EXPERIMENTAL STUDY OF HOT SPOTS
IN ACTIVE PACKED BEDS

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FIGURES
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>$C_s$</td>
<td>specific heat of solid</td>
<td>Joule kg$^{-1}$ °C$^{-1}$</td>
</tr>
<tr>
<td>D</td>
<td>packed bed diameter</td>
<td>m</td>
</tr>
<tr>
<td>$D_p$</td>
<td>particle diameter</td>
<td>m</td>
</tr>
<tr>
<td>$E_0$</td>
<td>A.C. field amplitude</td>
<td>volt m$^{-1}$</td>
</tr>
<tr>
<td>$f$</td>
<td>A.C. field frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>L</td>
<td>packed bed length</td>
<td>m</td>
</tr>
<tr>
<td>$P$</td>
<td>dissipated power</td>
<td>Watt</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
<td>[-]</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>sec</td>
</tr>
<tr>
<td>$T_s$</td>
<td>solid temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$V_0$</td>
<td>superficial velocity</td>
<td>m sec$^{-1}$</td>
</tr>
<tr>
<td>$v_s$</td>
<td>volume of solid</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>universal dielectric constant</td>
<td>M.K.S.A.</td>
</tr>
<tr>
<td>$\varepsilon_r , \text{tg} \theta$</td>
<td>dielectric factor</td>
<td>[-]</td>
</tr>
<tr>
<td>$\nu$</td>
<td>kinematic viscosity</td>
<td>m$^2$ sec$^{-1}$</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>solid density</td>
<td>kg m$^{-3}$</td>
</tr>
</tbody>
</table>
A test facility developed at the von Karman Institute to simulate hot spots in gas cooled thermal reactors using fuel packed beds is described.

A series of typical results is discussed which confirm the good tuning of the test set-up and proves the existence of hot spots.

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1. INTRODUCTION

In the field of nuclear power production the technology of gas cooled gas reactors based on coated particle fuel elements is being developed.

This advanced design should lead to higher heat fluxes, thus giving more compact units at a given nominal power.

Research has already been carried out on key thermo-hydraulic problems with emphasis on safety aspects (Refs. 1, 2, 3).

In particular, it is important to ascertain that no local temperature peaks develops in the reactor core as a result of local variations of the power dissipation due to local changes of the void fraction.

An experimental study is being conducted at the von Karman Institute using an original test facility which simulates the non uniform power dissipation of the real nuclear core.

The purpose of this note is to describe the test set-up in details and to discuss typical results which demonstrate the existence of hot spots.
2. HOT SPOT DEVELOPMENT

In a gas cooled fast reactor using coated particles, the core is formed by an assembly of fuel packed beds. Figure 1 shows typical fuel assembly arrangements. The coated particles are spherical ($D_p = 1$ mm), each dissipating about 1 Watt.

In fact the heat flux is not distributed uniformly in the core because of the following mechanisms:

- local variations of the fuel density which necessarily exist in a random packing (Refs. 4 and 5);
- local variations in heat production rate due to the variability of enrichment and of particle size (Ref. 3);
- local obstructions due to the retention of dust from the coolant gas by the packed bed (Ref. 2).

These different situations which are responsible for the development of hot spots in the reactor core are schematically represented in figure 2.

The present work is aimed at the study of the first mechanism.
3. SIMULATION METHOD

In the present experimental method, hot spots formation is simulated by the dielectric heating to a random packing of spheres.

3.1 Dielectric heating principle

This process of heating is based on the property of an insulating material, which electrical polarisation is not instantaneous.

The thermal dissipation which results from the dielectric hysteresis is homogenously and quickly distributed inside the entire volume of the material.

The power $dP$ dissipated in a small volume $dv_s$ of solid subjected to an A.C. field $E_0$ is expressed by the following equation

$$\frac{dP}{dv_s} = \pi \epsilon_0 (\epsilon_r \tan \theta) f E_0^2 \left[ \frac{W}{m^3} \right]$$  \hspace{1cm} (1)

where the product $\epsilon_r \tan \theta$ and $f$ are respectively the dielectric loss factor of the insulating material and the frequency of the A.C. field; $\epsilon_0$ being a universal dielectric constant ($0.885 \times 10^{-11}$ MKSA). The relation (1) may be slightly modified to obtain the rate of change of the solid temperature with time:

$$\frac{dT_s}{dt} = \frac{\pi \epsilon_0 (\epsilon_r \tan \theta) f E_0^2}{\rho_s C_s} \left[ \frac{^\circ C}{s} \right]$$  \hspace{1cm} (2)

$\rho_s$ is the density and $C_s$ is the specific heat of the solid.

The expression (2) plays an important role in the design of the test set-up. Indeed, it will enable the comparison between the theoretical predictions and the experimental results.
3.2 Simulation

Consider a random packing of spherical particles made of an insulating material which is placed in a strong electric field. Each particle becomes a heat source, the intensity of which is a function of its diameter and its dielectric properties.

The resultant temperature distribution depends on the particle concentration, i.e., on the void fraction variations in the bed and the type of cooling. With this method, it is possible to study either separately or at the same time, the effect of the different mechanisms of hot spots formations by just changing the following parameters:
- variation of void fraction  
  cause 1
- variation of particle size and dielectric properties  
  cause 2
- presence of blockages (artificial or not)  
  cause 3
4. PRELIMINARY TESTS

Some preliminary experiments were carried out in order to test the behaviour of the high frequency generator and the dielectric materials.

A packed bed of polyamide 6 spheres (3 mm in diameter) was located between the two electrodes of the generator (ELPHIAC type: 4 kw at 27 MHz). The rate of change of the mean bed temperature was first measured without cooling gas flow. Typical results are plotted in figure 3. They show a large increase of temperature. It may also be seen that the measured temperature increased faster than theoretically predicted by equation 2 above 40°C. This is due to the fact that the loss factor does not remain constant with temperature as shown in figure 4. Since this phenomenon amplifies the value of the temperature peaks, it does not prevent the correct location of hot spots. However, for the quantitative study of the temperature fluctuations, it is necessary to work in the linear range. Thus it is necessary to precool the packed bed by a cold gas flow before starting the generator.
5. TEST FACILITY

The general arrangement of the test facility is shown on the photograph in Fig. 5 and is schematically represented in figure 6.

5.1 Cooling circuit

Dry air is supplied from a high pressure reservoir. The mass flow rate is controlled by a pair of valves and is measured by a rotameter, the reading of which is corrected by the indicated static pressure measurement. In order to minimize the temperature effect on the dielectric properties of the packed bed material, the air may be precooled down to -10°C.

The cooling device involves an insulating tank containing 50 liters of methanol in which a freezer is immersed. A thermostat controls the temperature of the methanol bath in the range -20° to 12°C.

5.2 Active packed bed

Figure 7 is a close up photograph of the cylindrical test section. It is composed of three parts, each being contained in a pyrex tube:
- at the entrance, a calming zone composed of packed alumina particles, fine mesh screens and a honeycomb;
- the random packing of spheres (polyamide or glass) inserted between two electrodes which are made of fine mesh screens stretched across the tube. One electrode is connected to the high frequency generator whereas the other is connected to a Faraday box which protects the instrumentation chains against the powerful electromagnetic radiation. In order to ensure the electrical continuity, the Faraday box is earthed with the generator;
- a downstream extension of the tube to minimize the end effects.

These three parts are maintained together by straining screws.
5.3 Temperature measurements

Temperature distributions are measured at about 5 mm downstream of the active packed bed exit sections with a thermocouple mounted on a traversing mechanism which is shown in figure 8. This mechanism is supported by a plexiglass frame fixed on the Faraday box. It enables an angular displacement of the probe for any selected radial position. The displacements are electrically controlled. The temperature is recorded on Graphispot type recorder while the thermocouple rotates at constant velocity.

5.4 Method of testing

The gas flow is characterised by Reynolds number based on the sphere diameter $D_p$ and the superficial velocity $V_0$.

The test takes place according to the following process:
- the facility is operated at the desired mass flow rate until the inlet and exit temperatures are equal, i.e., until the bed is at a uniformly known temperature;
- then, the high voltage of the generator is switched on. After a rather short time a steady heat flow is established as shown in Fig. 9;
- the thermocouple is set in motion to explore the whole exit section.

The packed beds used are defined as following:

Model 1
- bed diameter $D = 33$ mm
- bed length $L = 40$ mm
- particle diameter $D_p = 3$ mm (polyamide 6)

Model 2
- bed diameter $D = 62$ mm
- length diameter $L = 40$ mm
- particle diameter $D_p = 3$ mm (polyamide 6) $2.5$ mm (glass-

For both models several random packings are tested.
6. RESULTS

6.1 Presentation and discussion

Figure 10 compares the temperature maps measured on model 1 for two random packings. The isothermal lines are labelled in percentage of the hot spot temperature. Reynolds number was not the same for the two surveys, however, tests made on one packing have proved that a variation in Reynolds number does not change the qualitative aspect of the temperature profiles. (see Fig. 11). Therefore, the main difference between the two results observed in Fig. 10 is only due to the random structure of the sphere packings. As may be seen there is only one hot spot in the first case while, for the second one, three temperature peaks of the same magnitude are detected.

In both cases, the hot spots are located between 0.5 and 1.5 sphere diameter from the container wall.
- A result which agrees with the finding of De Wasch and Froment (Ref. 6) who studied the heat transfer between the inert packed bed and the wall. Indeed, they noted the existence of a hump in the radial temperature profiles at about 1 \( \bar{d} \) from the wall.
- It is also confirmed by the results from several studies of local variations of void fraction in packed beds: the maximum amplitude of the solid concentration being found between 0.5 and 0.75 \( \bar{d} \) from the wall. Figure 12 gives some examples of void fraction profiles (Ref. 4).

Contours showing the complete average angular distribution as a result of smoothing a series of 50 histograms (Ref. 5) are shown in figure 13. A striking similarity with the temperature map of figure 10 is noticed.

Another test series, made with the second model, confirms the presence of hot spots. This packed bed being greater in size than the first one, the dissipated power is more important. This involves an increase of the solid temperature and, since the dielectric parameter rises like the temperature above
a certain level, that causes a self-supplied reaction in hot cells. This effect was such that occasionally clusters of spheres knitted together were observed after the test, as shown in fig. 14. It was noticed that, in these cells, the spheres tended to form either pyramidal or tetrahedral packings which had the smallest void fraction.

6.2 Conclusion

The test results demonstrated:
- the presence of hot spots,
- the stochastic nature of the phenomenon as a consequence of the random structure of the packing.
7. CONCLUSIONS

An experimental study on the development of the hot spots inside the core of gas cooled thermal reactors is being carried out at the von Karman Institute.

After describing the different mechanisms which are responsible for the temperature peaks, a simulation method is proposed in order to design an original test facility which is then presented in detail.

A series of tests demonstrate:
- on one hand, the existence of hot spots;
- on the other hand, the close correlation existing between the temperature profiles and the particle concentration.

Moreover, they proved the good tuning of the test facility.
REFERENCES


7. BASF Eigenschaften der Polyamide. Literatur s. 560.
FIG. 1 FUEL ASSEMBLY ARRANGEMENTS

SLAB BED

PARALLEL & OUTWARD FLOW

COUNTER FLOW
TEMPERATURE PEAK

CAUSE 1

GAS FLOW

CAUSE 2

CAUSE 3

FIG. 2 HOT SPOTS FORMATION
FIG. 3 TEMPERATURE INCREASE VERSUS THE RUNNING TIME OF THE GENERATOR

FIG. 4 DIELECTRIC LOSS FACTOR VERSUS THE SOLID TEMPERATURE: FROM REF. [7]
FIG. 5 GENERAL VIEW OF TEST FACILITY
FIG. 6 LAYOUT OF TEST FACILITY

- Probe displacement unit
- Electric drive
- Thermocouple
- Packed bed
- Electrode
- Faraday box
- High frequency generator
- Gas cooler
- Rotameter
- Control valve
- Dry air supply
- Calibration device
- Recorder
- Hot spot
- Insteady
- Steady
- Pressure measurement
FIG. 8 PROBE DISPLACEMENT MECHANISM
FIG. 9: TRANSIENT RELATIVE TEMPERATURE
FIG. 10 MAP OF TEMPERATURE FIELD FOR TWO RANDOM PACKINGS: MODEL 1.
FIG. 11 MAP OF TEMPERATURE FIELD AT TWO REYNOLDS NUMBERS: SAME PACKING, MODEL 1
a) VOID FRACTION IN BEDS OF UNIFORM SPHERES

b) INTEGRATED VOID FRACTION IN BEDS OF UNIFORM SPHERES

FIG. 12
FIG. 13 CONTOUR MAP OF SPHERES CONCENTRATION

P = PIC   V = VALLEY
FIG. 14 HOT SPOTS VISUALIZATION