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MIXING OF COLD AND HOT CO-CURRENT AIR-STREAMS IN A PACKED BED

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Abstract—The present paper studies how a discontinuity in the temperature distribution of the coolant gas in the inlet section of a packed bed of inert particles is attenuated at the exit section, with emphasis on the design of gas cooled nuclear reactors using coated fuel particles.

It is found, both theoretically and experimentally, that a large number of layers of particles is necessary to achieve a sufficient attenuation.

NOMENCLATURE

Geometrical characteristics

N,	number of layers of particles in the z-direction;
z,	principal flow direction coordinate [m];
Z,	characteristic number for the defined levels;
x, y,	coordinates in the horizontal bed section [m];
I, J,	characteristic number in x- and y-directions;
L,	length [m];
D,	diameter [m];
S,	area [m].

Fluid characteristics

ρ,	density [kg/m^3];
c_p,	heat capacity (specific) [m^2/s^2 deg];
ν,	kinematic viscosity [m^2/s];
μ,	dynamic viscosity [kg/m . s].

Thermal characteristics

T,	temperature [deg];
Q,	quantity of heat [kg m^2/s^2, W];
$k(k_e)$,	thermal conductivity (effective –) [kg m/s^3 deg, W/m deg].

Flow characteristics

$\dot{m}$,	mass flow rate [kg/s];
V,	velocity [m/s].

Non-dimensional number

Re,	Reynolds number defined by $Re = V_0 D_p/\nu$;
Pe,	Peclet number defined by $Pe = Pr . Re$;
Pr,	Prandtl number defined by $Pr = \mu . c_p/k$.

Subscripts

0,	upstream of the packed bed;
1,	cold side;
2,	hot side;
m,	arithmetic mean value;
g,	gas characteristic;
p,	particle characteristic;
t,	container characteristic.

INTRODUCTION

IN THE field of gas cooled thermal reactor, it is envisaged to use packed beds of coated fuel particles. This advanced technology leads to higher heat fluxes so that for a given nominal power more compact reactors seem to be workable. A great amount of research has already been carried out in this field but some problems, such as, for example, the choice of the best performing coated particles assembly, remain to be solved.

In particular, it is important to ascertain that no local temperature peak develops in the reactor core. In this respect, information is needed on the temperature equalizing capability of a coated particle bed.

The purpose of the present paper is to study how a discontinuity in the temperature distribution of the coolant gas in the inlet section of a packed bed of inert particles is attenuated at the exit section.

An ordered packed bed of spherical marbles has been used with the inlet temperature distribution shown in Fig. 1. Experiments were conducted at the von Karman Institute for Fluid Dynamics, under partial sponsorship of the G.B.R. Association,* with air at different Reynolds numbers.

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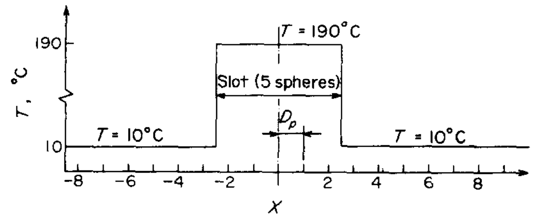

Fig. 1. Temperature profile in the inlet section of the packed bed.

Furthermore, a theoretical investigation, based on very simple flow models, enabled the determination of the temperature profile in any section of the bed, thus providing information on how the amplitude and width of the inlet temperature step varies with distance through the bed.

A more detailed description of this study is given in [7, 12].

DESCRIPTION OF THE EXPERIMENTAL SET-UP

The experimental set-up is shown in Fig. 2. It is designed to provide a non-uniform temperature distribution in the air entering a packed bed of square cross-section.

More precisely, the settling chamber, which is upstream of the packed bed, is constructed to produce a two-dimensional jet of hot air, 80 mm wide adjacent on each side to a uniform cold air stream. Section A–A shows how hot air exhausting from a perforated tube is uniformized in a secondary settling chamber before exiting from a slot as a hot jet. The external walls of this settling chamber are streamlined so as to minimize its influence on the uniformity of the adjacent cold air streams. The mass flows of hot and cold air are adjusted by regulating valves and measured by calibrated diaphragms.

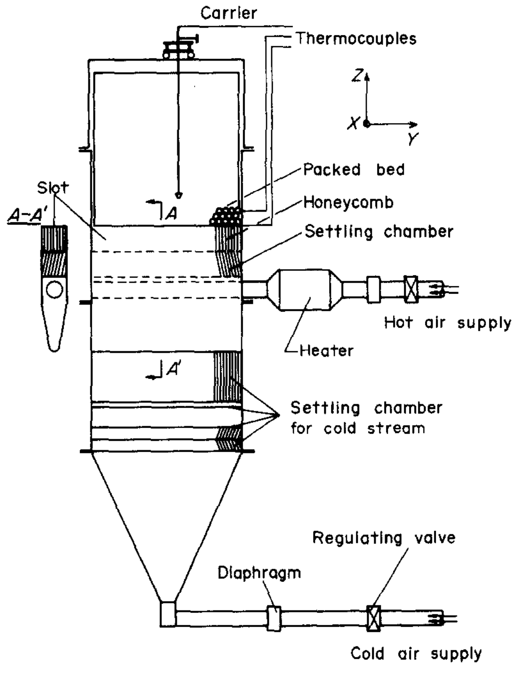

Fig. 2. Description of the experimental set-up.

This packed bed, contained in a cubic test section (528 mm as side), is formed of spherical elements of constant diameter and simulates the core of a nuclear reactor using coated fuel particles.

The size of the test section and the diameter of the spherical elements were selected to meet the requirement that in a practical configuration of nuclear reactor cooled by helium, a typical Reynolds number based on superficial velocity (V_0) and particle diameter (D_p) is of about 290, and also to minimize wall effects. Marbles of 16 mm in diameter were chosen so that $L_t/D_p = 33$ where L_t is equal to 528 mm.

The packed bed is supported by a honeycomb to maintain flow uniformity. It is of the octahedral type, characterized by a void fraction of 0·26. The distance separating the planes passing through the centers of the spheres of two successive layers is $D_p/\sqrt{2}$.

Wall effects are minimized by using half spheres at the walls and one-quarter spheres on the corners.

The test section is followed by a channel of constant cross-sectional area to minimize upstream effects caused by discharging the working air in the laboratory room.

EXPERIMENTS

Preliminary tests were conducted to compare the temperature profiles measured with thermocouples inserted inside the bed at a level Z (equal to a multiple of $D_p/\sqrt{2}$) and those obtained more easily in the outlet section of a bed ending at the same level Z, i.e. when all the spheres situated above this level were removed.

The results did not show any significant difference. It was thus justified to systematically measure the transverse temperature profiles in this easier way, by using a thermocouple mounted as a small carrier as shown in Fig. 2. During the tests, the temperatures of the cold and hot air streams were of about 10 and 190°C respectively. The accuracy of the temperature measurements was of about 2 per cent.

Two types of tests were performed. In a first series mass flows were adjusted to obtain an identical superficial velocity for both cold and hot air streams. Transverse temperature profiles were measured for a mean Reynolds number Re_m, of 290, 400 and 600, where Re_m is the mean arithmetic value of the Reynolds numbers evaluated for the cold and hot sides. The tests were repeated for various values of the number N, of layers of particles ranging from 0 to 27.

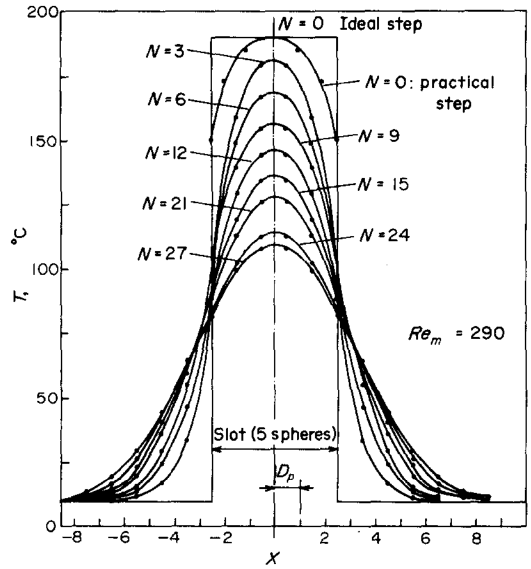

FIG. 3. Experimental results: temperature profiles downstream of N layers of spheres—$Re_m = 290$.

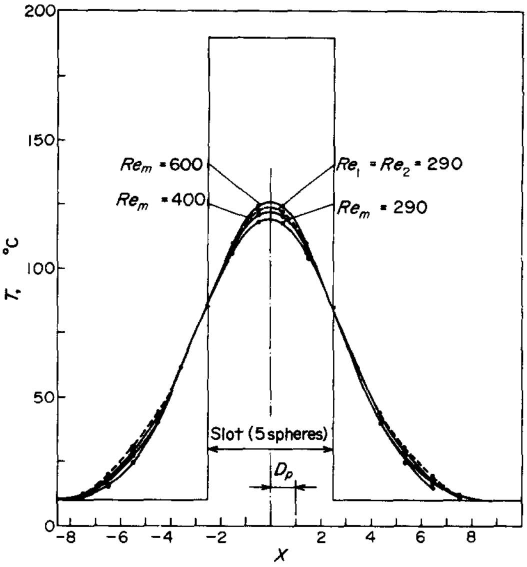

FIG. 4. Experimental results: temperature profiles downstream of 21 layers of spheres—comparison.

Some results are shown in Figs. 3 and 4. As may be seen, the amplitude of the temperature step decreases very slowly with increasing values of N. The rate of decrease is slightly lowered by an increase in the Reynolds number, although the theory predicts a larger effect.

In a second series, the inlet velocities were adjusted to have the same Reynolds number, i.e. 290, based on inlet temperature conditions, in both cold and hot air streams. The temperature distribution was measured downstream of $N = 21$ layers of spheres. The results are plotted in Fig. 4 and compared with the results of the first series of tests, showing no significant difference.

THE JET THEORY

Inside an octahedral packing arrangement, any sphere in a layer lays between four spheres of the preceding layer. Furthermore, as shown in Fig. 5, four characteristic levels may be defined which appear periodically throughout the bed. Each of these levels is characterized by a number Z. The distance between two successive levels is $D_p/2\sqrt{2}$.

Levels $Z = 1$ and $Z = 3$ pass through the centers of the spheres. The levels $Z = 2$ and $Z = 4$ pass through the contact points of the spheres of two successive layers. The situation at $Z = 3$ is the same as at $Z = 1$ except for a shift of one radius amplitude in the X and Y directions. The same is true for levels $Z = 2$ and $Z = 4$. The situation at $Z = 5$ is identical to that at $Z = 1$. A net with square meshes ($D_p \times D_p$) is attached to the plane $Z = 1$. The position of a mesh in the net is characterized by two indices (I, J) which are related to the coordinates of its center by the relations $X = (I-1).R_p$ and $Y = (J-1).R_p$. The flow passage area of one mesh is $0{\cdot}2146\,D_p^2$. The physical model used to develop the "jet theory" is based on the following assumptions.

It is first assumed that each mesh is crossed by a jet, the mass flow of which is $\rho.V_0.D_p^2$. It is also assumed that the jet which is hitting a sphere of the second layer splits into four equal parts which remix two by two in the interstices at the next level.

Applying these two assumptions to the five levels, we obtain the following complete model summarized in Fig. 6.

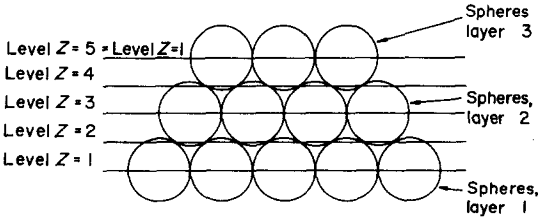

FIG. 5. Definition of the four levels.

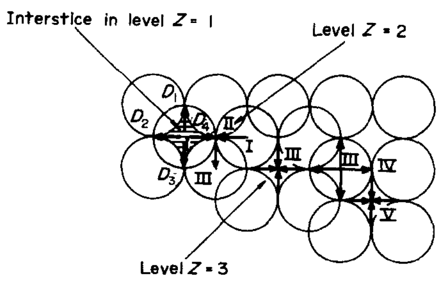

FIG. 6. Physical concept of the jet theory.

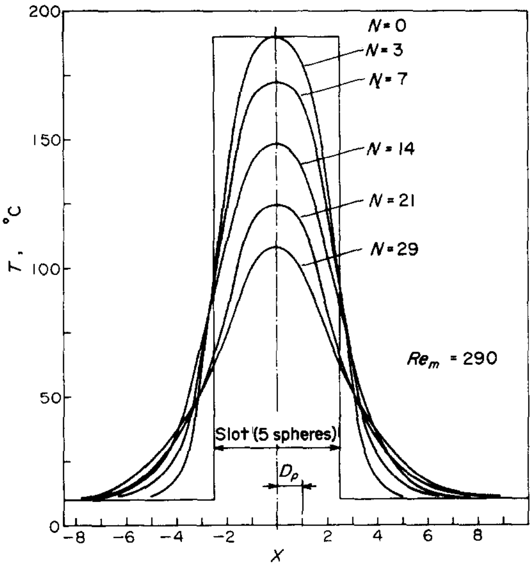

FIG. 7. Theoretical approach: the jet theory—temperature profiles downstream of N layers of spheres, $Re_m = 290$.

Level $Z = 1$. A jet traversing this level hits a sphere of the second layer and splits equally in the four directions D_i, towards the four interstices of the $Z = 2$ level.

Level $Z = 2$. A jet passing through an interstice at this level is formed by the mixing of two jet parts (two quarters) issued from the $Z = 1$ level in the X or Y directions.

Level $Z = 3$. A jet at this level is formed by the mixing of the four peripheral half jets passing through the interstices laying in the $Z = 2$ level.

Level $Z = 4$. At this level, a jet results from the mixing of two portions of jets (two quarters) coming from the $Z = 3$ level in the X or Y directions.

Level $Z = 5$. A jet is formed by the mixing of the four peripheral half jets passing through the interstices laying in the $Z = 4$ level. The situation is then similar to that at the $Z = 1$ level.

The mass flow crossing an interstice (I, J) is denoted $\dot{m}(I, J)$. The amount of heat convected away by the corresponding jet is thus $\dot{m}(I, J) . c_p . T(I, J)$ where c_p is the specific heat evaluated at a mean temperature. Passing from level $Z = 1$ towards level $Z = 2$, this amount of heat is distributed during splitting of the jets according to the following general expressions (I, J are even numbers in this formulation).

$$[\dot{m}(I, J+1)c_p . T(I, J+1)]_{Z=2} = \frac{[\dot{m}(I-1, J+1)c_p . T(I-1, J+1) + \dot{m}(I+1, J+1)c_p . T(I+1, J+1)]_{Z=1}}{4}$$

with

$$[m(I, J+1)]_{Z=2} = \frac{[\dot{m}(I-1, J+1) + \dot{m}(I+1, J+1)]_{Z=1}}{4}$$

and

$$[\dot{m}(I+1, J)c_p . T(I+1, J)]_{Z=2} = \frac{[\dot{m}(I+1, J-1)c_p . T(I+1, J-1) + \dot{m}(I+1, J+1)c_p . T(I+1, J+1)]_{Z=1}}{4}$$

with

$$[\dot{m}(I+1, J)]_{Z=2} = \frac{[\dot{m}(I+1, J-1) + \dot{m}(I+1, J+1)]_{Z=1}}{4}.$$

This process is repeated for planes $Z = 3$, $Z = 4$, $Z = 5$.

Knowing the inlet conditions, i.e. the mass flow distribution and the temperature profiles at level $Z = 1$, the mass flow distribution and the temperature profiles may be calculated at an arbitrary level Z.

Results obtained for $Re_m = 290$ are shown in Fig. 7 where the temperature T, in degC, is plotted vs the coordinate Y, normalized by D_p. The amplitude of the temperature profile decreases slowly with increasing Z. The advantage of such a purely convective method is that it can easily be extended to a three-dimensional analysis which is needed when arbitrary three-dimensional temperature distributions exist in the inlet section.

In addition, the method is applicable to other types of packings than the octahedral one. It has been extended to the present study by using the probability theory. The equations are analogous leading to results which are comparable with those of the "jet theory".

THE THERMAL THEORY

With no internal heat generation in the packed bed, the energy equation has the form:

$$\rho V c_p \frac{\partial T}{\partial z} = k_{ex} \frac{\partial^2 T}{\partial x^2} + k_{ey} \frac{\partial^2 T}{\partial y^2} + k_{ez} \frac{\partial^2 T}{\partial z^2}$$

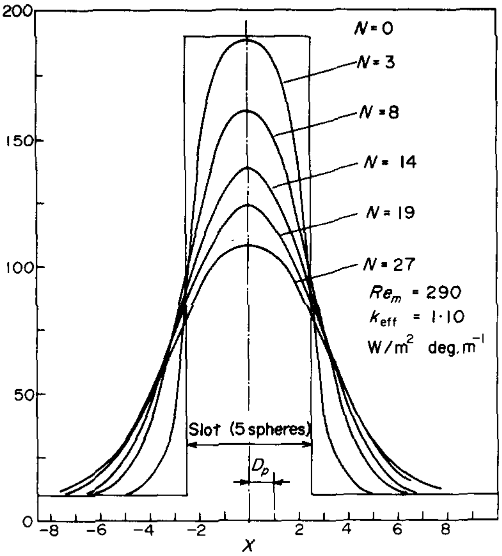

FIG. 8. Theoretical approach: the thermal theory—temperature profiles downstream of N layers of spheres, $Re_m = 290$, $k_{eff} = 1{\cdot}10$ W/m deg.

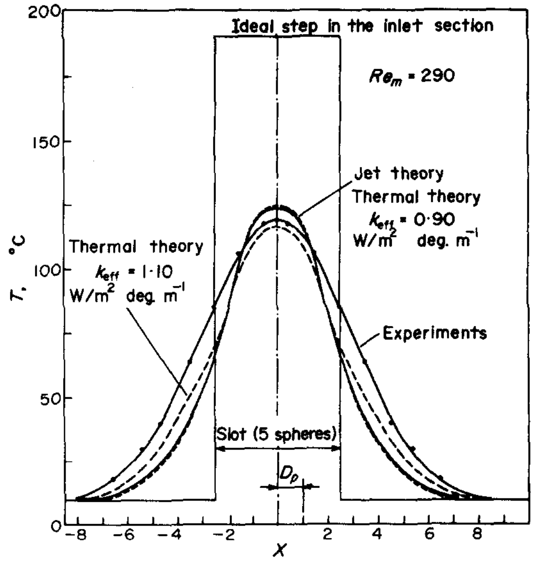

FIG. 9. Comparison between experimental and theoretical results—temperature profiles downstream of twenty-one layers of spheres.

where k_e is the effective thermal conductivity characterizing the system formed by the fluid and the particles.

In the present two-dimensional flow problem, the Peclet number is larger than 100 and this equation can be simplified. It reduces to:

$$\rho V c_p \frac{\partial T}{\partial z} = k_{ex} \frac{\partial^2 T}{\partial x^2}.$$

The effective thermal conductivity was estimated from available information in the literature. A mean value of 1·10 W/s °C m. The energy equation was solved using a finite difference method. In the application of such a numerical method a net has been constructed in the (X–Z) plane, the steps of which were taken equal to $D_p/2$ and $D_p/4$ respectively in the X and Z directions.

Results obtained for $Re_m = 290$ are shown in Fig. 8 which gives the temperature T vs distance x normalized by D_p. Here again, the amplitude of the temperature profile decreases slowly with increasing values of Z.

Furthermore, by selecting a value of k_{ex} of 0·90 W/m deg which would include only a convective mode of heat transfer one may verify the results of the jet theory. The comparison is done in Fig. 9 which shows good agreement.

THEORETICAL AND EXPERIMENTAL RESULTS: COMPARISON AND CONCLUSIONS

Figure 9 shows the theoretical and experimental temperature profiles downstream of twenty-one layers of spheres. The two theoretical methods give results which are very close to the experimental ones.

It seems that, by neglecting the conductive heat-transfer contribution, one decreases the precision of the calculated temperatures. Indeed, the thermal theory gives temperatures which are closer to the measured ones when a value of 1·10 is used for k_{ex}.

As may be seen from Fig. 4, the experimental results are not very sensitive to the Reynolds number. This is confirmed, although not so obviously, by the theoretical results.

It is also concluded that the amplitude of the peak in the temperature profile decreases slowly through the packed bed: for a typical bed thickness of about twenty-seven layers of spheres, this amplitude is reduced by 45 per cent only.

Practically, this means that a good attenuation of a temperature discontinuity will only be obtained by taking a sufficiently large number of layers of particles in the packed beds. This is a situation which will severely influence the pressure drop through the system.

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MELANGE DES ECOULEMENTS D'AIR A COCOURANT CHAUD ET FROID DANS DES LITS FIXES

Résumé—Ce mémoire étudie comment une discontinuité dans la distribution de température d'un gaz refroidissant dans la section d'entrée d'un lit fixe de particules inertes, est atténuée à la sortie. On insiste sur la conception des réacteurs nucléaires utilisant des particules de combustible refroidies par un gaz.

On montre, à la fois théoriquement et expérimentalement, qu'un grand nombre de couches de particules est nécessaire pour obtenir une atténuation suffisante.

DIE MISCHUNG GLEICHSINNIGER KALTER UND WARMER LUFTSTRÖME IN EINEM FÜLLKÖRPERBETT

Zusammenfassung—Im Hinblick auf den Entwurf gasgekühlter Kernreaktoren mit umhüllten Brennstoffpartikeln wird untersucht, wie eine Diskontinuität der Temperatur im Eintrittsquerschnitt eines Füllkörperbettes aus neutralen Elementen im Austritt abgeschwächt wird.

Theoretisch wie experimentell ergibt sich, daß eine große Anzahl von Füllkörperschichten nötig ist, um eine genügende Dämpfung zu erreichen.

ПЕРЕМЕШИВАНИЕ ХОЛОДНЫХ И ГОРЯЧИХ ПОПУТНЫХ ВОЗДУШНЫХ ТЕЧЕНИЙ В ПЛОТНОМ СЛОЕ

Аннотация — Исследуется выравнивание на выходе температурного скачка охлаждающего газа во входной секции плотного слоя инертных частиц, особенно в приложении к конструкции газоохлаждаемых ядерных реакторов, использующих частицы топлива с покрытиями.

Как теоретически, так и экспериментально найдено, что для досрочного выравнивания температурного профиля требуется большое число рядов частиц.