# Thermodynamic calculation of exploited heat used in glass melting furnace

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## Abstract

In this study $H_{ex}$ for melting the soda-lime glass is examined by thermodynamic calculations. Then, the heat balances of two furnaces, which are operated under difference conditions, are calculated. The output of this project will be used as a guideline for the industry to optimize the melting energy as well as to encourage glass technologists to use of thermodynamic calculations in analyzing their processes.

## 1. Introduction

The glass industry consumes substantial energy in high temperature melting process. Heat balance is considered as a guideline for promoting energy conservation program for a glass-melting furnace since it can monitor heat losses and efficiency in the furnace. To construct the heat balance, the amount of heat used for melting, which is the so-called exploited heat ($H_{ex}$), the heat input by fuel and electricity ($H_{in}$), the heat stored in the exhaust gas leaving the furnace ($H_{off}$), the heat stored in the offgas leaving the heat exchanger, ($H_{stack}$), and the heat recovered by the air passing through the heat exchanger ($H_{re}$) are calculated. Then the heat losses through the boundaries of the combustion space ($H_{wo}$) and the basin ($H_{wu}$) can be found by balancing.

## 2. Theory and Background

### 2.1. Exploited heat ($H_{ex}$)

$$H_{ex} = (1-y_c)\,\Delta H^{\circ}_{chem} + \Delta H_{melt}(T_{ex})$$

$y_c$ is the cullet (%) mixed in the batch.

$\Delta H^{\circ}_{chem}$ is the heat required for the batch-to-melt conversion at 298 K. It can be determined by the standard enthalpy difference (at 25°C, 1 bar) between the batch ($H^{\circ}_{batch}$) and the rigid glass ($H^{\circ}_{glass}$) plus the gases ($H^{\circ}_{gas}$) released from the batch [1] (see the data in Table 1).

$$\Delta H^{\circ}_{chem} = H^{\circ}_{glass} + H^{\circ}_{gas} - H^{\circ}_{batch}$$

$\Delta H_{melt}(T_{ex})$ is the heat stored in the homogeneous melt leaving the system boundary at a temperature $T_{ex}$ [1]. It is defined as the enthalpy difference between the glass at 298 K and the glass melt at $T_{ex}$.

$$\Delta H_{melt}(T_{ex}) = H_{T,melt} - H^{\circ}_{glass}$$

$H^{\circ}_{glass}$ and $H_{T,melt}$ can be calculated by

$$H^{\circ}_{glass} = \sum_k n_k \cdot \left(H^{\circ}_k + H^{vit}_k\right)$$

$$H_{T,melt} = H^{\circ}_{1673melt} + c_{p,melt} \cdot \left(T - 1673\text{ K}\right)$$

$$H^{\circ}_{1673,melt} = \sum_k n_k \cdot H^{\circ}_{1673melt,k}$$

$$c_{p,melt} = \sum_k n_k \cdot c_{p,melt,k}$$

Thermodynamic data of compounds k employed of industrial glasses, i.e. $H^{\circ}$, $H_{vit}$, $H^{\circ}_{1673,melt}$ and $c_{p,melt}$, can be found in [1] (see the data in Table 2-3).

### 2.2. Heat balance

The heat balance in the glass-melting furnace and heat exchanger is presented by the Sanky diagram in Fig.1.

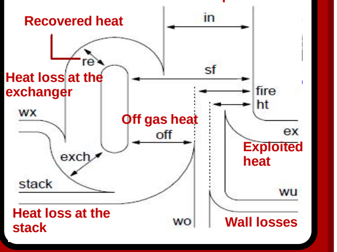


*Fig.1*

<u>Glass furnace</u>

$$H_{sf} = H_{in} + H_{re} = H_{off} + H_{ex} + (H_{wo} + H_{wu})$$

$$H_{w} = H_{wo} + H_{wu}$$

$$H_{fire} = H_{sf} - H_{off} = H_{ex} + H_{w}$$

$$H_{ht} = H_{ex} + H_{wu}$$

<u>Heat exchanger</u>

$$H_{off} = H_{stack} + H_{re} + H_{wx}$$

$$H_{exch} = H_{off} - H_{stack} = H_{re} + H_{wx}$$

The heat contributions related to the combustion space, e.g..$H_{off}$, $H_{stack}$, and $H_{re}$, can be calculated accurately from measured process temperatures,(see Table 4), and $H_{in}$ from the amounts of fuel and air used.

## 3. Data for calculations

Table 1. The amount of raw materials used for producing 1 ton of the soda-lime glass and their chemical composition and standard enthalpy ($H^{\circ}$ of $CO_2$ = 2.4837 kW/kg)

| Raw materials | $H^{\circ}$ (KW/kg) | Amount (kg) | Content (wt %) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MgO | CaO | $Na_2O$ | $CO_2$ |
| Silica sand | 4.2112 | 735.80 | 99.88 | 0.001 | 0.0002 | - | - | - | - |
| Dolomite | 3.4873 | 221.75 | - | - | 0.0002 | 0.20 | 0.31 | - | 48.81 |
| Alumina | 4.5652 | 15.12 | 99.99 | - | - | - | - | - | - |
| Sodium carbonate | 2.9608 | 231.83 | - | - | - | - | - | 58.48 | 41.52 |

Table 2. The chemical composition (%wt) of the produced soda-lime glass

| Compositions | Content (wt%) |
|---|---|
| $SiO_2$ | 73.49 |
| $Al_2O_3$ | 1.59 |
| $Fe_2O_3$ | 0.02 |
| MgO | 4.41 |
| CaO | 6.94 |
| $Na_2O$ | 13.56 |

Table 3. The compound k in the produced soda-lime glass and their thermodynamic data [2].

| Compound k | g/100g | $-H^{\circ}$ (KJ/mol) | $H_{vit}$ (KJ/mol) | $-H^{\circ}_{1673,melt}$ (KJ/mol) | $c_{p,melt}$ (J/mol·K) |
|---|---|---|---|---|---|
| $SiO_2$ | 26.99 | 908.3 | 6.9 | 809.6 | 86.2 |
| $Na_2O{\cdot}3CaO{\cdot}6SiO_2$ | 24.36 | 8363.8 | 77.3 | 7372.6 | 786.6 |
| $Na_2O{\cdot}2SiO_2$ | 29.50 | 2473.6 | 29.3 | 2102.5 | 261.1 |
| $MgO{\cdot}SiO_2$ | 10.98 | 1548.5 | 46.6 | 1318 | 146.4 |
| $Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$ | 8.16 | 7841.2 | 125 | 6870.1 | 648.1 |
| $FeO{\cdot}SiO_2$ | 0.0028 | 1196.2 | 36.7 | 962.3 | 139.7 |
| $FeO{\cdot}Fe_2O_3$ | 0.0148 | 1108.8 | 82.8 | 677.8 | 213.4 |

Table 4. The furnace data for calculating the heat balance for furnace A and B

| Day | Temperature (°C) | | | %Cullet ($y_c$) | Pull (ton/hr) |
|---|---|---|---|---|---|
| | Glass melt (Tex) | Exhaust gas | Offgas at stack | | |
| Furnace A | | | | | |
| 1 | 1348 | 1269 | 482 | 65.0 | 1.14 |
| 2 | 1347 | 1268 | 482 | 65.0 | 1.11 |
| 3 | 1348 | 1268 | 483 | 65.0 | 1.11 |
| : | : | : | : | : | : |
| Furnace B | | | | | |
| 1 | 1357 | 1395 | 536 | 40.0 | 3.84 |
| 2 | 1360 | 1398 | 540 | 40.0 | 3.84 |
| 3 | 1359 | 1396 | 544 | 40.0 | 3.83 |
| : | : | : | : | : | : |

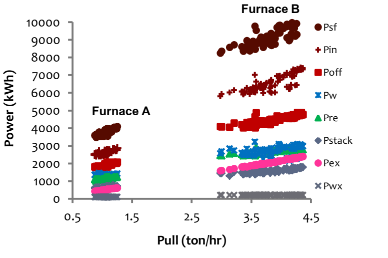


Fig. 2 The heat balance of the furnace A and B as a function of pull ( P (in kWh) = H × pull )

## 4. Results

Furnace A is operated at a lower capacity than the furnace B (Fig. 2). The efficiency of the furnace can be determined by the ratio of $H_{ex}/H_{in}$. In this case the efficiency of the furnace A is about 20% and furnace B is about 30%. Thus, furnace A should produce more glass in order to increase the efficiency. The total loss in the furnace is independent on the pull. The total loss of furnace A is about 1300 kWh and furnace is about 2500 kWh. This implies that the furnace B is rather old compared to the furnace A. The improvement of the wall losses may be needed.

## 5. Summary

The thermodynamic calculation of the exploited heat $H_{ex}$ for melting glass is the effective approach to analyze the energy used in the melting furnace. The efficiency of the furnace can be estimated by $H_{ex}/H_{in}$. Knowing the characteristic of the furnace such as the efficiency and the heat or power consumption of the furnace is very useful for planning the energy conservation direction.

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## References

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[2] Conradt, R. Chemical structure, medium range order, and crystalline reference state of multicomponent liquids and glasses. J. Non-Cryst. Solids 345&346; 2004, 16-23