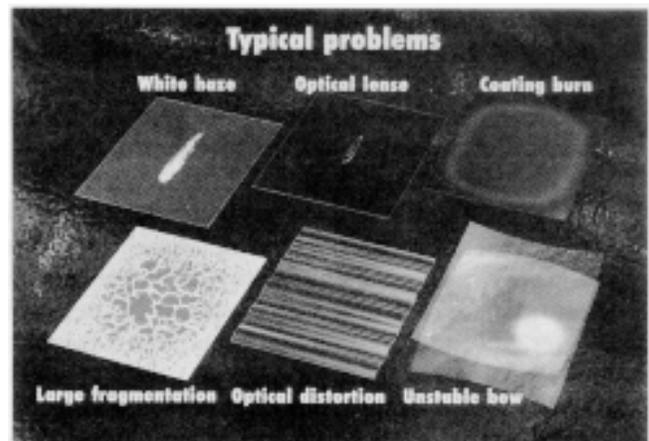


Figure 4: Typical faults of tempered glass

1. White haze/marks
2. Optical lense
3. Coating burn
4. Large fragmentation
5. Optical distortion
6. Unstable bow

Low-emissivity glass has been available on the market since the 80s. Its emissivity was, however, rather high by today's standards. It was not until the late 80s and early 90s that

toughenable Low-E glass with an emissivity of 0,1-0,23 became available.

The demand for Low-E glass is expected to grow very fast in the future. A typical indication of the preference put on this product is found in German legislation, where the requirements to save energy are so tough that Low-E glass is practically always required in window structures. The same trends are visible in other European countries as well.

TECHNOLOGY

Manufacturing technologies currently in use for the heating of glass are largely based on electrical heating. Gas-fired processes are sometimes also used.

The process starts by the glass being loaded on a conveyor for transfer into the heating furnace as displayed in Figure 5.

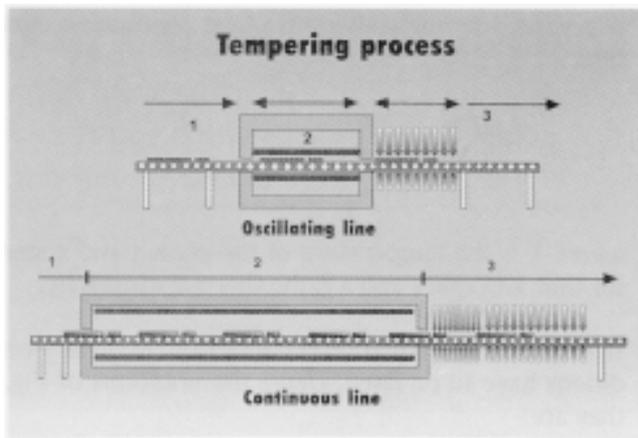


Figure 5: Schematic of the tempering process

The typical temperature in the furnace is 700-720° centigrade depending on the glass characteristics. For successful tempering, the glass has to be heated up to 610-650° centigrade. The heating time for clear glass is around 40 seconds per thickness millimeter. When the glass reaches the required temperature, it is quickly conveyed into the cooling section.

Tempering is performed by cooling air jets. The tempering and cooling process requires about half the time of the heating process. When the glass has been cooled down to handling temperature, it is transported into the unloading section. At this stage, quality inspection is performed, and the glass is forwarded for packaging and shipping.

It should be noted that all mechanical finishing of the glass must be done before the tempering stage, after which the products must no longer be subject to cutting, grinding or drilling.

In today's technologies the most common tempering method is based on horizontal oscillating. During this process, described in the above drawing on figure 5, the glass moves back and forth in the furnace. This method has been designed particularly for the production of short and flexible product runs. The drawing on figure 5 also displays a continuous tempering process where the glass moves in one direction only. In this operation, the heating and tempering/cooling sections become reasonably long. The furnace also benefits from larger capacity in this case. This kind of furnace is particularly suitable for long production runs.

The furnaces commonly in use today are displayed in Figure 6.

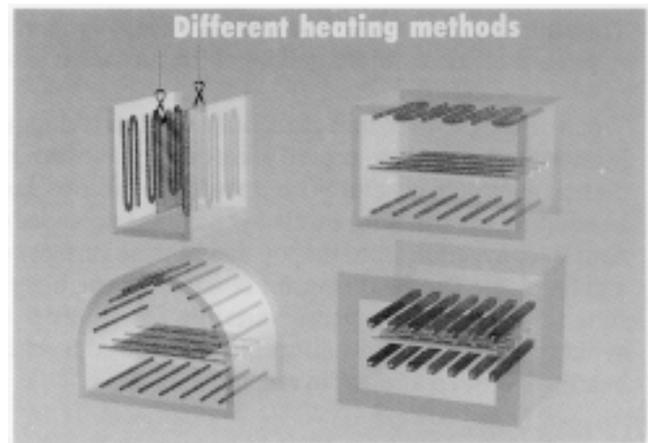


Figure 6: Different heating methods

The glass may be heated by means of different technologies, all having their advantages and drawbacks.

In this picture, top left, we have a vertical furnace. The glass to be heated is in a hanging position and the heating elements are placed on the sides of the furnace.

The other three drawings illustrate horizontal furnaces.

The bottom left and top right are versions where the heating elements have been placed in the furnace's ceiling and bottom. Bottom right is a furnace based on indirect radiation, and the radiators are close to the glass.

HEAT TRANSFER

A cold glass sheet to be heated in a furnace is affected by different types of heat transfer phenomena which are shown schematically in Figure 7.

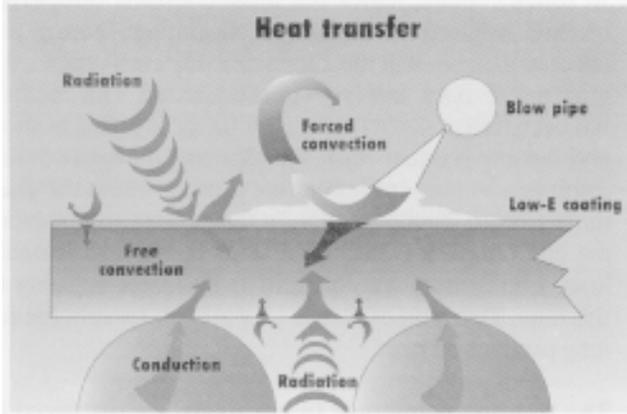


Figure 7: Heat transfer phenomena during heating

Traditionally, radiation from hot, electrically heated resistance elements in the ceiling of the furnace is used.

When dealing with coated glass, however, this technique is not suitable because coated glass does not absorb radiation as effectively and as symmetrically as clear glass. In addition to radiation, we always have the presence of natural convection from the top and bottom surfaces of a glass plate. The heat transfer is not uniform, but results in a large temperature variation [2]. In order to avoid temperature non-uniformities, forced convection heating has been applied in recent years [3].

Forced convection is applied by arranging small jets, from which air is injected in order to create a forced flow. The design of the jet configuration which leads to a uniform heat transfer coefficient is a complex problem [4].

Another heat transfer mechanism, in addition to those mentioned above, is the heat conduction from the rotating support rollers. That in turn, depends on the material properties of the rollers and on their geometry.

The design of the heating section in a tempering furnace requires that the heat transfer process between the glass plate and the furnace environment is understood. This is also necessary when the furnace behavior is adjusted to different types of glass. In order to understand the importance of different heat transfer processes, the conduction in glass, radiation, convection and conduction from the rollers must all be considered.

The temperature distribution of a glass plate is shown in Figure 8.

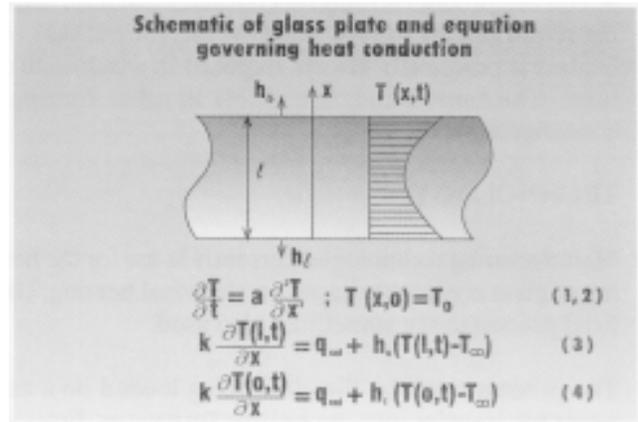


Figure 8: Schematic of the glass

is governed by the well-known heat conduction equation:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} \quad (1)$$

where T is the temperature of the glass, t and x stand for time and space and a is the thermal diffusivity.

In order to solve equation (1) initial and boundary conditions have to be fixed. Using the notations of Fig. 8 they are:

$$T(x,0) = T_0 \quad (2)$$

$$k \frac{\partial T(l,t)}{\partial x} = q_{rad} + h_u(T(l,t) - T_\infty) \quad (3)$$

$$k \frac{\partial T(0,t)}{\partial x} = q_{rad} + h_l(T(0,t) - T_\infty) \quad (4)$$

In the equations above q_{rad} is radiation heat exchange between the furnace and the glass, h_u and h_l are convective heat transfer coefficients of the upper and lower surfaces respectively. h_l also includes conduction heat transfer from the rollers. k is the thermal conductivity of the glass. T_0 is the glass temperature before it goes into a hot furnace.

The solution of equation (1) is straight-forward with a numerical method if the boundary conditions (3) and (4) are known. According to equations (3) and (4) heat transfer from the top and bottom surfaces should be the same and uniform. For instance, if the emissivity of the glass to be heated is changed, it affects the radiation heat transfer q_{rad} . In order to keep the heat exchange from the top direction constant, convective heat transfer should be changed by the application of forced convection. In addition, if we have a fixed jet configuration to create forced convection, the heat transfer is affected by the size of the glass plate.

In order to control the heat transfer process of tempered glass, theoretically, the spectral radiation properties of the glass should be known. The understanding of convective heat transfer is most difficult. It has been approached with numerical simulation as well as experimental measurements [4]. Heat transfer from the rotating rollers on the bottom side of the glass is also all but understood.

THE TEMPERING OF LOW-E GLASS

The heating of Low-E glass is affected by:

1. The Structure of the Furnace
2. Heating Control
3. Convection
4. The Control of the Movement of the Glass

All of these factors are dealt with below.

Our experiences of how to temper Low-E glass are based on the products listed in Figure 9.

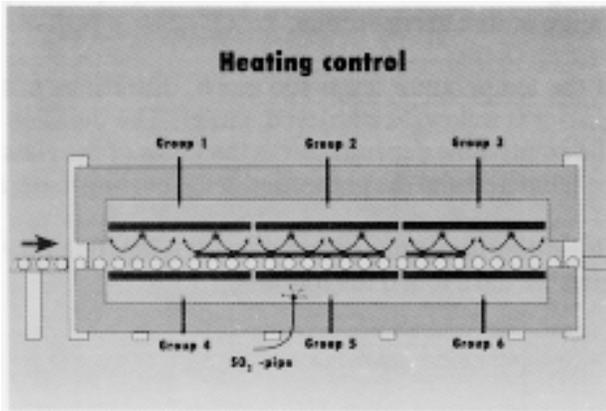


Figure 9: Low-E glasses

When new coating materials are introduced the first test runs are usually done at our factory in cooperation with the manufacturers of the glass. From time to time, we also get involved directly in the setting of process parameters with our customers.

At this point the structure of the furnace needs to be considered. In the furnace structure in Figure 10

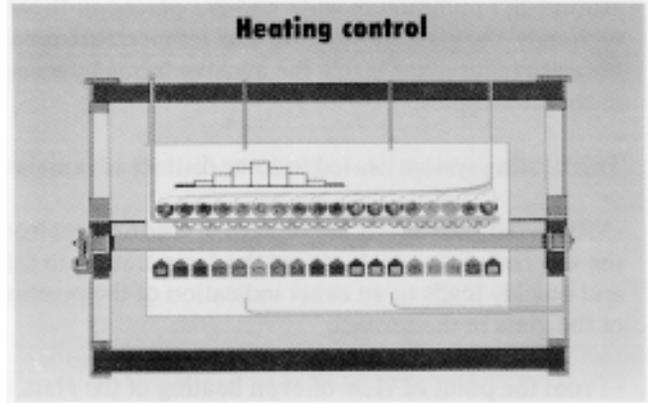


Figure 10: Heating control system of the furnace

the top heating elements are located close to the glass. The blow pipes which are used to create forced convection are placed below the top heating elements. Convection is used to compensate for the difference in emissivity between the top and bottom surfaces of the glass, and balanced heating is achieved.

The bottom heating elements are placed under the ceramic rollers and are divided into three groups, just as the top side elements are. As with the top side elements, the bottom elements are also placed as close to the glass as possible.

Figure 11 is a cross section of a furnace.

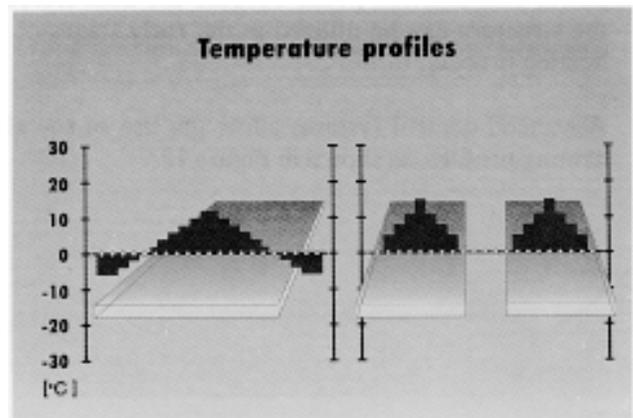


Figure 11: Furnace cross section

It shows both the structure and the control of temperature which are crucial for the achievement of even heating and end-product quality.

The picture shows the ceramic rollers carrying the glass, the top and bottom heating elements and the piping for the forced convection. The heating element itself is situated at the center of the massive frame. The element sections are divided into narrow sectors, which are around 100 millimeters wide and are placed in the direction of the glass movement. The temperature measurement takes place inside the massive frame by means of thermocouples.

This heating system has led to some distinct advantages:

- When cold glass enters the furnace, it absorbs heat from the top radiators which causes the temperature to fall, and quickly leads to an exact indication of the position of the glass in the furnace
- From the point of view of even heating of the glass, it is vital, that only those elements which are located above the position of the glass are activated. The other elements remain inactive. This prevents empty areas from being overheated. This is of particular importance in mixed production where the furnace is loaded with glass products of different sizes.

The heat control of the bottom heating elements is connected to those above so that both sides are switched on simultaneously. This ensures even heating of the surfaces of the glass. The bottom heating elements have a light structure which gives them fast reaction response to varying loading situations, and emissivity differences between the top and the bottom.

The construction with optimum heat-storing capacity for the top heating elements also acts as an equalizer of power consumption peaks because the heat stored in the structure can be utilized in the early stages of the heating process.

Advanced control systems allow the use of so-called heating profiles, as shown in Figure 12.

TOUGHENABLE Low-E glass		
	EMISSIVITY	MANUFACTURERS
K-glass	≈ 0,16	Pilkington
Comfort new	≈ 0,16	Glaerberel
Planitherm II (off line)	≈ 0,1	Saint Gobain
Eko Plus	≈ 0,16	Saint Gobain
Energy advantage	≈ 0,2	LOF
Performance Plus + HT™ (off line)	≈ 0,12	Guardian
Sungate 500	≈ 0,2	PPG

Figure 12: Focussing of radiation according to glass dimensions

These enable the operator to focus the heating. The focussing of heating is important because the edges of the glass always tend to heat up more quickly than the center of the glass. This can be helped by assigning higher setting values to the elements which radiate heat to the middle part of the glass pane.

The next thing to consider is the important factor of movement in the furnace.

When glass is heated in the furnace it absorbs heat from the surface of the ceramic rollers also. This means that the rollers must be given time to regain their temperature before a new load is inserted in the furnace /5/. This is particularly important in the case of Low-E glass.

Since the heat conductivity of ceramic materials is poor, the temperature drop of the rollers can be very significant if glass is inserted continuously. The furnace must therefore be given adequate empty-time for the rollers to regain the heat. This can be speeded up by the application of forced convection.

If the temperature drops too much, distortions to the glass will follow, as displayed earlier. The duration of the empty-time depends on the thickness of the glass to be tempered and the properties of the coating material.

Regarding the setting parameters for tempering Low-E glass we have found the following:

Compared to clear glass:

1. The furnace temperature usually has to be dropped 5-25° centigrades.
2. The duration of the heating is typically 45-75 seconds per thickness-millimeter of the glass.
3. The tempering pressure has to be increased by 10-25%.
4. The top and bottom cooling must be adjusted.

CONCLUSIONS

In summary our findings are, that successful tempering of Low-E glass requires proper control of the following vital factors:

- the Correct Heating Flow
- Proper Focussing of Heat in the Furnace
- the Application and Control of Forced Convection

The glass must remain flat in the furnace and be heated to an even temperature on both sides before the tempering process begins.

The process balance is illustrated in Figure 13.

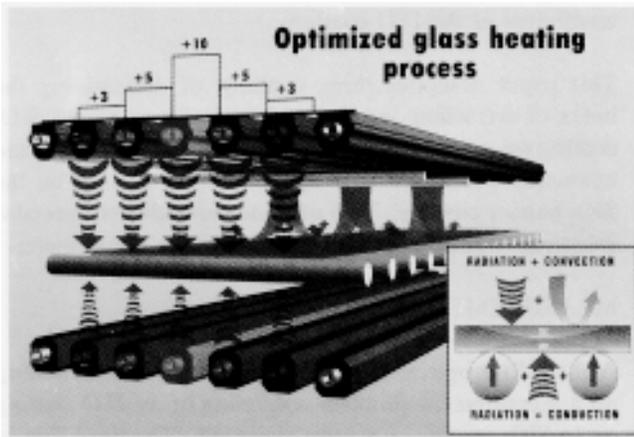


Figure 13: Optimized glass heating process

Mastering these factors, however, is not enough. The challenges raised in the tempering of Low-E glass require that furnace designers and glass manufacturers involve themselves in close cooperation with customers and glass coating researchers.

A combination of various fields of expertise usually leads to the best overall result. R & D requires input from the practical world of glass producers, coating experts, machinery and glass manufacturers. Machinery and glass manufacturers, are heavily dependent on the development of new findings and technology.

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