

THE INFLUENCE OF NATURAL CONVECTION AND RADIATION HEAT TRANSFER ON SINTERING OF POLYCARBONATE POWDERS

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ABSTRACT

The influence of surface radiation and natural convection on sintering of polycarbonate powders processed under non-isothermal conditions is investigated. These modes of heat transfer affect local powder temperatures and thus local sintering rates which in turn influence part growth (uncontrolled sintering). This paper presents a 2-dimensional sintering simulation of powder whose free surface exchanges energy with the surrounding enclosure surfaces. Modeling is accomplished using a commercial finite element code (FIDAP) in conjunction with a model for viscous sintering.

NOMENCLATURE

A	= sintering rate coefficient
C	= Ergun (inertial) coefficient
c_{pf}	= specific heat, fluid (J/kg K)
E_a	= activation energy for viscous sintering
g	= gravitational acceleration (m/s^2)
K	= permeability (m^2)
k_{eff}	= effective thermal conductivity (of powder) (W/mK)
k_f	= thermal conductivity (W/mK)
p	= pressure (Pa)
T	= absolute temperature (Kelvin)
T_c	= cold temperature (Kelvin)
u, v	= x and y velocity components (m/s)

- u_D, v_D = Darcian x and y velocity components (m/s)
 x, y = horizontal and vertical coordinate (m)
 β = coefficient of thermal expansion (K^{-1})
 ϕ = volume-averaged porosity
 μ_{eff} = effective (in-powder) viscosity (Ns/m^2)
 μ_f = fluid viscosity (Ns/m^2)
 ρ = density of fluid phase (kg/m^3)

INTRODUCTION

Selective Laser Sintering (SLS) is among the many Solid Freeform Fabrication techniques presently available. Freeform parts produced by SLS typically remain buried in a bed of loose powder until they have cooled enough to be handled. Non-isothermal conditions result in heat transfer from the part to the surrounding powder which can cause secondary, uncontrolled sintering, or part growth. Part growth (densification) is accompanied by the formation of gas-filled voids as required by conservation of mass principles. The extent of growth is dependent upon local sintering rates which increase exponentially with temperature (Nelson, 1993). Hence, the ability to predict the temperature distribution induced by various modes of heat transfer might aid in the development of thermal control techniques to produce accurate (minimal part growth) final freeform part shapes.

In this paper, a first attempt is made to quantify the influence of surface radiation and natural convection heat transfer on the temperature distribution within a polycarbonate powder under non-isothermal conditions. At steady-state, local temperatures and sintering rates are obtained for cases involving pure conduction within the powder along with radiative and convective cooling of the powder surface. These results are compared to the base case involving pure conduction heat transfer through the powder and surrounding air.

MODEL

The 2-dimensional, non-isothermal arrangement of Figure 1 depicts the idealized scenario under consideration. Two concentric, square, isothermal tubes serve as heat source and sink. The outer tube is maintained at 180 °C while the inner tube is held at 50 °C. The powder has an initial porosity of 0.5. The region above the powder surface is occupied by air. The 2-dimensional, steady-state temperature distribution within both the air and powder is determined using the commercial code FIDAP with the following descriptive equations.

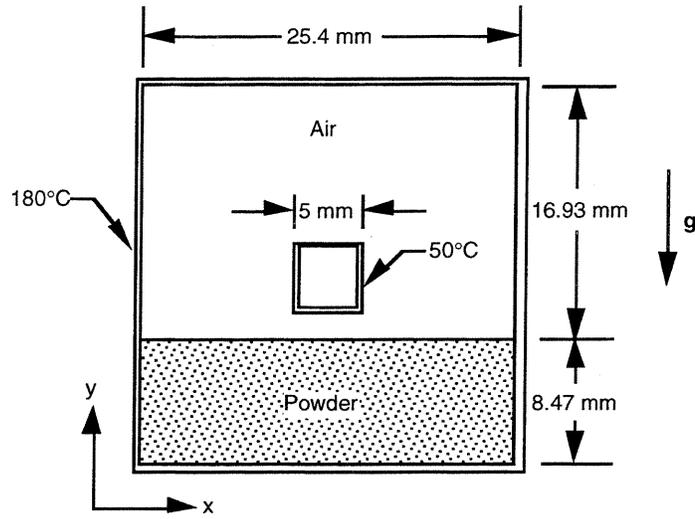


Figure 1. System configuration.

The governing equations for the pure fluid and the saturated porous medium are given separately. In writing the following equations it is assumed that fluid flow is laminar, steady, incompressible, and two-dimensional. For the pure fluid region, the two-dimensional, steady-state Navier-Stokes equations are used. Conservation of mass is given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

Conservation of momentum is described by

$$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\mu_r \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_r \frac{\partial u}{\partial y} \right) \quad (2)$$

and

$$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left(\mu_r \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_r \frac{\partial v}{\partial y} \right) + \rho g \beta (T - T_c) \quad (3)$$

Conservation of energy is expressed as

$$\rho c_{pf} \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial x} \left(k_f \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_f \frac{\partial T}{\partial y} \right) \quad (4)$$

All thermophysical properties of the pure fluid are assumed constant with the sole exception being density, where a Boussinesq approximation is used.

For the saturated porous medium, a Brinkman-Forchheimer extended version of the Darcy model is used, as discussed in Beckermann et al. (1987) and Kaviany (1991). It is important to note that the velocities within the saturated powder are Darcian, or volumetrically-averaged, velocities. Conservation of mass within the powder is given by

$$\frac{\partial u_D}{\partial x} + \frac{\partial v_D}{\partial y} = 0 \quad (5)$$

Conservation of momentum within the powder bed, given by

$$0 = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\mu_{\text{eff}} \frac{\partial u_D}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_{\text{eff}} \frac{\partial u_D}{\partial y} \right) - \left(\frac{\mu_f}{K} + \frac{\rho C}{\sqrt{K}} |\bar{u}_D| \right) u_D \quad (6)$$

and

$$0 = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left(\mu_{\text{eff}} \frac{\partial v_D}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_{\text{eff}} \frac{\partial v_D}{\partial y} \right) + \rho g \beta (T - T_c) - \left(\frac{\mu_f}{K} + \frac{\rho C}{\sqrt{K}} |\bar{u}_D| \right) v_D \quad (7)$$

incorporates the Brinkman extension (the second and third terms in the above equations) and the Forchheimer extension (the last term) to account for viscous and inertial effects.

Conservation of energy is described by

$$\rho c_{\text{pf}} \left(u_D \frac{\partial T}{\partial x} + v_D \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial x} \left(k_{\text{eff}} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{\text{eff}} \frac{\partial T}{\partial y} \right) \quad (8)$$

All thermophysical properties of the saturated powder are assumed to be constant, with the exception being a Boussinesq approximation for the air density. Permeability of the powder was measured to be $1.5 \times 10^{-10} \text{ m}^2$, as described in Norrell (1996). For the saturated powder μ_{eff} and k_{eff} are effective air viscosity and thermal conductivity, respectively. It has been found previously by Neale and Nader (1974) that using $\mu_{\text{eff}} = \mu_f$ within the Brinkman extension provides good agreement with experimental data. A simple weighted average given by

$$k_{\text{eff}} = \phi k_f + (1 - \phi) k_s \quad (9)$$

is used for the effective thermal conductivity. The C term in the Forchheimer extension is the inertia coefficient given in Ergun (1952) as

$$C = \frac{1.75}{\sqrt{175}} \phi^{-3/2} \quad (10)$$

Radiation view factors between the (radiatively black) powder and surrounding (black) surfaces are determined using the Hottel crossed-string method to obtain view factors at each powder surface node (Seigel and Howell, 1981). The radiative fluxes on the exposed powder surface are calculated and mapped into FIDAP as heat flux terms. Interparticle (within powder bed) radiation exchange is neglected here.

The model for viscous sintering is obtained from Nelson et al. (1993)

$$-d\phi/dt = K' \cdot (\phi - \phi_{\infty}) \quad (11a)$$

where the coefficient is

$$K' = A \cdot (-E_a / RT) \quad (11b)$$

The activation energy (E_a) and other powder properties are also obtained from Nelson et al. (1993). The sintering rate coefficient (A) used in this study is obtained from Kandis and Bergman (1996).

Solid shapes are estimated based upon the predicted steady state temperature distribution in the powder using an original consolidation model which is described in detail in Kandis and Bergman (1996). In short, the powder domain shape evolves in a stress-free manner, with local sintering rates inducing 2-dimensional solid phase velocities which are then integrated in time to yield the final powder region shape.

RESULTS

The pure conduction temperature distribution is presented in Figure 2a. Isotherms are separated by 10°C in all figures. The isotherms in the powder and surrounding air are roughly circular in shape with a discontinuity in slope at the powder surface. The highest sintering rates occur in the hottest regions (near the outer tube). Less sintering takes place near the central region of the powder surface where temperatures are lowest. The final predicted part shape as a result of part growth is shown in Figure 2b. This figure is

obtained by integrating local sintering rates in time for a period of 6 hours. The part contains a vertical crack in the center, surrounded by a shallow trough or semi-circular ditch. Crack formation is due to the migration of the solid phase toward rapidly-sintering, warm powder regions.

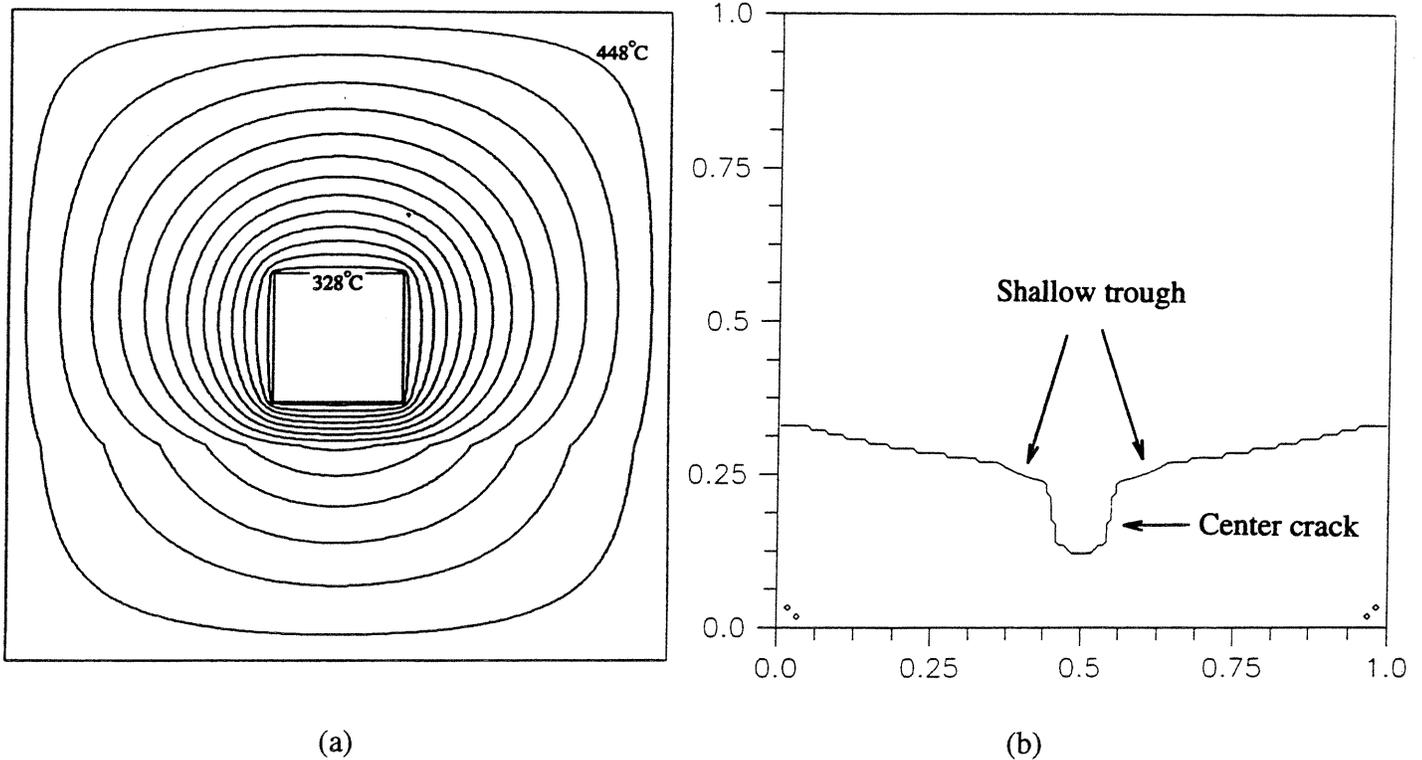


Figure 2. Temperature distribution and final part shape for conduction only case.

The temperature distribution and final part shapes for the case involving conduction and radiation are presented in Figures 3a and 3b. The shape and general features of the isotherms are similar to the pure conduction case, especially in the air gap region. Within the powder, temperatures decrease in the central region but increase slightly to the left and right of the center tube relative to the pure conduction case. Higher sintering rates near the outer tube provide for larger solid phase velocities toward the sides. Decreased sintering rates in the central region result in low porosity powder extending further into the bed (toward the bottom wall). The net result is a small decrease in the overall part growth or part size relative to the previous case.

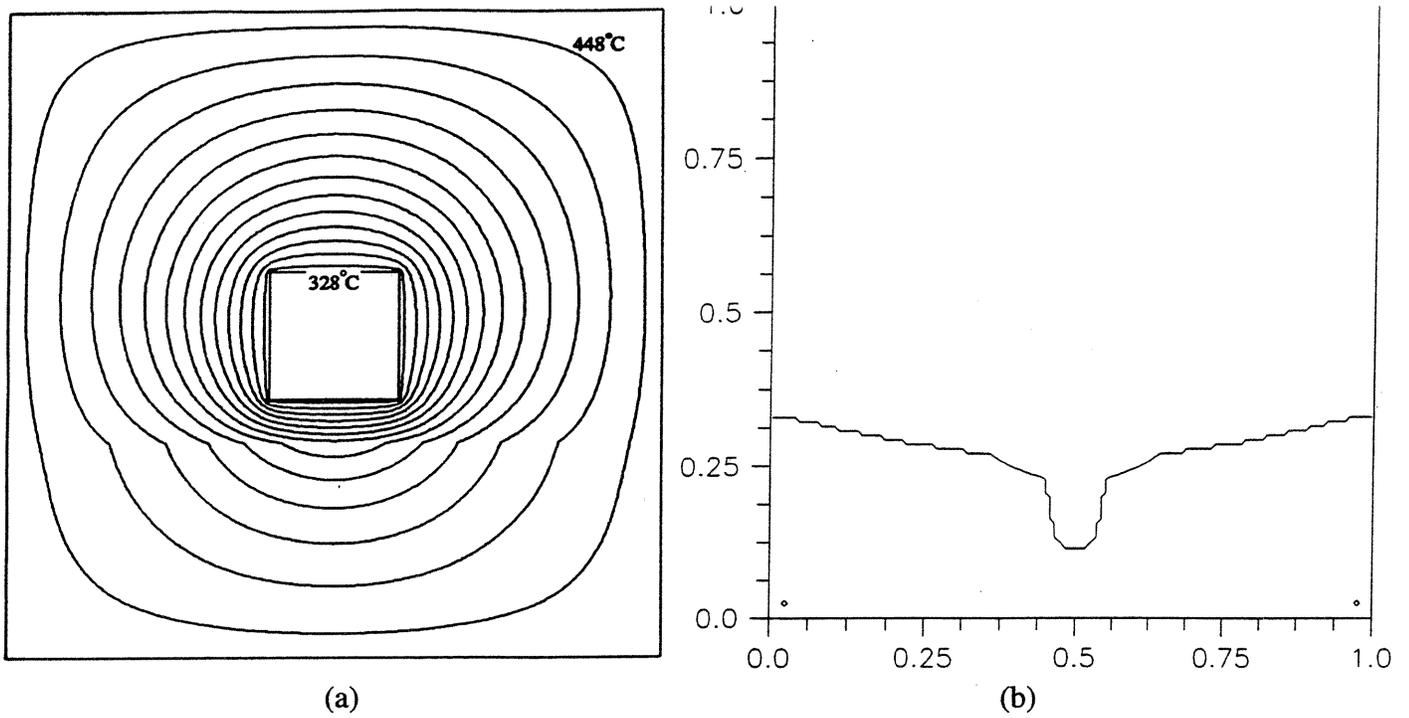


Figure 3. Temperature distribution and final part shape for conduction and radiation case.

Finally, adding convection to the previous case results in an increase in temperatures (Figure 4a) and sintering rates in regions to the left and right of the center tube. As a result of high sintering near the edges of the domain, the width and depth of the trough decrease as shown in Figure 4b. The crack dimensions change only slightly.

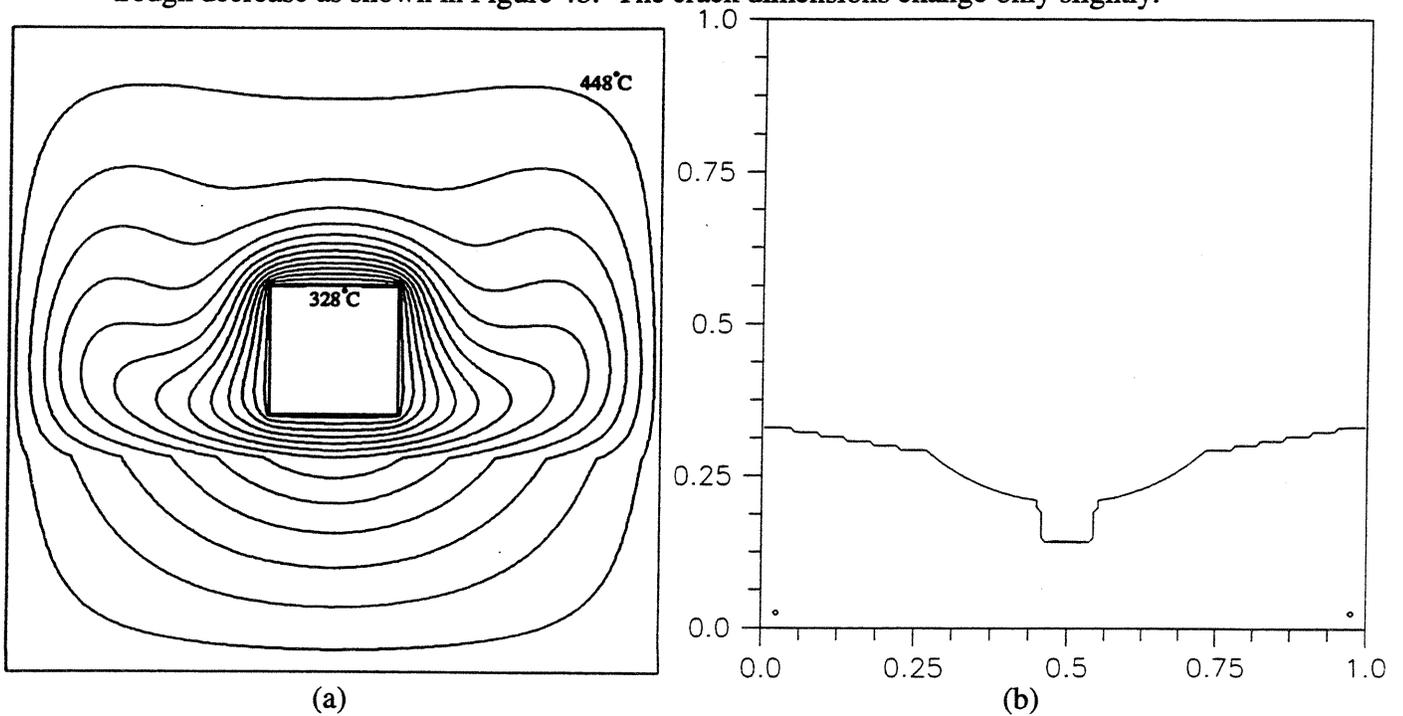


Figure 4. Temperature distribution and final part shape for conduction, radiation, and natural convection case.

Results from a sintering experiment (6 hours) of polycarbonate powder under identical conditions are presented in Figure 5. The sintered part has a solid and smooth texture along the bottom and sides (regions exposed to the hot outer tube) while the inner surface displays a soft, flaky appearance. Although not discernible from the photograph, a fine crack in the center of the trough runs axially along the length of the test specimen. Qualitatively, the part shape compares well with the shape in Figure 4b.

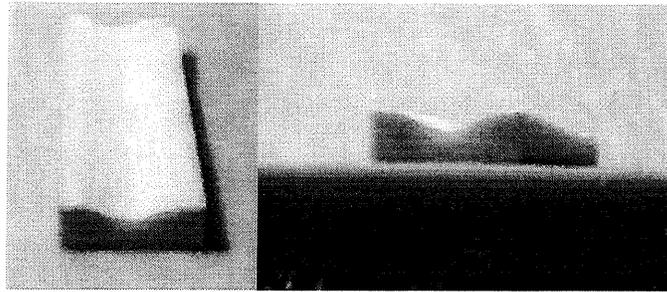


Figure 5. Experimentally-grown part shape.

CONCLUSIONS

The results presented in this study indicate that, for the material, geometry and thermal conditions considered here, surface radiation heat transfer has little effect on the temperature distribution and powder sintering. Only a marginal decrease in part growth is obtained with the inclusion of radiation. In contrast, natural convection (which may occur in large, buried voids which form in response to bed consolidation associated with part growth) can modify temperatures and sintering rates, in turn, affect part growth. Comparison with experimentally grown parts shows the influence of natural convection to be the more significant factor in determining part shape and growth.

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