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Dual-phase lag behavior of a gas-saturated porous-medium heated by a short-pulsed laser

Nazia Afrin, Yuwen Zhang*, J.K. Chen

Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO 65201, USA

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ABSTRACT

A dual-phase lag (DPL) model is used to investigate the heat conduction in a gas-saturated porous medium subjected to a short-pulsed laser heating. The energy equations for the powder and gas phase are combined together to obtain a DPL heat conduction equation with temperature of the powder layer as the sole unknown. A perfect correlation obtained from Laplace transformation is applied to analytically solve the DPL problem with internal heat source. The Riemann sum approximation is applied to find the inverse Laplace transform of the powder layer temperature distribution. Variations of powder temperature at heating and adiabatic surface and powder temperature distribution are studied. The results show that the analytical solutions are in a good agreement with the numerical solutions. The effects of phase lags times, pulse width, laser fluence, porosity on the DPL behavior of the gas-saturated powder layer are also investigated.

1. Introduction

Selective area laser deposition vapor infiltration (SALDVI) is a Solid Freedom Fabrication (SFF) technique in which porous layers of powder are densified by infiltrating the pore spaces with solid material deposited from a gas precursor during laser heating [1]. SALDVI process combines Selective area laser deposition (SALD) process and the Chemical vapor infiltration (CVI) process to directly fabricate ceramic and ceramic/metal structures and composites. Three dimensional object fabrications can be made in SFF from powder (Selective laser sintering; SLS), gas (SALD) and combination of both (SALDVI). It is very important to obtain the temperature distribution in the SALDVI process to understand the effect of the various processing parameters on the quality of the final products. The relative density of the powder layer continuously changes with processing time until it reaches near full density during the SALDVI process. Such continuous changes in the relative density cause the continuous changes in thermal conductivity of the SALDVI workpiece [2]. SALDVI utilizes Laser Chemical Vapor Deposition (LCVD) technique which can be based on reactions pyrolytically, photolytically or a combination of both [3]. Mazumder and Kar [4] presented a very detailed literature review about theory and applications of LCVD. A 3-D transient thermal problem for LCVD of a moving slab was solved analytically in Ref. [5]. They introduced Kirchhoff's transformation to linearize the heat conduction equation to account for the temperature-dependent properties; the boundary conditions are linearized by an effective convective heat transfer coefficient.

The SALDVI has a great potential due to several inherent features like to produce fully dense shapes without post processing, can make wide materials selection and can overcome the dimensional constraints that is present in traditional chemical vapor infiltration techniques. A significant change of porosity occurs during the SALDVI process and the properties of the powder layer structure are affected by the porosity change. The chemical reaction that occurs on the surface of the particles results the deposition on the surface of the powder and joining the powder particles together. The powder responds differently than a simple and fully dense material. Dai et al. [6] performed a numerical simulation of SALDVI using finite-element method. Before laser densification, the density of the powder layer was assumed to be 50% of its theoretical density and powder layer density become 100% of its theoretical value when the temperature of powder layer reaches to a maximum temperature. The same group also performed experiment using a closed loop control to achieve the constant temperature of powder layer by modifying the laser power from one time step to another [7].

* Corresponding author. Tel.: +1 573 884 6936; fax: +1 573 884 5090.
E-mail address: zhangyu@missouri.edu (Y. Zhang).

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They also improved the model that they used previously by introducing a densification model by vapor infiltration based on growth rate obtained experimentally [8].

Forced, mixed and free convection flows and heat transfer in fluid-saturated porous media are interesting topics to many researchers in geophysical and engineering applications [9–12]. Brouwers [13] investigated the heat and mass transfer between a permeable wall and a fluid saturated porous medium with the effects of wall suction or injection on sensible heat transfer. They applied thermal correction factor to investigate free, mixed and forces convection flows along vertical and horizontal permeable walls. Non-Darcy and Darcy effects on flow in fluid saturated porous media were reported. The generalized non-Darcy approach was applied to investigate double diffusion natural convection in a fluid saturated porous media [14]. Effect of surface fluctuation on the natural convection heat transfer of Darcian fluid saturated porous media was studied using finite element method [15]. Unsteady, laminar and 2-D hydro-magnetic natural convection in an inclined square filled with fluid saturated porous medium with transverse magnetic field was numerically investigated by Khanafer and Chamkha [16].

When the powder layer is heated by laser during SALDVI, the gas precursors are assumed to be transparent and the laser beam interacts only with the powder particles. Heat transfer occurs in two steps: first powder particles absorb the laser energy and then heat is transferred from the powder particles to the precursors. The time it takes that the temperatures of powder particles and gas phase reach to equilibrium is referred to as relaxation time. For long pulsed laser, the local thermal equilibrium assumption between powder particles and the gas is valid because the pulse duration is longer than the relaxation time. The short pulse laser has the advantage to control the porosity of the final product by controlling the LCVD on the powder layer surface via controlling pulse width and repetition rate. A non-equilibrium model for transport phenomena in the powder particles and gas needs to be developed if the laser pulse duration in the SALDVI is shorter than the relaxation time. Zhang [17] modeled the heat transfer in a gas saturated porous media with a short-pulsed volumetric heat source using a two-temperature model. The results showed that the degree of non-equilibrium in the process decreased with the increase of laser pulse width and become insignificant for the laser pulse width longer than 1 μs.

In this paper, the DPL behavior of the gas-saturated porous medium heated by a short-pulsed laser will be studied. The two energy equations are combined using operator method to obtain one equation with the temperature of the powder particle as the sole unknown. The analytical solution is compared with the finite-volume method solution, and the effect of phase lags in terms of heat capacities and coupling factor are discussed.

2. Physical model

Fig. 1 shows the physical model and coordinate system. A temporal Gaussian laser beam with a FWHM pulse width of t_p is irradiated to a power layer with a thickness L and initial temperature T_i. Due to the porous nature of the powder layer, the laser can penetrate the powder layer, which results in absorption of laser energy within the layer instead of at the surface of the layer. It is assumed that heat transfer is one-dimensional along the thickness of the powder layer because the size of the laser beam is much larger than thickness of the powder layer. The effect of chemical reaction heat on heat transfer along the thickness of the powder layer is negligible [18]. The porosity of the powder layer during irradiation of a single pulse is assumed to be constant due to the small amount of deposition in the duration of one short pulse. The convection effect

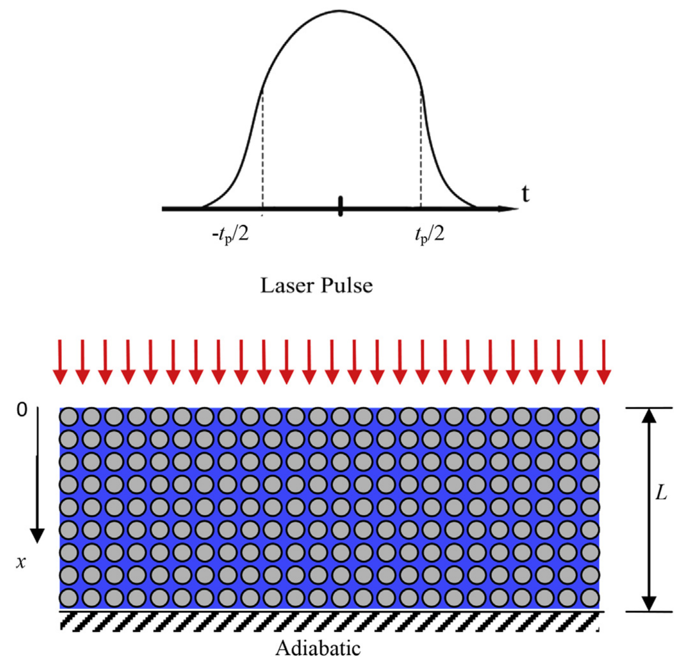

Fig. 1. Physical model.

in the gas phase is neglected since the pulse duration is very short. Under these assumptions, the problem becomes a simple heat conduction problem in a gas-saturated porous medium with an internal heat source.

A two-temperature model can be applied to describe the heat transfer in gas precursors and powder particles as they are not in thermal equilibrium. The energy equations of the powder particles (s) and the precursors (g) can be respectively expressed as:

$$(1-\varphi)(\rho c_p)_s\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k_{seff}\frac{\partial T_s}{\partial x}\right) + S - G(T_s - T_g) \quad (1)$$

$$\varphi(\rho c_p)_g\frac{\partial T_g}{\partial t} = G(T_s - T_g) \quad (2)$$

where k_{seff} and G are the effective thermal conductivity of the powder layer and the coupling factor between powder particles and precursors, respectively. In arrival to Eq. (2), heat conduction in the gas phase has been neglected because the conductivity of the gas is several orders of magnitude lower than that of the powder material. Light intensity of the laser beam appears as the volumetric heat source term in Eq. (1):

$$S(x,t) = 0.94J\left(\frac{1-R}{t_p\delta}\right)e^{-\frac{x}{\delta}-\frac{a|t-2t_p|}{t_p}} \quad (3)$$

where R is the reflectivity, δ is the optical penetration depth and $a = 4\ln(2) = 2.77$. The particular form of the light intensity is used to facilitate the direct use of the Riemann sum approximation for the Laplace inversion [19].

Combining Eqs. (1) and (2), the following energy equation can be obtained:

$$\frac{\partial^2 T_s}{\partial x^2} + \tau_T\frac{\partial^3 T_s}{\partial x^2 \partial t} + \frac{1}{k_{seff}}\left(S + \tau_q\frac{\partial S}{\partial t}\right) = \frac{1}{\alpha}\frac{\partial T_s}{\partial t} + \frac{\tau_q}{\alpha}\frac{\partial^2 T_s}{\partial t^2} \quad (4)$$

where the phase lag times of the heat flux vector and temperature gradient are: