# Modeling, approximation, and time optimal temperature control for binder removal from ceramics

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## Abstract

The process of binder removal from green ceramic components via firing in a furnace with temperature control will be discussed. Gas is produced as the binder burns away and the pressure it produces in the porous ceramic body leads to unwanted fractures if not suitably controlled. An important industrial problem is to determine minimum-time temperature protocols for the firing process that are constrained to avoid pressure damage to the ceramic body until the binder is burned out. A viable model consists of a coupled ODE and nonlinear parabolic PDE, which is a variant of the porous media equation. A pseudo steady state approximation (PSSA) for the PDE, which results in an exact formula, is shown to be sufficiently accurate for practical use in the physical regime relevant for binder removal in the root mean square sense via an energy argument and in the pointwise sense via a singular perturbation argument. A surprisingly simple time optimal control strategy is proved. It is amenable to numerical approximations using the ODE-PDE model or the ODE-PSSA model. From an applied point of view, the PSSA is useful beyond the qualitative information it provides because computation time is significantly reduced even for simple finite-difference schemes used to approximate solutions of the PDE for simple one-dimensional geometries.