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A Mechanical Analogy for Heat Transfer in Surface Films with Transformations

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Abstract:- **A model for describing effects of a variable frequency heat source on the surface of a film is developed. The effect of material parameters is analyzed to describe possible attenuation of the thermal fluctuations and sustaining these through coupling with the surrounding matrix. Application to amorphous alloy formation with phase field concepts is described. An analogy with a damped oscillator driven by surface fluctuations gives the relation of non-dimensional parameters like the Stefan, Fourier and Biot numbers to surface heating with convection. Recent discoveries of high-temperature superconductivity in the femtosecond regimes are included. Impurities and stress fields caused by large oxygen atoms and interaction with the phonon field may be responsible for such effects especially in the "crust" of oxide films. Phonon interactions with driven oscillators in the film may be possible and design of suitable materials to give sustained longer duration high-temperature effects is outlined.**

Keywords- Acrylonitrile Butadiene Styrene, Additive manufacturing, Copper, Electroplating.

INTRODUCTION

The heat transfer through a surface film with transformations and surface heat transfer is the focus of this study. In the following, I derive a mechanical analog to heat transfer in contrast to the well known electrical analog. Basically a second order differential equation , with first order terms, for the heat transfer process can be likened to a LRC circuit.
This analog has been used for transient heat transfer and radiative heat transfer successfully to model complicated geometries and interactions [1]. A recent study also used the analogy to optimize heat exchanger networks [2]. Table (1) illustrates the equivalent analogical parameters for electrical and mechanical analogies.

Table 1:Comparisons for the analogies

LUMPED HEAT TRANSFER ANALYSIS ANALOGY		
Electrical	**Coefficients in differential Eqn**	**Heat transfer**
L Mass	**coefficient of y"**	**ρCp/L**
R Stiffness	**coefficient of y**	**Bi**
C damping	**coefficient of y'**	**Fo**

In the area of heat transfer modeling, the hydraulic and electrical analogies have been used for steady state and transient states. Some of the earlier works described in [3, 4], outline earlier efforts at analog computational type of solvers before the digital computer became readily available. The analogy approach has been used to predict parameters for a particular physical basis using measurement from another physical system, as in the Chilton-Colburne analogy. However, the mechanical analog to the heat transfer equations has not been reported. The analogy is of relevance in that heat and mechanical motion are intimately connected through the molecular and atomic vibrations. The vibrations can be given a quantitative value through the temperature and it is conceptually easy to identify the vibration with heat content, whereas, for the electrical analog there is no direct physical relation.

ANALYSIS

It is well known that radiation and heat transfer models can be modeled by electrical circuits using various approximations. One of these is the lumped parameter approximation, using discrete electrical elements. Basically a second order differential equation for the heat transfer process can be likened to a LRC circuit.

The space and time parameters are combined into a similarity parameter η, resulting in an equation in one variable for the eqns (1) and (2). This artifice enables the equation in x and t to be treated as an o.d.e. As it turns out the diffusion equation with transient terms become linear. In

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the mechanical counterpart, we use a spring mass damper equivalent.

The coupled second order system of equations given in [5], is analogous to a coupled spring mass system and can be solved for the resonant frequencies using an exponential form for the solution.

$$K\nabla^2 T + \varepsilon L d\,c/dt = \rho C_p dT/dt \quad (1)$$

$$\alpha_m \nabla^2 c + \Gamma \alpha_m \nabla^2 T = dc/dt \quad (2)$$

The coupled equations can be written as, with simplifications on the parameters, and assuming a generic solution $T=\exp(\lambda t)\exp(\gamma x)$, $c=\exp(\mu t)\exp(\nu x)$

$$\lambda T = \alpha\gamma^2 T + (\varepsilon L/\rho c_p)\ \mu c \quad (3)$$

$$\mu c = \alpha_m \nu^2 c + a_m \Gamma\gamma^2 T \quad (4)$$

In eqn(4), if the term Γ is neglected is neglected as is usually done, the resonant frequencies are easily found in terms of λ and m. If the same disturbance is used, the time frequency may be set to the disturbing frequency.

In general the system of equations has two resonant frequencies which can be obtained from the above by evaluating the determinant of coefficients. When concentration-temperature coupling Γ is very small ,the second equation can be decoupled from the first with only one dominant resonant frequency. Making use of the artifice that the solvus line is linear, the first order derivatives in time can be related to each other through the slope. In the mass transfer equation, the mass transfer Biot number is used (Bi_m). In the analysis by [6,7] the lumped parameter can be used if the Bi_m is less than 0.1, that is the role of mass diffusion in the bulk is negligible.

Consider the equation for heat diffusion, coupled with a mass diffusion through transformation

$$K\nabla^2 T + \varepsilon L d\,c/dt = \rho C_p dT/dt \quad (5)$$

After some rearrangement, we get

$$\alpha\nabla^2 T + (\varepsilon L/\rho C_p) d\,c/dt = dT/dt \quad (6)$$

Similarly, for the mass component

$$\alpha_m \nabla^2 c + \Gamma d\,T/dt = dc/dt, \quad (7)$$

The derivative for concentration is related to surface flux through the mass transfer Biot number (Bi m). In the event the concentration equation has temperature derivative terms (Soret effect) then a coupled system of equations occurs with the eigenvalues found in the usual way. To simplify the analysis, I use here the temperature equation with the mass coupled (Dufour effect).

The space and time parameters are combined into a similarity parameter, given an equation in one variable. Using the well known combination $\eta = x/(\alpha t)^{0.5}$;the coupled differential equation transforms to

$$T' + \eta/2\ T' + (\varepsilon L/\rho c_p)\ \eta/2\ c' = 0 \quad (8)$$

Remains to relate the $(\mathbf{dc/d\eta})$ term to temperature. By making use of the phase solvus, for a phase change with latent heat L in eqn(8)

$$dc/dx = g\,dT/dx, \text{ where } g = dc/dT \quad (8a)$$

Incorporation of the surface boundary condition: the convection at the surface is used and the derivative term becomes the Biot number multiplied by the surface temperature difference. The condition appears as stiffness in the differential equation, and is equivalent to a coupling with the boundary. Thus we can have a loose coupling or a tight coupling depending on the heat transfer away or into the matrix from the surface, analogous to a mechanical boundary that may have variable attachment to a support.

$$[D^2 + \eta/2\ D + (eL/q_m c_p)\ Bi/2g\ ]\ T = 0 \quad (9)$$

$$[D^2 + Fo/2\ D + (e\ Ste)\ Bi/2g\ ]\ T = 0 \quad (10)$$

Transition from non-oscillatory to oscillatory solutions given by:

$$\mathbf{\eta^2/16 = \varepsilon L/(g\,\theta_m\,c_p)\ Bi} \quad (11)$$

$$\mathbf{Fo^2 = 16\,\varepsilon\ Ste\ Bi/g} \quad (12)$$

Let $\mu_o = g\,\theta_m\,cp/(\varepsilon L) = g/(\varepsilon\ Ste)$, a simplified equation for small parameter analysis :

$$\mathbf{\mu_o \theta'' + 0.5\mu_o Fo\ \theta' + 0.5Bi\ \theta = 0} \quad (13)$$

DISCUSSION AND RESULTS

The frequencies for the concentration and thermal equations need not be the same. However the thermal oscillations of the molecules and clusters would be related to the concentration fluctuations leading to homogenous nucleation, and may be related by the solvus or phase line slopes. A damping effect associated with the surrounding lattice field would slow down the oscillations of individual atoms and molecules which would enhance formation of

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clusters leading to homogenous nucleation. Admittedly there are many more factors associated with the phase field approach. This analysis indicates the possibility of such a mechanism from purely macroscopic and thermal parameters, using the lumped parameter approach. The advantage of using the similarity transform is in allowing the oscillations to be viewed as spatial at fixed time, or as time varying at any fixed location.

The verification for this analysis can be found in the experimental results reported for the production of glassy surface films. Use of the phase field approach relates the frequency of nucleation with the disturbing frequency set up by thermal vibrations. If a proper tuning can be set up it is possible to avoid homogenous nucleation and obtain glassy films. This has been reported by others, [8].

Another interesting effect may be found in reports of Lattice dynamics (phonon vibrations) as an aid in enhancing superconductivity, and evidence of short term superconductivity in SrRuO have been reported by [9] and [10]. The results given in [10] indicate the possibility of sustained superconductivity for small or larger times due to possible phonon interactions with the lattice distortions in certain alloys, among other causes. It is suggested here that macroscopic effects related to the boundary conditions may be responsible for sustaining oscillations caused by surface laser pulses and associated phonon oscillations together with electron pairing. The effect of the electron pairing may result from excess electrons present on the molecules or atoms together with the coupled vibrations. Electron concentration may then be related to the mass diffusion representation.
effects of boundary conditions on the stability and Since the effect of the Laplacian diffusive field given by the foregoing equations exhibit strong damping out tendencies, the values of the macroscopic parameters within the quadratic discriminant must be such that the exponent becomes imaginary so as to allow oscillations. It is acknowledged, that there are other factors which are not covered by the present field mode, which needs to be extended with more relevant data.

CONCLUSIONS

The coupled diffusion equations describing heat and mass transfer are shown to represent a coupled dynamic system after suitable transformations. The oscillatory properties of microscopic entities are highlighted. Coupling between the thermal and concentration/mass equations can be modeled as phonon and electron components, whereby sustained phonon electron oscillations could be sustained with appropriate external excitation. Applications to phase field concepts and amorphous structure formations are also possible.

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NOMENCLATURE

c concentration

c_p specific heat

D differential operator

Fo Fourier number

Bi ,Bi_m Biot numbers

Ste Stefan number

h heat transfer coeff.

a boundary length

g temperature concentration gradient

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K thermal conductivity

k thermal diffusivity

L latent heat

m mass

Q source strength

r radial variable

s interfacial position $s = 2\lambda \sqrt{(\alpha\tau)}$

T temperature

t time

x length coordinate

GREEK Symbols

α, κ diffusivity (subscript m for the mass component)

β Decoupling constant (depends on the problem)

δ Characteristic length

γ exponents

Γ thermo coupling parameter

ε porosity

η similarity variable

θ_m non dim temperature

ν exponent

λ exponent

μ_o small perturbation parameter (not to be confused with chemical potential) τ non-dimensional time

θ non-dimensional temperature

ρ Density

∇ nabla or gradient derivative

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