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Surface roughness effect as a source of hyperdiffusion ?

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Abstract : We have studied heat diffusion from rough surfaces in different materials exposed to a constant heating and we observed anomalously slow temperature rises over about 3 time decades which indicate a hyperdiffusion phenomenon.

1. INTRODUCTION

Heat diffusion in heterogeneous media is quite complicated and mixture-theories are often unable to explain heat transfer that is not stationary. For a few years, the development of the fractal formalism has enabled a very efficient description of the structure of disordered media and has even furnished some explanations to dynamical phenomena in these media. For example it was shown in 1982 [1] that diffusion in a fractal structure is anomalous in the sense that the diffusion length is no longer proportional to $\sqrt{t}$ but rather to t^α where $\alpha < 0.5$. In this case one refers to hypodiffusion (the diffusion is so slow that one cannot explain the phenomenon with a diffusivity value lower than expected: here the diffusivity is no longer defined), hyperdiffusion will occur when $\alpha > 0.5$. More generally one could talk about anomalous diffusion in a medium as soon as a random walk on this medium does not obey the central limit theorem in its classical form [2].

Here we are concerned with surface roughness effects on diffusion properties in homogeneous and heterogeneous materials. For both types, we noticed an effect which seems to be similar to a hyperdiffusion phenomenon and whose duration expands over about 3 time decades.

2. EXPERIMENTAL SET-UP

As shown in figure 1, we use an argon laser as heating source; using an electro-optical cell ("Pockels cell") followed by a polarizer, we generate an optical step from an electrical step. This light illuminates the surface of a sample placed at the first focus of an elliptical mirror and an IR detector (centered at 10.6 μm) located at the second focus allows us to follow the sample surface temperature elevation versus time. We have checked that our experiment corresponds to the following conditions :

- sample opacity for visible and IR lights in order to have surface absorption and surface emission.
- 1 D geometry : the laser spot and the sample sizes remain always greater than the diffusion length during the experiment (the conditions are those of a semi-infinite wall heated on its whole surface).

The steps are repeated at low frequency and we record a temperature elevation averaged over about one hundred steps.

Fig. 1: Experimental set up

3. EXPECTED RESULTS

With these conditions, for homogeneous material (i.e. well defined thermal diffusivity and conductivity) whose surface is smooth, the temperature elevation versus time and depth $T(z,t)$ is solution of the classical 1 D diffusion equation :

$$\frac{\partial^2 T(z,t)}{\partial z^2} - \frac{1}{D} \cdot \frac{\partial T(z,t)}{\partial t} = -q_0 \cdot \frac{H(t)\delta(z)}{K}$$

where D and K are the thermal diffusivity and conductivity, H the Heaviside function, δ the Dirac distribution and q_0 the absorbed power.

The solution is then easily obtained by a time integration of the Green function of this equation. One finds:

$$T(z,t) = 2H(t) \cdot \frac{q_0}{K} \cdot \sqrt{\frac{Dt}{\pi}} \cdot \exp\left(-\frac{z^2}{4Dt}\right) + H(t) \cdot \frac{q_0 z}{K} \cdot \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right)$$

In the case of surface emission, the observed signal is proportional to $T(0,t)$ and we expect : $T(0,t) \propto \sqrt{t}$

4. EXPERIMENTAL RESULTS

We present the results obtained with a low value carbon resistor (homogeneous composition) and with a composite sample made of graphite, alumina and other oxides (used in steel industry). In both cases, we studied in the same conditions a sample with a rough surface (made by sawing) and another one with a polished surface. The curves we present were obtained by superposition of two recordings; we show in log-log scale temperature rises during the period (30 μ s-10ms) for the composite and (100 μ s-100ms) for the carbon. The sawed composite sample presents a peak to valley roughness of 80 μ m and the carbon sample a peak to valley roughness of 40 μ m.

As it can be seen in figures 2 and 3, the polished samples present results very close to the expected ones (cf. lines with 0.49 and 0.48 slope in log-log scale), however, the rough samples show a temperature rise quite linear over about 3 time decades but with a slower slope than expected.

Rough carbon : we see an anomalous behaviour between 100 μ s and 100 ms with a temperature elevation proportional to $t^{0.42}$

Rough composite : we observe a temperature rise proportional to $t^{0.40}$ between 30 μ s and 10 ms

Fig. 2 : Temperature responses of carbon samples to a step heating

Fig. 3 : Temperature responses of composite samples to a step heating

5. DISCUSSION

These results were obtained for an irradiation of the sample close to normal incidence and we could fear some bias due to an inhomogeneous surface power distribution, this seems not to be the case: when we used an illumination with a very large aperture (about 120 degrees), the anomalous results remain i.e. the observed slopes are smaller than 0.5.

The temperature elevations that we recorded were of about a few degrees; under these conditions, radiation is completely negligible compared to the total heat transfer and it is quite easy to show that the convective transfer is much smaller than the conductive one, which justifies the use of a purely diffusive model. A simple approximation of the conductive flux is $\Phi_{cd} = K.(T_{surf} - T_{air})/\mu$ where K is the thermal conductivity and μ the thermal diffusion length (in a classical diffusion problem, $\mu = 2\sqrt{Dt}$), in a same way the convective flux is $\Phi_{cv} = h.(T_{surf} - T_{air})$ where h is the convective coefficient of our problem. For natural free convection, $h = 10 \text{ W.K}^{-1}.\text{m}^{-2}$ is a typical value of convective coefficient, if we consider alumina that is the main component of the composite we have studied, $K \approx 20 \text{ W.K}^{-1}.\text{m}^{-1}$ and $D \approx 10^{-5} \text{ m}^2.\text{s}^{-1}$ then for times smaller than one second $\Phi_{cv} / \Phi_{cd} \approx 10^{-3}$.

In terms of diffusion, for a given amount of absorbed energy, having a slower than expected temperature rise means that during the period of anomalous behaviour, because of the surface topography, the heated mass (and also the thermal diffusion length in our 1D problem) grows faster than $\sqrt{t}$. In that sense, what we observed is a hyperdiffusion-like phenomenon (the contrary of hypodiffusion encountered on percolation clusters at the critical threshold given for instance by [3] [4]).

To our knowledge this type of phenomenon has never been observed, a first attempt to explain it can be that roughness causes first an impediment in diffusion and that this impediment diminishes whereas the diffusion length grows with time compared with the roughness of the material. The great duration of this anomalous behaviour would be due to the great number of roughness scales that exist at the sawed surface. In recent years it has appeared that rough surfaces could be described very efficiently with a self affine approach (self affine sets are not purely fractal because they are not self similar but it is possible to keep the major concepts of fractals). In cooperation with S. Roux from ESPCI, Paris we aim also to model these hyperdiffusive phenomena thanks to this new formalism.

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