Thermal Homogeneity Index – the real truth

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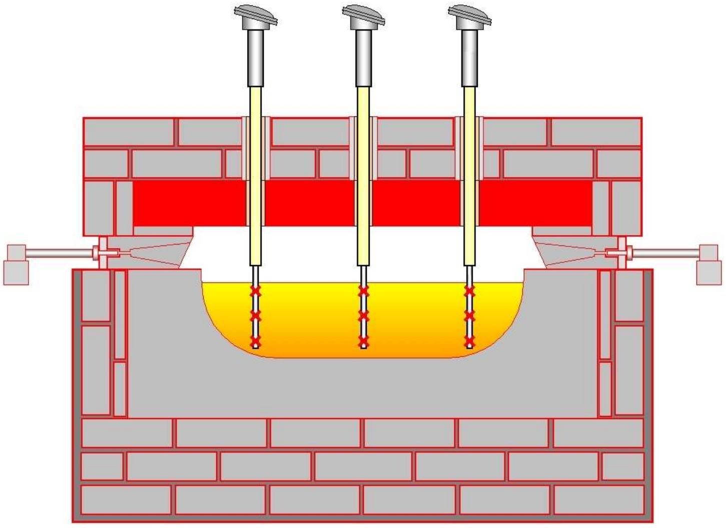
Introduction

A method of efficiency measurement is a basic requirement for the study and evaluation of any process, and the operation of glass conditioning systems (working ends and forehearths) is no exception. The job of this part of the glass manufacturing process is simply described – to provide glass with the required quantity with the correct viscosity and quality for the forming process. On-line viscosity measurement is available, but expensive, and only provides a local measurement. At the present time temperature distribution across the channel cross-section is regarded as an adequate substitute, being both easy and cheap to measure.

The accepted method of measuring the temperature distribution involves the use of three triplex thermocouples. These are normally installed vertically through the roof, and are designed to provide temperature readings at three different levels. One of the triplex units is located on the channel centre line, with the other two alongside and equidistant from the centre line to the left and right.

This arrangement provides a matrix of 9 temperatures that cover a defined part of the cross section of the glass bath at the location of the measurement (see figure 1).



In order to allow easy comparison of various sets of readings the nine temperature values of a single data set are treated mathematically to give a value, which is normally quoted as a percentage value. If all of the temperatures are exactly the same the formula will give a value of 100.

Today this “percentage” value – usually referred to as the Thermal Homogeneity Index (or THI) - is used as both a comparative and an absolute measure of forehearth performance, and there are many references to these values in the literature. However, there is little information available concerning the practical aspects of this type of measurement, and in particular, on the various inaccuracies that are inherent in the measurement. It is even not widely appreciated that there are several methods of calculating the final result in common use.

It is the object of the current treatise to shed some light on this neglected subject.

The calculation

There are three methods of calculating the THI, and although all begin with the same basic data, they can produce quite different results. Method 1, shown in figure 2, is usually attributed to Owens-Illinois, and utilises the sum of the 6 horizontal differences between neighbouring values and the 3 largest vertical differences.

$$\boxed{\mathrm{THI}_{(1)} = \left(1 - \frac{\text{sum of 9 vertical differences}}{\text{value in channel centre}}\right) \times 100}$$

Figure 2 – THI calculation attributed to OI

It should be noted that the exact vertical differences to be used are not specified, but those showing the largest difference are applied. The divisor is defined as the centre temperature (middle triplex, middle thermocouple).

The second version, shown in figure 3, is often referred to as the Emhart version. This is very similar to the first, but in this case the vertical differences used are the top-to-bottom differences at each of the three measurement locations, whilst the divisor is the highest temperature found in the middle vertical set of readings.

$$\boxed{\mathrm{THI}_{(2)} = \left(1 - \frac{\text{sum of 9 vertical differences}}{\text{highest value of centre triplex}}\right) \times 100}$$

Figure 3 – THI calculation attributed to Emhart

Both of these versions are relatively easy to calculate without the benefit of a computer.

Sorg utilises a somewhat different version, that has a better mathematical basis. This version is shown in figure 4.

$$\boxed{\mathrm{THI}_{(3)} = \left(1 - \frac{\text{standard deviation of all 9 values}}{\text{average of all 9 values}}\right) \times 100}$$

Figure 4 – SORG THI calculation

Here the sum of differences between adjacent temperatures is replaced by the standard deviation of all 9 values, whilst the average of all 9 values is used as the divisor.

The different methods of calculation give differing results, and the extent of the difference can vary, depending on the actual temperature distribution.

As all three methods have no mathematical basis as percentage values it is not possible to refer to any one of them as correct or incorrect. They are quite simply empirical values. This point must be borne in mind whenever results are compared, as a comparison is only valid when the same method of calculation is used.

The measurement

The actual temperature measurements that form the starting point of all the calculations are obviously important. A close examination of the actual practical aspects of these measurements reveals surprisingly large potential errors. Some of the largest sources of such errors are discussed below.

The location of the measurement

It has become accepted that the three triplex thermocouples are located as follows :

- one on the channel centre line

- one each side at a distance from the centre line of 33 % of the actual channel width at the measurement location

Moving the outside thermocouples towards the centre will almost always result in a reduction in the temperature differences and a consequent improvement in the THI value.

The three couples of the triplex element are usually arranged so that the top couple is 25 mm below the glass bath surface, the centre one is at the middle of the glass bath and the lower one is 25 mm above the channel bottom. Reducing the distance between the top and bottom elements will almost always lead to better results.

The vertical spacing has a second important aspect. The height of the glass bath surface is a nominal value derived from the planning of the installation, and this value will normally be used to design the triplex thermocouples.

In practice there is no guarantee that the glass bath surface is anywhere near the planned level. It may be higher, in which case the top measuring point will be further from the surface, but in most practical cases the glass level towards the front of the forehearth, where the measurement is made, will tend to be lower than nominal. The situation is even more complex in that the glass level at the measuring point may change, depending on the pull on the forehearth.

The location of the measurement along the forehearth axis is not standardised at all. The measurement should be made as near to the front end of the channel as is practically possible. However, it is well known that the action of the rotating tube used in most feeder bowls causes a stagnant area against the channel wall on one side of the channel. The glass in this area will always be colder than the flowing glass, and so this area would affect the measurement, although the phenomenon is completely independent of the forehearth. To avoid an unwanted falsification of the measurement it is moved backwards towards the furnace to ensure that the thermocouple is out of the stagnant are.

Positioning of the thermocouples

Once the location of the thermocouples has been decided there is still a significant amount of uncertainty about the exact position of the measuring points. Installing thermocouples on hot forehearths is not an exact science, and the holders generally used do not allow precise positioning.

Practical experience shows that the variation may easily be as much as ± 15 mm horizontally and ± 10 mm vertically. The side elements tend to be in areas in which there are temperature differences of several degrees within a short distance, and analysis of a typical temperature distribution shows that the position tolerance may result in temperature measurement differences of more than ± 5 ℃.

Tolerance of the thermocouples

All thermocouples are subject to a certain tolerance. According to the currently applicable European IEC 584-2 standard the commonly used type R and S thermocouples (13 % and 10 % rhodium respectively) have a permitted tolerance range of ± 1 ℃ at 1200 ℃, whereas type B thermocouples (30 % and 6 % rhodium) can vary by as much as ± 3 ℃.

Ageing of the thermocouples

In the case of typical high temperature couples the ageing results mainly from migration of rhodium from one wire to the other. This depends on temperature and atmosphere to which the individual couple is subjected, and therefore the effect of ageing is not quantifiable.

Connecting cables and indicator

Temperature results are displayed on some type of indicator, that is connected to the thermocouple by compensating cable. The display system also has a tolerance, and at the very best this will be ± 1 ℃, possibly more, depending on age and technology used.

Compensating cables can also introduce an element of uncertainty into the measurement, especially in view of the fact that the actual thermocouple signal is very small (a few millivolts). However, any effect on the temperature measurement is not quantifiable.

The effect of the measurement inaccuracies

Having demonstrated that there can be considerable inaccuracies in the measurement, and some of these are not even definable, it remains to determine what influence, if any, these uncertainties can have on the results. Two examples are used to illustrate this.

In the first case we will assume a theoretical temperature distribution in which all 9 temperatures are actually exactly the same. Of course, the THI calculation gives a value of 100. If we only consider the possible tolerance of the thermocouples themselves and the indicator on which the results are displayed each value may differ by ± 2 degrees from the correct value. If we then distribute the possible variation in the most unfavourable way, so that each individual value is now 4 degrees different to all neighbouring values, as shown in figure 5, we now find that the THI value has dropped to 96,7.

Figure 5 – "perfect" temperature distribution taking thermocouple and indicator tolerance into account

This simple example shows that any value above about 97 is mathematically uncertain, and this although the factors that exert the greatest potential influence on the accuracy of the actual temperature readings have not yet been taken into account.

The second example has a more practical basis, in that it is based on an typical temperature distribution as found on an operating forehearth. The basic data, shown in figure 6, gives a THI value of 95,3.

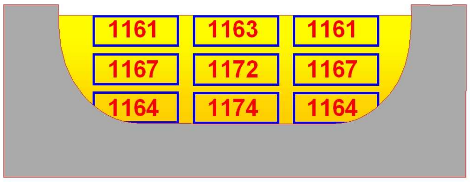


Figure 6 – actual temperature distribution THI = 95,3

As in the previous case we have applied the basic cumulative tolerance of the thermocouple and indicator, but in addition we have added a small displacement of the two outside thermocouples. One has been "moved" 8 mm laterally, which changes all three temperatures by 3 degrees whilst the other has been "moved" 5 mm vertically, which leads to a 1 degree change in the three temperatures.

If all adjustments are made in the most unfavourable way, the resulting temperatures are shown in figure 7, and the THI is reduced to 92,6, a drop of almost 3 points.

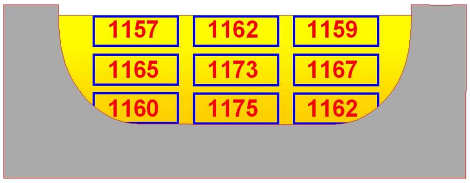


Figure 7 – "new" temperature distribution with unfavourable tolerances : THI = 92,6

Alternatively, if the resulting alterations are all favour the temperatures shown in figure 8 would be displayed and the THI rises to 97,4, an increase of over 2 points.

Figure 8 – temperature distribution with favourable tolerances : THI = 97,4

It is clear that the two examples detailed here are just that – examples, but they are representative enough to illustrate the following points.

- The THI calculations are based on measurements that harbour inherent inaccuracies
- The basic inaccuracies in the measurement hardware means that any value of the THI over 97 is mathematically uncertain and cannot be relied upon
- Further inaccuracies relating to the exact location of the measuring points introduce additional uncertainty into the THI calculations. This additional level of doubt can easily exceed ± 2 points.
- Some sources of inaccuracies are definitely present but not quantifiable. These include the ageing of thermocouples, changes in actual glass level and low-level thermocouple signal degradation.

These results show that the THI value is only really of limited value in the evaluation of forehearth operation.

Comparison of results of THI calculations under various operating conditions on one forehearth are probably acceptable, because the use of the same measurement arrangement effectively neutralises some of the error sources, although even this type of comparison must be treated with some caution.

The inherent errors in the measurement system effectively preclude it’s use to provide a meaningful comparison of the operation of different forehearths.

Stability of the temperature values

A further important factor that also has a significant impact on stable production is the stability of forehearth conditions. It can be argued that stable temperatures at a certain level may be of more value to the production than an attempt to optimise the THI value, that can lead to a prolonged period of instability.

The THI calculation does not address the stability question at all.

In view of the foregoing it is not surprising to find that there appear to be no reports of a direct connection between THI value and percentage pack. Although the THI value can often give a clear indication of how the production will run on a given line, , the so-called 80/95 syndrome is well known. This refers to a line on which the THI value is only 80 % (a poor value) but the production still runs at 95 % pack-to-melt. Alternatively, the THI value may reach 95 % (a very good value) but the pack-to-melt does not exceed 80 %.

There are doubtless many potential causes of the 80/95 syndrome, and blatant inaccuracies in the THI measurement is definitely one of them.