Numerical investigation of adhesive properties during heat-curing

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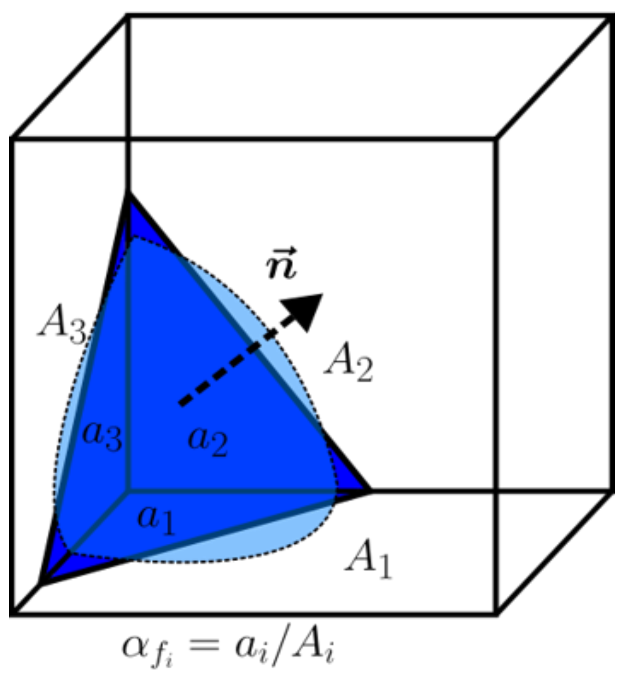
1. Introduction

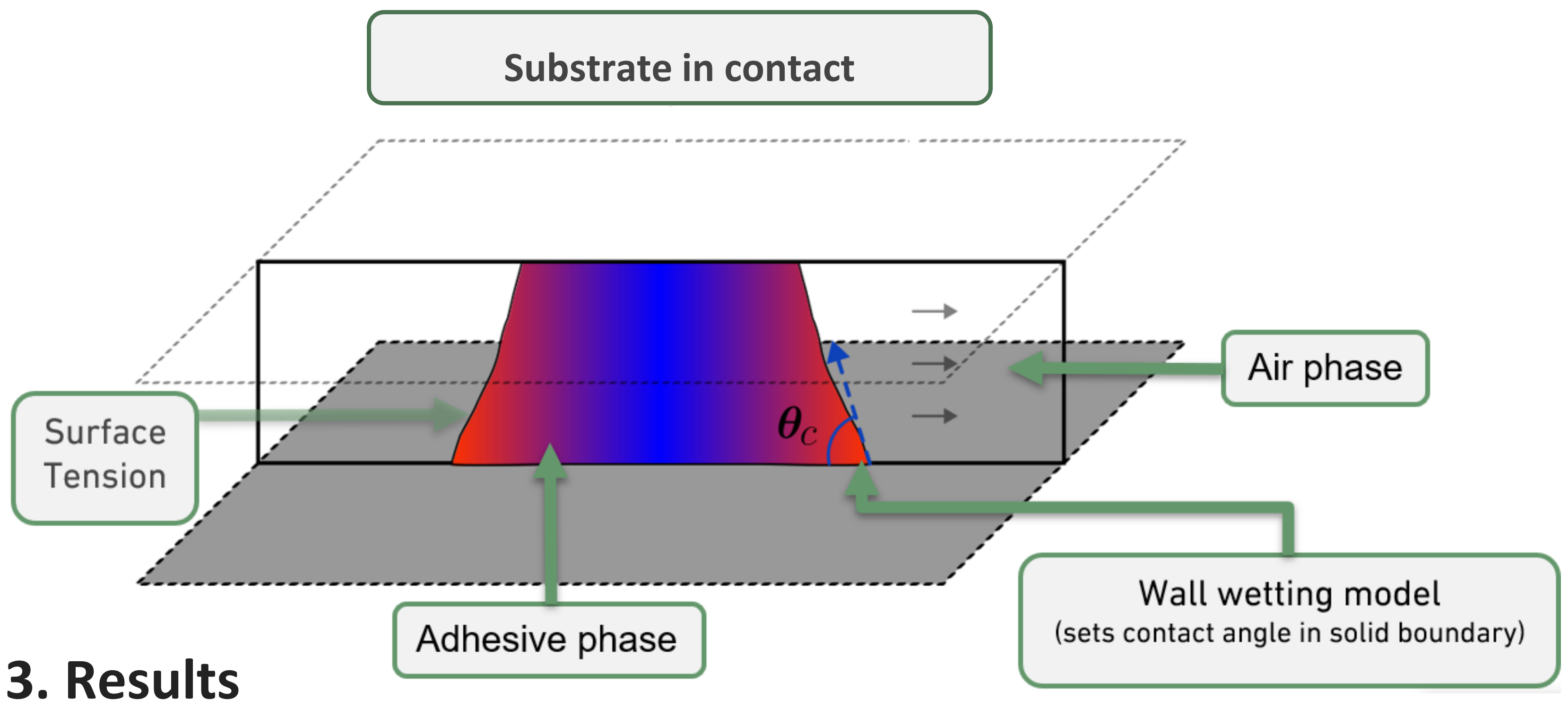
Temperature evolution during adhesive curing affects viscosity, reaction kinetics, and the development of residual stresses, thereby influencing the final performance of bonded joints. Numerical curing models often prescribe the oven temperature directly at the substrate surface, neglecting the finite heat-transfer rate between the circulating oven atmosphere, the substrates, and the adhesive layer.

2. Materials and Methods

A 3D transient computational framework was developed to evaluate heat transfer through an epoxy-like adhesive confined between aluminum substrates. The adhesive and surrounding air are represented as a two-phase continuum, while the substrates are modeled as solid regions. Temperature and heat flux are continuous across the fluid–solid interfaces.

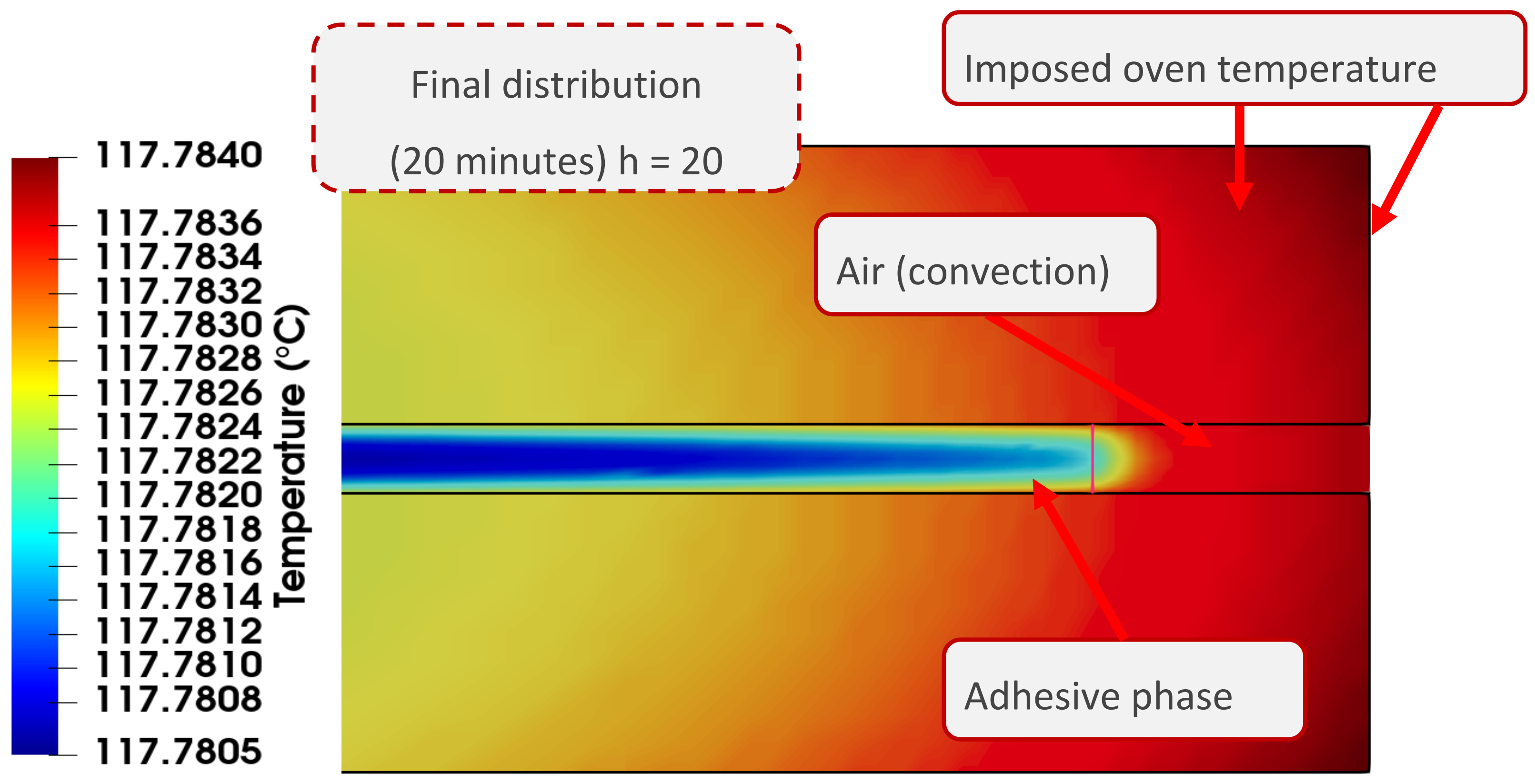


The model was implemented using the Finite Volume framework of OpenFOAM. Heat exchange between the oven atmosphere and the external aluminum surfaces is represented by a convective boundary condition, $-k_s \nabla T \cdot n = h(T_s - T_{oven})$, where the coefficient (h) controls the thermal coupling with the oven.

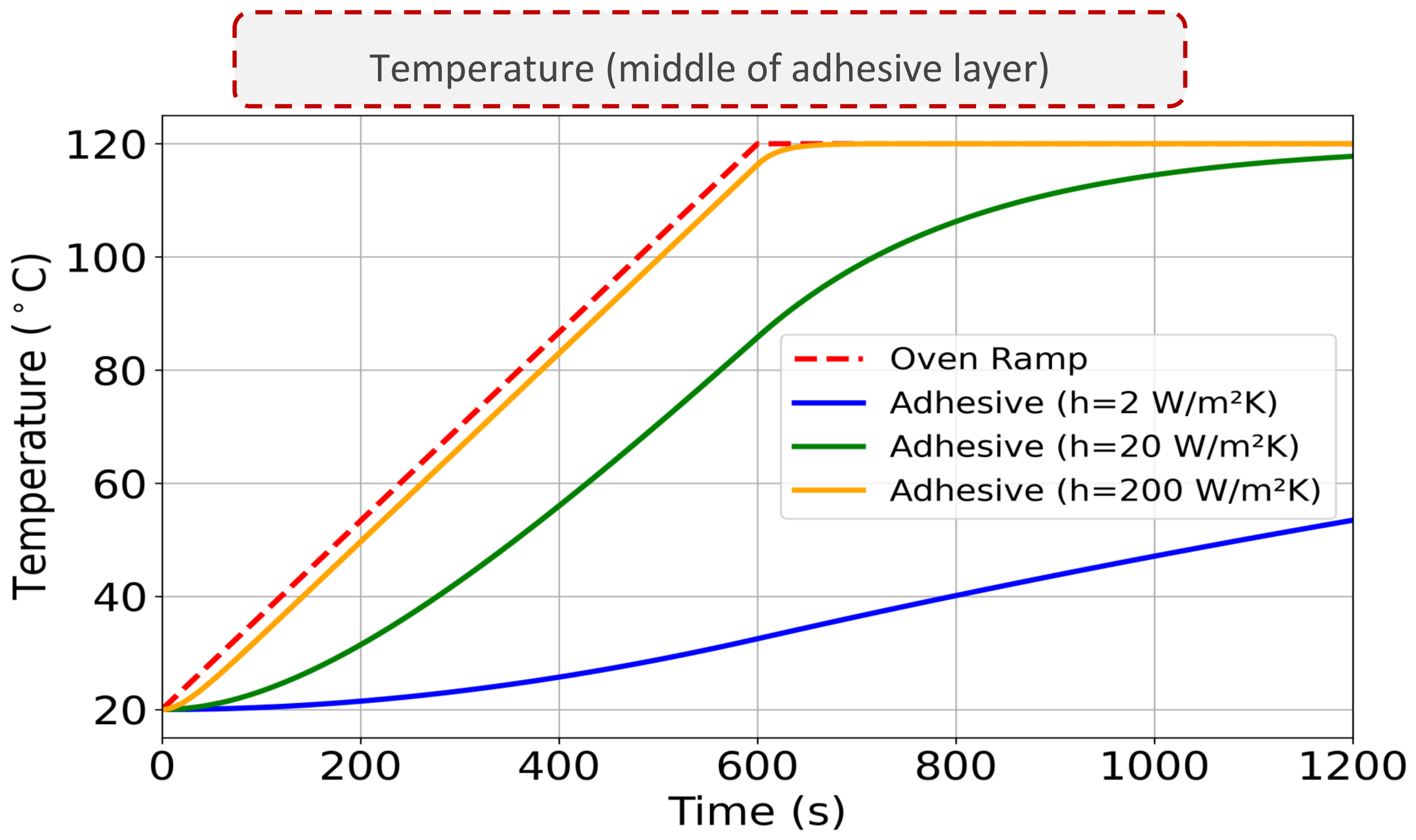


3. Results

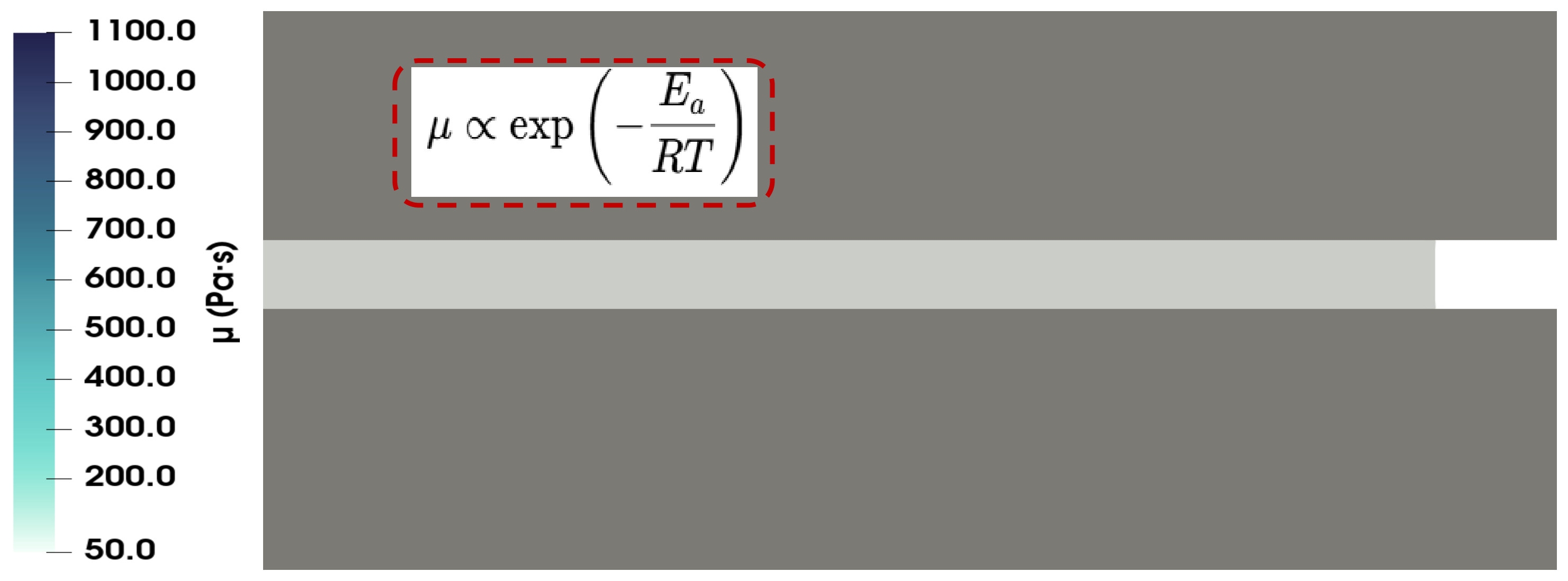
Values of 2, 20, and 200 $W \cdot m^{-2} \cdot K^{-1}$ were investigated. An Arrhenius relation was used to describe the temperature dependence of the adhesive viscosity. The prescribed oven cycle consists of a linear temperature ramp from 20 °C to 120 °C over 10 minutes, followed by a 10-minute isothermal plateau. Heat is transferred from the oven atmosphere to the external aluminum surfaces and subsequently conducted through the substrates toward the adhesive layer.



For h=20 $W \cdot m^{-2} \cdot K^{-1}$ the final temperature field is almost spatially uniform. The narrow interval between approximately 117.7805 and 117.7840 °C is therefore used to highlight the remaining gradients. Heat enters through the external substrate surfaces and is rapidly redistributed by the highly conductive aluminum, producing only minor temperature differences across the adhesive and air regions.



The adhesive temperature increasingly follows the imposed oven cycle as h rises. For h=200 $W \cdot m^{-2} \cdot K^{-1}$ the adhesive responds rapidly and approaches the 120 °C plateau shortly after the ramp. The h=20 case presents an intermediate response, whereas for h=2 the heating rate is strongly limited and the adhesive reaches only approximately 55 °C after the initial 10-minute ramp. The selected values may be interpreted as effective oven conditions: h=2 represents nearly stagnant air or weak thermal coupling, h=20 is representative of natural convection or moderate air circulation, and h=200 corresponds to strong forced convection. These classifications are approximate because the effective coefficient also depends on airflow velocity, oven geometry, surface orientation, and local flow conditions.



The final viscosity distribution for h=20 $W \cdot m^{-2} \cdot K^{-1}$ is nearly homogeneous over the displayed range of 50–1100 Pa·s This uniformity follows from the very small temperature gradients obtained at the end of the thermal cycle. Under the Arrhenius model, the heating history therefore affects the temporal evolution of viscosity more strongly than its final spatial variation.

4. Conclusions

The convective heat-transfer coefficient primarily controls the rate at which the adhesive follows the prescribed oven cycle. Weak convection produces substantial thermal lag, while strong forced convection rapidly brings the joint toward the oven temperature. Owing to the high thermal conductivity of the aluminum substrates, the final temperature and viscosity fields are nearly uniform, even though their transient evolution remains strongly dependent on (h). Accurate representation of the oven boundary condition is therefore necessary when predicting adhesive temperature and viscosity during curing.

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