The Continuous Drying of Refractory Concrete

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The aim of this paper is to help avoid a steam explosion during drying. Drying refractory occurs via the evaporation of water on the heated side and its drain on the cold side. With increasing temperature, the growing steam pressure pushes the water out to the cold end of the lining. If its discharge into the environment is disabled, it accumulates and is heated up so that a steam explosion may occur. Consequently, the removal of water is crucial for safe drying.
The integral mean value of the temperature determines the thermal conditions in the pore space, which is why it is used for the calculation of the continuous drying.

1 Basis

When a refractory lining, e.g. of an induction furnace, is dried, the aim is to remove the moisture in the shortest possible time and, at the same time, to avoid the destruction of the material as the result of a steam explosion.
In accordance with practice, the temperature control determines the process of drying refractory concrete. For example, the following recommendation on heating is given to customers by a manufacturer (H. Dünnes, Calderys. priv. comm.): After curing and discharging, the shells should be heated up at 15 K/h with a hold time of 1 h/0,01 m thickness inserted at 150 °C, 350 °C and 600 °C. The soaking time is for the purpose the temperature compensation. Often the process is controlled based on the exhaust gas temperature, which is equivalent to the surface temperature of the lining providing heat transfer is good.
To derive a simple model for the drying of refractory concrete, we make four assumptions:

- Not the mass transfer, but the temperature determines the drying process [1–7].
- The first and second phase of refractory concrete drying can be treated likewise, because the first is relatively short and no steam explosions are observed [3–9].
- As soon as the water has been largely removed, there is no danger of the concrete exploding on additional heating (>350 °C) [4, 5, 8, 9].
- On the basis of defined basic values, the position of the drying plane can be calculated from the temperature profile *T(x,t)*. Basic values are, for example, the integral mean value of the temperature T_{im} and the effective boiling temperature T_{110}.

2 Movement of the drying plane

The temporal change of the temperature in the lining during continuous heating is described by the following equation [10]:

$$\frac{T(x,t)-T_a}{T_O-T_a} = \left(1+\frac{1}{2Fo}\right)\cdot erfc\left(\frac{1}{2\sqrt{Fo}}\right)-\frac{1}{\sqrt{\pi Fo}}\cdot e^{-\frac{1}{4Fo}} \quad (1)$$

T(x,t) is the temperature dependent on position *x* and time *t*; T_a [°C] is the initial temperature (here continuously: T_a = 30 °C) and T_O [°C] their maximum right on the heated surface at L = 0 m. T_O depends on the linear heating rate *k* [K/h] and the elapsed time *t* [h]:

$$T_O = T_a + k\cdot t \quad [°C] \quad (2)$$

$$Fo = \frac{a\cdot t}{L^2} \quad (3)$$

Fo represents the Fourier number, formed from the thermal conductivity *a* [m²/s] of the lining, the time *t* [s] and the distance from the surface *L* [m]. If the thickness of the slab exceeds $L = 4\cdot\sqrt{a\cdot t}$, it can be considered as infinite ([11], [12] Section 2.2.2.2). In this example (L = 0,5 m, a = 10^{-6} m²/s), this limit is exceeded after approx 5 h. It is of no less importance for practical application of the model calculation.

Eq. (1) shows that the temperature distribution in the lining depends solely on the Fourier number. The three values (*a; t; L*) completely describe the course of temperature *T(x,t)*.
Fig. 1 shows the distribution of the temperature in the wall up to its thickness L = 0,5 m for four selected times. The heating takes place on the surface with the constant speed k = 7,5 °C/h. For the thermal conductivity, a = 10^{-6} m²/s is chosen and applies to a dry wall. The already dried-out area determines the penetration of heat as in the wet area the thermal conductivity is higher. It can increase up to a = 5 · 10^{-5} m²/s depending on the water content. Hence the temperature gradient in the damp area is flatter than in the dried material. The greatest risk of a steam explosion exists directly behind the drying plane.
The temperature T_{110} = 110 °C is highlighted by a horizontal line. We know that water boils at a low temperature exceeding approx 110 °C. At this temperature, steam and liquid water separate from each other. This temperature defines the drying plane L_{110}. With time, the steam pressure,

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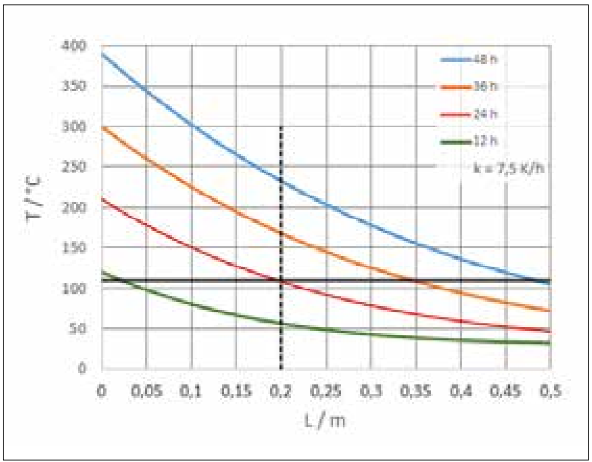

Fig. 1 Temperature distribution in the wall of the lining (eq. 1) in the case of the heating rate k = 7,5 K/h (a = 10^{-6} m²/s)

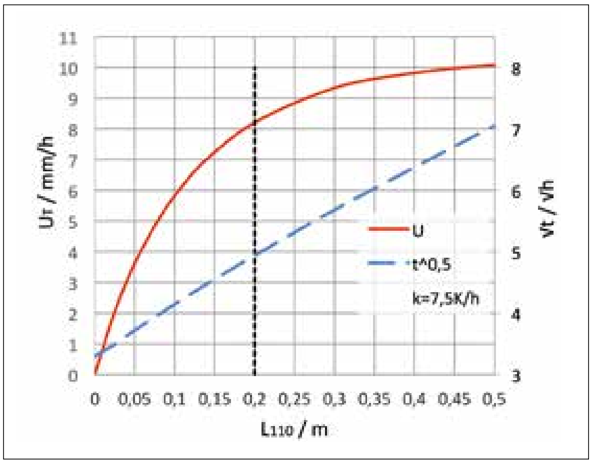

Fig. 2 Drying velocity U_T and square root of the drying time t as a function of distance L_{110} to the surface (T = 110 °C, k = 7,5 K/h, a = 10^{-6} m²/s)

generated by the progressing temperature, pushes the water into the colder part of the lining. From there it escapes through extra holes provided for this purpose into the environment. If the wall thickness is L = 0,2 m (dotted vertical line), the lining is dried after 24 h for a heating rate of k = 7,5 K/h. The drying is more rapid the faster the temperature increases, but the danger of steam explosion grows [11].

The medium velocity U_T of the isotherm T_{110} can be calculated as the quotient of the location L_{110} and the elapsed time *t*. In Fig. 1, we find at the temperature T = 110 °C for t = 24 h the length L_{110} = 0,2 m, i.e. U_T = 8,33 mm/h. Fig. 2 shows U_T [mm/h] and the square root of time *t* [√h] over the length L_{110} [m]. U_T increases approx logarithmically with distance. The required time increases approx linearly with its square root.

The calculation of U_T starts with the choice of the heating rate *k*. The needed time *t* is determined with eq. (2): k · t = T_0 –30. With the choice of *T(x,t)* = 110 °C the temperature term, eq. (1), is known. The correct Fourier number Fo_{110} is iteratively determined on the right-hand side of eq. (1). Now eq. (3) results in L_{110}, from which finally $U_T = L_{110}/t$ is calculated. Fig. 3 shows the course of the Fourier number *Fo*, and the surface temperature T_0 over the length L_{110} for k = 7,5 K/h.

For example, the lining is L = 0,2 m. From Fig. 3, one reads Fo = 2,16. The time is calculated from eq. (3) as t = 2,16 · 0,2²/10^{-6} = 8,64 · 10^4 s = 24 h. When the surface temperature reaches T_0 = 210 °C, the lining is dry (eq. 2).

3 Movement of the water

Starting from 30 °C with the heating rate of k = 7,5 K/h, it takes nearly 12 h until the temperature reaches T_0 = 110 °C (Fig. 1). The increasing vapour pressure shifts the water to the cold end of the lining. If the outflow of water is obstructed, the water is retained and heats up. Its velocity is calculated with the Hagen-Poiseuille equation [13]:

$$U_W = \frac{(P_w - P_o) \cdot d^2}{32 \cdot \eta_w \cdot (L_{110} - L)} \qquad (4)$$

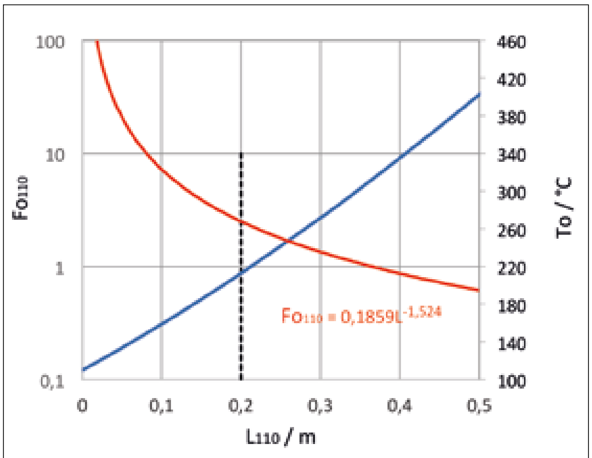

Fig. 3 Surface temperature T_0 and Fourier number Fo_{110} depend on the distance L_{110} to the surface of the lining (k = 7,5 K/h, a = 10^{-6} m²/h)

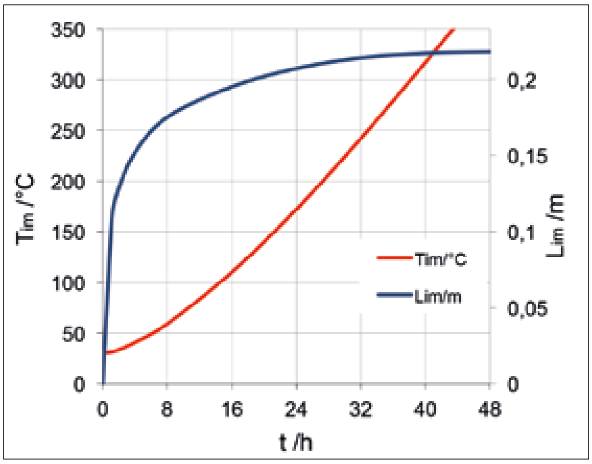

Fig. 4 Integral mean value of temperature T_{im} and the distance L_{im} as a function of the time t for L = 0,5 m, k = 15 K/h, a = 10^{-6} m²/h

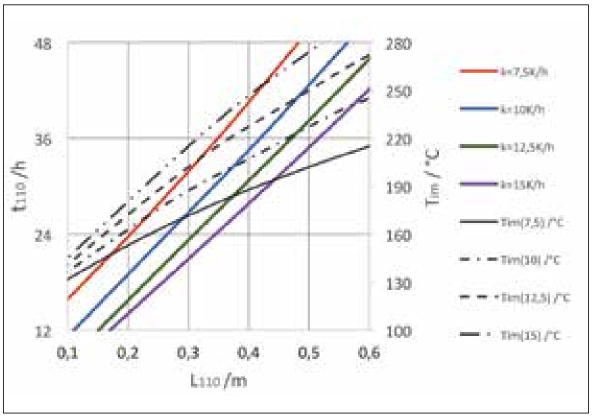

Fig. 5 **Time t_{110} and the corresponding average temperature T_{im} for reaching the length L_{110} ($a = 10^{-6}$ m²/s)**

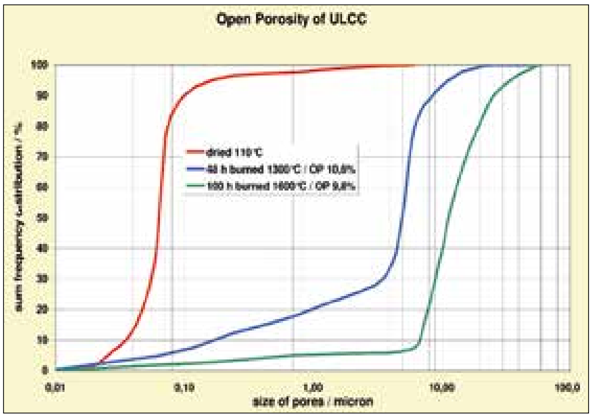

Fig. 6 **Pore size distribution of the examined lining (ULCC) [11]**

The vapour pressure P_w strongly depends on the temperature of the water [14]:

$$P_W = 5 \cdot 10^{10} \cdot \exp(\frac{-2257}{0,46 \cdot (T+273)})[Pa] \quad (5)$$

At 110 °C we find P_W = 1,43 · 10⁵ Pa ([12], Fig. 11.2). The ambient pressure is P = 10⁵ Pa (1 atm), if there is no lower pressure in the vessel. Therefore ΔP = 0,43 atm. at 110 °C.

The viscosity of hot water is $\eta_W = 3 \cdot 10^{-4}$ Pa · s [14].

The temperature of the steam room equalises itself by the fluctuation of the steam, which is why the steam pressure is calculated based on the integral mean value T_{im}.

The exact solution of eq. (1) [11] can be simplified: the course of temperature *T(x,t)* calculated according to *k* is approximated by an exponential function with the constants A and B, so that at a specified time *t* at the location *L* follows:

$$T_{im} = \frac{1}{L}\int_0^L A \cdot e^{-B \cdot L} dL \quad (6)$$

Fig. 4 provides the course of the integral mean values for the temperature T_{im} and the distance L_{im} for the calculated time t (L = 0,5 m, k = 15 K/h) [12]. L_{im} runs toward the value $L_{im} \cong 0,45$ L.

The numerical value equation (7) describes the course of *T(x, t)* (eq. 1) in a simplified form taking into account the integral mean value of T_{im} [11, 12]:

$$\frac{T_O - T_a}{T_{im} - T_a} = \frac{\sqrt{L}}{3000 \cdot a^{0,25}} \cdot \frac{3600 \cdot t}{13,32 \cdot t - 33,5} \quad (7)$$

In addition, eq. (2) delivers the surface temperature T_O.

The movement of the isotherm T_{110} is crucial for the drying process. The area of the steam room L_{110} increases with the time t_{110}. From Fig. 5 with L_{110} [m] and different heating rates *k* [K/h], the time t_{110} has been derived as follows:

$$t_{110} = -1,7k \cdot L_{110} + 96L_{110} + 0,15k^2 - 4,3k + 31 \quad (8)$$

With this data, the corresponding average temperature T_{im} can be calculated from eq. (7) (Fig. 5). If the end of the lining L = 0,2 m is reached with the heating rate k = 7,5 K/h, 24 h have passed, and the medium temperature is 155 °C (end of service). Heating up with k = 12,5 K/h, L = 0,2 m is already reached after t = 16 h at which T_{im} = 165 °C is reached.

The mean value of the pore diameter of the examined dried lining (ULCC) is d_{50} = 0,06 µm = 6 · 10⁻⁸ m [1] and rises to more than 0,3 µm (Fig. 6).

The mean flow velocity of the water U_W calculated with eq. (4), is shown in Fig. 7 for pore diameters of d = 0,06 µm up to d = 0,3 µm. U_W rises exponentially with temperature in the same way as the vapour pressure. For d = 0,3 µm, the velocity U_W = 6 mm/h reaches its identical speed U_T of the drying plane after 18 h at the point L_K = 0,11 m. Its average temperature reaches T_{im} = 135 °C. The water no longer impounds with this temperature but flows freely off the migratory drying plane, although the surface temperature continues to climb, reaching T_0 = 210 °C after 24 h (Fig. 1).

With the much smaller average pore diameter d = 0,06 µm, the flow velocity of the water at L = 0,2 m is only 0,7 mm/h (Fig. 7), i.e. it impounds continuously. However, the medium temperature does not rise above T_{im} = 155 °C until the end of the lining (L = 0,2 m). Experience [3–9] has shown that at this temperature no explosion occurs. The heating rate k = 7,5 K/h seems to be safe for all calculated pore diameters.

So far, all calculations are valid for the constant heating rate k = 7,5 K/h. Fig. 8 summarizes calculations for different *k*. The length L_k [m] shows as the abscissa where U_T and U_W are the same. Below L_k we find $U_W < U_T$, i.e. the water is not drained quickly enough and heats up further. Above L_k we find $U_W > U_T$ and the water flows. Consequently, there is a much lower risk of spontaneous steam explosion.

In addition to the movement of the water, its temperature has been taken into account. Because of its decisive influence on the pressure conditions in the steam room and the location of the drying plane, the integral mean value of temperature T_{im} is selected as qualifying size for selecting the heating speed [11, 12] and is added to Fig. 8.

For example, the pore diameter may be d = 0,2 µm. If the heating rate is k = 7,5 K/h, L_k = 0,18 m lies just barely inside the lining. If heated at k = 10 K/h, $U_T = U_W$ is at L_k = 0,275 m which is outside the lining. In this case, we find T_{im} = 175 °C, i.e. there would be danger for the lining. A steam explosion risk increases parallel to the size of the lining. Therefore, the calculation is extended to L = 0,5 m for practicality.

To calculate the time t, eq. (7) and the three data points (*k*, L_k, T_{im}) from Fig. 8 are used. With k = 7,5 K/h, L_k = 0,18 m

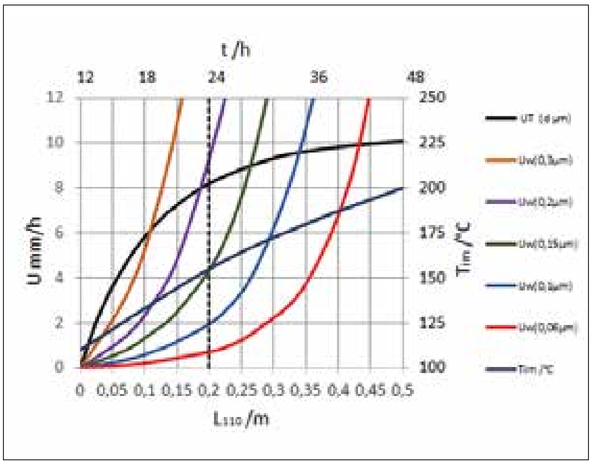

Fig. 7 **Change of speed U_T according to the progressive temperature T_{110} and of the water U_W along the length L_{110} of the lining and the average temperature T_{im} (k = 7,5 K/h, a = 10^{-6} m²/s)**

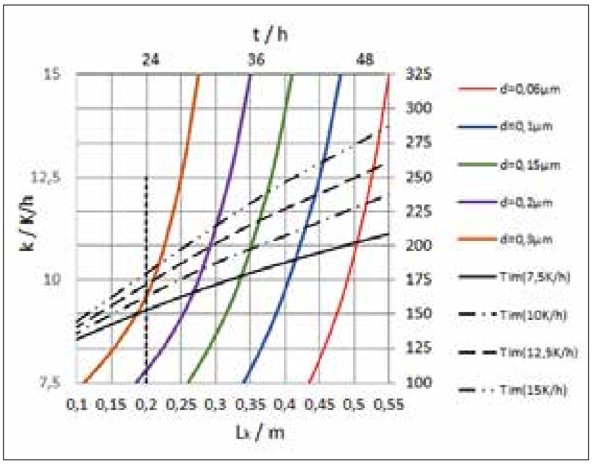

Fig. 8 **Correlation between the rate of heating k and the length L_k ($U_T = U_W$) with different pore diameters d and the average temperature T_{im} (k, L_k) (The times given are guiding values only for k = 7,5 K/h)**

and T_{im} = 150 °C, t = 22 h is calculated from eq. (7). If heating with k = 10 K/h, the average temperature is T_{im} = 180 °C and L_K = 0,275 m when t = 25 h passes. This time is not readable on the upper X-axis of Fig. 8, because this is valid only for k = 7,5 K/h.

All the information necessary for the selection of the best heating rate is summarized in Fig. 9 [11, 12].

If the size of the lining is L = 0,2 m and the medium temperature T_{im} = 150 °C appears to be safe, Fig. 9 shows a necessary heating rate of k = 7,5 K/h. The surface temperature T_0 = 210 °C should not be exceeded. This corresponds to a duration of t = 24 h.

Using the Hagen-Poiseuilles equation, eq. (4), the relationship between the mass flow of steam to the water is finally found. The boundary conditions, such as temperature and pressure, are almost equal for both media and the proportionality holds [14–16]:

$$\frac{\dot{m}_D}{\dot{m}_W} = \frac{\eta_W \cdot \rho_D}{\mu \cdot \eta_D \cdot \rho_W} = \qquad (8)$$

$$\frac{3 \cdot 10^{-4}[Pa \cdot s] \cdot 0,6[\mathrm{kg/m^3}]}{10 \cdot 1,4 \cdot 10^{-5}[Pa \cdot s] \cdot 10^3[\mathrm{kg/m^3}]} = 1,3 \cdot 10^{-3}$$

The proportion of the mass flow of steam is only about 0,1 %. It is therefore of crucial importance to avoid steam explosion by means of good water drainage. The empirical correction factor μ = 10 considers mass transport variation for vapour in capillary systems observed in practice [1, 2].

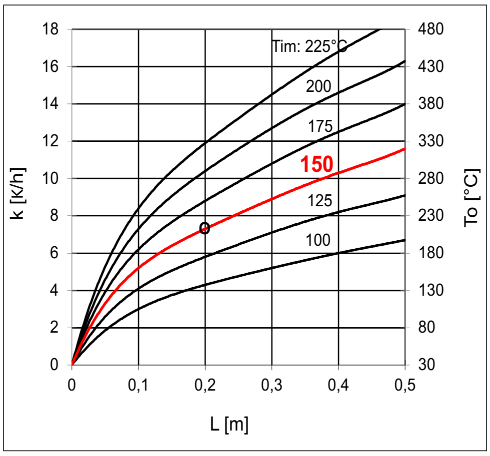

Fig. 9 **Heating rate k and maximum surface temperature T_0 as a function of wall thickness L and the mean temperature T_{im} (T_a = 30 °C, t = 24 h, a = 10^{-6} m²/ s)**

4 Risk of steam explosion

The aim of this paper is to help avoid a steam explosion during drying. The formation of vapour bubbles in superheated water has been discussed elsewhere [11, 12]. Heterogeneous nucleation can be excluded largely because water wets the refractory material. The principle of "boiling chips" is effective only in exceptions. Bubbles tended to develop, like in a microwave, primarily in the homogeneous phase. The "tensile strength" of water [17] provides reference values:

$$\Delta P = \frac{8 \cdot \sigma}{3 \cdot d} \qquad (9)$$

The surface tension of boiling water in the relevant temperature range (110–200 °C) is about σ ≈ 0,045 N/m. If the smallest pores occasionally contain gas, e.g. air, the diameter of a nucleus may have the size of a pore i.e. d ≈ 10^{-7} m. The required steam pressure for nucleation is calculated as ΔP ≈ 12 atm. This corresponds to the temperature T_N = 185 °C. Now it is questionable how far the refractory material can withstand such pressure. The answer is inaccurate because it depends on the mechanical stability of the material, which changes during the drying process.

The tensile strength of the material should not be less than 1 MPa (10 atm) [12] which represents an average. The information contained in the literature is spread strongly [18, 19]. In accordance with experience [3–9] the highest risk of a lining being destroyed by steam explosion exists above 170 °C. The average temperature T_{im} should therefore never exceed this value.

5 Application in practice

Three steps support a safe heating strategy:

- In the first step, we take the pore diameter d [µm] which is characteristic for the flow of the water and read off L_k [m] in Fig. (8) where both speeds U_T and U_W are equal. The calculated example is l_k = 0,11 m for the pore diameter of d = 0,3 µm and the heating rate k = 7,5 K/h.
- In the second step, we take from the same Fig. (8) the average temperature T_{im} [°C], if the drying ends at L = 0,2 m. In this case, we find T_{im} = 155 °C. For two heating speeds k = 10 K/h and 12,5 K/h, the medium temperature of the lining is T_{im} <175 °C as well. Because of $U_W < U_T$

the water heats up and there is always a risk of material explosion. k = 15 K h is not recommended since we find T_{im} >180 °C and the risk is already very large.

- With this knowledge, in the third step, the required maximum temperature must be read off Fig. (9) keeping in mind the heating rate selected in the second step. This is T_o = 210 °C after 24 h for k = 7,5 K/h. Alternatively, both T_o and T_{im} can be calculated from eq. (7) and eq. (2) when k, L_k and t are inserted.

The proposed industrial heating curves (k = 15 K/h) with the periods of holding at 150 °C, 350 °C and 600 °C (1 h/0,01 m thickness) are compared in Fig. 10 [12] to the continuous heating with k = 7,5 K/h according to the theory offered here. You can see that if the specified wall thickness is taken as l = 0,2 m, the temperature gradients are comparable, but the temporal increase in the holding temperature exceeds that of the lower heating rate, which is unfavourable. The method of selective continuous heating is gentle and leads more quickly to a dry lining. Practical testing is pending. In Fig. 10, the approximate position L = 0,1 m is drawn which corresponds to the integral mean value of temperature. It is located near L_{im} = 0,45 L.

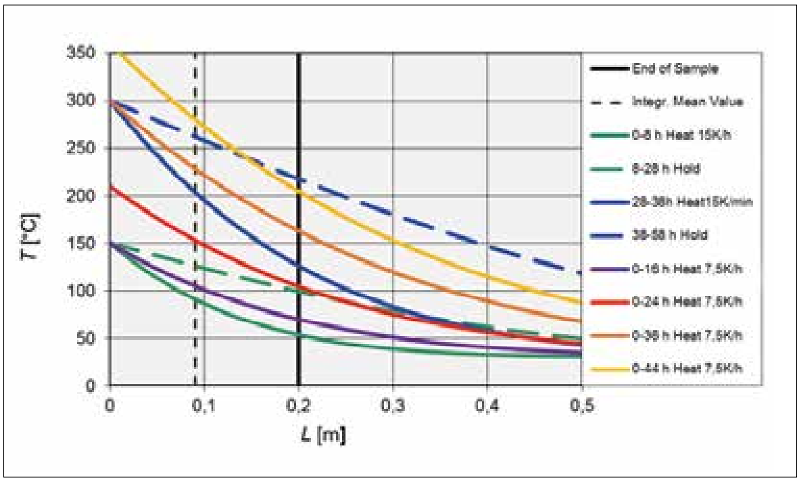

Fig. 10 Comparison between the gradual heating up (k = 15 K/h) after a recommendation from practice and continuous heating up (k = 7,5 K/h) after this calculated model [12] (T_a = 30 °, a = 10^{-6} m²/s)

6 Summary

Drying refractory occurs via the evaporation of water on the heated side and its drain on the cold side. The movement of the drying plane is calculated for the case in which the heating up takes place at a constant velocity. The average temperature does not significantly exceed the (practical) boiling temperature of 110 °C, if the speeds of the drying plane and the run-off water are equal from the outset. A steam explosion is not possible.

With increasing temperature, the growing steam pressure pushes the water out to the cold end of the lining. If its discharge into the environment is disabled, it accumulates and is heated up so that a steam explosion may occur. Consequently, the removal of water is crucial for safe drying.

The integral mean value of the temperature determines the thermal conditions in the pore space, which is why it is used for the calculation of the continuous drying.

The model describes quantitatively the drying process, even if the lining consists of two or more layers. The low temperature of the inner layer then represents the surface temperature To of the following layer ([12] Section 14.2). The material data (*a, d*) of each layer must be considered individually.

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