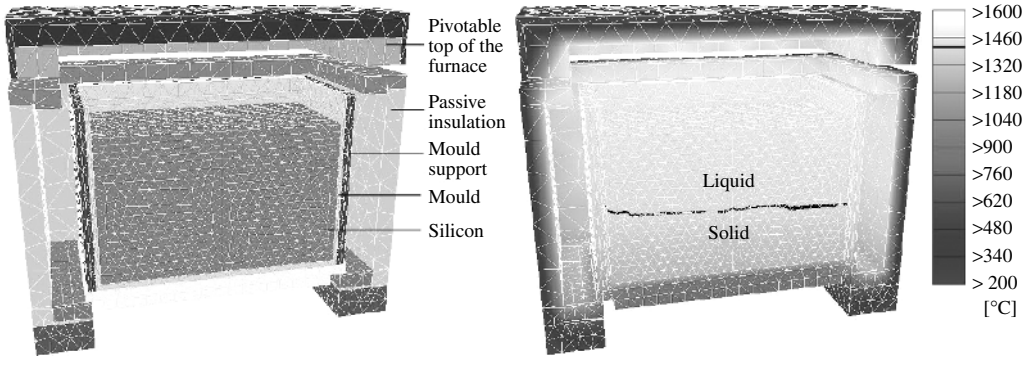

Figure 6.29 Finite element geometry of an ingot casting furnace and simulated temperature distribution during a reference process. The liquid–solid interface is marked by the black line

as shown in Figure 6.29. Because of confidentiality agreements with the industry, the heating and cooling systems are not shown in detail in this figure. All heat conductance and capacity effects as well as the non-stationary release of latent heat are taken into account. All material contact regions between silicon, mould or insulation materials are modelled by heat flow–resistance parameters. To describe the heat flux by radiation inside the furnace, a view-factor model is included in the software. All material data are treated in their temperature dependency and all the internal control systems of the furnace are added to the simulation software.

To start one simulation run, only the cooling water temperature and the time-dependent process control information are necessary as input data, as they are entered in the crystallisation furnace. Output from one calculation is the three-dimensional temperature history in the furnace, beginning after pouring the melt and ending with a homogeneous temperature of about 300°C inside the ingot. This calculation needs less than 6 h on a common one-processor workstation.

In Figure 6.29, an example of the temperature distribution during a reference process is shown in the middle, cut through the furnace. The liquid–solid interface is marked by the melting temperature isotherm. The solidification front is mostly flat, and a slight non-symmetry is caused by the specific construction of the heating system. These simulation results are verified in an experimental crystallisation furnace with good agreement to the measurement in the ingot volume during crystallisation.

In general, the shape of the solidification front is controlled by the lateral heat flux, while the vertical heating and cooling conditions control the solidification velocity. To investigate these general reflections for the described furnace, variations of the process control were simulated. In Figure 6.30, two variations are presented. By a 30% raise of heating power at the side walls of the ingot, the shape of the solidification front becomes more convex. Otherwise, a reduction of heating power by about 20% turns the solidification front to a more concave shape. Additionally, to this more or less predictable effect, simulation results show an increase in the solidification time for the convex crystallisation of 44% and a 30% reduced processing time for the concave solidification. Both effects are due to the total varying power input in the furnace. These simulation results enable