THE INDUCTIVE HEATING OF PACKED BEDS AND ITS APPLICATIONS TO COMPACT FLUID HEATERS AND TO THE REGENERATION OF SPENT ACTIVATED CARBON

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ABSTRACT

In this paper, a method is presented in order to predict the behaviour of a granular medium submitted to an inductive electromagnetic field. The resulting model is intented to give an easy and reliable characterization of energy transferred to the bed. A series of experiments was carried out and permitted a validation of the hypothesis formulated over a wide domain.

A first application was studied aiming at the sizing of heaters using a stainless-steel balls bed percolated by a cold fluid. Experimental investigation of temperature profiles in both solid and fluid phases and of heat transfer coefficients between them lead to the realization of a compact fluid heater working with small difference of temperature and good efficiencies.

This technique was then applied to the heating of activated carbon beds so as to allow a fast and performing regeneration.

INTRODUCTION

Although induction has proved for long to be an efficient way of bringing huge energy fluxes into electrically conductive materials, its applications remain almost restricted to the metallurgic industries, where it is devoted to the heating of homogeneous pieces.

On the other hand, process and chemical engineering assign a great importance to granular media whenever transfer phenomena occur between a solid and a fluid phase, since they provide considerable contact areas and ensure high values of transfer coefficients.

The matter with inductive heating is that, when applied to a homogeneous material, it generates what is called "skin effect", which means that eddy currents appear in a narrow depth nearby the piece periphery : thus, what is usually seen as an advantage of inductive heating, especially in surface treatment, may bring no betterment to a granular medium, by drastically reducing the active contact area. However, if inductive heating showed to be even in a packed bed, it would be an important improvement compared to all the existing techniques of heating a granular medium.

The aim of this work is then to investigate the behaviour of packed beds submitted to alternative magnetic fields, and especially in two domains basically different, for the chemical engineer as well as for the electrotechnician : in a first case, we will describe the heat transfer between a fluid and a granular bed of highly (electrically) conductive material, and then the mass transfer from a bed of spent activated carbon (comparable to a semi-conductor).

MODEL PRESENTATION

Maxwell's equations

The effects of a magnetic field generating the so-called inductive heating are ruled by Maxwell's equations :

$$\mathrm{rot}\,(H) = J \quad , \quad \mathrm{div}\,(D) = \sigma$$
$$\mathrm{rot}(E) = -\frac{\partial B}{\partial t} \quad , \quad \mathrm{div}(B) = 0$$

where $D = \varepsilon E$, $B = \mu H$, and $J = \gamma E$ if electric displacement is neglected.

One understands easily that the resolution of such a system of equations may cause some problems. It is generaly performed through the study of a given domain on the frontiers of which boundary conditions are known - this method requiring the use of a netting of this domain, this netting being hardly suitable with the notion of granular media.

Some simplifications may result of the inductor geometry : provided this inductor is long enough in regard of its diameter (in fact, its length must be at least equal to the diameter),it generates a magnetic field that can be considered as uniform inside the volume it delimits.

Moreover, some shapes allow facilities in the writing of the system above : for example, resolution can be carried out quite easily in the case of thin or infinite plates, cylinders, tubes [1]... Unfortunately, no such simplification may rise from the study of a granular medium. On the other hand, an analogy can be defined that could make this calculation readily feasable : as shown on fig.1, in a first step, randomly packed bed can be considered as a bundle of regular piles, each pile being then supposed to behave like a homogeneous cylinder.

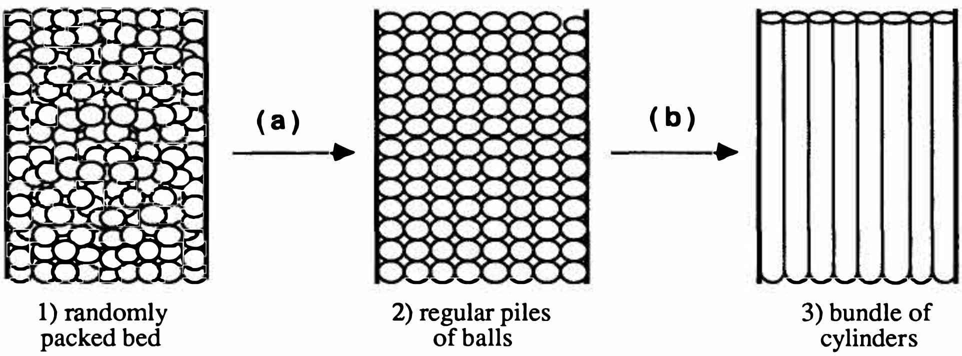


FIGURE 1 : case of a granular bed : two-step analogy

Hypothesis

In order to realize the calculations, we adopt the following hypothesis :

* the inductor is perfect, which means that its length-to-diameter ratio is greater or equal to one; in that case, the inductive field is uniform and parallel to the coil axis.

* the bed is made of spherical and identical particles; bed porosity is uniform and not influenced by reactor walls.

* the cylinders are identical, and their length is equal to the reactor height; they have the same diameter D_b as the balls constituting the bed, and are made with the same material; their total mass is that of the granular bed - so that the calculated behaviour keeps the same meaning in terms of heat generation.

Remembering that power dissipation in a cylinder can be expressed by [1] :

$$P_u = \frac{4\pi^2 R N^2}{L} \sqrt{\frac{10^{-7} \mu_r f}{\gamma}} \, F \, I_e^2$$

The load behaviour can thus be caracterized by an equivalent electric resistance [2] :

$$R_{eq} = \frac{4\pi^2 R N^2}{L} \sqrt{\frac{10^{-7} \mu_r f}{\gamma}} \, F$$

this resistance enabling the calculation of power dissipation in the load from the value of current in the inductor coil.

The conservation of the total mass present in the reactor gives the number of fictitious cylinders :

$$N_c = (1 - \varphi) \left(\frac{D_c}{D_b}\right)^2$$

Assuming these cylinders are electromagnetically independant (due to their high length-to-diameter ratio permitting to consider each of them as a perfect inductor), the total equivalent resistance of a load consisting in a granular bed symbolized by a bundle of Nc cylinders will then by expressed by :

$$R_{eq} = (1 - \varphi) \frac{2 \pi^2 D_c^2 N^2}{L D_b} \sqrt{\frac{10^{-7} \mu_r f}{\gamma}} F$$

EXPERIMENTAL APPARATUS

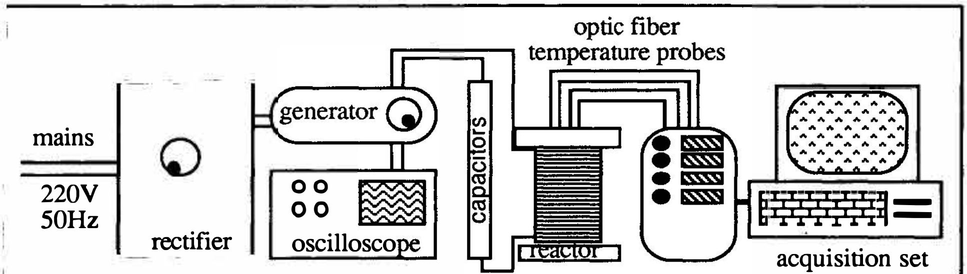


FIGURE 2 : experimental installation

The experimental installation is composed of (fig. 2) :

* a 82 mm - ID, 100 mm - high reactor circled with a 52 turns inductor coil. It is plugged to a generator delivering alternating current with a frequency ranging from 4 to 20 kHz; a set of capacitors enables the circuit to work in resonance conditions.

* an oscilloscope providing the electric characteristics of this circuit; from the values of current, voltage and frequency imposed to the coil one can deduce the load impedance by comparison with the behaviour of the empty reactor and thus the way energy is transferred from the inductor.

* a set of optic fiber temperature probes linked to a computer, allowing the recording of up to four temperatures; the use of optic fiber is made necessary since classic thermocouples would be inductively heated [3]. These probes are intended to make sure temperatures are even in the granular medium ; they also can give a thermodynamic definition

of the electric equivalent resistance :

$$P_u = R_{eq}\, I_e^2 = m\, Cp\, \frac{\partial T}{\partial t} \rightarrow R_{eq} = \frac{m\, Cp\, \frac{\partial T}{\partial t}}{I_e^2}$$

* the granular media investigated were lead balls beds with granulometries of 1.8, 3, 3.8, 5, and 7.65 mm. Lead was chosen for its amagnetic properties avoiding the problems linked to the determination of the permeability ($\mu_r = 1$).

MODEL VALIDATION

Figure 3 summarizes the comparisons of experimental equivalent resistances of the different granular beds we tested with the corresponding values predicted by the model.

The figure shows a good agreement between calculations and experimental measurements, which means that the idea of considering a granular bed as a bundle of cylinders is justified; moreover, the arbitrary hypothesis of assigning to these cylinders the same diameter than the particles constituting the bed is validated.

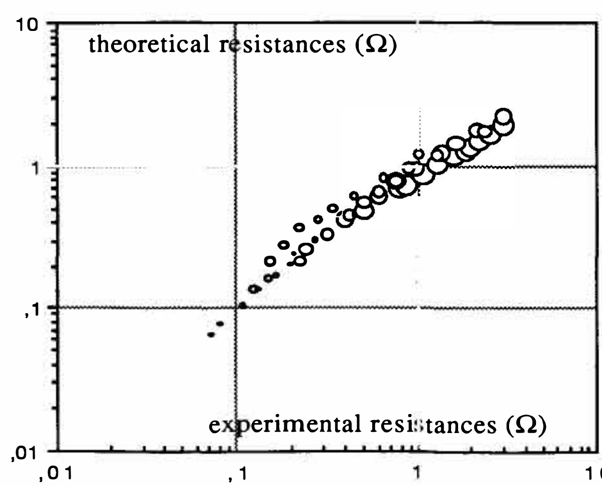
One can also notice a slight divergence for higher values of bed granulometry, the difference remaining negligible : in the aggregate, the model shows to be globally reliable.

The conclusion that rises from the observation of these results is that the modelling of a granular bed behaviour when submitted to an inductive electromagnetic field is easily feasible, despite the difficulty of a rigorous integration of Maxwell's equations.

FIGURE 3 :

equivalent resistances of lead balls beds : comparison between theory and experience.

- Pb 7,65 mm
- Pb 5 mm
- Pb 3,8 mm
- Pb 3 mm
- Pb 1,8 mm



APPLICATION TO FLUID HEATERS

Two of the main interests of granular beds are the considerable contact surface existing between them and the surrounding medium, and, when this medium is a percolating fluid, the high values of transfer coefficient resulting of the turbulent flow conditions. That is why their use is widely spread in process engineering each time a transfer (mass - as well as heat - transfer) takes place between a solid and a fluid [4].

Heat transfer coefficients have been investigated [5] : it showed that the traditional good values of coefficients are not affected by the inductive field. Experiments gave the following relation for the calculation of heat transfer coefficient :

$$Nu = 0{,}55\ Re^{0{,}8}$$

This expression, compared to that of Colburn-Mac Adams, predicts values of transfer coefficients about 20 times higher for a granular heater than for a classical tubular exchanger, with usual values of bed granulometries and tubes diameters. It results in especially compact apparatuses, allowing little pressure drops.Another point is that the high global energetic efficiencies usually encountered with induction are still available [2] : varying with frequency, they can easily exceed 80 % whereas traditional methods harly allow values of 40-50 %.

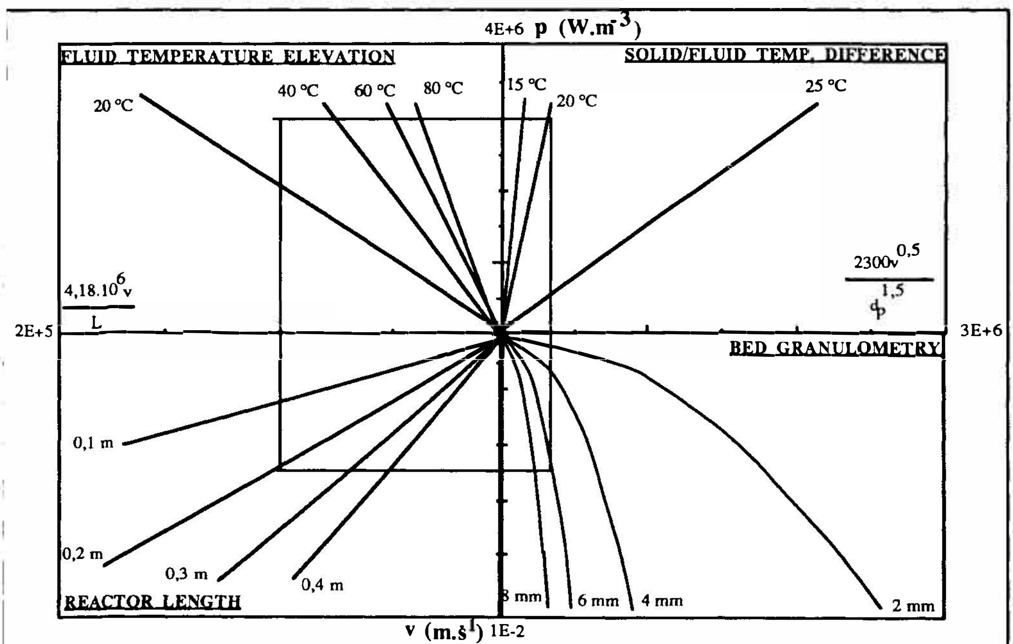


FIGURE 4 : SCALING ABACUS

This experience in both power transmission from inductor coil to granular medium and heat transfer between solid matrix and fluid enabled us to define a method for scaling a heater taking into account such parameters as fluid flow, maximum temperature difference between solid and fluid phases. Figure 4 displays an example of the thermal part of this scaling, adapted to a fluid with physico-chemical properties comparable to that of water. The case represented by a rectangle plotted on the abacus indicates that for a 0.2 m-long heater (bottom left corner) percolated by a fluid having a velocity of 5mm/s (intersection of base with vertical axis), an increase of 30 °C of the fluid temperature (top left corner) with a maximum solid/fluid temperature difference of 20 °C (top right corner) requires the use of 6 mm-diameters balls in the bed (bottom right corner) and a power dissipation of 3 MW/m^3 (intersection of the top with vertical axis). Working frequency and inductor/load energy transmission efficiency will then depend on the material the bed is made with.

APPLICATION TO SPENT ACTIVATED CARBON REGENERATION

Activated carbons have been known for long for their qualities as filtering agents for industrial effluents [6]. Their cost and environmental concerns make it necessary to regenerate spent beds and to recover or destroy desorbed products.

The regeneration requires an energetic supply to the bed, supply that takes three traditional forms :

* A first way consists in heating the bed through the vessel walls [7]: due to the poor thermal conductivity of activated carbons, high temperature gradients result between the core and the periphery of the bed, leading to either an unachieved regeneration in the former, or an overheating of the latter with possible damages to the products or even to the carbon itself.

* A technique permitting homogeneous energy input in the spent bed consists in having it percolated by hot gases [8] : homogeneity is then reached, but in the other hand, desorbed products are submitted to an important dilution, which is a nuisance to the downstream operations (aiming at their recycling or at their destruction).

* A third method uses steam in the place of hot inert gases [9], the main energy flux being brought in under the form of vaporization enthalpy of water.The resulting dilution is more acceptable, but this process requires a steam-production unit and can give rise to undesirable chemical reactions between water and desorbed products.

Inductive heating could then be a way of performing desorbtion with good efficiencies and little dilution, the carrier gas flow rate being hopefully limited to natural convection : indeed, the Chilton-Colburn analogy gives good hopes of obtaining enhanced mass transfer coefficients, as it is the case for heat transfer. Experiments were conducted on activated carbon beds at frequencies of 880 kHz and 3.3 MHz, with results concerning local power dissipation presented on fig. 5 :

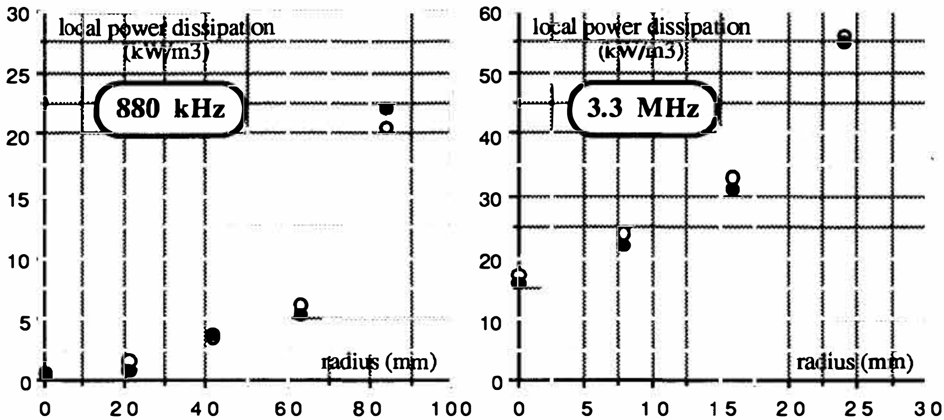


FIGURE 5 : evolution of local power dissipation profiles with frequency two different determinations (see text)

This power dissipation can be determined by two different ways : the first one (black dots) consists in following local temperatures, taking into account radial dispersion; the second (white dots) is focused on moments when this radial dispersion is negligible (beginning of the heating) or deduceable (reaction to the power input cut-off).

Experiments at 880 kHz were made with a 195 mm-wide, 200 mm-high bed. The power dissipation profile shows a behaviour identical to that of a homogeneous piece of electrically conductive material : this profile is characterized by high values at the periphery, rapid decrease linked to the skin effect and a value of zero at the very center of the bed.

In compensation, results obtained at 3.3 MHz (on a 57 mm-wide, 90 mm-high bed) reveal a neat evolution of the behaviour : skin effect is still observable with higher power dissipation in the periphery than in the core, but the energy generated is definitely non-null at r=0, which means that we cannot link this profile to one obtainable in a homogeneous medium.

Comparing these results with the even profile resulting of experiments at 4 to 20 kHz on metal balls beds, we can deduce that the induction effects on granular beds evolve progressively with frequency between two extremes : at "low" frequencies (as it is the case for activated carbon at 880 kHz), eddy currents develop themselves following the reactor periphery. On the opposite, at "high" frequencies (metallic beds), these currents remain confined in each granule independantly from its situation in the bed. And experiments on activated carbon at 3.3 MHz show that an intermediate domain lays where intra-granular and peripheric eddy currents coexist.

CONCLUSION

This study indicated that application of inductive heating to granular media is justified in terms of energetic efficiency and homogeneity. It also pointed out that a quite simple model exists providing good prediction of the behaviour of such an installation.

A consequence of this technique is the opportunity of sizing compact apparatuses allowing high energy transfer rates. Moreover, such equipments are interesting to operate since they are all-electrical : it makes them reliable, safe, clean and easy to automate.

The method investigated here for transfering energy shows qualities that can make it of great importance for many potential applications, provided working frequency is adapted to the load characteristics (granulometry and physico-chemical properties) in order to preserve homogeneity of heating.

NOMENCLATURE

B	magnetic induction	Tesla
Cp	load heat capacity	J/kg°C
D	electric displacement	C/m^2
D_c, D_b	cylinders and inductor diameters	m
E	electric field	V/m
f	frequency	Hz
F	power transmission factor	-
H	magnetic field	A/m
I_e	effective current in the inductor	A
J	current density	A/m^2
L	reactor length	m
m	load mass	kg
N	coil's number of turns	-
N_c	number of fictitious cylinders	-
Nu	Nusselt number	-
P_u	power dissipation in the load	W
R	cylinder radius	m
Re	Reynolds number	-
R_{eq}	equivalent electric resistance	Ω
T	temperature	°C
t	time	s

Greek letters :

ε	electric permittivity	F/m
γ	electric conductivity	$(\Omega m)^{-1}$
φ	bed void fraction	-
μ, μ_r	magnetic permeability, relative -	C/m
σ	electric charges density	C/m^3

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