Multi-Physical Simulation Based Analysis of Temperature Homogeneity in Vertical High Temperature Vacuum Furnaces

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Abstract
In the development of refractory metal hot zones for high temperature vacuum furnaces at PLANSEE SE a multi-physical model was applied for a detailed analysis of the influence of different heater configurations and gas system concepts on achievable temperature homogeneity and power consumption. The thermo-electric model allows a more accurate evaluation of temperature homogeneity than the current standard measurement procedure. The simulation results show that temperature homogeneity of vertical high temperature vacuum furnaces can be significantly improved by additional top and bottom heaters. Comparable temperature homogeneity can be achieved with the so-called "FlowBox"-concept developed at PLANSEE SE, without additional heaters at a significantly reduced power consumption.

Keywords: thermo-electric simulation, high temperature vacuum furnace, temperature homogeneity, energy efficiency.

Introduction
Temperature homogeneity is a critical issue for high temperature vacuum furnaces for heat treatment, as small temperature variations in the load volume can significantly influence the heat treatment result. It is generally defined by the so-called Temperature Uniformity Survey (TUS) measurement procedure described in Aerospace Material Specification (AMS) 2750. At this, depending on the size and geometry of the load volume, temperature is measured at dedicated positions with a defined number of thermocouples. For work zone volumes between 0.085 and 6.4 m³ AMS 2750 suggests a minimum number of nine sensors. Three should be located at the periphery of each end, one at the approximate center and the other two to best represent the qualified work zone [1].

In the development of refractory metal hot zones for high temperature vacuum furnaces at PLANSEE SE, multi-physical simulations are used as a tool for the optimization and evaluation of the influence of new design concepts on the hot zone's performance. In [2] thermo-electric and thermo-fluid dynamic simulations were applied to optimize horizontal high temperature furnaces with respect to energy efficiency, temperature homogeneity and fast cooling performance.

Numerical Model
In the following a thermo-electric model is applied for a detailed analysis of the influence of different heater configurations and gas system concepts on power consumption and achievable temperature homogeneity of a vertical high temperature vacuum furnace with a cylindrical load volume. It considers electric heating, heat transfer, surface to surface radiation and convective cooling. Figure 1 shows the model geometry, the major components of the vertical high temperature vacuum furnace and the considered physics. The shielding consists of 7 shielding layers (1 x molybdenum-lanthanum-oxide, 5 x molybdenum, 1 x steel). The gas system for fast cooling consists of sixty gas inlet nozzles in the side shielding and a gas outlet in the top shielding. The heating system has got three heating zones on the side and optional top and bottom heaters that are controlled by control thermocouples. The load is placed on a load carrier. The whole hot zone is placed inside a water-cooled containment.

The 3D stationary thermo-electric model was built with Comsol Multiphysics 6.2. It is based on the heat transfer and AC/DC module. Thin sheet structures are modelled as shells. Heat transfer is described by the stationary heat equation

$$-\vec{\nabla} \cdot k\vec{\nabla}T = Q_{rad} + Q_{ecis}$$

in the heat transfer in solids and heat transfer in shells interface with the temperature T, heat conductivity k and heat sources Q_{rad} for radiative heat transfer as well as Q_{ecis} for Joule heating.
The power transported by radiative heat transfer is described by the Stefan-Boltzmann law

$$P_{rad} = A\varepsilon\sigma T^4$$

with the temperature T, the surface area A, the emissivity ε and the Stefan-Boltzmann constant σ. It acts as a boundary heat source Q_{rad} on the surfaces of the domains and shells.
The power input by Joule heating is described by Joule's law

$$P_{ecis} = RI^2$$

with the resistance R and electric current I. It acts as a volume heat source Q_{ecis} in the shells of the heaters. The voltage at the heaters of the heating zones is controlled by the temperature of dedicated control thermocouples using global equations. The model tree of the thermo-electric model is shown in Figure 2.

The geometry of the furnace is built of fully parametrized parts. Symmetry in two orthogonal vertical planes is considered. Physics and mesh are controlled by selections. A Java-method is used to activate physics for optional components in a parameter sweep. Figure 3 shows the meshed geometry. It consists of 20,810 elements.

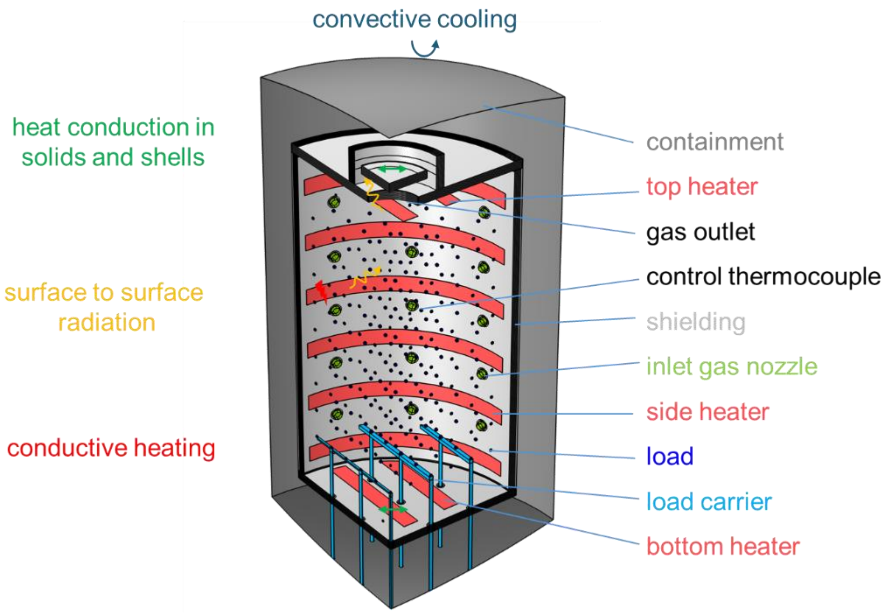

Figure 1 Multi-physical thermo-electric model of a vertical high temperature vacuum furnace.

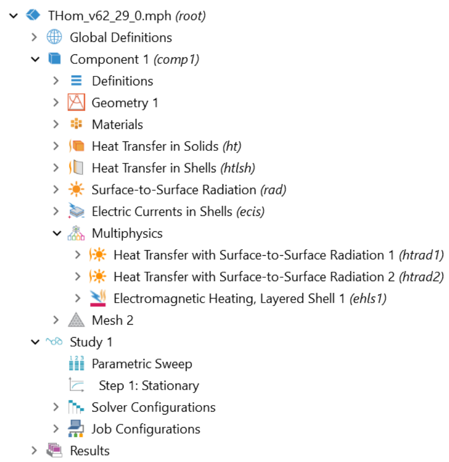

Figure 2 Model tree of thermo-electric model of a vertical high temperature vacuum furnace.

Based on the model a detailed analysis of the potential of a top and bottom heater for an improved temperature homogeneity of a vertical high temperature vacuum furnace with a cylindrical load volume with 1500 mm diameter and 1500 mm height and a classical gas system was performed. In addition to that the potential of the “FlowBox”-concept [3], a gas permeable multilayer structure shielding thermal radiation for the top gas outlet developed at PLANSEE SE, was evaluated.

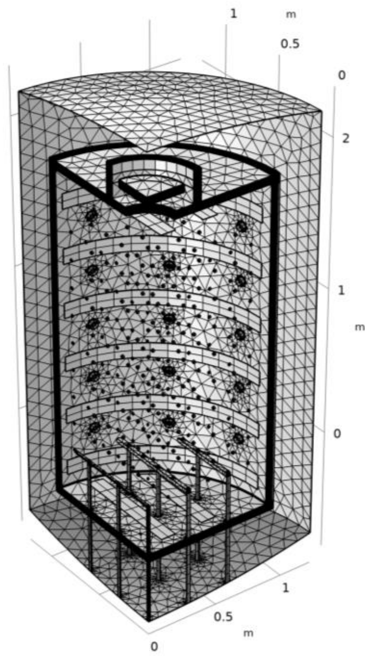

Figure 3 Mesh of thermo-electric model of a vertical high temperature vacuum furnace.

Figure 4 a shows the classical top gas outlet, Figure 4 b the “FlowBox”-concept. At this, temperature homogeneity was analysed by evaluating the maximum temperature difference in the load volume in two different ways. Firstly, according to the TUS measurement procedure [1] that is generally applied when determining the temperature homogeneity experimentally. Hereby, due to the two-plane symmetry of the model, in each case four measurement points were positioned at the circumference of the bottom and top end of the load volume as well as 3 measurement points on the bottom, centre and top of the axis. Secondly, a highly resolved measurement configuration with measurement points evenly distributed along the load volume, with positions at the levels of and between the heating rings, as well as the load carrier rails. Furthermore, the power consumption of the furnace was evaluated. At this, in the following the power consumption of the analysed quarter furnace is given. To obtain the power consumption of the full furnace the given values need to be multiplied by a factor of four (see Table 1).

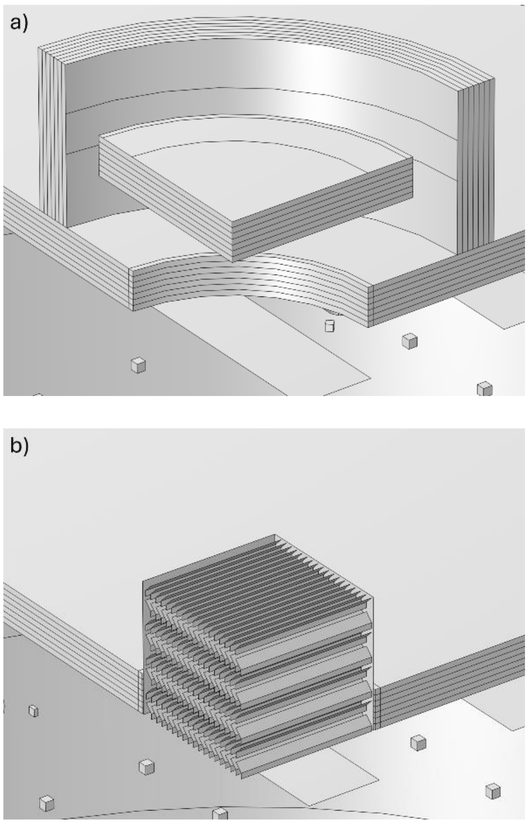

Figure 4 Gas outlet concepts: a) classical gas system; b) “FlowBox”-concept.

Simulation Results

Based on the thermo-electric model a detailed analysis of the potential of top and bottom heaters as well as of the “FlowBox”-concept for an improved temperature homogeneity and a reduced power consumption was performed. The simulation results for the five regarded configurations with different gas system and heating configurations as well as different evaluation procedures for the temperature homogeneity are summarized in Table 1 for an operation temperature of 1200 °C. The results demonstrate the limitations of the TUS measurement procedure for an objective evaluation of the temperature homogeneity of high temperature vacuum furnaces. Cold and hot spots in the load volume cannot be reliably detected with the limited amount of measurement points. The maximum temperature difference in the load volume evaluated by the TUS procedure is smaller than in the highly resolved measurement.

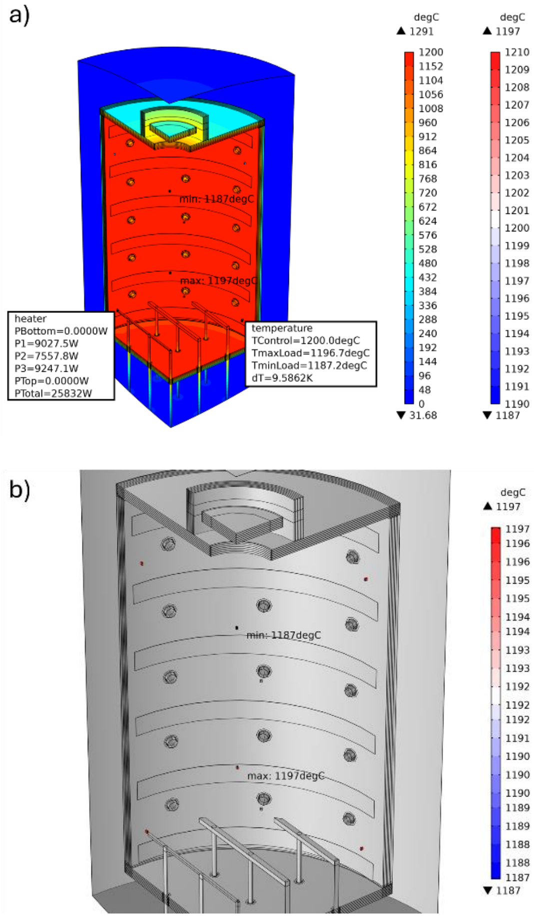

Figure 5 Power consumption and TUS temperature homogeneity (a) as well as temperature distribution in the load (b) of a vertical high temperature vacuum furnace with a classical vertical gas system (configuration 1).

Figure 5 and Figure 6 show the calculated temperature variations in a high temperature vacuum furnace with TUS (configuration 1) and highly resolved (configuration 2) measurement. In both cases the temperature minimum of the load is located in the region of the top gas outlet. Whereas the TUS measurement delivers a maximum temperature difference of 10 K in the load volume, the highly resolved measurement delivers a more realistic maximum temperature difference of 13 K, as the local temperature maximum close to the heater is detected. I.e., the thermo-electric model allows a more accurate evaluation of temperature homogeneity than the current standard measurement procedure.

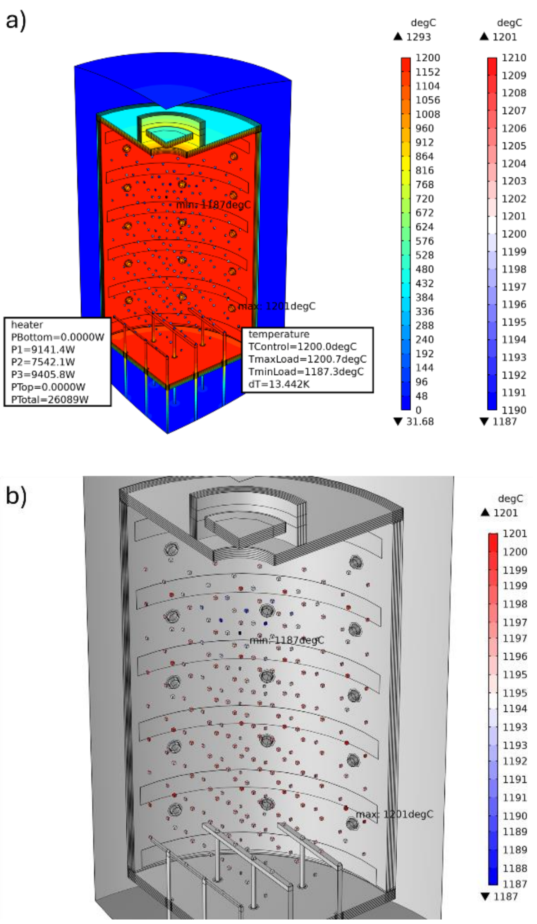

Figure 6 Power consumption and highly resolved temperature homogeneity (a) as well as temperature distribution in the load (b) of a vertical high temperature vacuum furnace with a classical gas system (configuration 2).

Additional top and bottom heaters (configuration 3) can help to reduce the cold spots induced by load carrier and top gas outlet, however at the price of an increased power consumption (see Figure 7). The maximum temperature difference decreases to 8 K. Additional top and bottom heaters lead to reduced heating powers in the top and bottom side heaters. However, the total required heating power slightly increases by 2 %.

A corresponding maximum temperature difference in the load volume of 8 K can be achieved with the "FlowBox"-concept (configuration 4), without additional heaters at a significantly reduced power consumption (see Figure 8). Power consumption decreases by 8 % compared to the configuration with additional top and bottom heater at a corresponding maximum temperature difference of 8 K in the load volume. With additional top and bottom heaters (configuration 5), a further improvement to 5 K is possible with a smaller decrease of 6 % in power consumption (see Figure 9).

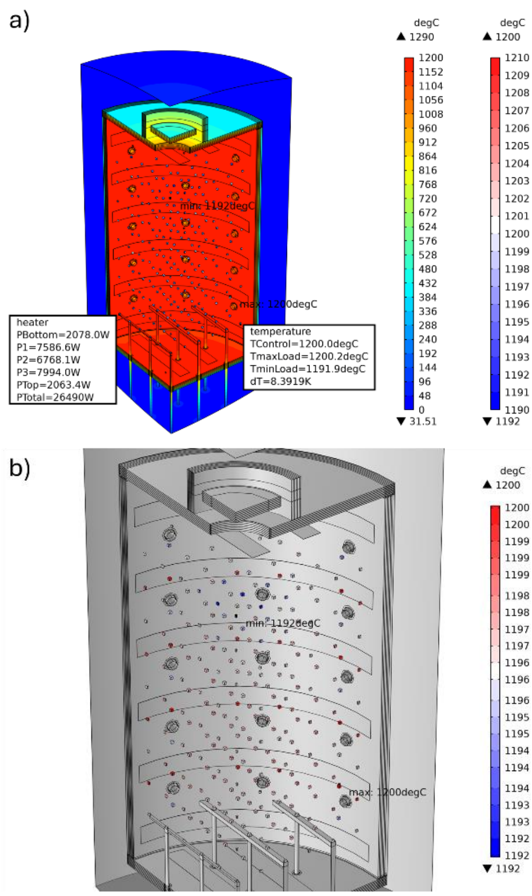

Figure 7 Power consumption and highly resolved temperature homogeneity (a) as well as temperature distribution in the load (b) of a vertical high temperature vacuum furnace with a classical gas system and additional top and bottom heaters (configuration 3).

Conclusions

Multi-physical thermo-electric models are a valuable tool for the optimization of high temperature vacuum furnaces and the evaluation of new design concepts. In this case, they allow a more accurate evaluation of temperature homogeneity than current standard measurement procedures. Temperature homogeneity of a vertical high temperature vacuum furnace can be improved by additional top and bottom heaters at a slightly increased power consumption. The "FlowBox"-concept allows a comparable or even improved temperature homogeneity at a significantly reduced power consumption.

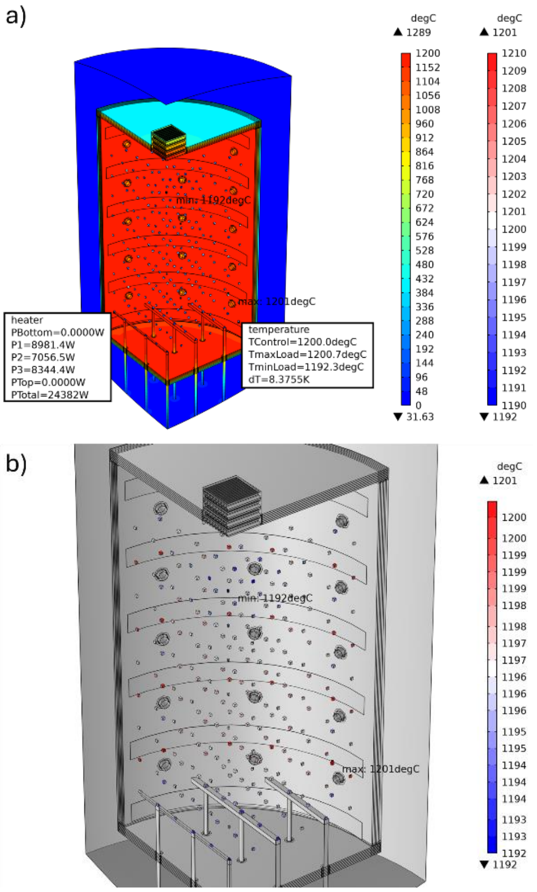

Figure 8 Power consumption and highly resolved temperature homogeneity (a) as well as temperature distribution in the load (b) of a vertical high temperature vacuum furnace with a "FlowBox" (configuration 4).

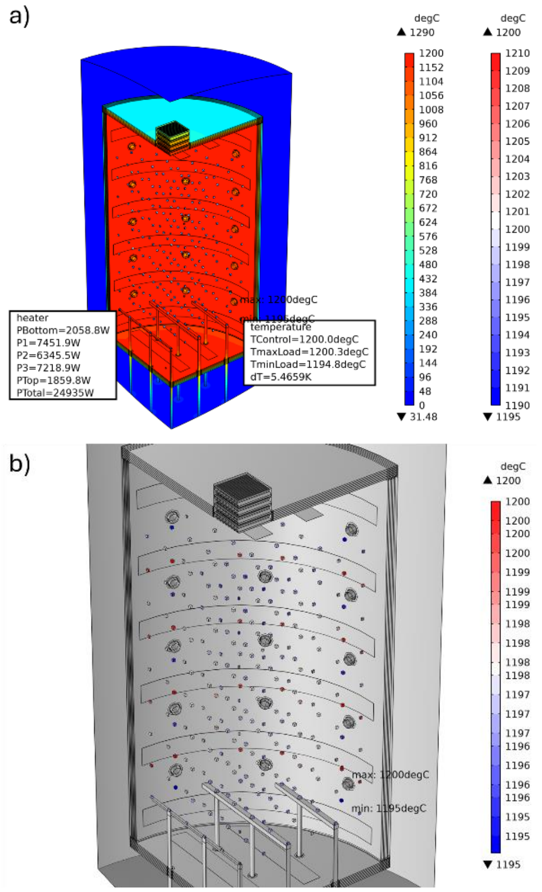

Figure 9 Power consumption and highly resolved temperature homogeneity (a) as well as temperature distribution in the load (b) of a vertical high temperature vacuum furnace with a "FlowBox" and additional top and bottom heaters (configuration 5).

configuration	gas system	top heater	bottom heater	temperature homogeneity	dT [K]	P_{total} [kW]
1	classical	no	no	TUS	10	103
2	classical	no	no	highly resolved	13	104
3	classical	yes	yes	highly resolved	8	106
4	FlowBox	no	no	highly resolved	8	98
5	FlowBox	yes	yes	highly resolved	5	100

Table 1 Maximum temperature difference dT in load volume analysed by different methods and power consumption for different gas and heating system configurations at an operation temperature of 1200 °C. The mentioned powers refer to the full furnace.

References

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