production. The RGS process [78] is now in preparation for a commercial production. The Cz crystal-pulling technique is the standard process for microelectronic single-crystal wafers and covers an essential part of the PV market share [79, 80]. The TriSi crystal is a new variation of this process, especially for photovoltaic applications [81]. The characteristics of ingot crystallisation can be explained by the shape of their liquid–solid interface. Anyhow, today's ingot crystallisation goes more and more towards a mostly planar solidification. For the use of numerical simulations of the Cold Wall process, see [82, 83]; for the Heat Exchange Method (HEM), see [84] and for the Solidification by Planar Interface (SOPLIN) processes, see [85, 86].

To simulate the temperature history during crystallisation, various thermal effects must be taken into account. In Figure 6.28 the scheme of thermal conditions for the ribbon growth and ingot crystallisation is presented. The biggest difference between the two is the strong variation of the cooled surface to volume relation (SV) during crystal growth. This relationship can be used to qualify the cooling behaviour of the different crystals in an equivalent surrounding. For ribbon growth SV is given as 2/ribbon thickness and for ingots as 1/ingot height. The high number for ribbon growth (e.g. SV = 66/cm) means that the surface affects the crystallisation, while the low number for an ingot geometry (e.g. SV = 0.033/cm) shows that volume effects are more important for crystallisation. By this, the SV parameter characterises the requirements for the modelling of different crystallisation techniques. In the case of bulk crystallisation, the latent heat at the liquid–solid interface must be lead away by a heat sink at the bottom of the ingot. By this, the crystallisation is propagated by a conductive heat flow through the solid ingot volume and the temperature gradients inside the volume have to be simulated with high attention. In the case of ribbon growth, heat flow by convection and radiation at the silicon surface is the dominant heat-transport mechanism to lead away latent heat and propagate the solidification. Therefore, simulation results are very sensitive to heat-transition coefficients and the emission behaviour at the ribbon surface.

Furthermore, both techniques can be distinguished into quasi-steady state and moving boundary processes. Assuming a constant pulling speed, the ribbon growth is

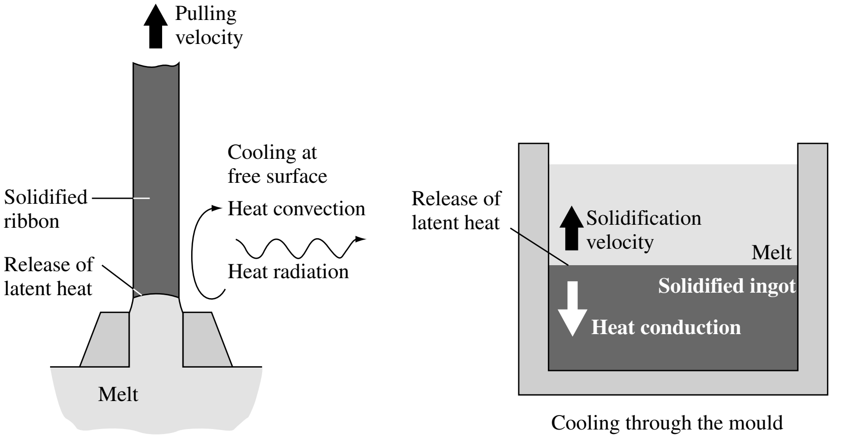

Figure 6.28 Scheme of thermal effects during ribbon growth and ingot crystallisation