INFLUENCE OF INTENSIFYING MEANS UPON TECHNOLOGICAL CHARACTERISTIC OF GLASS MELTING FURNACES

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Submitted May 7, 1999; accepted November 11, 1999.

The method of three-dimensional mathematical modelling by means of CFD program FLUENT was used to find the influence of means of intensification upon technological characteristics of glass melting furnaces. Two physical means, i.e. a mechanical barrier and melting tank insulation (or heat losses through walls and bottom) were selected to intensify a melting process. Technological characteristics were defined by the magnitude and shape of temperature and velocity fields and by the volume of glass melt with the temperature lower than the temperature liquidus. The results of mathematical modeling have shown the considerable influence of the pull of the furnace, of the magnitude of thermal losses through the walls and the bottom and of the height of a mechanical barrier. The temperature of glass melt flowing into the throat is increased by a height of a barrier and decreased by heat losses. The temperature 1200 °C which corresponds with glass melt viscosity $h = 10^3$ dPa s was considered to be the lowest limit of the temperature of glass melt coming to a throat. Variants with this temperature lower then 1200 °C have not satisfied this evaluating criterion. The velocity of the glass melt flowing into the throat is increased by the pull of the furnace (18 t day^{-1} corresponds with 9.38×10^{-4} m s^{-1}; 50 t day^{-1} corresponds with 2.62×10^{-3} m s^{-1}) and by the heat losses. The heat losses also influence the volume of "dead areas" (the higher the heat losses the larger the "dead areas"). Only the variants with $a = 1$ W m^{-2} K^{-1} and two variants with $a = 3$ W m^{-2} K^{-1} have satisfied the criterion of zero "dead areas". The height of a barrier influences the shape of velocity pro-files, i.e. the presence of the backward current. If this height $h = 0.75$ m, the return current cannot be observed. On the other hand, the mechanical barrier with the smallest height $h = 0.375$ m actually did not influence the current in a melting tank. All the above mentioned evaluating criteria have been satisfied by only 17 variants from the whole number of 92 investigated ones. The investigated glass melting furnace should be operated with very low coefficient of heat transfer at walls and bottom. The pull of the furnace can be kept at 40 t day^{-1}. The height of a mechanical barrier should range between 0.5 m and 0.625 m from the furnace bottom. Significant influence of distance between a mechanical barrier and a charge wall has not been proved, so the barrier can be situated across the melting tank with the proximity 4.75 – 5.5 m to the frontal charge wall.

INTRODUCTION

The quality of products plays an important role in glass industry, as well as in the other industrial branches. The quality together with energy consumption during melting process represent two most important economic data which are in the centre of attention of all glass producers. To determine glass quality is, however, very difficult, as there has not been a unified criterion of its objective evaluation yet. So far, there are three parameters which are used to evaluate glass quality. They are:

a) the degree of melting expressed by the number of stones in a glass volume unit
b) the degree of refining expressed by the number of bubbles in a glass volume unit
c) homogeneity expressed by measurable characteristics, i.e. refractive index and its deflections

It follows from these facts that the final quality of glass melt going out from the furnace is determined by processes which proceed inside this furnace. These processes are :

- heating and melting of batch
- dissolving of sand and refining
- homogenisation and conditioning
- corrosion of refractories
- volatilisation and evaporation from the surface of the glass melt

It follows from theoretical studies of processes carried out in glass melting furnaces that these processes are significantly influenced by the distribution of temperature and the shape of current in a melting tank. As the temperature field influences the current in a furnace, we can say that the quality of glass also depends on its current in the furnace. These parameters are, e.g., the construction (design) of a furnace and also means of intensification (or means accelerating melting).

To be able to evaluate the influence of means of intensification upon glass quality, it is necessary to define so called technological characteristics of glass melting furnaces and to derive evaluating criteria from them.

Our work deals with the investigation of the intensifying means influence upon technological characteristics of model glass melting furnace in which white container glass is melted.

THEORETICAL PART

Intensification tools

There are several ways to intensify a melting process. Means of accelerating a melting process in the glass technology can be divided into chemical and physical. The intensification of a chemical process by chemical means is provided on the base of the change of a glass chemical composition. To intensify the melting process by physical means, the following of them are used:

- mechanical barrier
- bubbling
- electric boosting
- furnace insulation

Technological characteristics of glass melting furnace

The distribution of temperature in the tank and the glass melt current characteristics significantly influence the quality of produced glass melt and the consumption of energy needed for melting. That is why technological characteristics of the investigated glass melting furnace have been defined by means of the quantities above.

They were following characteristics:

- the magnitude and shape of a velocity field in the melting tank
- the magnitude and shape of a temperature field in the melting tank
- the temperature at the throat input
- minimum temperature in the tank
- the volume of glass melt with the temperature lower than the temperature liquidus of glass melt in the tank
- the volume of glass melt with the temperature higher than the temperature liquidus of glass melt and lower than the temperature corresponding to the viscosity $h = 10^3$ Pa s in the tank
- the volume of glass melt with the temperature higher than the temperature corresponding to the viscosity $\eta = 10^3$ Pa s

Three evaluating criteria have been defined from those technological characteristics:

- the minimum temperature of glass melt at the throat input
- the areas in which glass with the temperature lower than the temperature liquidus can be found
- the shapes of velocity profiles in selected vertical cross-sections of the melting tank from the point of view of pull and return currents magnitudes and rates

Aim of the work

The task of our work was to find and evaluate the influence of two means of intensification, i.e. a mechanical barrier and furnace insulation, upon technological characteristics of a glass melting furnace. The method of mathematical modelling by means of CFD program FLUENT has been used for this evaluation.

In the case of a mechanical barrier, the influence of its height and its proximity to the charge wall were investigated. The second intensification tool was defined by means of a heat transfer coefficient through furnace walls and bottom. Parameters reached by the means of intensification during experiments can be seen in table 1.

CALCULATIONS

Calculation data

Following data were defined:

a) dimensions of the investigated area, i.e. the melting tank of a furnace.

the rectangular tank	the throat
- length 7 m	- length 2 m
- width 3 m	- width 0.5 m
- depth 1 m	- depth 0.25 m

Table 1. Parameters of the means of intensification.

Means of intensification	Height of a barrier (m)	Distance between barrier and charge wall (m)	Heat transfer coefficient (W m^{-2} K^{-1})
Mechanical barrier	0.375	4.75	-
	0.500	5.00	-
	0.625	5.25	-
	0.750	5.50	-
Furnace insulation	-	-	1
	-	-	3
	-	-	5
	-	-	10

b) glass melt properties

viscosity:
$\log \eta = -1.58 + 4332/(T-248)$ (dPa s, °C)
heat conductivity coefficient:
$\lambda = 30$ ($\mathrm{W\,m^{-1}\,K^{-1}}$)
density:
$\rho = -0.138.T + 2479.4$ ($\mathrm{kg\,m^{-3}}$, °C)
thermal expansion coefficient:
$\beta = 6.10^{-5}$ ($\mathrm{K^{-1}}$)
specific heat capacity:
$c_p = 1300$ ($\mathrm{J\,kg^{-1}\,K^{-1}}$)

c) boundary conditions

the temperature of the glass melt surface (see table 2)

Table 2. Temperatures at the glass melt surface.

Distance between barrier and charge wall (m)	0	2	5	7
Temperature (°C)	1250	1400	1550	1450

the pull of a furnace 18, 29, 40 and 50 t/day

Table 3. The values of evaluating criteria.

Variant No	T_p (°C)	V_{min} (%)	Q (t day^{-1})	α (W m^{-2} K^{-1})	l_{MB} (m)	h_{MB} (m)
21	1311	-	40	1	4.75	0.5
37	1312	-	40	1	5	0.5
53	1314	-	40	1	5.25	0.5
77	1316	-	40	1	5.5	0.5
29	1371	-	40	1	4.75	0.75
45	1373	-	40	1	5	0.75
61	1375	-	40	1	5.5	0.75
89	1377	-	40	1	5.5	0.75
24	1085	50.03	40	10	4.75	0.5
40	1088	50.58	40	10	5	0.5
56	1091	50.89	40	10	5.25	0.5
80	1096	51.20	40	10	5.5	0.5
32	1142	48.71	40	10	4.75	0.75
48	1149	48.95	40	10	5	0.75
64	1157	49.54	40	10	5.25	0.75
92	1163	50.35	40	10	5.5	0.75
17	1304	-	40	1	4.75	0.375
25	1330	-	40	1	4.75	0.625
65	1307	-	40	1	5.5	0.375
85	1337	-	40	1	5.5	0.625
20	1070	51.08	40	10	4.75	0.375
28	1106	50.89	40	10	4.75	0.625
68	1078	52.25	40	10	5.5	0.375
88	1126	49.52	40	10	5.5	0.625
18	1208	0.16	40	3	4.75	0.375
22	1220	1.41	40	3	4.75	0.5
26	1247	5.53	40	3	4.75	0.625
30	1294	10.75	40	3	4.75	0.75
19	1148	21.53	40	5	4.75	0.375
23	1162	24.84	40	5	4.75	0.5
27	1191	24.30	40	5	4.75	0.625
31	1235	28.56	40	5	4.75	0.75
33	1305	-	40	1	5	0.375
41	1331	-	40	1	5	0.625

T_p - the temperature of the throat input (°C)
V_{min} - the volume of glass melt in the tank with $T < T_{liquidus}$ (%)
Q - the pull of the furnace (t/day)
α - the heat transfer coefficient (W m^{-2} K^{-1})
l_{MB} - the distance between a mechanical barrier and a charge wall (m)
h_{MB} - the height of a mechanical barrier (m)

CALCULATION RESULTS

The results of several variants are shown in table 3. By means of them it is possible to express the influence of:

- pull
- heat losses
- mechanical barrier position
- mechanical barrier height upon the values of evaluating criteria.

Several selected dependencies from table 3 were described by means of graphs; they can be seen in figures 1-4.

There have been also made graphs describing the dependence of the shape and magnitude of velocity profiles upon:

a) heat losses through furnace walls and bottom - figures 5-8 (Q = 40 t day^{-1}, l_{MB} = 4.75 m, h_{MB} = = 0.375 m).
b) the height of the mechanical barrier - figures 9 - 13 (Q = 40 t day^{-1}, l_{MB} = 5 m, α = 1 W m^{-2} K^{-1})

DISCUSSION

The general evaluating criterion of a glass quality has not been known yet. That is why technological characteristics has been used as a substitution of this criterion.

The temperature 1200 °C which corresponds with glass melt viscosity $\eta = 10^3$ dPa s was considered to be the lowest limit of the temperature of glass melt coming to a throat, from the point of view of following forming process. From the calculated values it can be seen that all variants with α = 1 W m^{-2} K^{-1} (with or without a barrier), variants with α = 3 W m^{-2} K^{-1} (with a mechanical barrier) and variants with α = 5 W m^{-2} K^{-1} (with a mechanical barrier 0.75 m high), satisfy this criterion. From the whole number of 92 investigated variants only 49 ones have satisfied the first evaluating criterion.

The volume of glass melt with the temperature lower than its temperature liquidus, was the next

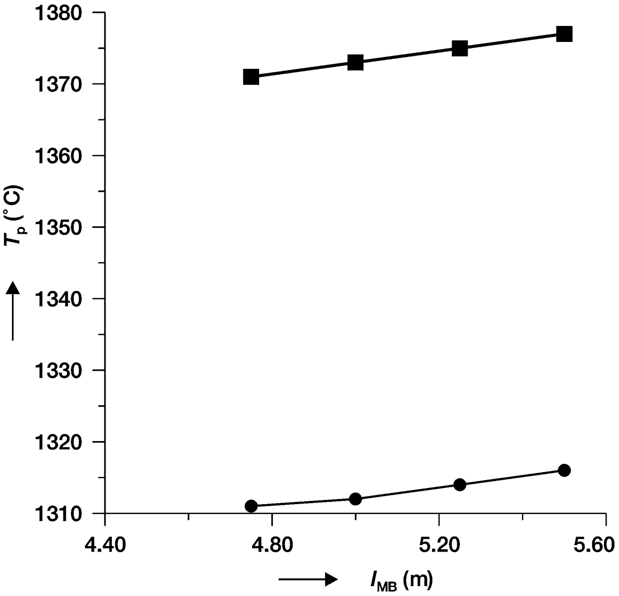

Figure 1. The dependence of glass melt temperature at the throat input upon the distance between a mechanical barrier and a charge wall.
Conditions: $Q = 40$ t day^{-1}, $\alpha = 1$ W.m^{-2}.K^{-1} ;• - $h_{MB} = 0.50$ m, ▪ - $h_{MB} = 0.75$ m

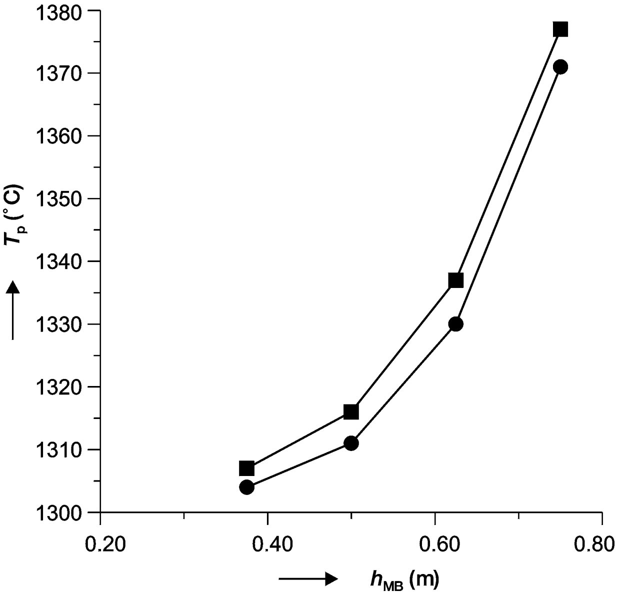

Figure 2. The dependence of glass melt temperature at the throat input upon the height of a mechanical barrier.
Conditions: $Q = 40$ t day^{-1}, $\alpha = 1$ W.m^{-2}.K^{-1}; • - $l_{MB} = 4.75$ m, ▪ -$l_{MB} = 5.50$ m

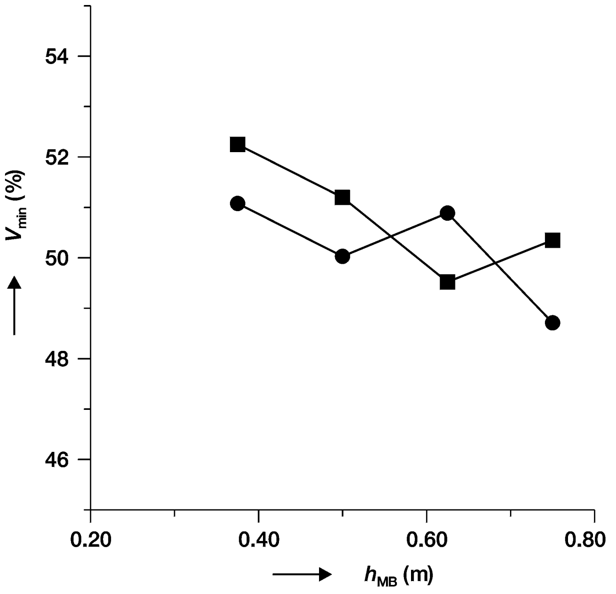

Figure 3. The dependence of glass melt volume in the melting tank with T<T $_{liquidus}$ upon the height of a mechanical barrier.
Conditions: $Q = 40$ t day^{-1}, $\alpha = 10$ W.m^{-2}.K^{-1}; • - $l_{MB} = 4.75$ m, ▪ - $l_{MB} = 5.50$ m

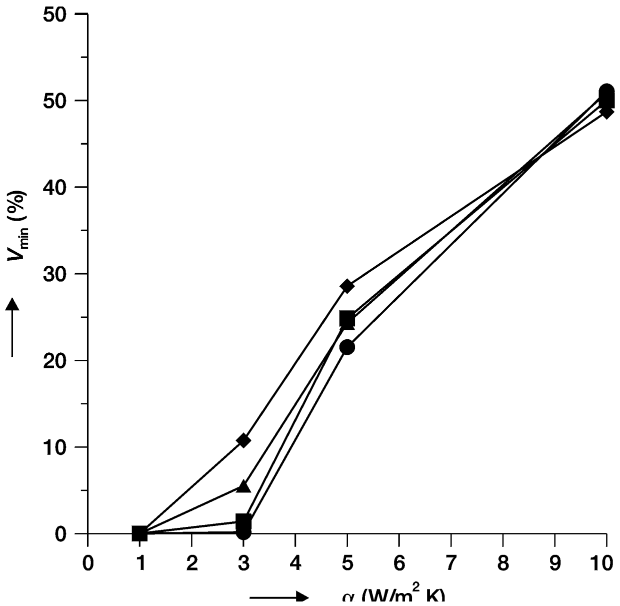

Figure 4. The dependence of glass melt volume in the melting tank with $T < T_{liquidus}$ upon its side walls and bottom cooling.
Conditions: $Q = 40$ t day^{-1}, $l_{MB} = 4.75$ m; • - $h_{MB} = 0.375$ m, ▪ -$h_{MB} = 0.500$ m, ▲ - $h_{MB} = 0.625$ m, ♦ - $h_{MB} = 0.750$ m

evaluating criterion. From the remaining 49 variants only those with zero value of this volume were considered to be suitable. This requirement was satisfied by all variants with $\alpha = 1$ W m^{-2} K^{-1} and by only two variants with $\alpha = 3$ W m^{-2} K^{-1}. The result is that only 25 variants, i.e. about 27 %, satisfied both the first and the second criteria.

When evaluating velocity profiles in the longitudinal axis of the melting tank from the graphic aspect, we have found that the height of a mechanical

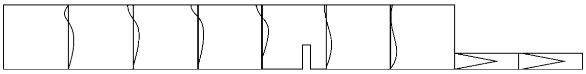

Figure 5. α = 1 (W m^{-2} K^{-1}).

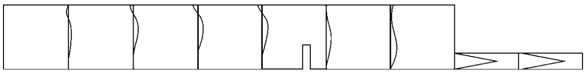

Figure 6. α = 3 (W m^{-2} K^{-1}).

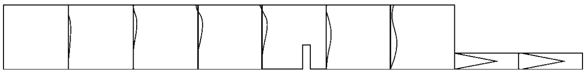

Figure 7. α = 5 (W m^{-2} K^{-1}).

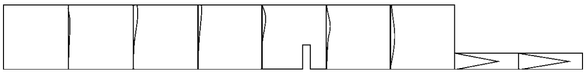

Figure 8. α = 10 (W m^{-2} K^{-1}).

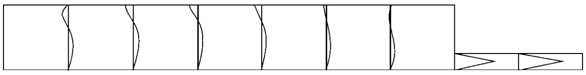

Figure 9. without mechanical barrier.

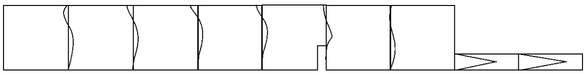

Figure 10. h_{MB} = 0.375 m.

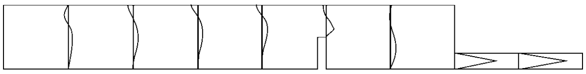

Figure 11. h_{MB} = 0.5 m.

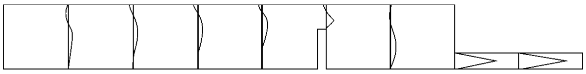

Figure 12. h_{MB} = 0.625 m.

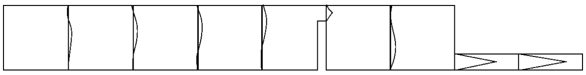

Figure 13. h_{MB} = 0.75 m.

barrier most significantly influences the reduction of return current in a melting tank. If this height h_{MB} = 0.75 m, the return current cannot be observed. Thus, in these variants the intensity of circulating currents is reduced. On the other hand, the mechanical barrier with the smallest height h_{MB} = 0.375 m actually did not influence the current in a melting tank. That means that larger volume of glass melt came into a throat without going through areas with the highest temperatures. That is why the variants with two heights of a mechanical barrier 0.375 and 0.75 m had to be excluded, too. It results that the barriers 0.5 and 0.625 high positively influenced glass melt current in a melting tank, it means that:

a) there exists a circulation current in a melting tank
b) all glass melt comes through the area with the highest temperature

All the above mentioned evaluating criteria have been satisfied by only 17 variants.

CONCLUSION

The investigated glass melting furnace should be operated with a very low heat transfer coefficient at the melting tank walls and bottom. The pull can be kept at 40 t day^{-1}, that means that the specific pull should reach 1.9 t m^{-2} day^{-1}. The height of a mechanical barrier should range between 0.5 m and 0.625 m from the furnace bottom. The influence of a distance between a mechanical barrier and a charge wall upon the evaluating technological characteristics has not been proved (see figure 1), so the mechanical barrier can be situated across the melting tank with the proximity 4.75 - 5.5 m to the frontal charge wall.

Acknowledgement

The present study was supported the Grant Agency of Czech Republic. Project No. 106/99/1419.

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VLIV INTENZIFIKAČNÍCH PROSTŘEDKŮ NA TECHNOLOGICKÉ CHARAKTERISTIKY SKLÁŘSKÝCH TAVICÍCH PECÍ

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Metoda 3D matematického modelování pomocí CFD programu FLUENT byla použita pro vyšetření vlivu intenzifikačních prostředků tavicího procesu fyzikální povahy na technologické charakteristiky sklářských tavicích pecí. Jako intenzifikační prostředky byly použity jednak mechanická bariéra a jednak isolace tavicího bazénu, resp. tepelné ztráty stěnami a dnem bazénu pece. V prvém případě byl vyšetřován vliv přítomnosti mechanické bariéry v peci, tj. její poloha a výška a ve druhém případě vliv velikosti tepelných ztrát na technologické charakteristiky.

Pomocí teplotního a rychlostního pole v tavicím bazénu a pomocí objemu skloviny o teplotě nižší než je teplota liguidus (mrtvé prostory) byly definovány technologické charakteristiky.

Výsledky z matematického modelu ukázaly podstatný vliv tavicího výkonu pece, tepelných ztrát stěnami a dnem bazénu a výšky mechanické bariéry na procesy probíhající v tavicím bazénu. Teplota skloviny natékající do průtoku je ovlivněna tepelnými ztrátami (čím vyšší jsou ztráty, tím nižší je teplota), a výškou mechanické bariéry (čím vyšší je bariéra, tím vyšší je teplota). Teplota 1200 °C, která odpovídá viskozitě taveniny $\eta = 10^3$ dPa s, byla považována za nejnižší hranici teploty skloviny, která vtéká do průtoku (s ohledem na následný proces tvarování). Varianty, kde byla teplota nižší, nevyhověly tomuto hodnotícímu kritériu. Rychlost skloviny natékající do průtoku je zvyšována tavicím výkonem (18 t/den odpovídá rychlosti $9{,}38.10^{-4}$ m s^{-1}; 50 t/den odpovídá rychlosti $2{,}62.10^{-3}$ m s^{-1}) a tepelnými ztrátami, tj. koeficientem prostupu tepla. Tepelné ztráty také ovlivňují objem tzv. “mrtvých prostor” (čím vyšší jsou ztráty, tím větší jsou tyto prostory). Kritériu nulových mrtvých prostor vyhověly pouze varianty s $\alpha = 1$ a 3 W m^{-2} K^{-1}. Výška bariéry ovlivňuje tvar rychlostních profilů, tj. přítomnost zpětného proudění. Pokud je výška bariéry $h = 0{,}75$ m, zpětný proud se nevytváří. Na druhou stranu mechanická bariéra o výšce 0,375 m proudění v tavicím bazénu prakticky neovlivní.

Všem výše uvedeným kritériím vyhovělo pouze 17 z celkového počtu 92 vypočtených variant. Můžeme říci, že modelovaná sklářská tavicí pec by měla být provozována s velmi nízkými tepelnými ztrátami stěnami a dnem tavicího bazénu. Vhodný tavicí výkon je 40 t/den. V peci by měla být zabudována mechanická bariéra, jejíž výška by se měla pohybovat v rozmezí 0,5 a 0,625 m ode dna. Významný vliv vzdálenosti mechanické bariéry od zakládací stěny zjištěn nebyl, takže bariéra může být umístěna v tavicím bazénu v rozmezí 4,75 a 5,5 m od zakládací stěny.