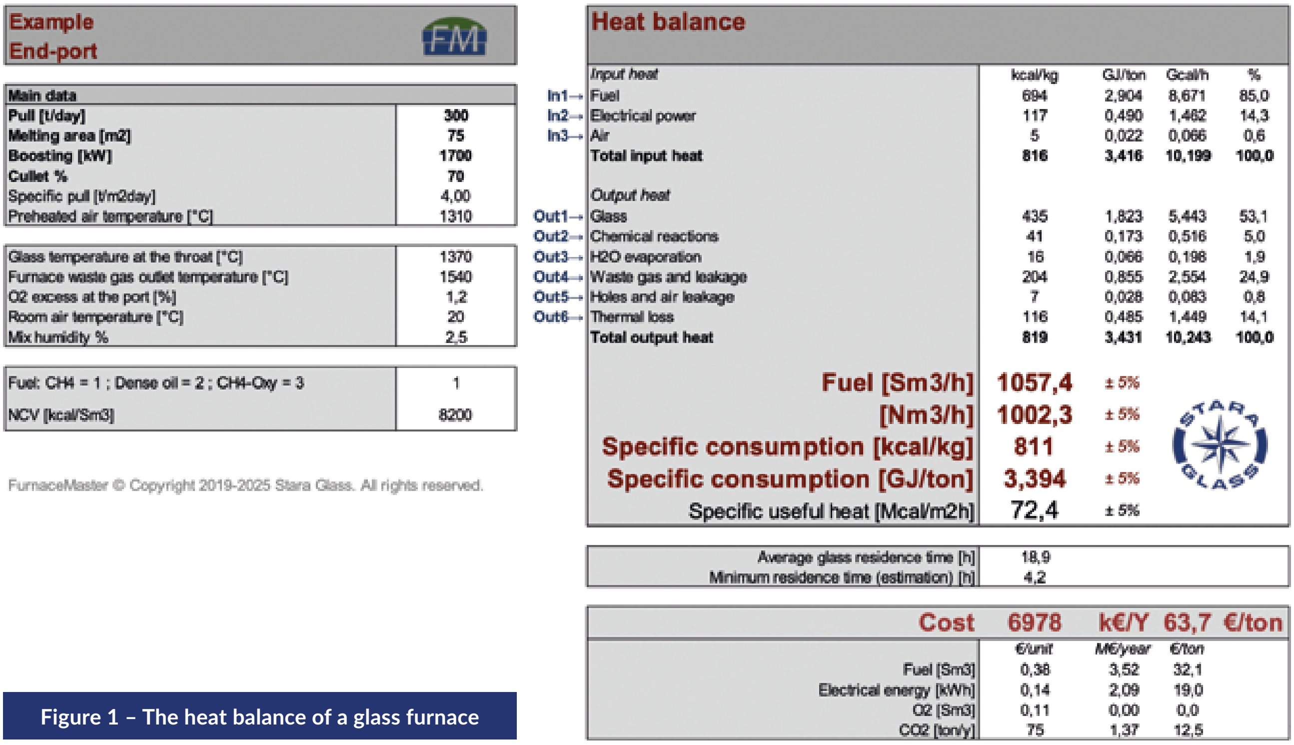
Glass furnace design and data detection, courtesy of STARA GLASS



Example End-port

Main data	
Pull [t/day]	300
Melting area [m2]	75
Boosting [kW]	1700
Cullet %	70
Specific pull [t/m2day]	4,00
Preheated air temperature [°C]	1310

Glass temperature at the throat [°C]	1370
Furnace waste gas outlet temperature [°C]	1540
O2 excess at the port [%]	1,2
Room air temperature [°C]	20
Mix humidity %	2,5

Fuel: CH4 = 1 ; Dense oil = 2 ; CH4-Oxy = 3	1
NCV [kcal/Sm3]	8200

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Heat balance

	Input heat	kcal/kg	GJ/ton	Gcal/h	%
In1→	Fuel	694	2,904	8,671	85,0
In2→	Electrical power	117	0,490	1,462	14,3
In3→	Air	5	0,022	0,066	0,6
	Total input heat	**816**	**3,416**	**10,199**	**100,0**
	Output heat				
Out1→	Glass	435	1,823	5,443	53,1
Out2→	Chemical reactions	41	0,173	0,516	5,0
Out3→	H2O evaporation	16	0,066	0,198	1,9
Out4→	Waste gas and leakage	204	0,855	2,554	24,9
Out5→	Holes and air leakage	7	0,028	0,083	0,8
Out6→	Thermal loss	116	0,485	1,449	14,1
	Total output heat	**819**	**3,431**	**10,243**	**100,0**

Fuel [Sm3/h]	1057,4	± 5%
[Nm3/h]	1002,3	± 5%
Specific consumption [kcal/kg]	811	± 5%
Specific consumption [GJ/ton]	3,394	± 5%
Specific useful heat [Mcal/m2h]	72,4	± 5%

Average glass residence time [h]	18,9
Minimum residence time (estimation) [h]	4,2

Cost	6978 k€/Y	63,7 €/ton	
	€/unit	M€/year	€/ton
Fuel [Sm3]	0,38	3,52	32,1
Electrical energy [kWh]	0,14	2,09	19,0
O2 [Sm3]	0,11	0,00	0,0
CO2 [ton/y]	75	1,37	12,5

Figure 1 – The heat balance of a glass furnace

What's the difference between the design of a glass furnace and its practical operation? And what stands between the computed and measured performance of a plant? In the following article we will explore precisely these differences - providing formulas and methods to design and detect the analyses values. Here Figure 1 represents the heat balance of a well performing glass furnace producing 300 tons per day of coloured glass. Indeed Figure 1 is the most typical chart that Stara Glass customers receive together with the drawings when they buy a glass furnace design, except that power Input and Output voices have been indicated in blue for the purposes of this article. On the left is the input data, on the right the computing output, and on the bottom the production cost, depending on the indicated unitary values. The table is the main output of the design and simulation software FurnaceMaster©, that Stara Glass has been constantly maintaining and implementing in the last 15 years.

In our view, the highest value of Stara Glass design activity stands on the fact that the people that code and utilize FurnaceMaster are the same people that oversee our furnace heat balance detection operation. This implies that every time I input, for example, the value of a waste gas temperature in the software, my mind will inevitably go to the one-hundred times I have

Exploring the critical gap between glass furnace design and real-world performance, STARA GLASS Head of Innovation Ernesto Cattaneo blends simulation and on-site data detection here to reveal how true furnace optimization stems not from theory alone but, significantly, from systemic experience as well.

been sampling that same number on an operating furnace with our suction thermocouple on my shoulder. It is not about mistake avoidance; it is about having a deep awareness of the process. A glass furnace is a complex thermal-dynamic system. All the physical formulas that describe its operation are freely available on Wikipedia, but the real expertise in glass furnace design lies in a wide systemic awareness of the operational parameters, that can exclusively come for a longstanding experience in both furnace simulation and data detection. In this article, we will examine all the heat balance input and output voices from both points of view: the designer's and the data detectors.

INPUT

In1 – Fuel

Computing

Fuel represents the main energy input of non-fully electric glass furnace, which is:

Q = Mc Hi where:

Q = heat flux [kW - kcal/h]

Mc = fuel flow rate [Sm3/h]

Hi = (lower) calorific value of the fuel [kJ/Sm3 - kcal/Sm3]

Detecting

When collecting heat balance data, the flow rate is measured from the present gasometer, and the calorific value of the fuel can be analyzed by consulting and verifying the data from the fuel supplier.

In2 – Electric booster

Computing

The electric booster supplies heat to the glass by the Joule effect, normally its power is expressed in kW. The design of a boosting system is a complex activity that we will explore in a successive article. It is crucial to design a system able to provide the requested power to the glass, considering losses and phases.

Detecting

During the heat balance data collection phase, this quantity can be consumptively seen from the bill of electrical power utilized for the glass melting.

In3 – Air

Computing

In this model, the calculations relating to the heat balance of the furnace refer to normal (0°C) temperature conditions. Therefore, considering, for example, referring an analysis to normal conditions, an air flow will add a thermal flow:

%	Specie	Air Sm3/Sm3	Air Sm3/kg	Fumes Sm3/Sm3	Fumes Sm3/kg	CO2 %	H2O %	N2 %	Ar %	LHV kcal/Sm3	HHV kcal/Sm3	MW	ρ kg/Sm3
99	CH4	9,62	14,18	10,62	15,65	9,42	19,29	70,38	0,91	8112	9002	16	0,71
0,4	C2H6	16,83	13,24	18,33	14,42	10,91	16,83	71,34	0,92	14436	15771	30	1,34
0,1	C3H8	24,04	12,90	26,04	13,57	11,52	15,82	71,73	0,92	20665	22446	44	1,96
0,05	C4H10	31,25	12,72	33,75	13,74	11,86	15,28	71,94	0,93	26878	29103	58	2,59
0,02	C5H12	38,46	12,61	41,46	13,60	12,06	14,94	72,08	0,93	33082	35752	72	3,21
0	C6H14	45,67	12,54	49,17	13,50	12,20	14,70	72,17	0,93	39290	42410	86	3,84
0	C7H16	52,88	12,49	56,88	13,43	12,31	14,53	72,24	0,93	45510	49071	100	4,46
0	C8H18	60,10	12,45	64,60	13,38	12,38	14,40	72,29	0,93	51725	55730	114	5,09
0	C9H20	67,31	12,42	72,31	13,34	12,45	14,30	72,33	0,93	57941	62391	128	5,71
0	C10H22	74,52	12,39	80,02	13,31	12,50	14,21	72,36	0,93	64156	69051	142	6,34
0,43	N2	0,00	0,00	1,00	1,00	0,00	0,00	100,00	0,00			28,00	1,25
100													

	Air Sm3/Sm3	Air Sm3/kg	Fumes Sm3/Sm3	Fumes Sm3/kg	CO2 %	H2O %	N2 %	Ar %	LHV kcal/Sm3	HHV kcal/Sm3	ρ kg/Sm3
	9,519231	14,03737	10,50923	15,49726	9,306222	19,05966	69,52822	0,894829	8030,596	8911,681	0,706701
	0,067308	0,052957	0,073308	0,057677	0,075202	0,115966	0,491814	0,006327	57,74339	63,08344	0,005354
	0,024038	0,012897	0,026038	0,01397	0,028201	0,038731	0,175576	0,00226	20,66549	22,4455	0,001963
	0,015625	0,00636	0,016875	0,006869	0,0188	0,024235	0,114125	0,001469	13,43895	14,55146	0,001294
	0,007692	0,002522	0,008292	0,002719	0,0094	0,011842	0,058184	0,000723	6,616342	7,150363	0,000642
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0,0043	0,0043	0	0	0,040421	0	0	0	0,005372 0
	9,63	14,11	10,64	15,58	9,44	19,25	70,41	0,91	8129	9019	0,721326
									34035	37760	
					Calc		Kcal/Nm3		8575	9514	0,683778
				Test		Kcal/Sm3		8134			

Table 2 – Example of fuel heating value verification

$Q = M\ c\ \Delta T$ where:
Q = heat flux [kW - kcal/h]
M = air flow [kg/h]
c = specific heat of the air [kcal/kg °C]
ΔT = temperature difference with respect to the conditions considered

Naturally, in conditions of temperature outside the system below 0°C, the thermal contribution of the air will assume a negative value and will be zero at the reference temperatures.

This apparent heat contribution, positive or negative, will be algebraically included in output waste gas heat, it is in fact possible to notice in Table 1 that specific consumption [kcal/kg] is only the sum of gas and electrical boosting [kcal/kg] with no contribution of the ambient air heat value.

Detecting

There is no need to describe thermometers. Let's use this space to imagine producing glass on a 1500°C hot planet, of course the energy expense would decrease almost completely, but it would be challenging to keep the product formed. In the exoplanet HD 189733b, sometimes it rains glass. On HD 189733b we all would be unemployed, and dead, of course.


Image 3 – HD 189733b (Wikipedia)

OUTPUT

Out1 – Heat transferred to the glass

Computing

The transfer of heat to the melting glass is the primary function of our furnaces, this considerable energy contribution can be evaluated as:

$Q = Cs\ (Tg - Trif)$ where:
Q = heat transferred to the glass [kW/kg - kcal/kg glass h]
Tg = glass temperature at the throat [°C]
Trif = reference temperature for calculations (typically, 0 or 15°C)
Cs = specific heat of the glass [J/kg °C - kcal/kg °C] can be evaluated according to the composition and temperature of the glass. There are several empirical formulas consolidated in technical literature.

Detecting

To detect this value on the field, we utilize an indirect analysis: we measure the glass temperature at the raiser with an optical pyrometer, we compute the heat loss by raiser and throat, and we compute the glass temperature at the throat inlet by adding to the glass the successively lost heat.

Out2 – Chemical reactions

Computing

The heat required by chemical reactions varies according to the composition of the glass.

The chemical reactions that take place in a glass furnace produce, among other compounds, a certain amount of H_2O and CO_2, which implies that:

Not all the vitrifiable mass will become glass, because these gases are released into the fumes, of which they become part

The flow rates of these substances (loss on ignition) will absorb part of the heat produced.

This thermal contribution is computable by considering the formation enthalpies of the different chemical species. In a first but solid approximation, any percentage of cullet introduced in the mix reduces the value of the same percentage. If all glass mix were made of cullet, this contribution would be null. This is why the utilization of cullet reduces consumption and CO_2 emission.

Detecting

We commonly rely on the recipes shown by the glassmakers and their mix weighing systems.

Out3 – Water evaporation

Computing

In the vitrifiable mixture there is a percentage of water which will absorb a non-negligible part of the energy supplied to the plant to transform into steam, to which is added the water coming from the chemical reactions in the basin.

The evaporation heat of water is $\lambda = 540$ kcal/kg. In the common practice of calculating the heat balance, it is a reasonable approximation to assume

Cullet %	**70**
Humidity %	**3,5**
Glass mix	
Na2CO3 [%]	19,45
CaCO3 [%]	12,20
CaMg(CO3)2 [%]	4,50
Na2SO4 [%]	0,48
K2CO3 [%]	0,00
BaCO3 [%]	0,00
Tot. anhydrous bo	0,00
CaF2 [%]	0,00
Na2SiF6 [%]	0,00
NaNO3 [%]	0,00
Al(OH)3 [%]	0,00
SiO2 [%]	63,37

Main

USE THISMIX

MIX	kg	kg H2O	%
soda	147		19,30
Sand	432		56,73
marble	81		10,64
feldspar	51		6,70
dolomite	47		6,17
sulphate	3,5		0,46
slag [vitritis]	0		0,00
Sodium fluosilicate	0		0,00
CaF2	0		0,00
barium carbonate	0		0,00
Na2NO3	0		0,00
K2CO3	0		0,00
Borax anhydrous	0		0,00
Borax pentahydrate	0	0,0	0,00
powder	0		0,00
Al(OH)3	0	0,0	0,00
Tot	**761,5**	**0,0**	**100,00**

Increasing	Loss on ignition
1,1884	18,84

Total exothermic heat + LOI [kcal/kg] 137,71

Primary reactions	Components	Molecular weight	Mix %	Mix % after dolomite dissolution	Carbonate dissolution reaction [kcal/mole]	Carbonate dissolution reaction [kcal/kg]	Exothermic heat [kcal/kg]	Glass mix	Loss on ignition
	Na2CO3	106	19,45	19,45	76,9	725,00	141,01	11,38	8,07
	CaCO3	100	12,20	14,64	42,5	425,00	62,23	8,20	6,44
	MgCa(CO3)2	184,3	4,50	0,00	8,8	47,75	0,00		
	MgCO3	84,3	0,00	2,06	28,1	333,45	6,86	0,98	1,07
	K2CO3	138	0,00	0,00	93,5	677,39	0,00	0,00	0,00
	BaCO3	197,3	0,00	0,00	63,9	323,62	0,00	0,00	0,00
	Na2SO4	142	0,48	0,48	160,5	1130,56	5,43	0,21	0,26
	Na2B4O7	201,2	0,00	0,00	74,3	369,28	0,00	0,00	0,00
	CaF2	78	0,00	0,00	-32,2	-412,82	0,00	0,00	0,00
	NaNO3	85	0,00	0,00	73,4	864,00	0,00	0,00	0,00
	Al2O3	102	0,00	0,00	0,0	0,00	0,00	0,00	0,00
	Na2SiF6	188	0,00	0,00	160,4	853,19	0,00	0,00	0,00
	SiO2	60	63,37	63,37				**Total** **84,14**	**Total** **15,85**

Secondary reactions			Tot. silicate [%]	Silicate [%]	kcal/mole	kcal/kg	kcal/kg
	MgSiO3	100,3	1,47	2,45	-8,7	-86,74	-2,12
	Na2SiO3	122	11,21	22,80	-58,2	-477,05	-108,76
	CaSiO3	116	8,79	16,98	-20,1	-173,28	-29,43
	K2SiO3	154	0,00	0,00	-75,0	-487,01	0,00
	BaSiO3	213,3	0,00	0,00	-20,7	-97,05	0,00
	Al2O3.SiO2	162	0,00	0,00	-37,71	-232,78	0,00
	SiO2	60	21,46	41,91	2,9	48,33	40,67
	B2O3	69,6		0,00	4,4	63,22	0,00
				Tot 84,14		dehydration	0,00
				LOI Verification 15,86		**Total exothermic heat**	**115,9**

Table 4 – Example of chemical reaction computing

that, by bringing this value to 600 kcal/kg, in addition to the heat necessary for the evaporation of the liquid, the heat necessary to bring the water vapor to the temperature of the fumes is considered too. Therefore, this outgoing energy flow will be worth:

Q_{ev} [kcal/h] = [T 0.01U (100-PR)/100 + PF] λ' where:

T = pull [kg/s]

U = humidity of the mixture [%]

PR = cullet percentage [%]

PF = losses on ignition [kg/s]

λ' = 600 kcal/kg

Detecting

The simple procedure to evaluate mix humidity consists in sampling a cup of mix from the batch charger, weighing it, heating it up in a furnace until the complete evaporation of water, and weighing it again.

Out4 – Residual heat in the fumes

Computing

The heat contained in the fumes leaving the chimney is a portion of the thermal energy obtained by burning fuel which is thrown away. The maximum theoretical efficiency of a furnace would be obtained if the exhaust gases were evacuated exactly at the temperature of the external environment: this is impossible for practical reasons. The amount of energy which is released into the external environment is:

$Q_f = M_f \, c_f \, \Delta T$ where:

Q = heat flux [kW - kcal/h]

M = flue gas [kg/h]

cf = specific heat of the fumes [J/kg °C - kcal/ kg °C]

ΔT = difference between the flue gas outlet temperature and the reference temperature

It is possible to evaluate the specific heat of the fumes by knowing their composition and having, for each species of gas they contain, a curve of the specific heat as a function of the temperature, similar to

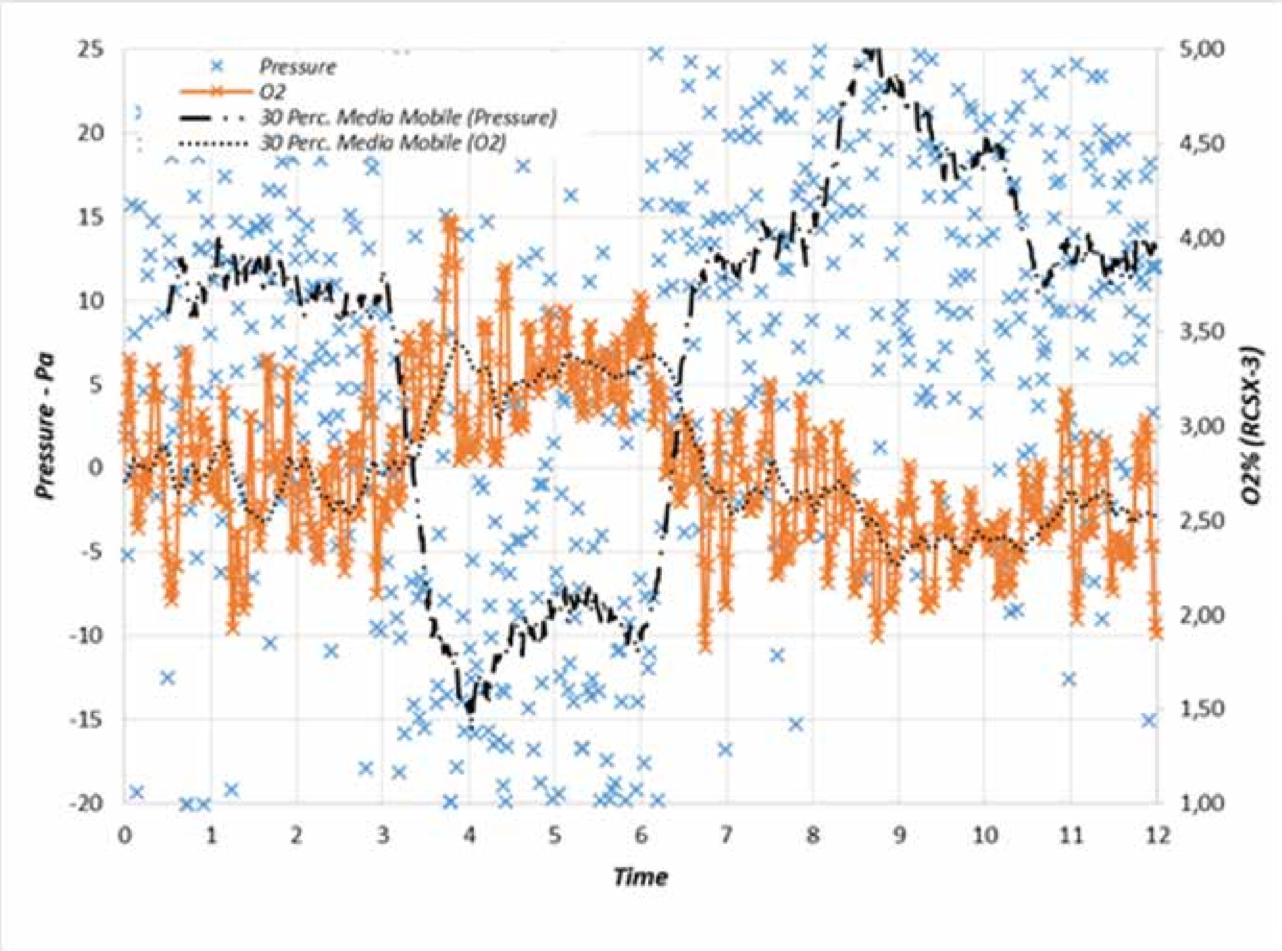

Figure 5 – Example of pressure test report

that proposed for the air. The stoichiometric composition of waste gas can be computed by the composition of the fuel.

Detecting

The measured oxygen content will define how much air needs to be added to the stoichiometric composition, and the detected temperature will confirm it. It is recommended to evaluate the waste gas specific heat with an integral methodology. It is necessary to measure the temperature with a suction thermocouple, which shields the detection elements from the wall radiation.

Out5 - Holes and leakage Computing

A glass furnace, however much the design and construction efforts must be aimed at in this direction, is never a perfectly sealed system. Therefore, in areas where the pressure inside the system is lower than the outside, there will be an entry of air into the furnace which will lower the temperature, harmfully.

In areas where the pressure is higher than the external one, there will be air and fumes leaks through imperfect sealing or real holes, with the consequent loss of the energy contained in the heated gases. In the points where it is possible to see the inside of the furnace from the outside, for example, through an open sight glass, in addition to the losses described above, there will be a loss of heat due to thermal radiation. Obviously, in the design phase it is impossible to establish the presence of holes in the system, and the estimation of their importance is entrusted to the experience and common sense of the technician. In our case, an empiric statistical hypothesis of the infiltration level is integrated in FurnaceMaster, such as for the total heat loss.

Detection

To evaluate the infiltrations, it is necessary to sample the oxygen content in waste gas in successive zones of the fumes path. In order to estimate the leakages, it is possible to measure the oxygen content in waste gas at the port under different positive and negative pressure set points. This allows to create an infiltration/leakage curve depending on the internal pressure.

Out6 – Thermal loss

Depending on the insulation level and furnace size, between 15 percent and 40 percent of the total thermal output is represented by heat loss. It is possible to evaluate

Customer	-	
Furnace	EP	
Zone	Mcal/h	kW
Tank	473	550
Tank thermal bridges	525	610
Total tank	*998*	*1160*
Air port	43	50
A.P. thermal bridges	16	19
A.P. total	*59*	*69*
Waste gas port	58	67
W.G.P. thermal bridges	20	23
W.G.P. total	*78*	*91*
Air chamber	71	82
A.C. thermal bridges	26	30
A.C. total	*96*	*112*
Waste gas chamber	103	120
Air chamber - bottom	32	37
W.G.C. total	*134*	*156*
	Total 1306	*Total* 1588

Zone	Structure	Th. [mm]	Area [m2]	q [kcal/m2h]	q [W/m2]	Q [kcal/h]	Q [W]	Ti [°C]	Te [°C]	Layers	Hc
Tank	Bottom	760	84,30	780	907	65769	76475	1400	20	7	4
Tank	Deep bottom	715	16,95	786	914	13324	15493	1400	20	7	4
Tank	Free soldier blocks	250	8,35	18186	21146	151858	176577	1500	20	1	100
Tank	Lower soldier blocks	531	23,58	1415	1645	33358	38788	1450	20	7	20
Tank	Higher soldier blocks	521	7,79	1608	1870	12521	14560	1450	20	7	20
Tank	Lower soldier blocks - deep	531	15,29	1415	1645	21628	25149	1450	20	7	20
Tank	Higher soldier blocks - deep	521	3,91	1608	1870	6282	7304	1450	20	7	20
Tank	DH soldier blocks	521	2,99	1608	1870	4811	5594	1450	20	7	20
Tank	Side superstructure	565	39,75	888	1033	35302	41048	1550	20	7	20
Tank	Throat wall superstructure	565	28,45	888	1033	25263	29376	1550	20	7	20
Tank	Port wall superstructure	565	21,88	888	1033	19433	22597	1550	20	7	20
Tank	Burner zone	565	1,29	2163	2515	2788	3241	1500	20	4	20
Tank	Tank crown	787	90,36	893	1038	80653	93781	1580	20	6	20
Air port	Air port - chamber side bottom	390	8,34	1545	1796	12876	14972	1250	20	7	20
Air port	Air port - furnace side bottom	231	2,41	4737	5508	11406	13263	1250	20	4	20
Air port	Air port - Sidewalls	565	11,90	782	909	9299	10812	1250	20	7	20
Air port	Air port - crown	605	11,82	767	892	9063	10539	1250	20	7	20
Waste gas port	WG port - chamber side bottom	390	8,34	2088	2428	17408	20242	1550	20	7	20
Waste gas port	WG port - furnace side bottom	231	2,41	6357	7392	15308	17800	1550	20	4	20
Waste gas port	WG port - Sidewalls	565	11,90	1081	1257	12857	14950	1550	20	7	20
Waste gas port	WG port - crown	605	11,82	1047	1217	12373	14387	1550	20	7	20
Air chamber	Air chamber - crown	650	22,55	666	775	15024	17469	1250	20	5	20
Air chamber	Air chamber - port wall	720	18,03	673	782	12126	14100	1250	20	6	20
Air chamber	Air chamber - high walls	720	34,65	673	782	23307	27101	1250	20	6	20
Air chamber	Air chamber - medium walls	720	43,68	307	357	13399	15580	800	20	5	20
Air chamber	Air chamber - low walls	720	43,68	147	171	6424	7470	700	20	4	20
Air chamber	Air chamber - below	950	11,80	21	25	249	289	100	20	3	20
Waste gas chamber	WG chamber - crown	650	22,55	932	1084	21019	24440	1550	20	5	20
Waste gas chamber	WG chamber - port wall	720	18,03	908	1055	16365	19029	1550	20	6	20
Waste gas chamber	WG chamber - high walls	720	34,65	1055	1227	36574	42528	1550	20	6	20
Waste gas chamber	WG chamber - medium walls	720	43,68	462	537	20189	23475	1100	20	5	20
Waste gas chamber	WG chamber - low walls	720	43,68	174	202	7598	8835	800	20	4	20
Waste gas chamber	WG chamber - below	950	11,80	102	118	1200	1395	500	20	3	20

FurnaceMaster

Table 6 – Total heat loss report for a regenerative furnace

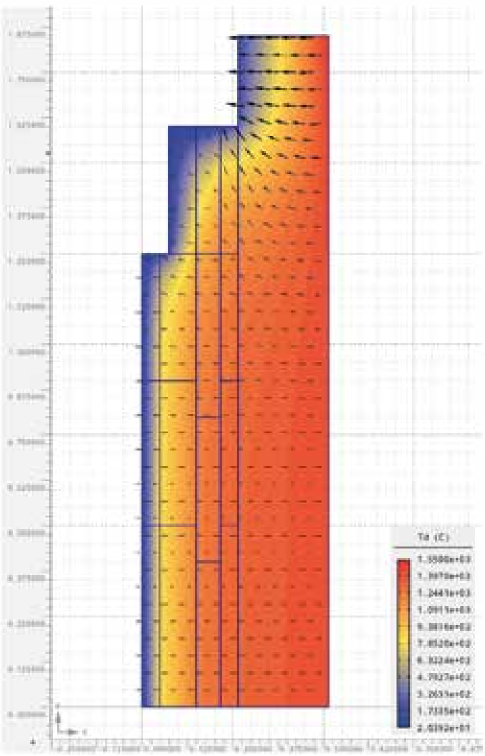

Figure 7 – Example of thermal bridges of a palisade

the heat loss mathematically, by considering dimension and conductivity of all material constituting the furnace and its recovery system. It is important to create an interactive computing environment where conductivities and temperatures are codependent. Stara Glass has a database including more than 600 construction materials.

Heat losses through homogeneous surfaces like sidewalls and bottom are evaluated zone by zone with a simple one-dimensional analysis, yet typically more than half of the furnace heat loss is given by the different relevant thermal bridges of the oven, like soldier block cooling, soldier block joints, tuckstones, skewback, electrodes, etc. For the accuracy of the computing, it makes sense to evaluate all these thermal bridges one by one with proper finite element models.

Conclusion

The carbon footprint of a glass plant largely depends on the furnace consumption. Besides radical changes such as electrification or hydrogen combustion, the first two actions that need to be taken to limit a furnace carbon emission are an optimized design and a regular maintenance of the melter and its performance. By law, we all need to have professionals regularly check the performance of our 2 kW domestic boilers and our 100 kW cars: it probably makes sense to regularly check our 10 MW furnaces too. ■

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