

Multiphysics Simulation Based Development of LPBF Components for High Temperature Furnaces

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Abstract

To develop the next generation of energy efficient refractory metal hot zones for high temperature vacuum furnaces at Plansee SE, multiphysics simulations were employed to design and optimize thin-walled, gas permeable structures that reduce thermal radiation losses while maintaining low flow resistance. The developed structures were fabricated by laser powder bed fusion (LPBF) of molybdenum and integrated into a test furnace to evaluate power consumption, temperature homogeneity and cooling efficiency. The results confirmed the predictions of the multiphysics modelling. Power savings of 13 % and significantly improved temperature homogeneity as well as improved cooling efficiency could be demonstrated.

Keywords: high temperature vacuum furnace, temperature homogeneity, power consumption, cooling efficiency, laser powder bed fusion, thermal model, fluid dynamic model.

Refractory Metal Hot Zones for High Temperature Furnaces

High temperature vacuum furnaces typically operate at power levels of several hundred kilowatts. Assuming an average power consumption of 100 kW over 200 days¹ a year, the annual energy consumption of one single furnace is 480,000 kWh. This corresponds to annual energy costs of 96,000 €².

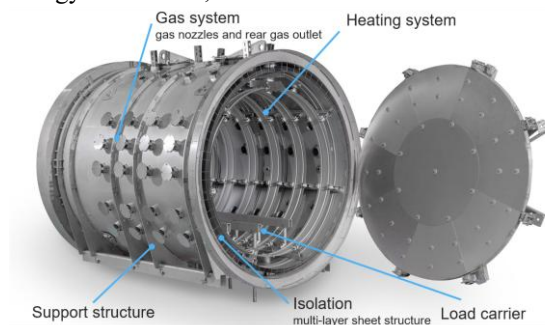


Figure 1 Refractory metal hot zone for a high temperature furnace.

High temperature vacuum furnaces are generally equipped with rapid cooling systems to achieve the cooling rates required for heat treatment processes. Figure 1 shows a refractory metal hot zone of a high temperature vacuum furnace manufactured by Plansee SE. The rear gas outlet and gas inlet nozzles (Figure 2) of the rapid cooling system, commonly in state-of-the-art furnaces implemented as simple openings with recessed shielding, represent a dominant source of radiative heat losses, contributing approximately one third of the total

energy losses of a furnace and adversely affecting the temperature homogeneity in the load volume.

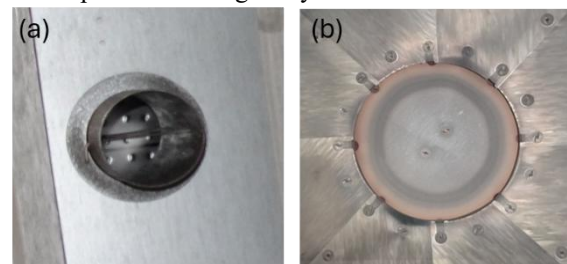


Figure 2 Classical gas system: (a) gas inlet nozzle; (b) rear gas outlet.

New Gas System Concept

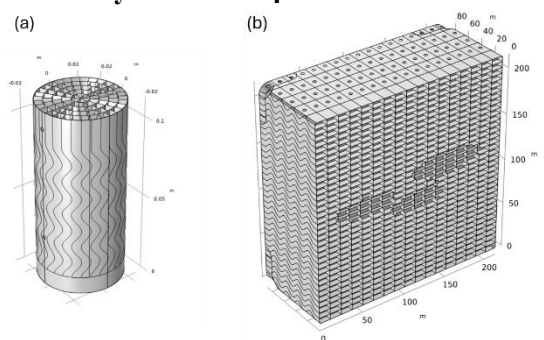


Figure 3 New gas system concept: (a) gas inlet nozzle; (b) gas outlet FlowBox module.

In order to address this issue and develop the next generation of energy efficient refractory metal hot zones for high temperature furnaces, at Plansee SE a new concept for the gas system was developed [1]. Multiphysics simulations were employed to design and optimize thin-walled, gas

¹ 24 h per day run time.

² Assumed energy costs of 0.20 €/kWh.

permeable structures that reduce thermal radiation losses while maintaining low flow resistance. For the rear gas outlet, a so called FlowBox consisting of an array of thin-walled cosine shaped rectangular channels was developed (Figure 3 b). This concept combines multiple effective shielding layers for thermal radiation with a low resistance for the gas flow. Additionally, the required installation space is significantly smaller compared to a state-of-the-art rear gas outlet. I.e. the length of the furnace containment can be reduced by about 0.1 to 0.2 m. The corresponding concept was applied to the gas inlet nozzles, featuring an array of cosine channels arranged circumferentially with increasing amplitude in radial direction (Figure 3 a). The design of gas inlet nozzles and FlowBox was implemented fully parametrized utilizing methods in COMSOL Multiphysics®.

Numerical Models

Before manufacturing of the first prototypes of the new gas system concept, thermal and fluid dynamic COMSOL models were employed to evaluate the shielding effectiveness and flow resistance of the suggested structures for the rear gas outlet and gas inlet nozzles as well as for the optimization of their design.

Thermal Model High Temperature Furnace

A stationary thermal model of the full high temperature vacuum furnace was applied to analyze the potential of a rear gas outlet based on the FlowBox concept for an improved temperature homogeneity (Figure 4). For this purpose, the Heat Transfer Module was used to model the temperature distribution throughout the furnace components at a prescribed operating temperature.

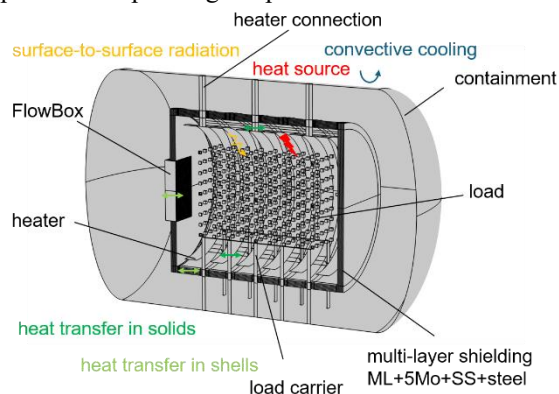


Figure 4 Thermal model high temperature furnace.

Plane symmetry was considered and temperature was ramped up by an auxiliary sweep in the stationary analysis. The load was modelled as an array of molybdenum cubes evenly spread across the load volume. Heat transfer in the massive components of load, load carrier and heater connection was modelled based on the Heat Transfer in Solids interface, whereas the Heat Transfer in Shells interface was applied for

modelling heat transfer in shielding, containment and FlowBox. Those two interfaces were coupled using pointwise constraints. Radiative heat transfer was modelled based on the Surface-to-Surface Radiation interface. Heating power in the heaters of the three heating zones was controlled by the temperature of three control thermocouples using Global Equations.

Thermal Submodels Gas Nozzle and Gas Outlet

Stationary thermal submodels of the rear gas outlet and gas inlet nozzles were used to estimate the energy saving potential of the new gas system concept compared to a state-of-the-art classical gas system. Figure 5 shows the geometry and included physics of the thermal submodels for gas inlet nozzle and rear gas outlet.

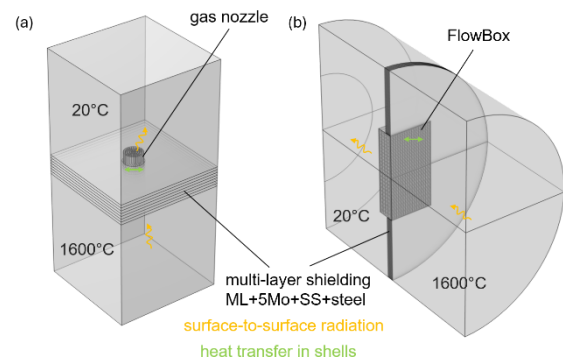


Figure 5 Thermal submodels: (a) inlet gas nozzle and (b) rear gas outlet.

For this, the Heat Transfer in Shells and Surface-to-Surface Radiation interfaces of the Heat Transfer Module were applied. For the gas nozzle a square unit cell element of the side multi-layer shielding with an inner temperature of 1600 °C and an outer temperature of 20 °C was analyzed. For the rear gas outlet a corresponding modelling setup of the rear furnace wall with plane symmetry was applied.

Fluid Dynamic Submodels Gas Nozzle and Gas Outlet

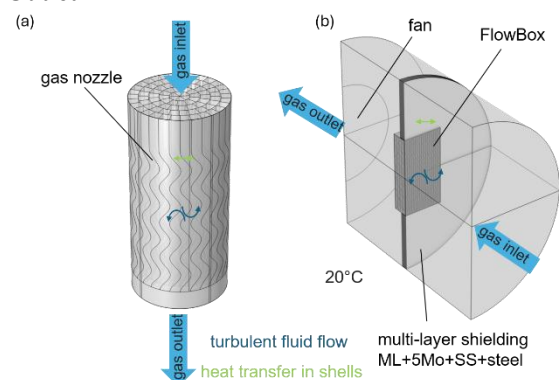


Figure 6 Fluid dynamic submodels: (a) gas nozzle and (b) rear gas outlet.

In addition, submodels for gas flow and pressure decay, as a measure of cooling efficiency, were evaluated based on stationary and time-dependent

fluid dynamics calculations. Figure 6 shows the geometry and included physics of the fluid dynamics submodels for the gas inlet nozzle and rear gas outlet. For these analyses, a Turbulent Flow interface and the Heat Transfer in Fluids interface of the Heat Transfer Module were applied. For the gas nozzle a stationary simulation at a prescribed Argon gas flow at 6 bar and 20 °C was performed. For the gas outlet a corresponding modelling setup with plane symmetry and a fan boundary condition for the gas outlet was applied.

Simulation Results

Based on the numerical models, temperature homogeneity, power consumption and flow resistance were analyzed for the suggested gas system concept in comparison to a classical state-of-the-art gas system with recessed shielding.

Temperature Homogeneity

Based on the stationary thermal model of the high temperature vacuum furnace, temperature homogeneity in the load volume at an operating temperature of 1200 °C was evaluated for a classical rear gas outlet with recessed shielding (Figure 7) as well as for a rear gas outlet based on the newly developed FlowBox concept (Figure 8). The simulation results clearly show that the rear gas outlet is the dominant factor restricting temperature homogeneity in the load volume.

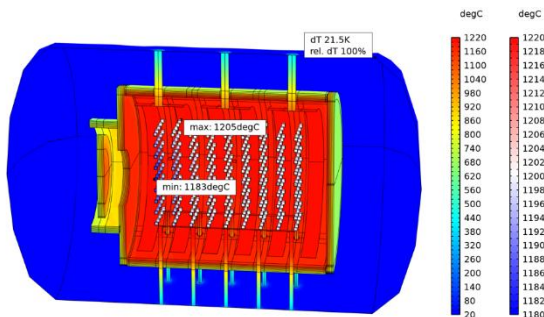


Figure 7 Temperature homogeneity in high temperature vacuum furnace with classical rear gas outlet (left legend: furnace components; right legend: load volume).

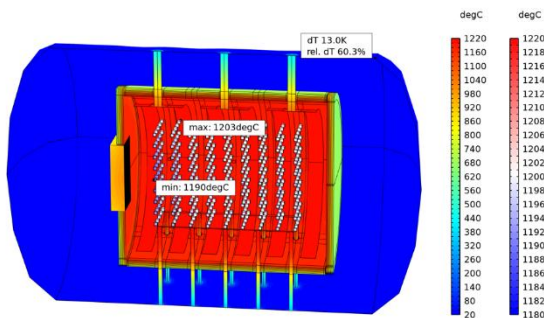


Figure 8 Temperature homogeneity in high temperature vacuum furnace with new rear gas outlet FlowBox (left legend: furnace components; right legend: load volume).

The model predicts a maximum temperature difference in the load volume reduced by 40 %

from 22 K to 13 K for a high temperature vacuum furnace equipped with the suggested new rear gas outlet FlowBox concept. With a FlowBox the cold spot in the region of the rear gas outlet can be significantly reduced. Its structure acts like a multi-layer shielding in the rear shielding plane, shielding thermal radiation significantly more efficiently than the state-of-the-art rear gas outlet concept with recessed shielding.

Power Consumption

Based on the thermal submodels for the inlet gas nozzles the energy saving potential of the suggested new gas system concept was evaluated. Figure 9 shows the losses through a classical gas nozzle with recessed shielding. Both total losses of the regarded unit cell as well as losses through the gas inlet nozzle were analyzed.

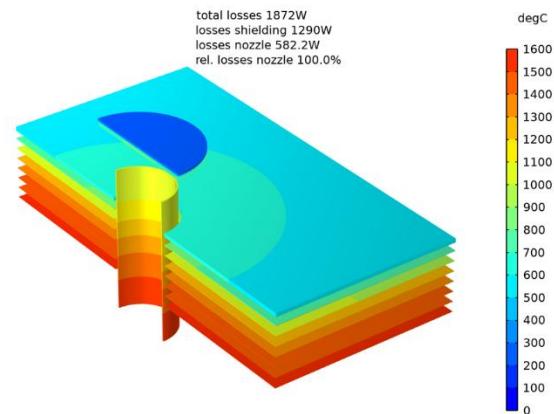


Figure 9 Power losses classical gas nozzle.

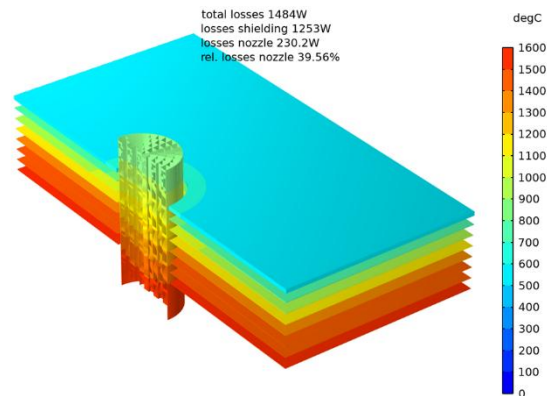


Figure 10 Power losses new gas nozzle concept.

With the new gas nozzle concept (Figure 10) losses through the nozzle can be reduced by 60 % from 582 W to 230 W. Given that a typical hot zone is equipped with 30 to 60 gas nozzles, this results in reduced power losses of about 10 to 20 kW.

A corresponding result is obtained for the rear gas outlet (Figures 11 and 12). With the FlowBox concept, power losses through the rear shielding can be reduced by 45 % from 23 kW to 13 kW. Based on those results, assuming 50 gas nozzles, an overall power consumption reduced by 28 kW can

be expected for a furnace equipped with the new gas system concept.

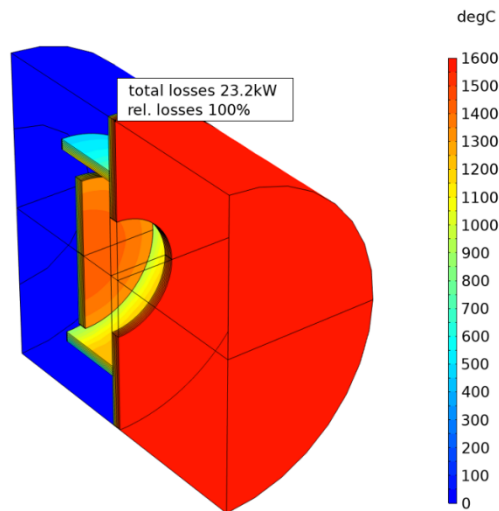


Figure 11 Power losses classical rear gas outlet.

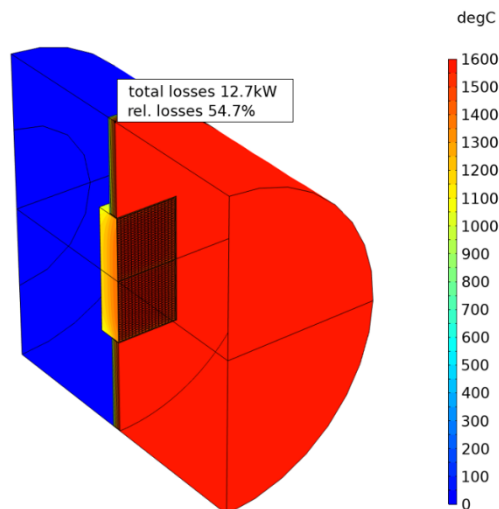


Figure 12 Power losses new rear gas outlet FlowBox.

Flow Resistance

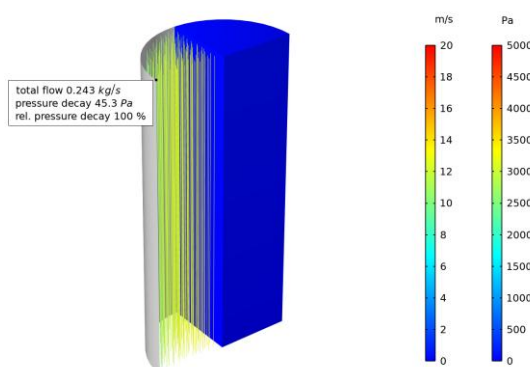


Figure 13 Flow resistance classical gas nozzle (left legend: velocity; right legend: pressure decay).

Based on the fluid dynamic submodels gas flow rate and pressure decay were evaluated for the new gas system concept for an Argon gas flow at 6 bar and 20 °C. Figures 13 and 14 show the predicted

gas flow rate for the classical and new gas nozzle concept. At a given flow rate, pressure decay within the nozzle is approximately 100 times higher for the new gas nozzle concept. Gas velocities are slightly higher.

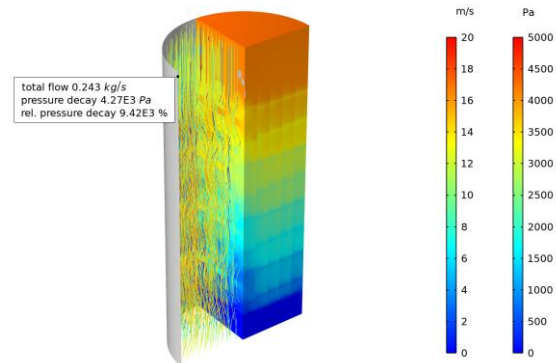


Figure 14 Flow resistance new gas nozzle concept (left legend: velocity; right legend: pressure decay).

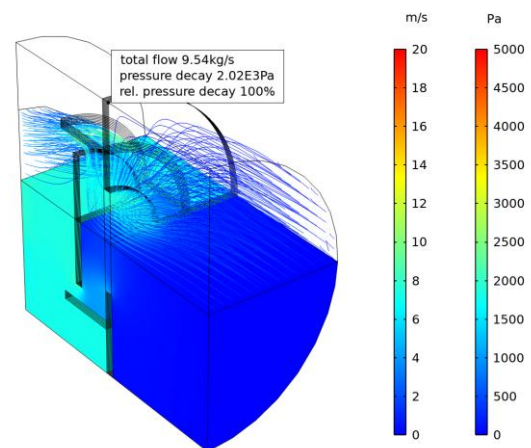


Figure 15 Flow resistance classical rear gas outlet (left legend: velocity; right legend: pressure decay).

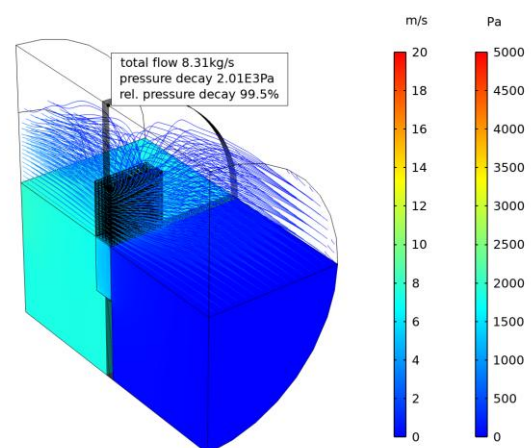


Figure 16 Flow resistance new rear gas outlet FlowBox (left legend: velocity; right legend: pressure decay).

In a next step the corresponding analysis was performed for the rear gas outlet at a prescribed fan curve. Static pressure at no flow was ramped up to obtain a gas flow rate on the level expected from

the gas nozzle calculations for 50 gas nozzles. The model predicts only a moderately reduced flow rate for the new rear gas outlet concept at an identical pressure decay (Figures 15 and 16). Based on those results only a minor influence of the new gas system concept on cooling efficiency can be expected as for a typical fan curve; a moderate increase in pressure decay only slightly changes the gas flow rate.

Next Generation LPBF Gas System

Based on those results the developed structures were subsequently fabricated using laser powder bed fusion (LPBF) of molybdenum and implemented in a furnace. Figure 17 shows the LPBF gas nozzles as well as a LPBF FlowBox module. Figure 18 shows the installed components in a test furnace at Plansee SE.

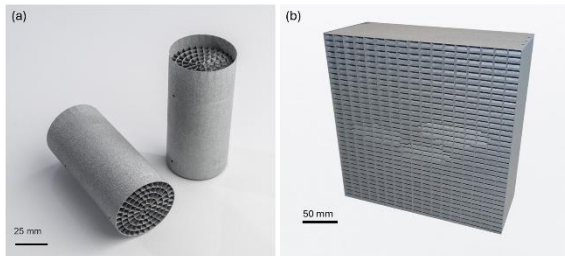


Figure 17 Components LPBF gas system: (a) nozzles and (b) FlowBox module.

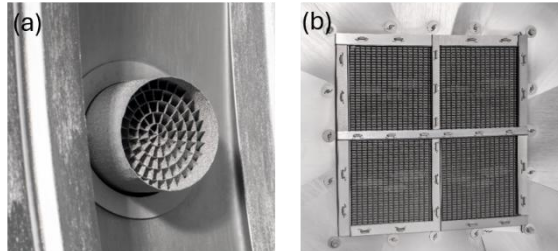


Figure 18 LPBF gas system implemented in a high temperature vacuum furnace: (a) LPBF gas inlet nozzle and (b) LPBF rear gas outlet FlowBox with four modules.

Experimental Results

Dedicated test runs were performed with the test furnace equipped with the newly developed LPBF components to evaluate temperature homogeneity, power consumption and cooling efficiency. The measured data was compared to corresponding test runs performed with the classical state-of-the-art gas system before upgrading the furnace with LPBF components.

Temperature Homogeneity

Figure 19 shows the measured maximum temperature difference in the load volume for the classical and LPBF gas system. At an operating temperature of 1200 °C maximum temperature difference can be reduced by 51 % from 21 K to 10 K. The results obtained are in good accordance with the prediction of the thermal model (Figures 7 and 8).

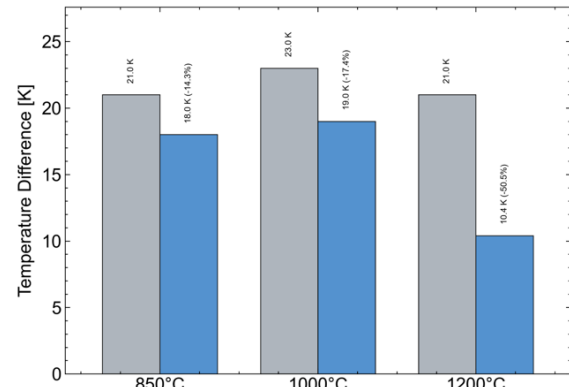


Figure 19 Measured maximum temperature difference in load volume at different temperature levels for classical gas system (grey) and LPBF gas system (blue).

Power Consumption

Furthermore, power consumption of the test furnace was evaluated for different operating temperature levels (Figure 20). At an operating temperature of 1600 °C the power consumption of the furnace could be reduced by 27 kW (-13 %) from 213 kW to 186 kW with the LPBF gas system. Again, this is in good accordance with the results of the thermal submodels for gas inlet nozzles and rear gas outlet, that predicted a power saving potential of 28 kW.

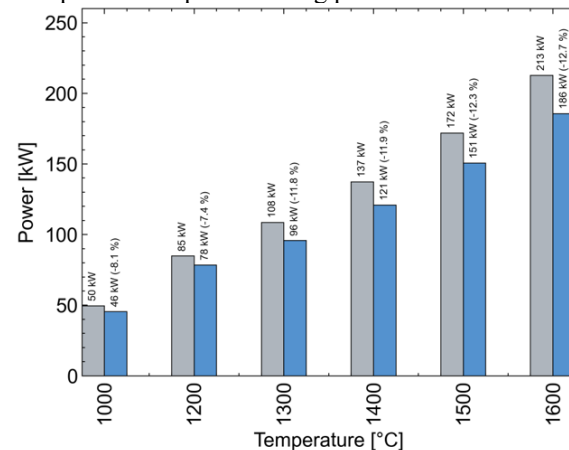


Figure 20 Measured power consumption at different temperature levels for classical gas system (grey) and LPBF gas system (blue).

Cooling Efficiency

Finally, cooling efficiency of the furnace was evaluated by measuring the cooling time of a 600 kg molybdenum load with Argon at different gas pressure levels. Here, with the LPBF gas system, in accordance with the prediction of the fluid dynamics model, cooling efficiency did not change significantly. It was even slightly improved (Figure 21). In order to clarify the effects leading to an improved cooling efficiency, a more sophisticated fluid dynamics model of the full furnace, taking into account all gas nozzles, the rear gas outlet, the multi-layer shielding and the load would be required.

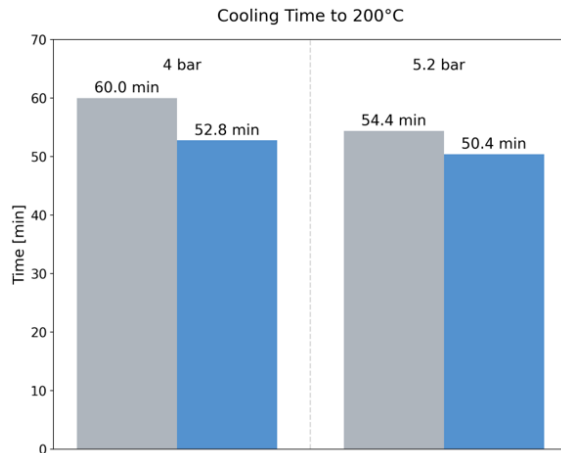


Figure 21 Measured cooling time of a 600 kg molybdenum load from 1200 °C to 200 °C at different Argon pressure levels for classical gas system (grey) and LPBF gas system (blue).

Conclusions

Based on multiphysics modelling, a new gas system concept with LPBF components for high temperature vacuum furnaces was developed at Plansee SE. In accordance with the predictions of the numerical modelling, in a test furnace energy savings of 13 % at an improved temperature homogeneity without a loss of fast cooling efficiency could be demonstrated. This corresponds to energy savings of 70,000 kWh/a assuming typical operation conditions. This equates with cost savings of 14,000 €/a and a CO₂ footprint reduced by 21 tons per year³.

The developed LPBF gas system is available in the next generation of energy efficient Plansee refractory metal hot zones with even higher energy savings due to further optimizations of the gas system with respect to number and location of gas nozzles and the gas system cross section that have been made based on multiphysics modelling in the previous years [2 - 4].

References

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³ Assumed CO₂ emissions of 300 g/kWh.