

Multi-physical simulation based optimization of the next generation of energy efficient high temperature vacuum furnaces

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Abstract

Multi-physical simulations are a valuable tool for the development and optimization of high temperature vacuum furnaces for heat treatment. Based on thermo-electric and thermo-fluid dynamic simulations at PLANSEE SE new concepts for the rear gas outlet and the gas nozzles of the fast cooling gas system were evaluated and optimized with respect to energy efficiency, temperature homogeneity and fast cooling performance. At this, at the price of a moderately reduced fast cooling performance, the power consumption of the next generation of PLANSEE refractory metal hotzones could be reduced by 15 % in combination with a significantly improved temperature homogeneity.

Keywords: thermo-electric model, thermo-fluid dynamic model, high temperature vacuum furnace, gas system, fast cooling, energy efficiency, temperature homogeneity.

Introduction

To achieve the goals of the Paris Agreement [1] and limit global warming below 2 K compared to pre-industrial level, significant energy savings in all fields of industries will be required. One example of energy intensive processes in industrial fabrication is heat treatment. The applied high temperature vacuum furnaces are generally equipped with a fast cooling system and offer a big potential for energy savings, as they typically have operation powers of several hundred kilowatts and process times can go up to more than 24 hours. Assuming an average power consumption of 100 kW over 200 days¹ a year, the annual power consumption of one single high temperature vacuum furnace is 480000 kWh. This equates the annual electric power consumption of 200 average households².

Numerical Models

In the development of energy efficient refractory metal hotzones for high temperature vacuum

furnaces at PLANSEE SE, multi-physical simulations are a tool for the identification of major sources of energy losses and the evaluation of the influence of new design concepts on the performance of the furnaces. Multi-physical models are applied for an optimization of high temperature vacuum furnaces with respect to energy efficiency, temperature homogeneity and fast cooling performance. For the analysis of the heating process in vacuum, a thermo-electric model is applied. A thermo-fluid dynamic model is used for an analysis of the fast cooling process with gas atmosphere.

Thermo-electric model

A 3D transient thermo-electric model of a full high temperature vacuum furnace, based on the heat transfer [2] and AC/DC [3] module of Comsol Multiphysics 6.1 [4], allows an analysis of its power consumption, the thermal loading of the furnace components as well as of the temperature in the load. It considers electric heating, heat transfer in solids, surface to surface radiation and convective cooling of the containment.

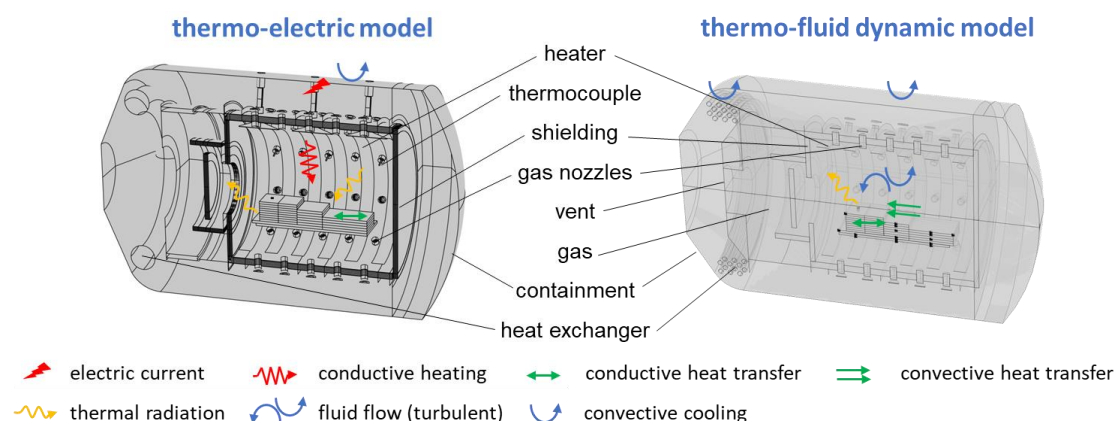


Figure 1. Thermo-electric and thermo-fluid dynamic models for a high temperature vacuum furnace with fast cooling system.

¹ 24 h per day run time.

² Assumed annual consumption of 2400 kWh.

In order to reduce the model size only half of the furnace is modelled, and respective symmetry boundary conditions are applied. Based on a temperature control curve, the heater voltages necessary to achieve a prescribed temperature at three control thermocouples are calculated based on global equations. Thin structures like the heating bands, ribs of the support structure, gas guidance shields, nozzle tubes and the containment wall are modelled as shells in order to limit the element number. Furthermore, in order to limit the computational effort for surface to surface radiation, the shielding structure consisting of a stack of sheets is modelled as a multi-layer solid with radiative gap conductance between the layers and surface to surface radiation at the exterior faces. Cooling of the containment is modelled by a convective heat flux. Figure 1 shows the geometry of the thermo-electric model for a high temperature vacuum furnace with its major components and the included physics.

Thermo-fluid dynamic model

For the evaluation of the cooling performance of the furnace, a 3D transient thermo-fluid dynamic model is applied. It is based on the heat transfer [2] and CFD [5] module and considers heat transfer in gas and solids, turbulent fluid flow, surface to surface radiation and convective cooling. It uses a similar geometry and model setup as the thermo-electric model. Gaps in the shielding as well as radiative heat transfer between the layers of the shielding are neglected and the shielding is modelled as a homogeneous solid with reduced density and heat conductivity. The calculation starts from a fixed temperature level of 1200 °C inside the hotzone, linearly decaying over the shielding to 500 °C at the support structure and 20 °C at the containment wall. Besides heat transfer in solids and shells as well as surface to surface radiation, heat transfer in and energy transport by the gas phase are taken into account. The gas flow inside the furnace is calculated based on a compressible gas description with a RANS L-VEL turbulence model. It is induced by a fan with a pressure, temperature and rotation speed dependent characteristic curve. Both the containment wall as well as the heat exchanger in the form of a bundle of ring tubes at the rear of the furnace are cooled by a convective heat flux. Constant pressure in the system is assured by a gas inlet. Between the sheets of the load thermal contact is taken into account. Figure 1 shows the geometry of the thermo-fluid dynamic model as well as the included physics.

The thermo-electric and thermo-fluid dynamic models were applied for simulation of heating and cooling cycles with a high temperature vacuum furnace equipped with a PLANSEE refractory metal hotzone. Material data for the single components was taken from [6] and the Comsol Material Library [7].

Submodels

Apart from that, based on the previously described models, submodels of the rear gas outlet and the gas nozzles were applied for a more detailed analysis and optimization of those components. At this the shielding structure was fully resolved by shells and thin layers, respectively.

Simulation Results

The multi-physical models were applied for a detailed analysis and optimization of a high temperature vacuum furnace with a refractory metal hotzone and its components with respect to power consumption, temperature homogeneity and fast cooling performance.

Temperature evolution and power consumption

In a first step, based on the thermo-electric model heating of a 600 kg molybdenum load in a high temperature vacuum furnace equipped with a PLANSEE Premium 2022 refractory metal hot zone [8] with 7 shielding layers (1 x molybdenum-lanthanum-oxide, 5 x molybdenum, 1 x steel) and a usable space of 600 mm x 600 mm x 900 mm was regarded. The gas system for fast cooling consists of 50 gas nozzles of 50 mm diameter aligned in 5 rings with 10 nozzles and a rear gas outlet with a central hole, a set back shielding disk and a surrounding cylindrical shielding. The regarded heating cycle had heating rates of 15 K/min and dwell times at 1200 °C and 1600 °C.

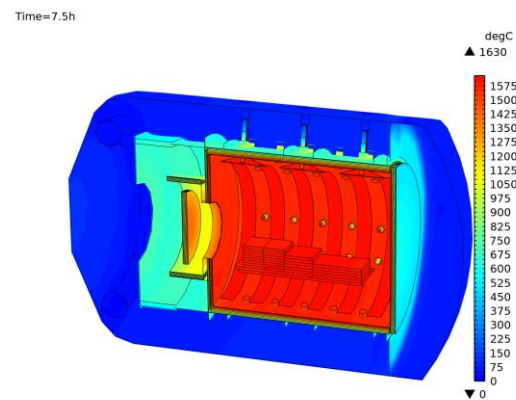


Figure 2. Temperature distribution in a high temperature vacuum furnace with 600 kg molybdenum load at the end of a 1600 °C heating cycle.

Figure 2 shows the temperature distribution in load and furnace at the end of a 1600 °C heating cycle. The control temperature and heating power of the furnace are shown in Figure 3. The calculated power consumption of the furnace is 64 kW during stationary operation at 1200 °C and 186 kW at 1600 °C.

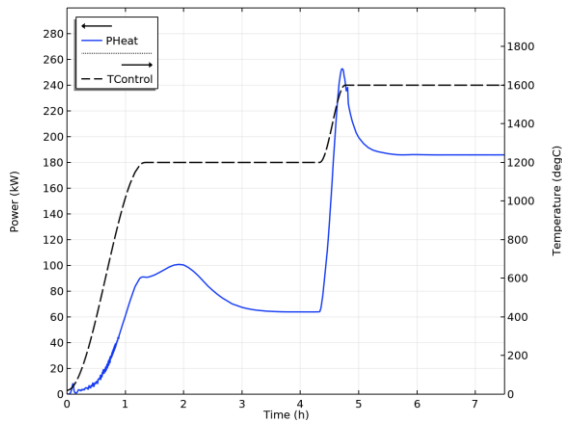


Figure 3. Control temperature and calculated heating power of a high temperature vacuum furnace with 600 kg molybdenum load during heating cycle.

Fast cooling

In a second step, the thermo-fluid dynamic model was applied to analyze the fast cooling performance of the high temperature vacuum furnace. At this fast cooling of a 600 kg molybdenum load from an initial temperature of 1200 °C with Argon at a pressure of 4 bar and a fan rotation frequency of 3000 min⁻¹ was regarded. The back fan induces a gas flow entering the hotzone through the gas nozzles and leaving it through the rear gas outlet. Figure 4 shows the temperature distribution in gas, load and shielding after 300 s.

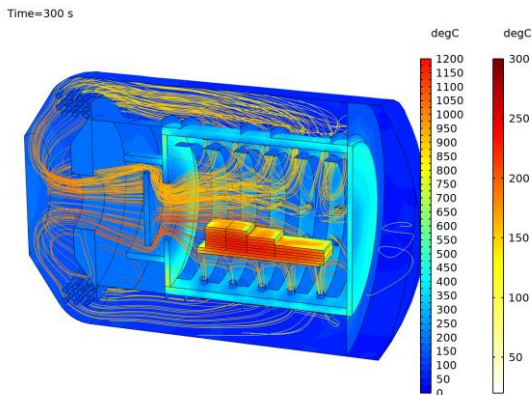


Figure 4. Temperature of solid furnace components (left legend) and gas atmosphere (right legend) during fast cooling of a 600 kg molybdenum load from an initial temperature of 1200 °C.

The temperature in the front, mid and rear stack of the load during cooling is shown in Figure 5. It takes more than 50 minutes until the temperature in the center of each load stack is below 200 °C. Cooling rate in the front and rear stack is higher than in the central one.

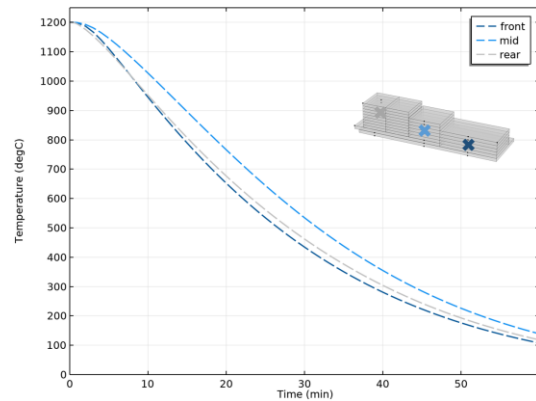


Figure 5 Fast cooling (Argon, 4 bar, 3000 min⁻¹) of a 600 kg molybdenum load from an initial temperature of 1200 °C.

Based on the thermo-electric and the thermo-fluid dynamic model a detailed analysis of the power consumption and fast cooling efficiency of a high temperature vacuum furnace with a PLANSEE Premium 2022 refractory metal hotzone was performed. Those results were discussed in detail in [9, 10]. It was found that the rear gas outlet and gas nozzles of the gas system are major sources of energy losses and that by a reduction of the cross section of the gas system energy savings of up to 20 % become feasible, without significantly losing cooling efficiency.

Gas system optimization

On this basis, the thermo-electric and thermo-fluid dynamic models were applied for a more detailed analysis of the two major components of the gas system, the rear gas outlet and the gas nozzles. Emanating from the PLANSEE Premium 2022 refractory metal hotzone design, new concepts for rear gas outlet and gas nozzles were developed and evaluated with respect to energy efficiency, temperature homogeneity and fast cooling performance.

In a first step, the potential of a gas permeable cassette with eight layers of beveled fins, a so called “flowbox”, for the rear gas outlet was evaluated with respect to power consumption and temperature homogeneity in the load volume. The new gas outlet was designed to effectively shield thermal radiation at a low resistance for the cooling gas flow. For its evaluation a modified version of the thermo-electric model was applied. The stationary model fully resolves the shielding by shells and takes into account the load carrier. Gas nozzles were neglected in order to reduce computation time. Temperature homogeneity was analyzed in small solid blocks evenly distributed in the load volume. Figure 6 shows the calculated power consumption and temperature distribution in the load volume for the PLANSEE Premium 2022 hotzone design. The calculated power consumption is 39 kW. This value is lower compared to the previous results as gas nozzles were not taken into account. The maximum temperature difference in

the load volume (represented by the small solid blocks) is 19 K.

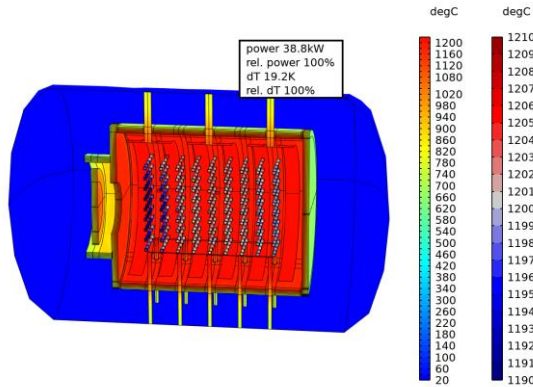


Figure 6. Temperature in furnace (left legend) and load volume (right legend) as well as power consumption of a high temperature vacuum furnace with old gas outlet design.

Figure 7 shows the corresponding results for the new concept for the rear gas outlet. It becomes obvious that with the “flowbox” temperature homogeneity in the load volume can be significantly improved. Maximum temperature difference reduces by 65 % to 7 K. In addition to that power consumption is reduced by 15 % to 33 kW.

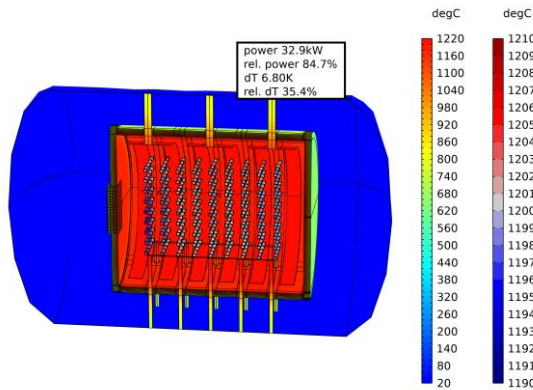


Figure 7. Temperature in furnace (left legend) and load volume (right legend) as well as power consumption of a high temperature vacuum furnace with new gas outlet design.

In a second step the influence of the new permeable “flowbox” on the fast cooling efficiency was evaluated. At this, a reduced 2D version of the thermo-fluid dynamic model, taking into account only the rear wall, was applied in order to allow sufficient resolution of the gas flow through the channels between the fins. Dimensions and depth of rear shielding, “flowbox” and fan were scaled according to the real 3D rear wall module. Based on a stationary thermal calculation the losses were calculated for an operation temperature of 1600 °C. The analysis of the flow was based on a 2D transient thermo-fluid dynamic calculation at 20 °C.

The results for the old gas outlet design are shown in Figure 8. The losses are 28 kW and the mass flow rate is 18 kg/s.

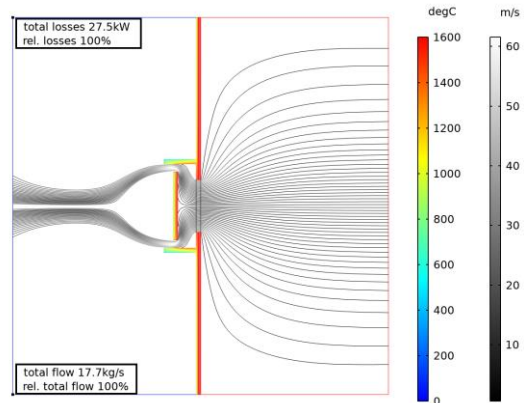


Figure 8. Shielding efficiency and cooling gas flow of old gas outlet design.

As already known from the temperature homogeneity calculations, the power losses with the new gas outlet design are significantly reduced (see Figure 9). With 19 kW they are 32 % lower, however at the price of a 25 % lower cooling gas mass flow rate of 13 kg/s.

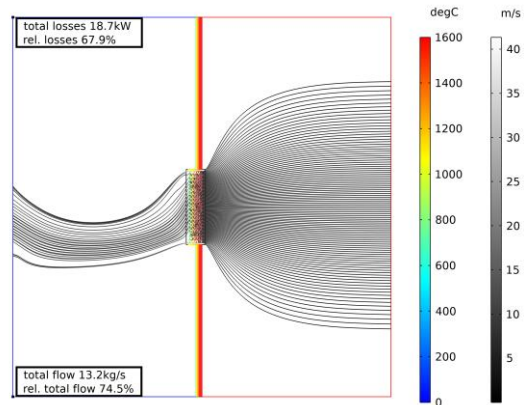


Figure 9. Shielding efficiency and cooling gas flow of new gas outlet design.

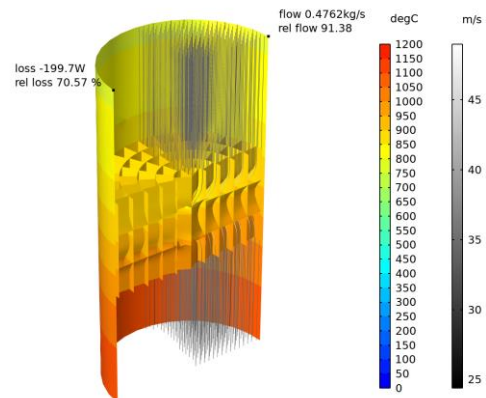


Figure 10. Shielding efficiency and flow resistance of gas nozzle with insert compared to one without.

As the second part of the gas system, the gas nozzles were regarded. Here a similar approach as for the rear gas outlet was followed. In order to reduce thermal radiation losses through the gas nozzle at still low flow resistance, a grid structure of sinusoidal channels was designed (see Figure 10) as an insert for the gas nozzles with a diameter of 50 mm. Based on the thermo-fluid dynamic model stationary calculations of thermal losses as well as of the gas flow at 20 °C were performed. At this, the walls were modelled as shells.

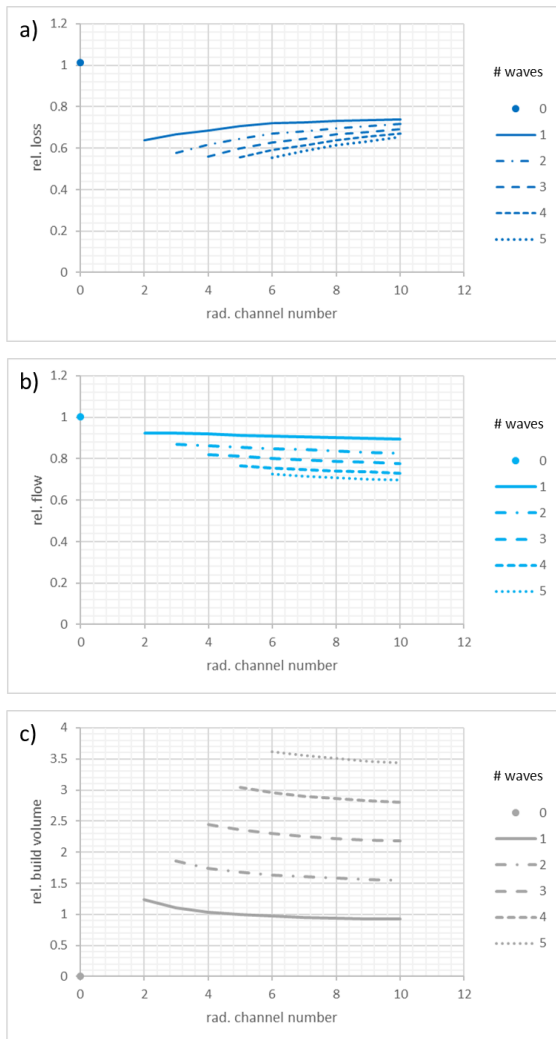


Figure 11. Geometry optimization of gas nozzle inserts: a) relative energy loss; b) relative mass flow; relative build volume.

The gas nozzle insert design was optimized with respect to shielding efficiency and flow resistance. At this the number of channels in radial direction as well as the number of sinusoidal waves in axial direction were varied with respect to power losses, flow resistance and part volume. Part volume was evaluated, because this design needs to be fabricated by additive manufacturing, where part costs in general correlate with the build volume. The results are shown in Figure 11. Based on this analysis a design with 5 radial channels with one sinusoidal wave in axial direction was chosen. This design reduces the power losses at 1200 °C by 29 %

at a moderately reduced gas flow and low building costs (see Figure 10).

Experimental Validation

Based on the previously presented results of multi-physical calculations, the next generation of PLANSEE refractory metal hotzones was realized and tested in a high temperature vacuum furnace at PLANSEE SE in Reutte, Austria. Figure 12 shows the furnace equipped with a rear shielding with the new “flowbox” and gas nozzles with gas nozzle inserts. The gas nozzle inserts were additively manufactured by laser powder bed fusion of molybdenum (see Figure 13). Rear gas outlet and gas nozzle inserts have been filed for patent. In this furnace, a series of experiments was performed in order to validate the developed multi-physical models for high temperature vacuum furnaces and to characterize the next generation of PLANSEE refractory metal hotzones with respect to temperature homogeneity, cooling efficiency and power consumption.



Figure 12. Test furnace with next generation of PLANSEE refractory metal hotzone equipped with “flowbox” and gas nozzle inserts [11].

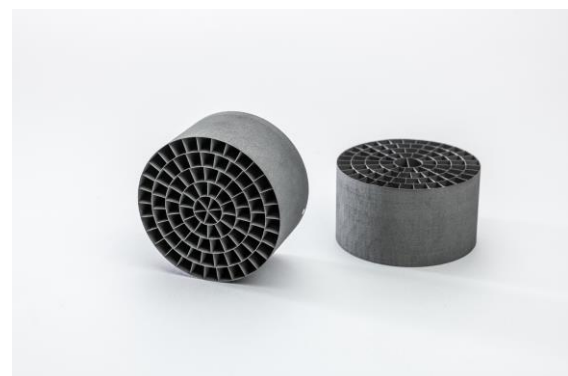


Figure 13. Additively manufactured molybdenum gas nozzle inserts for a high temperature vacuum furnaces.

Temperature homogeneity

Figure 14 shows the measured temperature distribution in the load volume during stationary operation at 1200 °C. With the newly developed components, temperature differences in the load

volume could be significantly reduced from 23 K to 8 K (see Figure 14). Those values only slightly deviate from the calculated values of 19 K and 7 K (see Figure 6 and Figure 7).

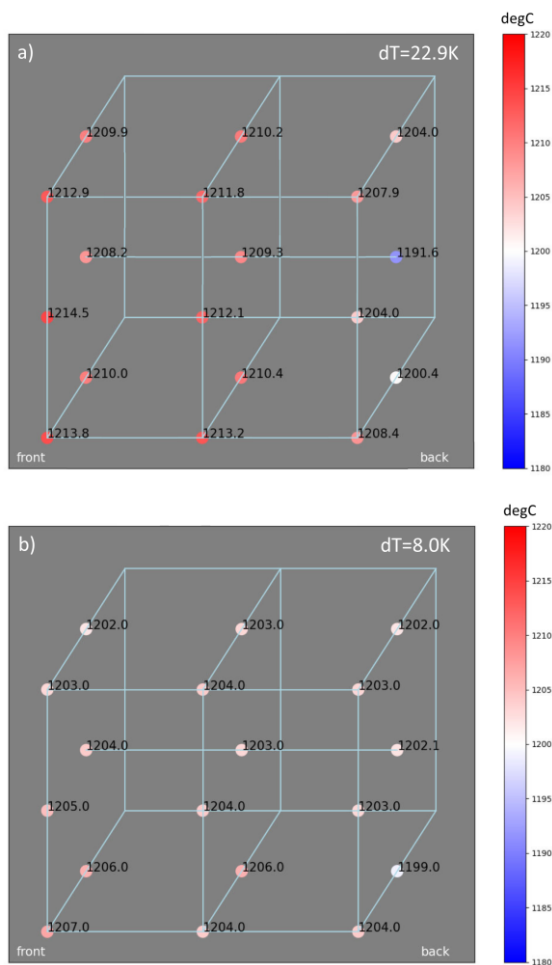


Figure 14. Measured temperature homogeneity of high temperature vacuum furnace with old (a) and new (b) hotzone design.

Fast cooling

In addition to that, in order to characterize cooling performance, temperature in the center of a 600 kg molybdenum load was measured during fast cooling with Argon at a pressure of 4 bar and a fan rotation frequency of 3000 min^{-1} . Figure 15 shows the measured cooling curves. For the old hotzone design it took 26 minutes to cool the center of the load below $600 \text{ }^\circ\text{C}$. This value nearly perfectly matches the cooling time of 27 minutes obtained from the thermo-fluid dynamic model (see Figure 5). As predicted by the simulation, cooling efficiency decreases with the new concept for rear gas outlet and gas nozzle inserts. With the new concept for rear gas outlet cooling time to $600 \text{ }^\circ\text{C}$ is 38 minutes³. With additional gas nozzle inserts it is 43 minutes. This is the price to pay for an improved temperature homogeneity and a reduced power consumption.

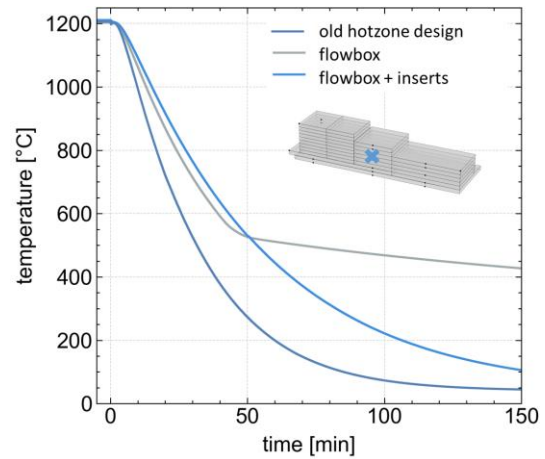


Figure 15. Measured cooling of 600 kg molybdenum load with old hotzone design as well as with new concept for rear gas outlet (“flowbox”) without and with gas nozzle inserts.

Power consumption

The measured power consumption at different operation temperature levels of the old and new hotzone design is shown in Figure 16. With the old hotzone design a power consumption of 85 kW at $1200 \text{ }^\circ\text{C}$ and 213 kW at $1600 \text{ }^\circ\text{C}$ was measured. Those values are higher than the predictions of 64 kW and 186 kW made by the thermo-electric model (see Figure 3). This can be attributed to assumptions made for the calculation, e.g. the neglect of heat conducting bolts. With the new “flowbox” for the rear gas outlet power consumption could be reduced by 4 kW at $1200 \text{ }^\circ\text{C}$. This value is slightly lower than the 6 kW predicted by the thermo-electric simulation model (see Figure 6 and Figure 7). At $1600 \text{ }^\circ\text{C}$ the new concept for the rear gas outlet led to power savings of 16 kW. The 9 kW predicted by the 2D thermo-fluid dynamic model (see Figure 8 and Figure 10) are lower. At $1200 \text{ }^\circ\text{C}$ the gas nozzle inserts led to additional power savings of 8 kW. This value is higher than expected from the thermo-fluid dynamic gas nozzle calculation, predicting a value of $50 \times 85 \text{ W} = 4.3 \text{ kW}$ (see Figure 10). Even if the multi-physical models do not deliver the exact value, the trend and order of magnitude fit quite well. This can be attributed to the assumptions and simplifications made in the submodels for the respective components. Altogether the presented developments led to power savings of 13 – 15 % over all temperature levels. More details on the next generation of PLANSEE refractory metal hotzones can be found in [11].

³ At this test run fast cooling was stopped after reaching a temperature of $600 \text{ }^\circ\text{C}$.

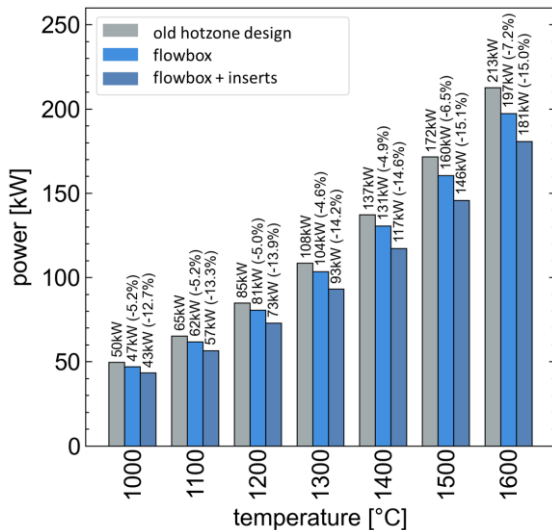


Figure 16. Power consumption of test furnace with old and new hotzone design.

Conclusions

In the development of refractory metal hotzones for high temperature vacuum furnaces at PLANSEE SE multi-physical simulations were applied to evaluate and optimize new concepts for rear gas outlet and gas nozzle inserts. At this the power consumption of the next generation of PLANSEE refractory metal hotzones could be reduced by 15 % at an improved temperature homogeneity at the price of a moderately reduced cooling efficiency. The realized power saving potential for each high temperature furnace equipped with the next generation of PLANSEE refractory metal hotzones of this size is 72000 kWh per year. This equates to the power consumption of 30 average households⁴, cost savings of 15000 € per year⁵ and a CO₂ footprint reduced by 21.6 tons per year⁶.

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⁴ Assumed annual consumption of 2400 kWh.

⁵ Assumed energy costs of 0.21 €/kWh.

⁶ Assumed CO₂ emissions of 300 g/kWh.