International Refereed Journal of Engineering and Science (IRJES)
ISSN (Online) 2319-183X, (Print) 2319-1821
Volume 7, Issue 6 Ver. I (Jun 2018), PP. 01-04

Higher Energy State In The Conduction Band Regarding Quantum Of Optical Energy
(Study On Quantum Mechanical Treatment Of Radiant Energy)

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Abstract : *The temperature rise produced by absorbed laser flux densities below the levels which produce melting and vaporization of the surface has already been considered. Methods of calculating heating effects in various cases of interest are found in literatures. The results on metallic absorbing surfaces are easily adapted to other surfaces. Use of classical thermodynamics formalism is generally made. In metals, light is absorbed by interaction with electrons. A quantum of optical energy is absorbed by an electron which is raised to a higher energy state in the conduction band. The excited electrons collide with lattice photons and with other electrons and give up their energy. These are the same collision processes which govern the transfer of heat. We will, however, find an expression for temperature distribution for a slab moving with a definite velocity. Using hyper-geometric function, in the mathematical treatment, we will show that the temperature distribution is continuous across the boundary of a pencil-shaped source. Brugger's result will be shown to be a particular case of the above result. We can therefore, regard the optical energy as being instantaneously turned into the heat at the point at which the light was absorbed. Therefore, the concept of temperature will* be valid and we are justified in applying the usual equations for heat flow.

Date of Submission: 09-07-2018 Date of acceptance: 23-07-2018

THEORY:

The idea of the instantaneous point source of heat i.e. of a finite quantity of heat instantaneously liberated at a given point and time in an infinite solid has proved most useful in the theory of conduction of heat. The solution for the instantaneous point source is taken as fundamental. By integration with respect to time the solution for the continuous point source, corresponding to release of heat at a given point at a prescribed rate has been obtained. Solutions for instantaneous and continuous line, plane spherical surface, and cylindrical surface sources, have also been obtained by integration under simple physical interpretation. The problem in which sources of heat move through a fixed medium or as cases of heat production at a fixed point past which a uniformly moving medium flows, were also solved by in of the solutions for instantaneous sources.

The temperature rise produced by absorbed laser flux densities below the levels which produce melting and vaporization of the surface has already been considered. Methods of calculating heating effects in various cases of interest are found in literatures. The results on metallic absorbing surfaces are easily adapted to other surfaces. Use of classical thermodynamics formalism is generally made. In metals, light is absorbed by interaction with electrons. A quantum of optical energy is absorbed by an electron which is raised to a higher energy state in the conduction band. The excited electrons collide with lattice photons and with other electrons and give up their energy. These are the same collision processes which govern the transfer of heat.

In time of the order of the duration of a laser pulse, the electrons which absorb the photons will make many collisions, both among themselves and with lattice photons. The energy absorbed by an electron will be distributed and passed on to lattice. We can therefore, regard the optical energy as being instantaneously turned into the heat at the point at which the light was absorbed. The distribution occurs so rapidly on the time scale of Q-switched and normal laser pulses that we can regard a local equilibrium established rapidly during the pulse. Therefore, the concept of temperature will be valid and we are justified in applying the usual equations for heat flow. This assumption may break down for the case of picoseconds pulses. During the absorption of picoseconds duration pulse, there will not be time for the energy to be distributed among particles by the collision processes. The energy received by the electron which absorbs a quantum may be coupled into the lattice relatively slowly on a picoseconds time scale. Several types of heat of conduction of heat–transfer applications involve the determination of transient temperature in a material heated over a portion of its surface. Typical applications include the heating of metal plates with laser. High powered lasers have been used to drill holes in high purity high-temperature fired-alumina ceramic material. Un-Chul Paek and Francis P. Gagliano in their paper consider thermal and mechanical effects in the alumina material due to the interaction of a high-powered ruby laser beam with the surface. They found it possible for the material to be fractured simply because of the thermal stresses include during the drilling process. Hence the range of drilling parameters of a laser which govern the fracture phenomenon could be determined.

We will, however, find an expression for temperature distribution for a slab moving with a definite velocity. Using hyper-geometric function, in the mathematical treatment, we will show that the temperature distribution is continuous across the boundary of a pencil-shaped source. Brugger's result will be shown to be a particular case of the above result.

1.1 Axially **symmetric heat source regarding quantum of optical energy:**

Starting from the well known temperature distribution due to an instantaneous point source in an unbounded medium, we formulate a solution in a moving slab for the axially symmetric heat source. Let us consider the instantaneous point source located at the point (X', Y', Z'). It liberates an amount of heat Q ρ C_p instantaneously in an infinite medium where Q, ρ and C_p stands for instantaneous point source strength, material density and specific heat respectively.

The differential equation of unsteady conduction of heat,

$$\frac{1}{K}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \tag{1.1}$$

is satisfied by

$$T(x, y, z, t) = \frac{Q(X',Y',Z')}{8(\pi kT)^{3/2}} \exp\left\{\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4kt}\right\} \tag{1.2}$$

where k represent thermal diffusivity.

The above solution for temperature is only valid in the infinite medium and it should be modified to satisfy the following boundary conditions:

(i) for the semi finite body (half space)

$$\frac{\partial T}{\partial z} = 0, \quad z = 0, \quad T = 0, \qquad z = \alpha \tag{1.3}$$

(ii) for a plate of thickness d (d is finite)

$$\frac{\partial T}{\partial z} = 0, \quad z = 0, \quad T = 0, \qquad z = d \tag{1.4}$$

Suppose that heat is emitted at the origin for time t > 0 and that an infinite medium moves uniformly past the origin with velocity U parallel to the axis of x. Hence the above expression for T modifies to, (for point source)

$$T(x, y, z, t) = \frac{Q(X',Y',Z')}{8(\pi kT)^{3/2}} \exp\left\{\frac{\{(x-U\,t)-x'\}^2+(y-y')^2+(z-z')^2}{4kt}\right\} \tag{1.5}$$

The distance R between any point (x, y, z) and the source point (X', Y', Z') can be described in polar co-ordinates as

$$\begin{aligned} R^2 &= \{(x-U\,t)-x'\}^2 + (y-y')^2 + (z-z')^2 \\ &= (X-X')^2 + (y-y')^2 + (z-z')^2 - 2(x-x')\,U\,t + U^2t^2 \\ &= \underline{\gamma}^2 + \underline{\gamma}'^2 - 2\underline{\gamma}\,\underline{\gamma}'\cos(\theta-\theta') + (z-z')^2 + 2\underline{\gamma}\cos\theta\,U\,t + 2\underline{\gamma}'\cos\theta\,U\,t + U^2t^2 \end{aligned} \tag{1.6}$$

The above instantaneous point source may now be considered being distributed around the origin with radius r' in the plane z' = 0 and having its strength Q r'$d\theta'$ for the angle $d\theta'$. Assuming rotational symmetry of the source strength, the expression for T is given by

$$\begin{aligned} T(\gamma, z, t,) = \frac{Q(\underline{\gamma}')\underline{\gamma}'}{8(\pi kt)^{3/2}} \int_0^{2\pi} exp\left[-\frac{\underline{\gamma}^2 + \underline{\gamma}'^2 - 2\underline{\gamma}\,\underline{\gamma}'\cos(\theta-\theta') + z^2}{4kt}\right] \\ .\, exp\left[\frac{2\underline{\gamma}'\cos\theta\,U}{4k}\right] \cdot exp\left[-\frac{2\underline{\gamma}'\cos\theta'\,U}{4k}\right] \cdot exp\left[-\frac{U^2t}{4k}\right] d\theta' \end{aligned} \tag{1.7}$$

A continuous source solution can be obtained from the above expression by simply superimposing the solution from 0 to t and by integrating it with respect to r' from 0 to a, the radius of the disc.

$$\begin{aligned} T(\gamma, z, t,) = \int_0^a \int_0^t \frac{Q(\underline{\gamma}', t')\underline{\gamma}'\,dr'}{8[\pi k(t-t')]^{3/2}} \cdot \int_0^{2\pi} exp\left[-\frac{\underline{\gamma}^2 + \underline{\gamma}'^2 - 2\underline{\gamma}\,\underline{\gamma}'\cos(\theta-\theta') + z^2}{4k(t-t')}\right] \cdot \\ exp\left[\frac{2\underline{\gamma}'\cos\theta\,U}{4k}\right] \cdot exp\left[-\frac{2\underline{\gamma}'\cos\theta'\,U}{4k}\right] \cdot exp\left[-\frac{U^2(t-t')}{4k}\right] dr'dt' \end{aligned} \tag{1.8}$$

where the differential thickness dr' of the ring in the direction of r' has been taken into account resulting in,

$$Q(r') = q\,(r't')dr' \qquad (1.9)$$

According to the method of images for an insulated boundary at which $\frac{T}{2}$ = 0, all image points are sources. For a boundary maintained at T = 0, equidistant points are occupied by source and sink pairs. For the material having finite boundary thickness d, the sources and sinks are located at z' = $\pm$ 2.n.d along the z-axis, where n is zero or integer.
The solution is given as

$$T(\gamma, z, t,) = \int_0^a \int_0^t \int_0^{2\pi} [\ \frac{Q(\underline{\gamma}',t')\underline{\gamma}'d\underline{\gamma}'}{8[\pi k(t-t')]^{3/2}} exp\left[-\frac{\underline{\gamma}^2 + \underline{\gamma}'^2}{4k(t-t')}\right] exp\left[\frac{2\underline{\gamma}\,\underline{\gamma}'\cos(\theta-\theta')+z^2}{4k(t-t')}\right]$$

$$\cdot \left[1 + 2\sum_{n=1}^{\infty} cos\frac{n\pi z}{d}\ \exp[-\frac{kn^2\pi^2(t-t')}{d^2}]\right] . \exp\left[\frac{2\,\gamma\cos\theta.U - 2\gamma'\cos\theta' U}{4k}\right]$$

$$. \exp\left[\frac{U^2\,(t-t')}{4k}\right]\ ]\ d\gamma' dt' d\theta' \qquad (1.10)$$

Integration of θ part gives,

$$T(\gamma, z, t,) = \int_0^a \int_0^t \ \{\ \frac{q(\gamma',t')}{2dk(t-t')} \cdot \exp[-\frac{\gamma^2+\gamma'^2}{4k(t-t')}] \cdot$$

$$\left[1 + 2\sum_{n=1}^{\infty} cos\frac{n\pi z}{d}\ \exp[-\frac{kn^2\pi^2(t-t')}{d^2}]\ \exp\{\frac{U\gamma\cos t}{4k}\}\right]$$

$$\cdot \exp\left[\frac{-U^2(t-t')}{4k}\right] I_0\left(\sqrt{\alpha^2 + \beta^2 + 2\,\alpha\beta\cos\theta}\right)\}\ \ d\gamma' dt' \qquad (1.11)$$

Where I_0 is the modified Bessel's function,

$$\propto = \frac{U\gamma'}{2k} \qquad \text{and} \qquad \beta = \frac{\gamma\gamma'}{2k(t-t')} \qquad (1.12)$$

For further calculations we assume that the axially symmetric laser beam is incident along the z-axis and heat the slab. The slab is assumed to be homogeneous and isotropic. Consequently for a time t lager than the duration of laser pulse the beam can be considered as an instantaneous heat source of strength

$$q\,(\gamma' t') = Q_0 t(r')\ \exp(-\frac{z}{\underline{z}}) \qquad (1.13)$$

where it has been assumed that the laser intensity decays exponentially with characteristic length $\underline{z}$. Thus we can write

$$T(\gamma, t, x,) = \int_0^a \int_0^t \int_0^d \ \{\frac{Q_0 f(\gamma)\gamma'}{3k(t-t')d}\ \exp[-\ \frac{\gamma^2+\gamma'^2}{4k(t-t')}]\ \cdot\exp\{\frac{\gamma U\cos\theta}{-2k}\}$$

$$\cdot \exp[\ \frac{-U^2(t-t')}{4k}]\ I_0\left(\sqrt{\alpha^2 + \beta^2 + 2\,\alpha\beta\cos\theta}\right) \exp(-\frac{z}{\underline{z}})$$

$$\left[1 + 2\sum_{n=1}^{\infty} cos\frac{n\pi z}{d}\ \exp\{-\frac{kn^2\pi^2(t-t')}{d^2}\}\right]\ \ \}\ dz\ d\gamma' dt'$$

(1.14)

If both boundaries are insulating and the characteristics length $\underline{z}$ is much larger than the slab thickness d (thin plate), we get radial flow of heat as

$$T(\gamma, t,) = \int_0^a \int_0^t \ \{\frac{Q_0 f(\gamma)\gamma'}{2k(t-t')}\ \exp[-\ \frac{\gamma^2+\gamma'^2}{4k(t-t')}]\ \cdot\exp\{\ \frac{\gamma U\cos\theta}{2k}\}$$

$$\cdot \exp[\ \frac{-U^2(t-t')}{4k}]\ I_0\left(\sqrt{\alpha^2 + \beta^2 + 2\,\alpha\beta\cos\theta}\right)\ \}\ d\gamma' dt' \qquad (1.15)$$

Assuming the beam intensity to be constant over the cross section r$\leq$ a, we can put f (r') = 1, for r $\leq$ a = 0, outside. Hence for such sources we have

$$T(\gamma, t,) = \int_0^a \int_0^t \ \{\frac{Q_0}{2k(t-t')}\ \exp[\ -\ \frac{\gamma^2+\gamma'^2}{4k(t-t')}]\ \cdot\exp\{\ \frac{\gamma U\cos\theta}{2k}\}$$

$$\cdot \exp[\ \frac{-U^2(t-t')}{4k}]\ \exp\left[-\frac{\gamma'^2}{4k\,(t-t')}\right] I_0\left(\sqrt{\alpha^2 + \beta^2 + 2\alpha\beta\cos\theta}\right)\ \}\ d\gamma' dt' \qquad (1.16)$$

Putting,

$$\lambda = \left\{U^2(t-t')^2 + \underline{\gamma}^2 - 2\underline{\gamma}U(t-t')\cos\theta\right\}^{\frac{1}{2}} \qquad (1.17))$$

We can write equation (1.16) as

$$T\,(\underline{\gamma},t) = \int_0^t Q_0\{\frac{1}{2k(t-t')}\int_0^a \exp\,[-\ \frac{\gamma^2+\gamma'^2}{4k(\,t-t')}]\ I_0[\,\frac{\gamma'}{2k(t-t')}]d\underline{\gamma}'\}dt'$$

$$=\int_0^t Q_0 a\left\{\int_0^\infty e^{-k(t-t')\mu^2} T_0(\mu\lambda)\, T_1(d\mu)d\mu\right\} dt' \tag{1.18}$$

The integral,

$$\int_0^\infty e^{-k(t-t')\mu^2} T_0(\mu\lambda)\, T_1(d\mu)d\mu = \frac{a}{4k(t-t')}\sum_{m=0}^{\infty}\frac{1}{k\underline{\gamma t}}\left\{-\frac{\lambda^2}{4k(t-t')}\right\}^m$$

$$=\frac{1}{a}\left\{1-exp\left(\frac{a^2}{4k(t-t')}\right)\right\}+\exp\left\{-\frac{a^2}{4k(t-t')}\right\}\left[-\frac{a\lambda^2}{\{4k(t-t')\}^2}-\frac{a\lambda^4}{4\{4k(t-t')\}^3}\left\{2-\frac{a^2}{4k(t-t')}\right\}\frac{a\lambda^6}{36\{4k(t-t')\}^4}\left\{\left(-\frac{a^2}{4k(t-t')}\right)^2+6\left\{-\frac{a^2}{4k(t-t')}\right\}+6\right\}+\cdots\cdots\right]$$

$$(\text{ for } \lambda > a\ ) \tag{1.19}$$

where ${}_2F_1\left(-m,\ -m;\ 2;\ \frac{a^2}{\lambda^2}\right)$ is Gauss's hyper- geometric function.

Substitution of (1.9) in (1.18) yields the final expression for temperature distribution for a pencil source. For U=0 and r=0 this final result reduces to

$$T = Q_0\int_0^t\left[1-exp\left\{-\frac{a^2}{4k(t-t')}\right\}\right]dt' \tag{1.20}$$

This is the same as obtained by Brugger (1992).

Same expression for the right hand side of the above equation (1.19) is obtained for the case $\lambda < a$.

CONCLUSION:

Consideration of case $\boldsymbol{\lambda} > a$ or $\boldsymbol{\lambda} < a$ suggests that the temperature distribution is continuous across the boundary of the spot of the laser beam. As has already been suggested previously (Paek, U.C 1972) regarding fracture, the above consideration of velocity of medium can, therefore, have control over fracture phenomena. Thus, the above result may extend help in the desired estimation of power of incident radiation for several requirements. Further works in this field may be done with different types of source under different physical conditions of the material. The problem in which sources of heat move through a fixed medium or as cases of heat production at a fixed point past which a uniformly moving medium flows, were also solved by in of the solutions for instantaneous sources.

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Inchina V.I''Phytocorrection Of Metabolic Disorders In Glucocorticoid Hyperglycemia ” International Refereed Journal of Engineering and Science (IRJES), vol. 07, no. 06, 2018, pp. 01-04.