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Temperature Fields Characteristics on Removal Rock by High-Energy Lasers

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Abstract. Laser drilling technology is a new feasible and developing method of rock destruction. Th unified modeling method of laser and rock interaction is a complicated subject of heat transfe science. According to the energy conservation law, the fundamental equation of heat transfer i established. Some primary parameters such as enthalpy, thermal conductivity and specific heat ar simplified respectively on the liquid-gas interface or the liquid-solid interface. The genera mathematical model of temperature fields on laser drilling process is proposed. Using the Galerkin method, the numerical investigation of a practical example in laser drilling rock is analyzed.

Introduction

The removal rock by high-energy lasers recently becomes one new approach of rock destruction methods [1]. The basic principle of laser drilling technology is that high-power laser beam exposures directly the surface of rocks, which makes the rock into melting or gasifying state by a sudden surge and produces the gas-liquid mixture. Then, the high-speed aided gas flow is used to carry the mixture away in order to form borehole rapidly. The results on rock sample test show that, when the energy density of laser beams exceeds critical specific energy, the penetrating speed of laser rock destruction is highly faster than the mechanical rate of penetration of traditional rotary methods with roller cone bits or PDC bits on the corresponding formations. Meanwhile, as the high-energy laser beam drills through the rock sample, the skin burn points on rock surfaces occur in varying degrees, which definitely will change the physical properties of original rocks. Therefore, it is necessary to further analyze the temperature field by high-energy laser removal rock and research about its heat effect.

In the progress of removal rock by high-energy lasers, the rock surfaces in laser spot center and its surroundings will go through the immediate rock phase transitions from solid to liquid, and then from liquid to gas. The rock transition is a complex 3D unsteady thermal problem that revolves heat conduction, heat convection, mass transfer, heat radiation transfer and other branches of cross-disciplinary sciences. Based on heat transfer theory, the mathematical model of temperature fields which stimulates the rock transition from solid, liquid to gas state is established, which lays the foundation for the further study of the removal rock by high-energy lasers.

The Basic Equations for Heat Transfer

In the experiments of laser rock destruction, the focal length of lens is larger than the thickness of rock samples, and the high-energy laser beam can be regarded as Gauss Beam. It is known that the heat affected zone around laser spots mainly focuses on the partial regions of the rock, and this zone is very small comparative with the size of the whole rock. Thus it is allowed that the heat transfer problem of the removal rock by high-energy lasers can be analyzed as the semi-infinite object's thermal conductivity [2]. Based on heat transfer theory, therefore, the transient thermal balance differential equation of any infinitesimal in the inner part of rock body under the condition of constant pressure is as follows:

$$\frac{\partial}{\partial t}(\rho H)=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q_v$$

Here, ρ is the density of rock, its unit kg/m^3; t is the time of progress, its unit s; k is the thermal conductivity, W/(m·K); q_v is the inner heat source strength of the temperature field caused by the physical or chemical effect, w/m^3; T is the absolute temperature, K and H for the heat enthalpy, J/kg. There is another equation $H = Q + CT$, Q is the latent heat of material while crystallization or phase transformations, J/kg; C is the specific heat capacity of rock at constant pressure, J/(m^3·K); x, y and z are the coordinate components of right-hand coordinate system, m. Fig.1 is a diagram of high-energy laser beam penetrating through the rock.

The general rule of temperature field distribution inside the homogeneous isotropic continuity in Cartesian Coordinates is described in Eq.1. Combining the specific boundary conditions with initial conditions, the quantitative solution about temperature field distribution of laser rock destruction can be obtained.

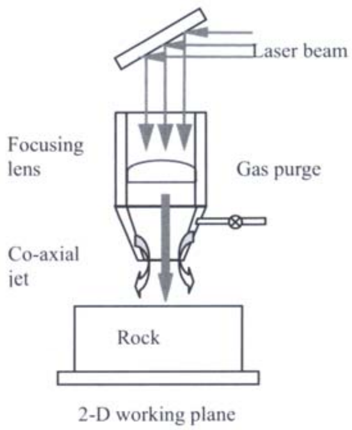

Fig. 1 Scheme of laser rock destruction

Modeling Phase Transition in Heat Transfer

In the operation of rock destruction by high-energy lasers, the rock phase transition happens instantaneously, which means that multiple complex interfaces such as solid-liquid mixed interface, liquid-gas mixed interface exist in the rock under laser spots. On these mixed interfaces large amount of latent heat can be absorbed or release. Even though rock transition occurs momentarily, the temperature difference is enormous from solid to liquid or from liquid to gas so it is very different to classify the temperature field with the simple geometric interfaces. When the temperature field goes through the transition zone of rock, endothermic or exothermic action emerges on the interface of phase transition so that a strong non-linear problem and instability frequently appear. Hence, the temperature field of multi-phase mixed interfaces of laser rock destruction is more complex than the moving boundary hypothesis of two-phase interfaces proposed by J. Stephan [3].

Solid-liquid Zone. Assuming the factor, f_S, present the dimensionless rate of solid substance in solid-liquid zone. While f_S=0, it presents that only liquid state exists in solid-liquid zone. While f_S=1, it presents that only solid state exists. If $0< f_S <1$, it presents solid and liquid co-exist in solid-liquid zone.

It is supposed that the endothermic latent heat of rock transition is proportional to the factor f_S, and f_S is proportional to the square of temperature. Thus, the following equations are given.

$$Q = Q_L(1 - f_S) \tag{2}$$

$$f_S = [(T - T_{BL})/(T_{BL} - T_{TS})]^2 \tag{3}$$

Here, Q_L stands for the latent heat value of rock transition from solid to liquid, J/kg; T_{TS} stands for upper critical temperature of rock keeping solid state, K; T_{BL} stands for the lower threshold temperature of rock changing into liquid state, K.

Then, the relationship between the enthalpy and temperature is

$$H = \begin{cases} C_S \cdot T & f_S = 1 \\ (C_S + C_L) \cdot T/2 & 0 < f_S < 1 \\ C_L \cdot T & f_S = 0 \end{cases} \tag{4}$$

Here, C_S, C_L stand for the specific heat capacity of rock at constant pressure in solid state or liquid state respectively, J/(m^3·K).

Similarly, the relationship between the density and temperature is

$$\rho = \begin{cases} \rho_S & T \le T_{TS} \\ (\rho_S + \rho_L)/2 & T_{TS} < T < T_{BL} \\ \rho_L & T \ge T_{BL} \end{cases}$$

Here, ρ_S and ρ_L stand for the density of rock in the solid and liquid state, kg/m^3.
The relationship between the thermal conductivity and the temperature of rock is

$$k = \begin{cases} k_S & T \le T_{TS} \\ k_S + \frac{(k_L - k_S)}{2} \cdot \frac{(T - T_S)}{(T_L - T_S)} & T_{TS} < T < T_{BL} \\ k_L & T \ge T_{BL} \end{cases}$$

Here, k_S and k_L stand for the thermal conductivity of rock in solid or liquid state respe W/(m·K).

Liquid-gas Zone. Similar to the solid-liquid zone, it is assumed that the factor, f_G, pre dimensionless rate of gas substance in liquid-gas zone. While f_G=0, it presents that only liqu exists. While f_G=1, it presents that only solid state exists. If 0< f_G <1, it presents gas and co-exist. It is supposed that the endothermic latent heat of rock transition is proportional factor f_G, and f_G is proportional to the cube of temperature. Thus, the following equations are

$$Q = Q_G \cdot f_G$$

$$f_G = [(T_G - T)/(T_G - T_{TL})]^3$$

Here, Q_G stands for the latent heat value of rock transition from liquid to gas, J/kg; T_G sta upper critical temperature of rock keeping gas state, K; T_{TL} stands for lower threshold tempera rock changing into gas state, K.

Then the relationship between the enthalpy and temperature of rock is as follows.

$$H = \begin{cases} C_G \cdot T & f_G = 1 \\ (C_G + C_L) \cdot T / 2 & 0 < f_G < 1 \\ C_L \cdot T & f_S = 0 \end{cases}$$

Here, C_G stand for the specific heat capacity of rock at constant pressure in gas state, J/(m^3·
Similarly, the relationship between the density and temperature is

$$\rho = \begin{cases} \rho_L & T \le T_{TL} \\ \rho_L + \frac{(\rho_G - \rho_L)}{2} \cdot \frac{(T - T_{TL})}{(T_G - T_{TL})} & T_{TL} < T < T_G \\ \rho_G & T \ge T_G \end{cases}$$

Here, ρ_G stands for the density of rock in the gas state, kg/m^3.
Further the relationship between thermal conductivity and the temperature of rock is

$$k = \begin{cases} k_L & T \le T_{TL} \\ k_L + \frac{(k_G - k_L)}{2} \cdot \frac{(T - T_{TL})}{(T_G - T_{TL})} & T_{TL} < T < T_G \\ k_G & T \ge T_G \end{cases}$$

Here, k_G stands for the thermal conductivity of rock in gas state, W/(m·K).

Case Analysis

Under the atmospheric pressure and temperature, the measured rock density of water-saturated sandstone samples for laser rock destruction is 2.27×10^3 g/m^3, with thermal conductivity being 2.754 W/(m·K), and special capacity 1.055×10^3 J/(Kg·K) [3, 4] . The laser spot diameter is 6.35 mm, with the laser pulse width being 4 s, and the maximum pulse power 6.5 KW.

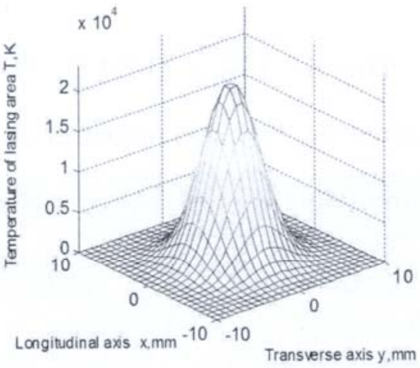

Fig. 2 Temperature field of drilling rock

Galerkin's differential equation is used to analyze the laser temperature field based on the above-established model. To simplify the work of the mathematical calculation, it is assumed that the thermal physical parameters of rock materials in every phase transition are only related to the temperature while other variables such as the pressure and the surrounding factors have nothing to do with it. Fig.2 shows the instantaneous distribution of temperature field above the rock surface during high-energy laser radiating on rock samples as t=2 s.

It is seen that in the light spot region(x= ±2.54 mm, y= ±2.54 mm), the average temperature of rock is greater than 15500K, far over the gasifying point temperature of a given sandstone. The temperature within the spot center is highest and it gets lower along the fringe of laser beam. The temperature distribution is basically the same to the spatial distribution of laser beam energy. Away from the light spot centre, the surface temperature would decrease rapidly. In addition, with the growth of pulse time in a laser single pulse, the average spot temperature increases, its vaporizing core extended and the evaporating rock aggrandized. However, there is no obvious increase of temperature around the outer region of laser light spot field.

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