The annealing of cellular glass

Hans Strauven* discusses the annealing of cellular glass, a process which is integral to the design and operation of a foamed glass plant.

Cellular glass (or foamed glass) is the oldest solid man-made foam. I.I. Kitaygorodskiy, a Soviet scientist, made the first public reports in 1932. Two years later, a French scientist, B. Long, working at Saint-Gobain, reported about the foaming of glass after having filed a patent in 1933 with a priority date of 1932. Cellular glass can be used for thermal insulation, acoustic absorption and as a kinetic energy absorber.

It can be produced as a closed cell foam or open cell foam, depending on the recipe that is used. The most popular application is thermal insulation with closed cell foams. Pure waste glass can be foamed at 800°C with glycerin, while special glass compositions are usually foamed with carbon black.

Cellular glass can be produced in moulds or as an endless ribbon, which is generally called the continuous process. Production started in moulds a long time ago, while today the continuous process becomes ever more popular due to the large dimensions that are possible.

In fact, the same evolution is seen as with window glass: in the past only small glass plates were available, while today up to 5m length and width glass panes are (in principle) possible with the float method.

In the case of moulds, the foamed blocks can be annealed vertically in the same way as hollow glass in a forced convection lehr. For continuous production a lehr is used ***(Fig. 1)***. This principle is also used for float and flat glass down to 400°C.

In all cases, annealing is a critical issue, which takes a lot of time in the production cycle. In that way, long lehrs (annealing furnaces) are required for a large capacity production line, generating a lot of CAPEX. A typical cooling time is around 18 hours, compared with three hours foaming time. As a consequence, in the case of continuous production where annealing happens horizontally, it is clear that rather long lehrs are needed for a perfect annealing. A good understanding of the annealing of cellular glass is of major importance, so as to avoid over-dimensioning of the lehr.

The good annealing of cellular glass has a different meaning than, for example, the good annealing of float glass. In the case of float glass, the ribbon has to reach the cold end unbroken and good cutting must be possible. In the case of cellular glass, good annealing is considered when the following conditions are all fulfilled:

- The ware leaves the lehr unbroken and can be ground or cut to the requested dimensions without breakage;
- It must be possible many months, even years, after production to saw and grind without generating breakage.

Calculating the annealing

In order to eliminate extensive trial and error, there is a need to develop a calculation programme for annealing which involves the following:

- Calculation of the temperature distribution in the foam during the cooling;
- Calculation of the thermal strain relaxation during the glass transition;
- Calculation of the temporary and residual strain;
- Checking whether the maximum strain is not exceeded.

Fig. 2 shows a finite element algorithm for the above calculation.

For the calculation of the temperature distribution, a one-dimensional approximation was assumed, therefore it is assumed that the ribbon (block) has an endless width and length.

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Fig 1. Continuous foaming furnace and lehr for cellular glass.

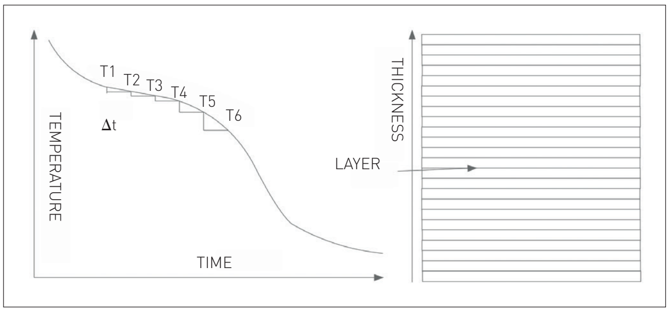
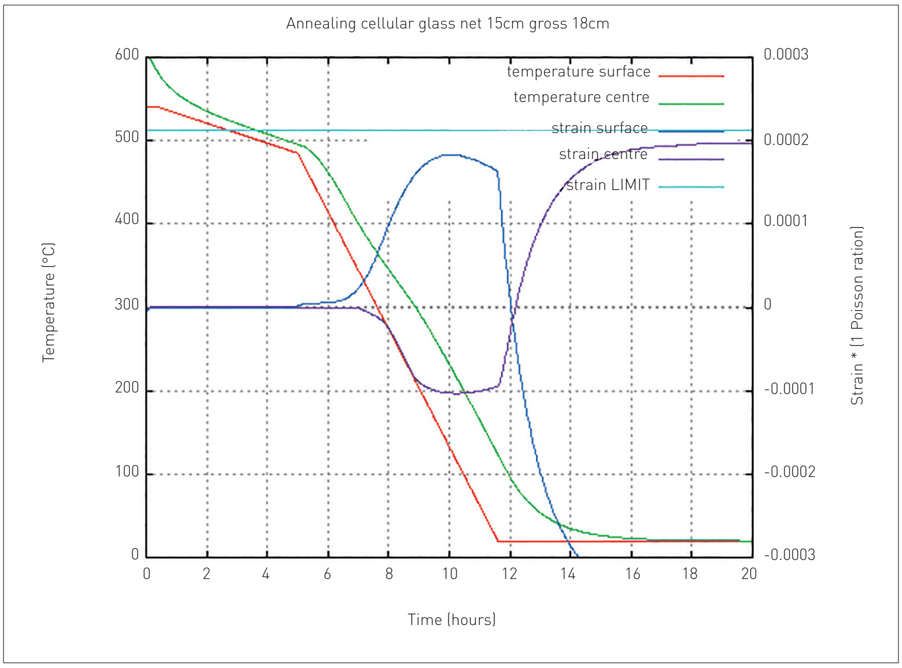


Fig 2. Linearisation of the plate and temperature curve.



▲ Fig 3. Calculation of the strain during cooling.

After cooling, the internal temperature equilibration induces the residual stress, being at a maximum level after several hours.

As can be expected, the quadratic strain depends on the thickness. ***Table 1*** gives the minimum annealing times required for different thicknesses based on Glapor ware. Glapor is a producer of cellular glass and builds cellular glass production plants around the world. These times have to be compared with a typical foaming time of about two hours. If a net width of 5m is asumed(in our opinion, this is around the limit for reasons of furnace and roller stability), the length of the lehr for a capacity of 100m³/day cellular glass in the case of continuous foaming for several thicknesses can be calculated.

Industrial cellular glass thermal insulation, such as pipe shells and elbows, are today cut or ground from well annealed foamed blocks, which induces a lot of waste.

The block is assumed to be composed of many thin layers. We approximate the temperature curve with a staircase curve with finite time steps. For each step, let the heat flow during a finite small time step, as given by the temperature gradients over each layer.

After this step, calculate the temperature change with the transported heat to each layer and the heat capacity.

With the new temperatures after each step, the newly generated thermal strain with the thermal expansion coefficient of the glass. This newly generated strain is allowed to relax viscous during the finite time step. This numerical approach allows working with a temperature dependent thermal conductivity, specific heat (thermal diffusivity), thermal expansion coefficient and viscosity, without having to solve large mathematical problems. In this way, the temporary strain during cooling and the residual strain born after cooling can be calculated.

The thermal expansion and viscosity depend strongly on the thermal history being responsible for the structural residual stress. Typical glass is annealed in several minutes while cellular glass takes several hours.

In the latter case, it is assumed that the glass is in equilibrium during cooling, and so an equilibrium viscosity and expansion coefficient can be used. In case soda lime glass is foamed, these parameters are extensively measured and published.

In case of normal glass, it is the habit to work with thermal stress instead of thermal strain, although they are connected with the elasticity modulus and the Poisson ratio. In case of a cellular solid, the elasticity modulus depends on the density, while the Poisson ratio for foam can range between 0.1 and 0.5. In a first approximation, we can assume that the glass (on the level of the cell wall) breaks at a certain strain, independent of the density of the foam. This allows work with a limit strain (instead of stress) for all densities foamed from the same glass composition. In the case of soda lime glass, we can work with a safe strain limit of about 300μ.

With the above programme, the strain for all temperature curves possible can be calculated. ***Fig. 3*** is an example as based on an imaginary type of cellular glass. The annealing curve for (cellular) glass starts with a homogeneous cooling to the annealing point of the glass.

Furthermore, we have a slow (but homogeneous) cooling to 480°C. Below that temperature, the cooling rate is increased to generate temporary strain.

For reasons of thermal stress, a pipe shell or elbow in cellular glass is never thicker than 5cm. Therefore, as has already been suggested by Demidovich, it is more logical to foam these particular shapes directly in a specially shaped mould. As an extra advantage, these pipe shells or elbows already have a skin, making them less sensitive to frost.

Because the annealing of thin objects is not critical, it should even be possible to foam and anneal these particular shapes in the same furnace directly at the job site, eliminating a large part of the cost, because only glass powder has to be transported.

A good understanding of the annealing of cellular glass is of major importance for the design and operation of a foamed glass plant. ■

Net thickness (cm)	Gross thickness ribbon (cm)	Annealing time (hours)	Length lehrs (m)
4	7	2.3	47
10	13	7.8	65
12	15	10.4	72
14	17	13.4	80
15	18	15.0	83
16	19	16.7	87
18	21	20.4	95
20	23	24.5	102

Table 1. Estimation of annealing times and lehr lengths for a certain net thickness

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