VIBRATORY DENSIFICATION OF DISPERSION-TYPE FUEL ELEMENTS FOR NUCLEAR REACTORS

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The vibratory densification technique has not yet found extensive application in the manufacture of powder metallurgical materials, although it is undoubtedly superior in many respects to other methods of shaping of metal powders. Using this technique, it is possible to produce parts of complex configuration and attain greater homogeneity and a more uniform stress distribution, thereby reducing the shrinkage and deformation of sintered specimens and, consequently, increasing the yield of sound material. Because of this, hot vibratory pressing and vibratory densification followed by sintering must be regarded as extremely interesting powder metallurgical operations, whose potentialities have not yet been adequately explored.

Vibratory densification has been employed more widely in the manufacture of various types of nuclear fuel elements, which may be attributed to the fact that moderately and highly enriched fuel elements for reactor applications must fulfill certain unusual requirements. Although the production of fuel elements by the vibratory densification technique has already been studied by a number of authors [1–6], there are still many problems, whose solution would increase the competitiveness of this process in relation to other, more orthodox methods, such as pressing and rolling.

In the approach to vibratory densification described in this article, the process is examined from a geometric viewpoint, and the results obtained can, of course, be applied to any material subjected to this form of densification. Some of the more important shapes of fuel elements for fast, high-temperature, and light-water nuclear power reactors, which are commonly produced by vibratory compaction, are considered individually. Analysis of these particular geometric shapes may well indicate also lines of action likely to yield desired results with some more complex elements encountered in practice. It should also contribute toward making vibratory densification applicable to other methods employed for the shaping of parts in powder metallurgy.

The theory of particle packing is concerned with the choice of the most suitable distribution of particle sizes and weight fractions of materials, ensuring that the voids between large particles become filled with smaller particles, the voids created by the displacement of these smaller particles are filled with still smaller particles, and so forth.

The packing of particles in vessels of various geometric shapes is mainly controlled by two key factors:

a) the ratio between the particle size and the size of the vessel in which packing is taking place;

b) the ratio between the sizes of particles being stacked in succession.

In this study, the above relationships are examined in some detail for the three most frequently used types of reactor fuel elements (Fig. 1). One common feature of all these types is that the tubular, or cylindrical, shape of the first is also the basis of the other two types. The relatively large ratio between the length of the fuel element and the other two sizes, the high degree of circular symmetry in each cross section of the packed material, and the periodic repetition of the same distribution, in which the diameter of the largest particles determines the magnitude of the period, enable the two composite shapes, too, to be analyzed without much difficulty.


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Fig. 1. Diagrammatic representation of three shapes of nuclear fuel elements: 1) tubular; 2) annular; 3) inversed.

Fig. 2. Effect of shell diameter on effectiveness of packing of equal-sized spheres. D/\(\phi_1\) = vessel diameter/sphere diameter. The figures represent the numbers of spheres in individual layers in the vessel.

Tubular Shape (Fig. 1, Type 1). The maximum density attainable with equal-sized particles in a cylindrical vessel is, according to McGeeary's experimental investigations and calculations [7], about 60% of theoretical (in the case of the most favorable ratio between the diameters of the vessel and the particles, D/\(r_1\) = 3) (Fig. 2). However, even with a highly enriched fuel (enriched with a fissionable component), such densities are insufficient for the satisfactory operation of a reactor. In view of this, the packing density must be increased by adding particles of a smaller size. The particle size of the next fraction, enabling these smaller particles to be accommodated in the empty voids between the larger particles, can readily be determined from simple geometric relationships (Fig. 3a). It is given by the expression:

\[
\frac{r_2}{r_1} \approx 0.15 \approx 1/7, \tag{1}
\]

where \(r_1\) and \(r_2\) are the radii of the larger and smaller particles, respectively. However, from Fig. 3a it follows that this relationship holds for the particles contained between the large particles, but not for those that can fill the voids between the large particles and the vessel walls (Fig. 3b).

When the ratio between the diameter of the vessel in which packing is taking place and the diameter of the larger particles is D = 3\(\phi_1\), it is possible to determine also, by means of simple geometric calculations, the ratio of the diameters of the first- and second-fraction particles forming an array in the region of the vessel wall:

\[
\frac{r_2}{r_1} \approx 0.36 \approx 1/3. \tag{2}
\]

This relationship is valid for all fractions. Data upon the sizes of second-fraction particles are of vital importance from the viewpoint of uniformity of density in materials densified by vibration, even in the case of geometrically regular particles; they show that the particles of the second fraction cannot be of one size only.