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Investigation of the thermal insulation for a high temperature furnace under varying atmospheres and pressures

Dipl.-Ing. Roland Waitz, Dipl.-Phys. Anton Wilfart, Linn High Therm GmbH, Eschenfelden (Germany)

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Editor: Dipl.-Ing. Stephan Schalm, Tel. +49 (0) 201/82002-12, E-Mail: s.schalm@vulkan-verlag.de

Investigation of the thermal insulation for a high temperature furnace under varying atmospheres and pressures

The thermal conductivity of porous refractory and insulating materials depends on the type of material, the temperature, the gases that fill the pores and the pressure. In general, manufacturers are stating the thermal conductivity of materials only for air under normal pressure. The measured values for other gases and pressures are hardly available. A reliable method for the conversion of measured values to other gases and pressures is not yet known. For the manufacturers of furnaces this means that thermal losses in the walls of the furnaces for special gases, high pressures and vacuum could only be estimated with a high uncertainty. In the past, the mentioned problem has caused under- and/or overdimensioning of heaters or insulations. For the solution of this problem we utilized an electrical resistance-heated high temperature furnace "Rubistar 100", manufactured by Linn High Therm GmbH. This furnace is equipped with a three layer fibre insulation for a maximum temperature of 1800 °C under air and protective gas atmosphere, with a working pressure up to 100 bar. For technically interesting combinations of temperature, pressure and gas atmosphere the required heating power is determined. With these measured data an extrapolation for higher temperatures and pressures is carried out. The calculated specific power values allow an economical power dimensioning of other sizes of furnaces. Finally the temperature uniformity inside the furnace chamber is measured to clarify whether such types of furnaces can meet the requirements of the customers.



Dipl.-Ing. Roland Waitz
Linn High Therm GmbH,
Eschenfelden (Germany)

Tel. +49 (0)9665 / 91400
Email: waitz@linn.de



Dipl.-Phys. Anton Wilfart
Linn High Therm GmbH,
Eschenfelden (Germany)

Tel. +49 (0)9665 / 91400
Email: wilfart@linn.de

Introduction

For dimensioning of highly effective insulation systems and for cost optimisation an exact knowledge of the thermal conductivity of the insulation material is necessary. In most cases the available, measured data do not cover suitably the intended field of application. This is especially true if an insulation under vacuum should be realised, because herein the vacuum pressure serves as an additional parameter besides the characteristics of the material and the temperature. Also the operation under overpressure is an interesting application. From the literature [1, 2] a number of investigations is known where model equations for calculating the effective thermal conductivity are derived with simplified consideration of physical conditions.

Because of the amorphous heterogeneous structure of most insulation materials, each model requires the introduction of constants in order to adjust to the data which have been found in experiments. For doing comparison and optimization calculations it is necessary that at least small groups of insulation mate-

rials are described through a unified set of adaptable constants. Herein especially the influence of the bulk density and the particle size or the fibre thickness has to be considered in a quantitative and correct way.

The models in literature which have been checked regarding the experimental data do not fulfill these requirements. Although they allow a description of the dependence of the effective thermal conductivity on pressure, gas type and temperature, but not on the insulation material itself.

The aim is, therefore, to check and improve the knowledge of the influence of gas pressure and gas composition as well as the temperature and the type of material.

Thermal transport mechanisms in porous materials

Heat insulation materials are heterogeneous porous multi-phase bodies. For modelling the thermal transport in such bodies, the analogous laws of electrical and thermal conductivity are often used. The relation between characteristic

length l_k to the product of thermal conductivity λ and conducting cross section A is called thermal resistance R , so that

$$\dot{Q} = \frac{\Delta T}{R} \quad (1)$$

is analogous to the Ohm's law for the heat current \dot{Q} . Analytical models for the description of the thermal conductivity in porous bodies are mostly constructed with the help of parallel and serial circuits of thermal resistances. Thermal resistances are assigned to the individual components of the structure according to the conditions of the thermal transport. Depending on the modelling of the different connections this results in mathematical equations which contain the thermal conductivity as a function of porosity, other structure characteristics, temperature and the thermal conductivity of the solid and gas phases. **Fig. 1** shows an example of the possible interconnection of the resistances, which covers all well-known thermal transport processes.

Thus thermal energy can be transported via four ways from the position with tem-

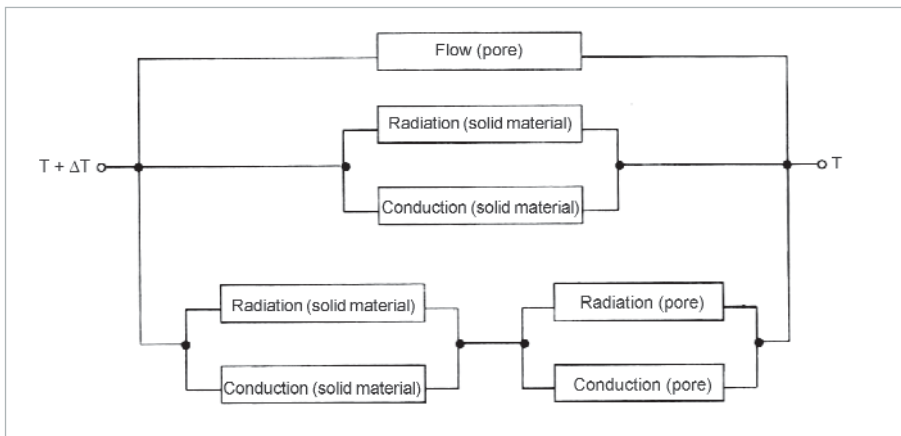


Fig. 1: Model schematic of thermal transport in multi-phase, porous and heterogeneous materials, shown as a network of resistances [1]

perature $T + \Delta T$ to the position with the lower temperature T :

- By a flow through the pores, where the flowing medium transports the energy
- By conduction and/or radiation of the pore-free solid material
- By conduction and/or radiation of the solid material interrupted by the pores
- By conduction or radiation of the pores

The model shown in Fig. 1 can be displayed a lot more simply for different insulation materials. In common materials, e.g. in fireclay bricks, the thermal transport is effected through thermal conductivity in the solid material and radiation inside the pores. In Fig. 1 this special case only includes the resistances conduction (solid material) in the middle path and the resistances conduction (solid material) and radiation (pores) in the lower path. On the other

hand for each fibre insulation a large thermal load can be transported by a flow through the fibres with their low density and by the radiation inside the amorphous fibres which makes the analytical description much more difficult.

The standard experimental setups for determining the thermal conductivity do not consider the thermal transport caused by gas flow through the insulation materials. However, in practical use this kind of transport occurs.

The general case of the behaviour of the thermal conductivity, using a mixture of two phases with different ϵ_s , is shown in **Fig. 2** where the model from Ref. [2] is applied. The ratio between the l_s is used as a parameter in the curves. Thus the porosity reduces the thermal conductivity quite a lot, if the gas phase is continuously present. If the gas phase is distributed discontinuously inside the pores, the thermal conductivity decreases in approximately linear fashion with the porosity. This was confirmed in experiments with fireclay bricks and alumina refractory up to 60 % porosity for temperatures up to 1500 °C.

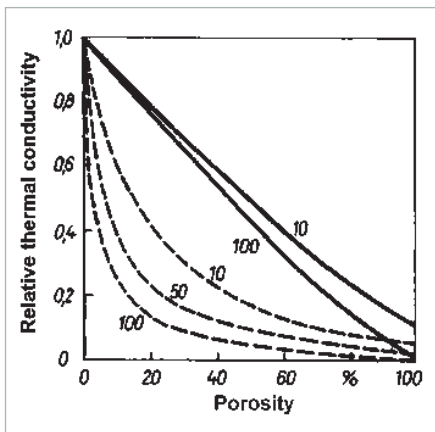


Fig. 2: Relative thermal conductivity for different mixture ratios of two phases with different thermal conductivity. This relation is plotted as a function of the porosity [1]

For increasing porosity the processes mentioned in **Fig. 3** are deviating from the models which were mentioned before. In Fig. 3 the dashed lines are showing different thermal transport processes. When the porosity increases, the relative quantity of gas inside the insulation material is increasing and the thermal transport in the gas phase will grow, simultaneously the thermal conductivity through the solid phase will be reduced. The components of the thermal flows due to different transport mechanisms add up to the effective thermal conductivity which is shown in fig. 3 with the solid lines. The effective thermal

conductivity always has a minimum depending on the porosity, when radiation or convection participate in the thermal transport. The minimum is shifted to lower porosities with increasing temperatures, because the radiation heat transfer increases more with higher temperatures than the conductive transfer. At porosities below the minimum of the thermal conductivity, the effective thermal conductivity becomes very similar to the pattern in Fig. 2. The occurrence of a minimum thermal conductivity in dependence of the porosity means that there exists an optimal porosity and raw density, where the thermal insulation has a maximum.

The thermal conductivity is roughly linearly dependent on the pore size as shown in different models. When the pore size is smaller than the average free length of the gas molecules (smaller than 100 nm), a large reduction of the thermal conductivity of the pore gas can be observed. Thus it is explained that the so called microporous insulation materials have a lower thermal conductivity than static air.

Definitions regarding the effective thermal conductivity

The effective thermal conductivity of an insulation material is the result of the elementary thermal transport processes. The differential equation

$$\frac{d}{dA} \left(\frac{\partial Q}{\partial t} \right) = -\lambda \cdot \text{grad } T \quad (2)$$

is not only applied for homogeneous, but also for heterogeneous multi-phase and porous materials, wherein: $\text{grad } T$ = local temperature gradient, Q = thermal energy, λ = thermal conductivity, t = time,

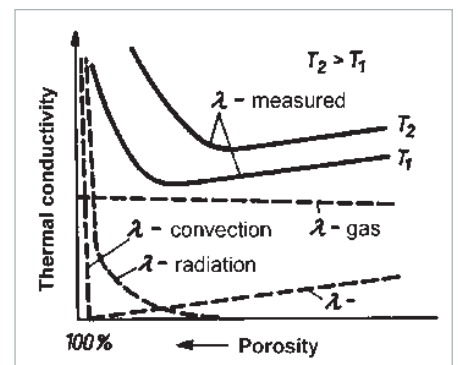


Fig. 3: Thermal transport mechanisms (dashed lines) and effective thermal conductivity (full lines) concerning high porosities [1]

$$\frac{d}{dA} \left(\frac{\partial Q}{\partial t} \right) = \text{differential heat flow through}$$

the area element dA .

The thermal conductivity of an insulation material determined in experiments and given in tables is not only a value for thermal transport by conduction, but it is valid for the complete thermal transport independent of the mechanism inside the material. This effective thermal conductivity includes the complete thermal transport caused by conduction, radiation and eventually convection. The effective thermal conductivity is a material property, which gives an information about the heat flow inside a temperature field, which flows due to the temperature difference over a defined length across an area in direction to the normal axis.

The thermal conductivity of insulation materials increases with the temperature, if it is lower than $1 \text{ W} / (\text{m} \cdot \text{K})$ at room temperature and it decreases, if it is much higher than $1 \text{ W} / (\text{m} \cdot \text{K})$ at room temperature. This behaviour can be explained by the different proportions of pores and solid material and the radiation heat transport in highly porous materials (very low thermal conductivity at room temperature; however, high thermal conductivity at high temperature). In contrast to this, low porosity materials have a high thermal conductivity because of the high thermal conductivity at room temperature of the solid phase. At high temperatures the thermal conductivity is lower because of the negative temperature coefficient of these solid materials.

For porous multi phase materials the empiric relation with the effective thermal conductivity λ_{eff} can be written according to Ref. [1] as:

$$\lambda_{\text{eff}} = a \cdot \frac{1}{T} + b \cdot \sqrt{T} + c \cdot T^3 \quad (3)$$

The first item in equation (3) describes the pure thermal conduction of the pore free crystalline phase. Therein the constant a describes how the thermal conductivity depends on the material. The second item gives information about the pure thermal conduction inside the pores and in a non-crystalline material. The constant b should be inverse proportional to the total porosity. The third item is responsible for the inner radiation, wherein the quantity constant c is a measure for the heat transport by radiation. Thus for insulation materials the following facts can be derived from equation (3):

- The share of internal radiation increases much more with higher temperatures than the conduction portion. At high temperatures the heat transfer takes place mainly by internal radiation.
- The share of conduction decreases with increasing total porosity at constant temperature.
- The share of radiation decreases with smaller average pore size at constant temperature. It strongly depends on the distance between the radiating surfaces and thus on the pore size distribution.
- An insulation material with a high share of empty space and with smaller average pore size will show a lower increase of the effective thermal conductivity depending on the temperature.
- The effective thermal conductivity can depend on the direction, in the case of anisometry or textures, especially at random pore volume structures.

When all facts are summarized, the following are the requirements for an insulation material with minimum thermal conductivity:

- The porosity has to be adjusted to the working temperature and the respective temperature gradient. The thermal conductivity decreases with increasing working temperature.
- The pore size should be as small as possible.
- Cracks and large pores, which allow a convective thermal transport, have to be avoided. This has to be taken care of when layering plates of several insulation materials.

An insulation material with maximum thermal conductivity can be obtained in the following way:

- The material must be essentially free of pores.
- The solid phase should consist of a crystal structure with high density, where atoms with very low relative mass are used. Furthermore the crystal size should be large with high order lattice structure, without microcracks or amorphous components. The material should be single phase and have a high transparency.
- Additions of graphite and silicon carbide (SiC) improve the thermal conductivity of the most refractory materials. For special applications BeO and AlN are the best choice with the highest thermal conductivity.

Influence of pressure on thermal conductivity

Experiments have shown that the thermal conductivity of a gas inside a porous medium can differ from the pure gas value. Thus dimensioning of the enclosing space, e. g. pores in insulation materials, is an important factor. This phenomenon can be explained by the kinetic gas theory, where the Knudsen number Kn describes the relation between the average free path length of the gas molecules l_g and the pore size d_p .

$$Kn = \frac{l_g}{d_p} \quad (4)$$

According to the kinetic gas theory, the thermal conductivity λ_{g0} of an ideal free gas is calculated as follows (with c_g = specific heat capacity, ρ_g = density, v_g = average velocity of the gas molecules, l_d = average free path length of the gas):

$$\lambda_{g0} = \frac{1}{3} \cdot c_g \cdot \rho_g \cdot v_g \cdot l_d \quad (5)$$

For more details see Ref. [3].

In summary three cases can be distinguished:

- $l_g \ll d_p$, the thermal conductivity λ does not depend on pressure
- $l_g \gg d_p$, the thermal conductivity λ is proportional to the gas pressure at constant temperature, at constant pressure λ is proportional to $1/\sqrt{T}$
- $l_g \approx d_p$, the thermal conductivity is dependent on the pressure, a more accurate statement cannot be made

The first case occurs, when the pore size or the distance between the surrounding walls d_p is constant and much larger than the average free path length l_g of the gas molecules. The second case will occur, when the pores are too small and they all have the same diameter. However, this cannot be observed in reality because most pores have different shapes and diameters.

This is shown in **Fig. 4** (left): At constant pore size the pore diameter can be compared with the average free path length of the gases. The Knudsen number is 1 or larger than 1 at low pressures. The average free path length decreases with an increase in pressure [3], which causes a decrease in the Knudsen number. Thus the thermal conductivity does not depend on the pressure.

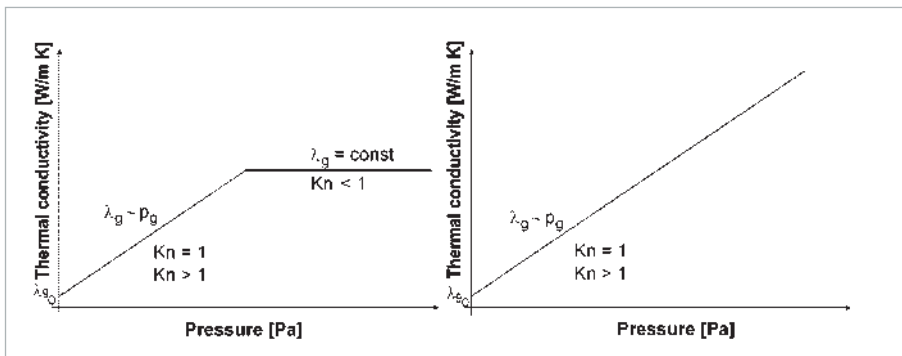


Fig. 4: Dependence of the thermal conductivity on the pressure at constant (left) and variable (right) pore sizes

For variable pore sizes (Fig. 4, right) the size of the micro pores is very important. These pores, where the size is much smaller than the average free path length of the gas molecules, have an influence on the thermal conductivity of the insulation material.

When verifying this theory in experiments, one faces the difficulty that in general thermal process systems the thermal conductivity of the insulation materials cannot be determined easily. However, there is a direct relation to the required heating power, which has to be installed by the furnace builder, in order to fulfill a customer's requirements of heat-up time and temperature accuracy. Power can be measured easily, and trends can be relayed directly to the effective thermal conductivity. Thus the measurement results can be compared with the theory. That's why in all reported experiments only the required heating power is measured.



Fig. 5: High pressure furnace, "Rubistar 100", made by Linn High Therm GmbH on the left; upper right: treated corundums, like rubies and sapphires (Corundum Mine Co. Ltd., Bangkok); lower right: hard metal cutting devices (Boehlerit)

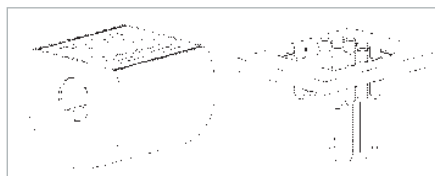


Fig. 6: Insulation set (left) and Kanthal Super 1900 heating elements (right)

Experimental set-up

For the experiments a high pressure furnace, type "Rubistar 100", made by Linn High Therm GmbH is used (Fig. 5). This furnace is applied for heat treatment of corundums (rubies, sapphires) using the diffusion method (Fig. 5) in order to improve the colour or for sintering of powder metals (used for hard metal cutting devices).

The furnace has a box shaped useful volume with the dimensions 70 mm x 80 mm x 120 mm (w x h x d). In these experiments a three layer insulation (combination of fibre and microporous materials) is used and allows a short time temperature of max. 1800 °C and 1750 °C continuous temperature under oxidizing atmosphere. The highly effective insulation promises a temperature accuracy of ± 10 K, the high pressure vessel allows pressures up to 100 bar under air, argon and nitrogen (or mixtures of these gases with hydrogen [max. 5 % H₂]). Before starting the process the chamber is evacuated down to 5 · 10⁻³ mbar by a vacuum pump. Kanthal Super 1900 heating elements with a typical power of 5 kW are installed.

The double walled vacuum chamber consists of the furnace body and two lids. Despite the elaborate insulation, the chamber has to be water cooled, in order to reach a maximum surface temperature of less than 60 °C. Simple tap water is sufficient for this. The furnace has two connectors for protective gas and air, the latter one can also be used

for a second protective gas. The front side of the chamber has a square opening for charging, at the top side the lead-throughs for the heating elements are installed (Fig. 6 left).

The chamber is equipped with five Kanthal heating elements, which are installed vertically and connected with an aluminium rail at the high pressure current lead-through (Fig. 6 right).

A maximum temperature of 1800 °C in combination with the applied protective gases is allowed. Only when using hydrogen (5 %) the maximum temperature decreases down to 1650 °C. As in every resistance heated furnace, the chamber temperature is 30 to 100 K lower than the heating element temperature.

Four thermocouples are used for temperature measurement, two are responsible for measurement inside the furnace chamber (Pt40Rh/Pt20Rh). The first one is connected to the safety controller, the second works together with the standard controller.

The third thermocouple (type S Pt-Rh), which is installed inside the central insulation layer, detects temperature changes during heat up. The fourth thermocouple (type K NiCrNi) is integrated at the inner surface of the pressure vessel and it shows changes of the inner wall temperature. Fig. 7 shows the complete thermocouple setup.

Practical experiments

The following program was the basis of the experiments:

- Heating up as fast as possible starting from the cold state to the final temperature of 1000 °C respectively 1700 °C

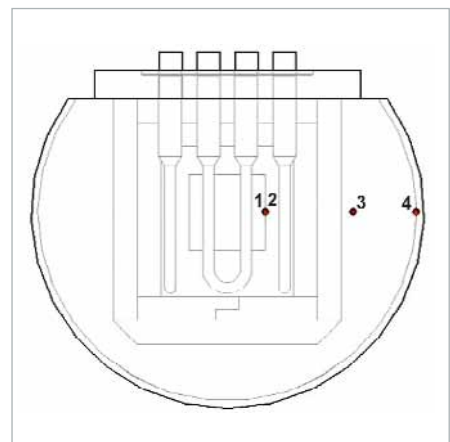


Fig. 7: Setup of the thermocouples in front view into the furnace chamber

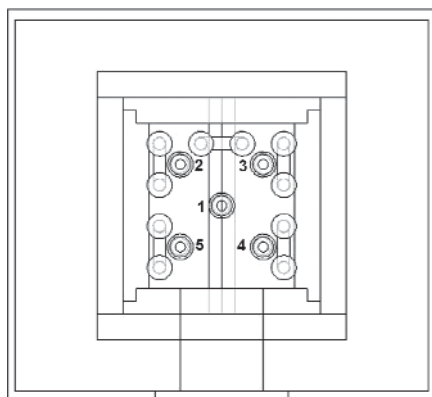


Fig 8: Arrangement of the ceramic rings inside the furnace chamber (top view). Left, right and at the back side the heaters are visible in cross section

- Keeping this temperature constant over three hours
- Cooling down to 300 °C with water flowing while lowering the gas pressure
- Opening the furnace at less than 300 °C

All experiments were done under the following atmospheres with the following pressures:

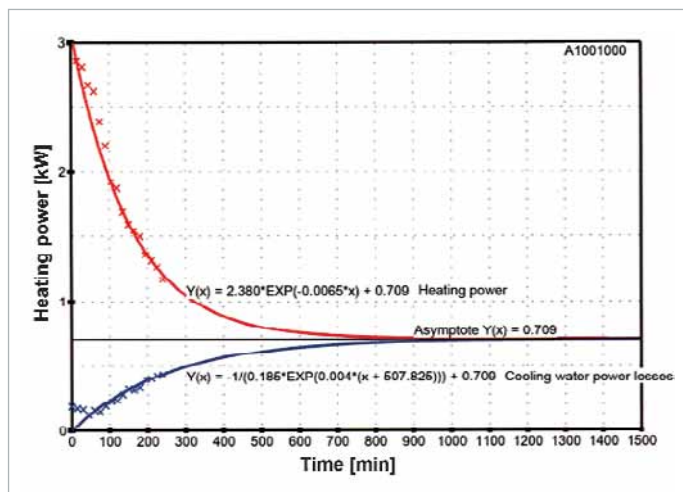
- Vacuum better than $5 \cdot 10^{-3}$ mbar
- Air: normal pressure, 10 bar, 25 bar, 50 bar, 75 bar and 100 bar
- Argon: normal pressure, 10 bar, 25 bar, 50 bar, 75 bar and 100 bar

The following temperatures were measured:

- Chamber (thermocouple 2)
- Center of insulation (thermocouple 3)
- Inner surface of pressure vessel (thermocouple 4)

Furthermore the following values were measured:

Fig. 9: Measurement curve for 1000 °C final temperature under 100 bar argon atmosphere



- Vacuum pressure (only in experiments under vacuum)
- Heating power
- Cooling water flow
- Cooling water inlet and outlet temperature

Furthermore the temperature uniformity inside the chamber was determined using ceramic rings (diameter app. 25 mm). These rings consist of ceramic materials and they are available for different temperature ranges from nearly 1000 °C up to app. 1800 °C. This temperature measurement is based on the fact that the rings shrink depending on the maximum achieved temperature. After measuring the final ring diameter, the corresponding temperature can be found in the tables of the rings' manufacturer. However, the rings should be placed on fine aluminium oxide powder in order to reduce friction which can falsify the measurement. Furthermore such an experiment is only reliable, when the furnace temperature was held constant for at least three hours. **Fig. 8** shows the arrangement inside the furnace chamber

where all rings were positioned at the half height. Thus the investigation of the temperature uniformity was only done in one horizontal plane.

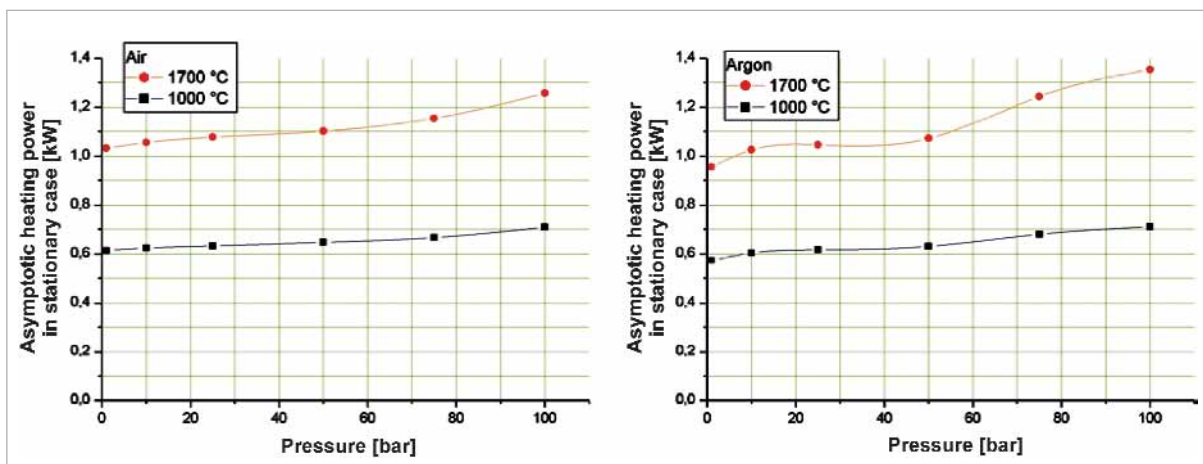
Dependence of the heating capacity on pressure and temperature

For every combination of gas, pressure and temperature the heating curve is plotted. Because the furnace requires much time for reaching the final temperature (heating power around 5 kW), the theoretical heating power is calculated by extrapolation. **Fig. 9** shows the heating power and the required water cooling power over time (example for 1000 °C final temperature under 100 bar argon pressure).

After four hours the measurement was stopped and the power values for the stationary state were calculated by extrapolation. The cooling water power losses can be calculated from the temperature difference between inlet and outlet and the constant water flow.

The asymptotic value of the heating power is not equivalent to the real value,

Fig. 10: The stationary heating power levels, calculated by extrapolation, depending on pressure for air (left) and argon (right)



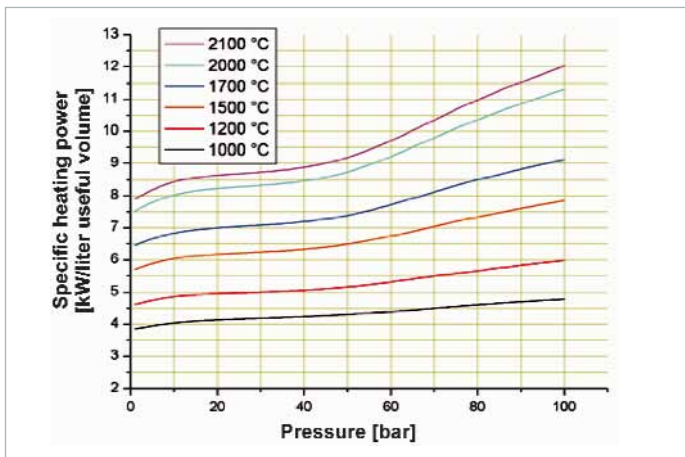


Fig. 11: Group of curves for dimensioning the power of high temperature furnaces at pressures up to 100 bar under air or argon atmosphere

which has to be installed by the furnace manufacturer. However, the user can determine relative heating power levels depending on atmosphere, pressure and final temperature. The detected asymptotic heating power values for the stationary case are plotted as a function of the pressure (Fig. 10).

As the results of air and argon do not differ much, the following analysis is only done for argon, where the required power is maximum 10 % more than for air.

The investigations were only done for the temperatures 1000 °C and 1700 °C. However the product range of Linn High Therm goes up to 2100 °C. Higher temperatures could only be realized with other insulation materials and heaters. Because the thermal conductivity differs from those which were used here, the results cannot be transferred easily.

With constant pressure for the interpolation between 1000 °C and 1700 °C and

for the extrapolation to 2100 °C approximately a polynomial function of third degree can be assumed. For every pressure three measuring points are taken (0 kW for room temperature and the measured values for 1000 °C and 1700 °C) for the interpolation with a polynomial of third degree.

In order to transfer the results to other furnace chamber sizes it is useful to use the specific power, the power per liter useful volume, instead of the absolute power. In the last step finally the conversion of the stationary power to the real installed power is done. However, this is not easy to do by only using the measured data; here the long experience in furnace building is a great advantage. As reference, the fact is used, that a specific power between app. 12 and 15 kW is required, if 2100 °C maximum temperature has to be reached within two hours at a pressure of 100 bar. Fig. 11 shows the thus calculated group of curves.

These curves only may be transferred to high pressure furnaces of the same type, this means the thickness of all insulation layers and the type of material may not differ essentially in their thermal conductivity (also depending on the temperature).

The shape of the curves can be explained by the dependence of the thermal conductivity on pressure. Obviously the applied insulation materials have approximately a constant pore size, thus the curve in Fig. 4 can be transferred directly to the above mentioned group of curves. First the thermal conductivity increases ($Kn \geq 1$), thus the required power also increases in the same way. This corresponds to the range up to 80 bar. At higher pressures the Knudsen number decreases to 1, which explains why up to 100 bar the group of curves flattens out.

More values were measured in vacuum operation: The same calculation of the specific heating power and the same calibration were done as in the high pressure operation. As a result it can be stated that the required power is only 2/3 of the value in normal pressure operation (1 bar). Fig. 12 shows the comparison of the specific power between vacuum mode and normal pressure mode for the temperature range from 1000 °C to 1700 °C. This behaviour can also be explained by the linear increase of the Knudsen number at lower pressures – a reduction of the pressure down to 10^{-3} mbar causes a reduction of the thermal conductivity in accordance with Fig. 4. Also in Reference [6] it is mentioned that the thermal conductivity in vacuum is only app. 70 % of the value at normal pressure.

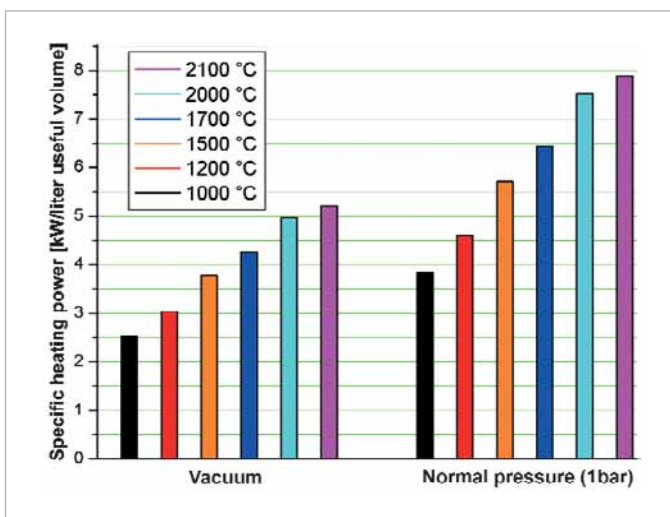


Fig. 12: Rough specific power values for dimensioning of high temperature furnaces under vacuum

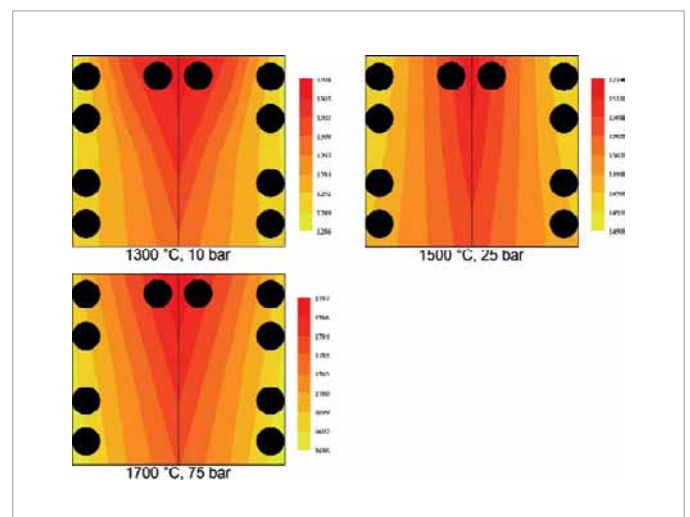


Fig 13: Temperature distribution inside the furnace chamber, viewed from above

Temperature uniformity

In air the temperature uniformity was investigated by using ceramic rings, in order to detect the influence of the pressure on temperature homogeneity. This is a very important fact, because there is an increasing market demand for a uniformity better than ± 10 K, this means between the hottest and coldest point inside the chamber a maximum difference of 20 K is allowed. The installation of many thermocouples in such a small furnace chamber is too difficult. Therefore, the ceramic rings are used. **Fig. 13** shows the temperature distribution for the ranges 1300 °C to 1700 °C and 10 bar to 75 bar.

The cross sections of the heating elements are shown in black colour. It can be clearly recognized that the temperature has a maximum at the backside because of the additional heater. When pressure and temperature are increased, the accuracy is improved. At 1700 °C and 75 bar the maximum difference is 11 K, while at 1300 °C and 10 bar 22 K difference are observed. This can be explained by improved thermal conductivity at higher pressures and temperatures (Fig. 4). Finally an accuracy of approx. ± 10 K could be obtained for this furnace, if it is operated under nitrogen or air. Measurements under argon atmosphere were not carried out. However, a higher temperature difference is expected because of the lower thermal conductivity of argon ($0.017 \text{ W / m} \cdot \text{K}$) in comparison to air or nitrogen ($0.026 \text{ W / m} \cdot \text{K}$, both values at room temperature).

For each atmosphere the temperature uniformity could be optimized by an additional heater at the front side, however charging would become more difficult.

Conclusion

The general aim of these experiments was the investigation of the relationship between the effective thermal conduc-

Fig. 14: "Rubistar Special" in toploader design. On the left side is the water cooling system



tivity of porous insulation materials and different operational factors such as temperature, gas atmosphere and pressure. General guidelines, how to install the correct heating power depending on the mentioned parameters, were formulated using a high pressure furnace. This will make it much easier to correctly design similar furnace types, because until now no reliable layout data were available. Under- and overdimensioning of the heating power were often the consequence.

Furthermore it can be stated that the temperature accuracy of ± 10 K will be attainable. Better uniformity will require optimization of the heating elements' arrangement and/or modification of the basic furnace design, e. g. top or bottom loading instead of front loading.

The described measurements generated useful knowledge for the design of a 60 bar high pressure furnace for 2000 °C maximum temperature under nitrogen or argon atmosphere (**Fig. 14**). A better temperature accuracy (lower than ± 10 K) was the result of the design as a top loader with heating elements installed

along the cylindrical perimeter. In order to reduce heat up time (app. 45 minutes), 60 kW heating power was installed for 5 liters useful volume in combination with graphite fibre insulation. This corresponds to 12 kW/liter, whereas the above described theory yielded 9,5 kW/liter. Although the graphite fibre insulation is highly effective, a water cooling power of 17 kW is required, as was shown in experiments.

Literature

- [1] Schulle W. Feuerfeste Werkstoffe - 1. Edition, Leipzig, 1990
- [2] Euken A. Die Wärmeleitfähigkeit keramischer feuerfester Stoffe, Forschung auf dem Gebiet des Ingenieurwesens, Berlin 83 (1932) 3/4, VDI report 353
- [3] Kittel C. Einführung in die Festkörperphysik, Oldenburg, München, 1973
- [4] Dubbel H. Taschenbuch für den Maschinenbau, Springer-Verlag, Berlin, 1993
- [5] VDI Wärmeatlas. Berechnungsblätter für den Wärmeübergang, 8. Edition, Springer-Verlag, Berlin, 1997
- [6] Baems M., Hofmann H., Renken A., Chemische Reaktionstechnik, Band 1, 2. Edition, Georg-Thieme-Verlag Stuttgart 1992
- [7] Handbook of Thermoprocessing Technologies. A. von Starck, A. Mühlbauer, C. Kramer, Vulkan Verlag, Essen, 2005