Computer Based Materials Selection for Furnace Walls

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Calculating the temperature field in the walls of industrial kilns and the heat flux loss with the aid of computer programms has since long been standard practice. However, it is also possible to optimise the material choice according to exact criteria. The criterion for doing this, are minimum overall costs. In this paper suitable mathematical principles as well as a computer programme will be presented. In the dialog with the programme the designer is guided from the point of inputting operating conditions to dimensioning the walls. Additionally, he can use the experiences made during this process. Practical applications will be presented in this paper.

1 Introduction

The stationary temperature distribution in the walls (including covers, furnace roofs and doors) of industrial furnaces and the heat flow through such walls as well as the heat accumulation can be calculated simply using computer programmes. This has been standard for many years. This does not apply to the choice of materials and to evaluate the dimensions of the layer thickness. Here the rules of thumb are still applied in many cases. However, computer programmes can provide significant help in material choices and determining the layer thickness. *Rath Group* offers computer-aided material selection to its customers using the interactive program STAWA.

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Often a multi-layer construction of the walls is the most appropriate.

STAWA uses two criteria to determine the optimum choice of materials and layer thicknesses:

- the observance of permissible temperatures on the layer edge surfaces between the different materials and
- the minimisation of total costs of the wall.

Additional criteria, such as the required chemical resistance and the required stability of the materials are inputted by the designer making a general pre-selection of those materials being considered for this optimisation. The designer has a further input option, after the programme has suggested the first material choice.

The compliance to specific maximum outer wall temperatures and the compliance to certain construction-practical rules laid down by the furnace operator or the legislator (e.g., the use of standardised components) can necessitate a deviation away from the optimum material choice and optimum layer thickness.

STAWA shows the designer how much the costs deviate from the optimum. The designer can therefore decide objectively whether it is cost-effective to deviate from the set values or not.

2 Basic formulae

In the following the formulae are listed which STAWA uses for material selection and for dimensioning. No derivation is listed here; it is given in former publications, e.g. [1].

One can achieve a cost-optimum material selection, if one selects those materials, with the properties of which the integral

$$S = \int_{\vartheta_{W,a}}^{\vartheta_{W,i}} \underbrace{\left(f \cdot \lambda \cdot I_V + \frac{n \cdot P_B}{\eta_f \cdot h_u} \lambda \cdot \rho \cdot \bar{c} \cdot (\vartheta - \vartheta_0) \right)}_{\kappa(\vartheta)} d\vartheta \qquad \text{(Eq. 1)}$$

assumes a minimum. The following sizes depend on the material. The thermal conductivity λ, the density ρ and the medium specific thermal capacity $\bar{c}$ as material properties as well as the volume-related investment costs I_V. The latter includes the material price, the costs for auxiliary material (mortar, adhesive, anchor...), the processing costs and specific consequential costs. The integrand is a function of the temperature and is abbreviated here with $\kappa(\vartheta)$.

Optimal cost means that the sum originating from the annual interest and repayment costs for building the wall and the fuel costs caused by the wall losses is minimal. Therefore, the investment factor is included in (Eq. 1)

$$f = \frac{(1+p)^y\, p}{(1+p)^y - 1} + b_1 + b_2 + b_3 \qquad \text{(Eq. 2)}$$

The wall losses refer to heat losses as a result of heat transfer as well as of heat storage. How STAWA minimises the symbol S, will be explained in the following paragraph. The result is a list of materials used and their temperatures on the layer surfaces.

Before the layer thicknesses are calculated, the cost-optimum heat flow density is determined with a stationary temperature field:

$$\dot{q}_{st,opt} = \left(\frac{\eta_f \cdot h_u}{b \cdot P_B} f \int_{\vartheta_{W,a}}^{\vartheta_{W,i}} \lambda \cdot I_V \, d\vartheta + \frac{n}{b} \int_{\vartheta_{W,a}}^{\vartheta_{W,i}} \lambda \cdot \rho \cdot \bar{c} \cdot (\vartheta - \vartheta_0) \, d\vartheta \right)^{\frac{1}{2}} \quad \text{(Eq. 3)}$$

The thickness of a material layer j is then calculated from

$$s_{j,opt} = \dot{q}_{st,opt}^{-1} \int_{\vartheta_{j,a}}^{\vartheta_{j,i}} \lambda_j \, d\vartheta \quad \text{(Eq. 4)}$$

3 Interactive programme STAWA

The STAWA programme takes the material properties from a database. For every material it has registered a name, the thermal conductivity $\lambda(\vartheta)$, the density ρ, the medium specific heat capacity $\bar{c}\,(\vartheta)$, the maximum allowable temperature and the volume-related investment costs I_V. In the data base-servicing mode new materials can be added and existing data changed.

The optimisation of a wall construction begins with the input of the kiln operation data: design temperature of the inner wall $\vartheta_{\omega,t}$, calorific value of the fuel h_u, fuel price P_B, combustion efficiency η_f, number of the firings per year n and annual hours of operation b as well as the accounting values of operational service life of the plant l, interest rates p, tax rates b_1, insurance rates b_2 and repairs b_3.

The theorem of this data is given an identifier and saved for future calculations.

The programme then asks whether the wall is level or cylindrical, and also the position – vertical or horizontal, top-side or bottom. Additionally, a safety sheet can be agreed upon of the maximum allowable material temperatures.

Composition of the wall commences with the pre-selection of the materials suitable for the wall. Additionally whole material groups can be eliminated, for example, all refractory concrete, or only single specific materials.

However, the complete material file could in principle also be included in the optimisation. These could then include several hundred materials.

After pre-selection has been concluded, STAWA selects the cost-optimal materials. Initially, the design temperature is checked $\vartheta_{\omega,t}$, for which material the symbol $\kappa(\vartheta)$ according to (Eq. 1) assumes the lowest value. Additionally, only those materials, which are within the permissible temperature range, are considered.

This selected material is then the material for the internal wall layer. Now in increments of 1 K the temperature down to the external wall temperature is reduced, and the described procedure is carried out for every temperature.

The results are listed with the materials suggested by STAWA and the temperatures on the bordering surfaces. The designer now has the option to change this list according to his own practical experience. For example, materials can be deleted if many or single very thin layers have been listed, which is impractical.

Once concluded, then according to (Eq. 3) the cost-optimum heat flow density is calculated. All values required are available from the preceding stage. With the help of (Eq. 4) the layer thicknesses S can finally be calculated, resulting in the ideal dimensions. Now the designer will round up or down these dimensions. He may increase all dimensions, notably then, when the outer wall temperature does not meet customer specification or regulation. Then the programme checks the temperatures and the heat losses with the altered dimensions. Principally, the now increased costs are calculated, so that the designer can compare how far he has deviated from the cost minimum through his changes. Once the designer has found the final variant, the results are documented.

4 Practical applications

In a large number of practical applications certain types of refractory lining have established themselves and are employed according to current state-of-the-art technology. Nevertheless questions often arise, which then make necessary a comparison of different lining systems, including

- high temperature wool (HTW) lining
- lightweight insulating brick lining
- dense brick lining
- refractory castable lining or according to mixture variations under specific operating conditions, and requiring clear-cut statements concerning operating expenses or overall economic viability of the refractory lining.

Very often these questions concern industrial furnaces in metallurgy and ceramics in the high temperature range. In the following section some examples for application of the STAWA programme are presented.

4.1 Walking beam furnace metallurgy

In the first example the STAWA programme is used to choose the refractory lining for a furnace roof of a walking beam furnace in a stainless steel works.

Whilst large walking beam ovens for heating billets in the past were lined almost without exception with heavy tops of refractory castables or ramming mixes, i.e. suitable components, the main focus now is on the most economically viable lining. This is due to the increased requirements on flexibility of production with more frequent shutdowns, i.e. firing and shutdown cycles. Additionally, the demand to reduce carbon dioxide emissions of industrial furnaces must also be met. In addition to considering the cost of materials, this also requires an analysis of the energetic losses (outer wall loss, stored heat).

In this specific example, two lining systems have been considered for the roof.

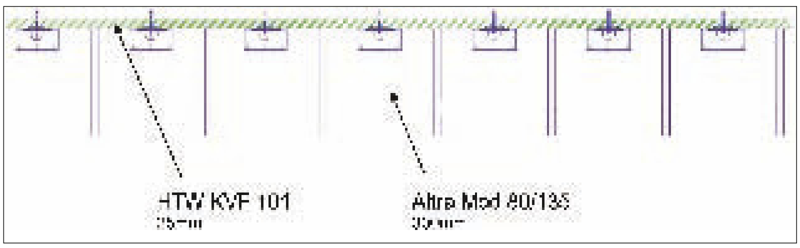

Fig. 1 Schematic diagram Altra module lining

Option 1:
HTW lining, with following composition (Fig. 1)
- 300 mm Altra Mod 80/135 (1600 °C HTW)
- 25 mm HTW board Kerform KVF 101

325 mm

Option 2:
Heavy lining with refractory castable (Fig. 2)
- 180 mm castable Carath 1550 LC
- 40 mm Alsitra Mat 1400/128
- 80 mm insulating castable Carath FL-1052

300 mm

The furnace data as shown in Fig. 3 are used for the calculations. The results of the STAWA calculations for option 1 are illustrated in the output mask in Fig. 4.

When comparing the calculations carried out, it is evident that a HTW lining with Altra modules incurs higher investment costs, however, due to the lower energy costs break-even is achieved after approximately 3 years. Therefore, the HTW lining is more economic when used for longer than 3 years.

4.2 Shuttle kiln for refractory ceramics

In the second example the STAWA programme is used for choosing a refractory lining for a shuttle kiln for firing lightweight insulating bricks. This kiln (Fig. 5) was originally equipped with a side-wall lining of lightweight insulating bricks from the ASTM Group 33.

The high energy costs of this specific process raised the question, what savings could be made by using a HTW lining with Altra modules (1600 °C) in place of the lightweight insulating brick system. Following wall lining options were compared:

Option 1:
Lining with lightweight insulating bricks with following layer composition
- 250 mm Porrath FL 33-13/2
- 64 mm Porrath FL 26-08
- 30 mm of calcium silicate

344 mm

Option 2:
Lining with HTW Altra modules with the following layer composition:
- 300 mm of Altra Mod 72/160
- 25 mm of HTW board Kerform KVF 121

325 mm

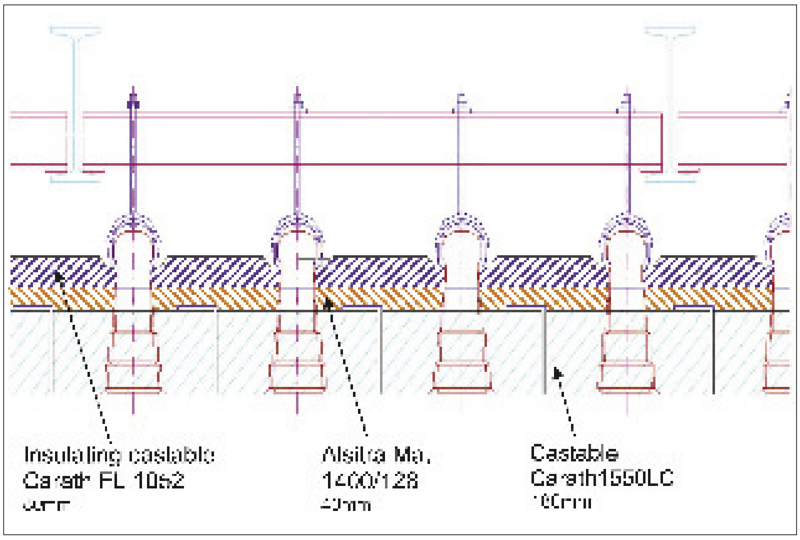

Fig. 2 Schematic diagram of refractory castable-prefabricated roof

Description of furnace data: Walking beam furnaces LOI

General details

Fuel:	Natural gas
Fuel price:	0.36 EUR/m³
Calorific value:	35.93 MJ/m³
Inner temperature:	1250 °C
Ambient temperature:	20 °C
Combustion efficiency:	60 %

Furnace usage

Firings:	22	1/a
Operating h/a:	7500	h/a
Operating period:	5	a
Annual interest:	0	%
AGT:	50	K

Coefficient of heat transfer

$\alpha = a + b \cdot T_s$ [W/(m² K)]	
a	8.2
b	0.041

Wall dimensions *(endlessly smooth)*

Inner diameter:	-	m
Width:	-	m
Height:	-	m

Fig. 3 STAWA input mask for furnace data for calculating roof of walking beam furnace

Name of calculation: HTW-Module Roof of walking beam furnace

Material number	Material name	AGT [°C]	Layer temperature [°C]	Thickness [mm]
5455	KMod 1600/130(132)	1500	1250	300
[illegible]	KVS 101	850	229	25

stationary heat flow density:	702.83 W/m²
specific heat accumulation:	32.47 MJ/m²
wall loss flow density:	624.39 W/m²
wall thickness:	325 mm
outer wall temperature:	81.01 °C
heat transfer - external:	[illegible] W/m²K
investment costs:	2367.60 EUR/m²
operating costs:	328.82 EUR/m²a
total costs:	802.38 EUR/m²a

Fig. 4 STAWA output mask with results of calculations HTW roof walking beam furnace

Fig. 5 Shuttle kiln 1600 °C (Laeis)

From the calculations carried out it is evident that there are serious differences in investment costs between both options. The reason for this is the high price of the Altra modules:

Altra module lining: 2707 EUR/m2
Lightweight refractory brick lining: 1883 EUR/m2

The comparative STAWA calculations for different operating periods (1 year, 3 years and 5 years) confirm, that after about 2 years operation cost parity is achieved. Then considerable cost-savings are to be expected due to the reduction in energy costs of the Altra lining. For this reason the lightweight insulating brick lining was replaced in 2005 with a HTW lining with Altra modules. The anticipated energy savings have been achieved. Additionally, the kiln has become more thermally flexible and due to lighter lining allows for additional technological possibilities in the firing process. Similar quality- and cost improvements have also been achieved in a large number of other kilns in the ceramics field, including kilns for firing cordierite ceramic for exhaust gas catalytic converters. These kilns are operated up to a temperature of 1500 °C and due to their extremely periodical operating mode are appropriately lined with Altra modules.

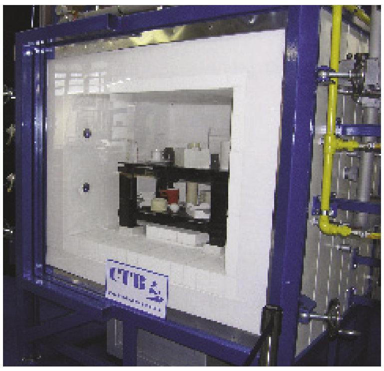

Fig. 7 Chamber kiln of CTB Berlin used to fire cordierite ceramic

Description of furnace data: Shuttle Kiln

General details

Fuel:	Natural gas
Fuel price:	0.36 EUR/m³
Calorific value:	35.93 MJ/m³
Inner temperature:	1600 °C
Ambient temperature:	20 °C
Combustion efficiency:	65 %

Furnace usage

Firings:	35	1/a
Operating/pa:	7800	h/a
Operating period:	5	a
Annual interest:	0	%
ΔT:	50	K

Coefficient of heat transfer

$\alpha = a + b \cdot T_w$ [W/(m² K)]	
a	6.4
b	0.038

Wall dimensions *(endlessly smooth)*

Inner diameter:		m
Width:	12	m
Height:	2	m

Fig. 6 Kiln data shuttle kiln 1600 °C

4.3 Bogie forging furnaces

Lining concepts for bogie forging furnaces have been a matter of much debate recently. For the refractory lining of these furnaces essentially the following options are under consideration for the lining surfaces (roof, walls and doors):

- HTW lining
- lightweight insulating brick lining or
- heavy lining with refractory castable or dense bricks.

4.3.1 Roof lining

Option 1: HTW lining (Fig. 8)
-300 mm HTW combination module (combination of 1600 °C and 1400 °C HTW)
- 25 mm HTW board Kerform KVS 121
<u>- 25 mm HTW blanket Alsitra Mat 1300</u>
350 mm

Option 2:
Heavy lining with refractory castable (Fig. 9)
-160 mm castable Carath 1650 D
- 50 mm insulating castable Carath FL 1401
- 25 mm HTW board Kerform KVS 121
<u>- 65 mm insulating castable Carath FL 1052</u>
300 mm

4.3.2 Wall lining

Option 1 (Fig. 10): HTW lining
-300 mm Alsitra Mod 14/200
- 25 mm HTW board Kerform KVF 121
<u>- 25 mm HTW Blanket Alsitra Mat 1300</u>
350 mm

Option 2 (Fig. 11):
Lining of lightweight insulating bricks
-230 mm LW insulating brick FL 28-10
-115 mm LW insulating refratory brick FL 24-06

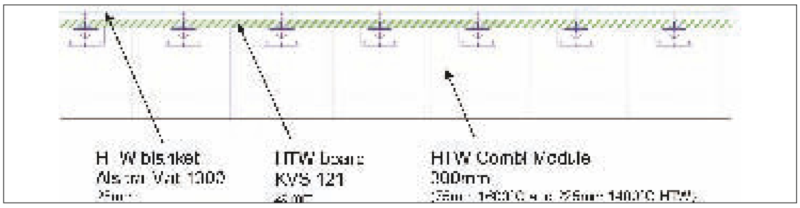

Fig. 8 Roof lining with HTW combination modules

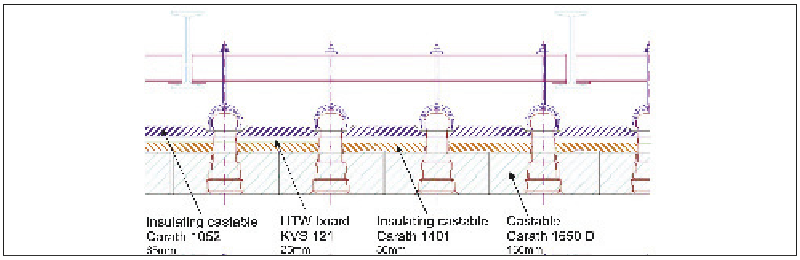

Fig. 9 Prefabricated castable roof component for forging furnace

- 50 mm calcium silicate
- 50 mm mineral wool sheet

445 mm

Option 3 (Fig. 12):
Heavy lining with refractory castable
- 235 mm castable Carath 1550 LC
- 125 mm lightweight insulating brick FL 26-08
- 65 mm lightweight insulating brick FL 24-06
- 75 mm calcium silicate

500 mm

The optimisation calculations were performed in Fig. 13 according to the listed requirements:
The STAWA programme provided the following results when considering total costs of the refractory lining for a fixed operating period of 5 years:

Roof:
a) Option 1: HTW combination modules
605 EUR/m²/a
b) Option 2: Castable lining
1268 EUR/m²/a

Wall:
a) Option 1: HTW-Alsitra modules
390 EUR/m²/a
b) Option 2: LW insulating brick lining
543 EUR/m²/a
c) Option 3: Castable lining
1006 EUR/m²/a

A comparison of the different lining concepts under the stated conditions confirms that for the roof the HTW combination modules (see Fig. 8) are the cheapest solution. HTW lining with Alsitra modules (1400 °C) is the most economical for the wall lining. However, certain practical considerations, such as for example erosion resistance, stable burner installation, resistance against tundish powder etc. indicate that lightweight insulating bricks in the wall area are a better option. Lately the European market leader for forging furnaces, *Andritz MAERZ*, has often successfully applied this, for instance in Kapfenberg/Austria (Fig. 14) and in Gröditz/Germany (Fig.15).

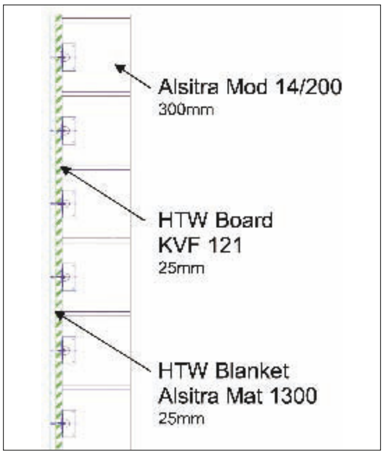

Fig. 10 Side wall lining with Alsitra modules

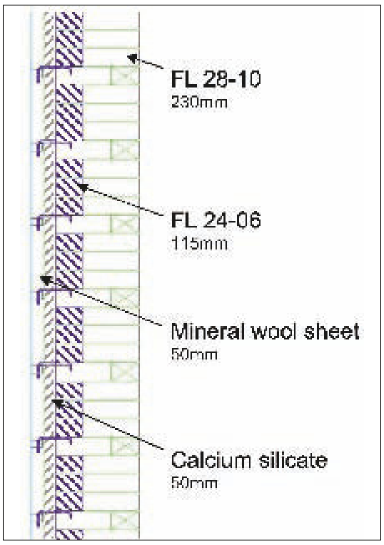

Fig. 11 Side-wall lining with lightweight insulating bricks

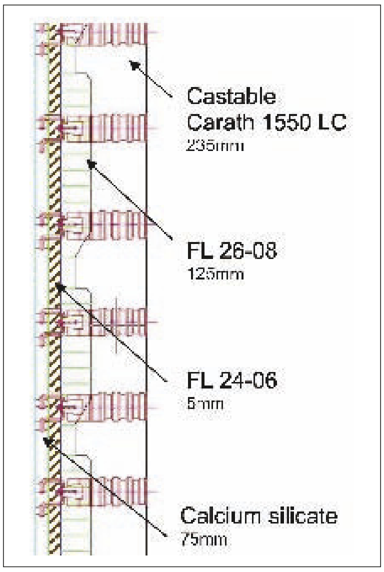

Fig. 12 Side-wall lining with refractory castable

The many different optimisation options for refractory linings of the walls using the STAWA programme are also documented in the publication of W. Klinger [2].
Within four temperature ranges,
- 80 – 900 °C
- 900 – 1300 °C
- 600 – 1600 °C
- 1300 – 1800 °C

the economic efficiency of appropriate heat insulating materials typically used for these temperature ranges was analysed. Included were lightweight insulating bricks, micro-

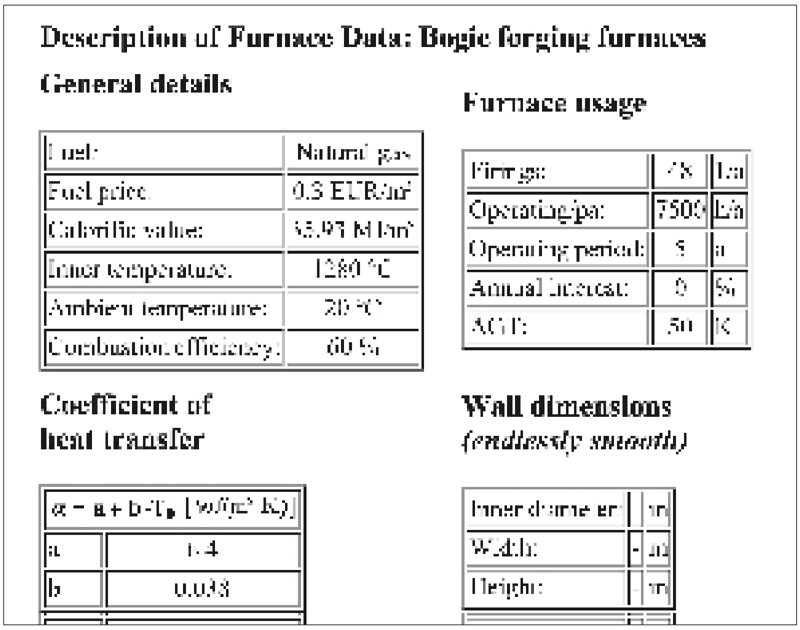

Fig. 13 STAWA input mask for furnace data to calculate side wall Bogie forging furnaces

Fig. 14 Forging furnace Andritz MAERZ in Kapfenberg (Böhler Edelstahl GmbH & Co KG)

Fig. 15 Forging furnace Andritz MAERZ in Gröditz (Schmiedewerke Gröditz GmbH)

porous insulating materials, insulating castables and HTW products.

In Fig. 16 the calculation results of a furnace with 1 m^3 usable capacity have been listed for the comparative group 80 – 900 °C, listing the relative costs, whereby one representative of this group has been assigned the value of 100 %. The relative total expenses include the proportionate investment and energy costs.

The significant differences are clearly recognisable in this evaluation.

From the different calculations carried out it is clear that the optimal heat insulating materials can be determined for each application group using the STAWA programme.

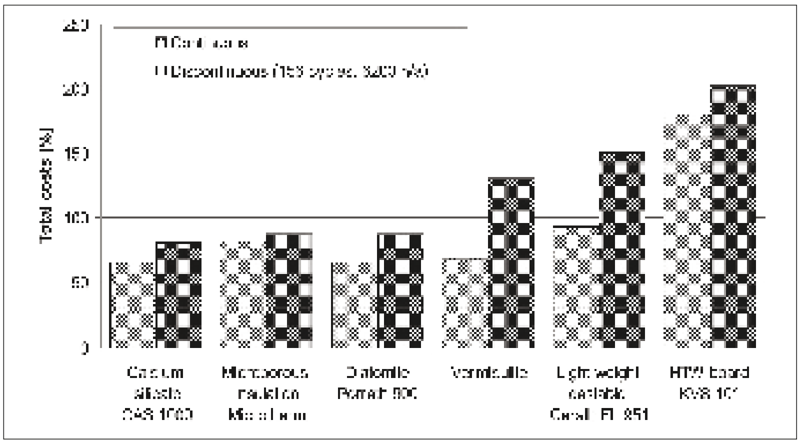

Fig. 16 Heat insulating materials from 900 – 80 °C relative total costs after 3 years of operation

5 Conclusion

The interactive programme STAWA assists the industrial furnace designer in choosing wall materials and in dimensioning them. Minimum overall costs of investment and energy costs are used as a criterion.

In practice it has shown itself as an important aid in choosing the most effective furnace linings.

The STAWA calculations have been successfully applied to realise the refractory linings of a large number of industrial furnace production facilities.

Nevertheless, to achieve the optimum type of lining the designer must take into account a whole series of criteria such as for example:

- chemical influences
- erosion resistance
- accessibility of the building site
- re-lining or repair
- permissible dimensions/materials
- transportability (durability) during pre-assembly.

Nomenclature

b_1, b_2, b_2 – Tax rate, insurance rate, repair rate [1/a]

$\bar{c}$ – medium specific thermal capacity [kJ / (kg · K)]

f – investment factor according to (Eq. 2) [1/a]

h_u – calorific value [MJ/kg]

I_V – volume-related investment costs [€/m^3]

l – service life [a]

n – firing frequency [1/a]

p – interest rate [1/a]

P_B – fuel price [€/kg]

$\int$ – integral according to (Eq. 1) - € [W/(m^4 · a)]

η_f – heating-technical efficiency [1]

κ – Integrand in Eq. 1 – € [W/(K · m^4 · a)]

λ – thermal conductivity [W/(m · K)]

ϑ – temperature [°C]

p – density [kg/m^3]

Indices:

a – outer surface

i – inner surface

j – layer number. j

opt – optimal

st – stationary

W – wall

0 – initial state

References

[1] Walter, G.: Materials selection for heat insulation on an economic basis. 3rd Europ. Conf. on Industrial Furnaces and Boilers, Lisbon

[2] Klinger, W.: Moderne Wärmedämmstoffe im Industrieofenbau, Fachtagung der Deutschen Gesellschaft Feuerfest und Schornsteinbau, Düsseldorf, 2004