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The use of air permeametry for the assessment of external surface area and sphericity of pelletized granules

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Summary

Permeametry surface areas which compared favourably with surface areas calculated from analysis of granule dimensions by microscopy and ring gap sizing were measured with a steady-state and a transient permeameter for beds of coarse (0.9–1.0 mm), spherically shaped, porous granules. The permeametry surface areas were calculated with an aspect factor pre-determined on beds of mono-dispersed steel balls and with an effective bed voidage calculated from the effective particle density of the granules. The permeametry methods were also found to be capable of giving significantly different surface areas between granule masses of similar granule size but of small differences in granule shape. Hence, the air permeametry principle is suitable for the assessment of the external surface area and the geometrical shape (sphericity) of granules. As test materials, six granule masses (microcrystalline cellulose-lactose mixtures) prepared by extrusion-spheronization were used.

Introduction

Aggregation of particles into granules is a common procedure in pharmaceutical production. Granules are normally processed further and the processing procedure governs the requirements concerning the physical properties of the granules. For granules which should be coated, the particulate characteristics are of special importance and ideally, monosized smooth spheres is the goal of the aggregation process, in order to obtain a reproducible coating layer with respect to thickness and surface area. Consequently, methods for the assessment of granule shape and external surface area are important for a comprehensive characterization of pelletized granules.

Different methods have been suggested in the literature for the quantification of the sphericity of particles, e.g., the ratio between different particle diameters (Ridgway and Rupp, 1969; Beddow et al., 1976) or the calculation of the one plane critical stability (Chapman et al., 1988) of a particle. In these cases, the analysis is normally based on microscopy measurements of particles which rest in their most stable position. This

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means that the obtained shape factor is based on a two-dimensional analysis of the particles, i.e., of their length and breadth. However, shape is also related to the third dimension of a particle, i.e., thickness. The most well known shape factor, which describes the three dimensions in one figure, is the surface to volume shape coefficient developed by Heywood (1954).

Two alternative ways of assessing this surface to volume shape coefficient for particles have been presented. The first one is based on the measurement of all three particle dimensions (Nyström, 1978). The other alternative combines measurements of the external surface area and the surface to volume diameter of the particles, normally measured as the projected area diameter when the particles rest in their most stable position (Heywood, 1954). This latter alternative is attractive because it excludes the need for thickness measurements of particles, which requires a special technique, such as the ring gap sizer (Nyström, 1978). Furthermore, the external surface area in itself is an important characteristic of pelletized granules.

We have earlier shown (Eriksson et al., 1990) that the air permeability principle can be used to assess the external surface area of coarse particles. However, the application of the technique to pelletized granules, i.e., coarse, porous particles, has not yet been evaluated. Potential difficulties of the measuring principle in relationship to granules concern, firstly, the determination of the effective voidage of the granule bed, secondly, the use of a suitable aspect factor within the permeability equation in order to obtain an accurate surface area value and, finally, the capacity of the method to detect small surface area differences between granule masses, e.g., due to small changes in granule shape.

The intention behind the following study was therefore to investigate the possibility to assess the external surface area of pelletized granules. The questions of a suitable aspect factor in the permeability equation for such measurements, the estimation of the effective voidage and the ability of the method to detect small differences in granule surface area are addressed. As a model system for this study, a series of granule masses with small surface area variations were prepared by collecting a consistent sieve fraction from a number of granules obtained by extrusion-spheronization.

Experimental

Preparation of granules

Lactose (crystalline, α-monohydrate, DMV, The Netherlands) and microcrystalline cellulose (Avicel PH 101, FMC Inc., U.S.A.) in the proportions 85:15% by weight, were dry mixed in an intensive mixer (Eirich RO 2) for 1.5 min. A predetermined amount of water was then added at a flow rate of 0.5 ml/min and the wet mass was mixed for 2 min. The wet mass was extruded in a radial screen type extruder (NICA Extruder E 140) with screen openings and a screen thickness of 1 mm at an extrusion rate of 2000 g/min. The extruded mass, 400 g, was thereafter spheronized (NICA Spheroniser 320) with a 320 mm spheronizing plate and the wet granules were finally dried in a fluid bed drier (NICA FB Laboratory drier) at an air inlet temperature of 70°C for 10 min to an outlet temperature of 50°C.

By varying the amount of water and the process conditions during the spheronization, six granule masses were produced (Table 1). From each batch, the sieve fraction 0.9–1.0 mm was separated by hand sieving with laboratory test sieves. These granule masses represent materials with a consistent size but with a small variation in granule shape.

Ball bearing balls in stainless steel (SKF, Sweden) was chosen as a suitable material to determine an aspect factor for these types of materials. The steel balls are considered as perfect spheres with an extremly narrow size distribution and with a very smooth surface texture. The steel balls were used as supplied and the size for the balls was 1000 μm, the density 7.7 g/cm^3 and the surface to volume shape coefficient (Heywood, 1954) was visually estimated to 6.0.

Characterization of granules

The sampling of the granules for the granule characterization was in all experiments per-

TABLE 1

Processing parameters during pelletization and densities of granules

Granule mass (–)	Processing parameters			Densities		Porosities		
	Water content (%)	Spheronization time (min)	Spheronization speed (rpm)	Apparent particle density (g/cm^3)	Effective particle density (g/cm^3)	Granule porosity (%)	Voidage of granule bed [a] (%)	Voidage of granule bed [b] (%)
A	25.0	6	550	1.54	1.24	19.5	40.2	40.3
B	24.5	2	550	1.54	1.24	19.5	41.0	40.5
C	25.0	3	750	1.54	1.26	18.2	41.1	40.7
D	25.0	6	750	1.54	1.27	17.5	40.1	39.8
E	24.5	4	750	1.54	1.27	17.5	40.9	39.9
F	24.5	6	750	1.54	1.28	16.9	40.4	40.8

[a] For the transient permeameter.
[b] For the steady-state permeameter.

formed by a spoon due to the narrow size distributions of the materials.

Densities The apparent particle density of the granules, which excludes open pores and includes closed pores (B.S. 2955:1958), was measured in an air comparison pycnometer (Model 930, Beckman, U.S.A.). Presented results are mean values of three determinations. The effective particle density, which includes open (a radius smaller than approx. 7 μm) and closed pores (B.S. 2955:1958), was measured using a mercury displacement method (Strickland et al., 1956; Wikberg and Alderborn, 1990).

The porosity of each granule mass was calculated from the density values.

Size The granules were photographed in a Vanox Universal Research Microscope (Japan) and the projected area diameter was thereafter measured with a particle size analyser (Zeiss TGZ3, Germany) for at least 100 granules from each granule mass. Because of the narrow size distribution of the sieve fractions, this number was considered to be sufficient to obtain a good estimate of the mean granule size. The median and the surface to volume diameter (Allen, 1981a) based on a number distribution were determined from these size distributions. Also the length and breadth of the granules were determined from the photographs by measurements with a ruler, for at least 100 granules, and the median granule size based on a number distribution were calculated.

Finally, the thickness of the granules was determined by a ring gap sizer as described earlier (Nyström, 1978). A sample of 1 g was used for this analysis. Also here, the median granule size based on a number distribution was calculated. Mean values of three determinations are presented.

Shape from microscopy analysis Samples from all granule masses were photographed in a scanning electron microscope (Philips SEM 525, The Netherlands), and with the aid of these photomicrographs, a qualitative estimate of the shape and the surface texture of the granules was obtained.

As quantitative measures of the granule shape, some shape factors were calculated from the size analysis. Heywood's surface to volume shape coefficient (Heywood, 1954) was calculated as described by Nyström (1978) with values of C and α_e assuming the rounded geometrical form. This shape coefficient includes measures of all three size dimensions of a particle, as discussed above. Furthermore, the elongation (the ratio between length and breadth) and the flakiness (the ratio between breadth and thickness) were calculated as shape factors based on two particle size dimensions.

Surface area by transient permeametry The permeametry surface area of all granules was

measured as described elsewhere (Eriksson et al., 1990). Granules were poured into the container (diameter 1.008 cm) to a height of approx. 60 cm and the container was then tapped 10 times with a tapping equipment. The weight and height of the bed of granules were determined and the permeability measured. The specific surface area was calculated with the Kozeny-Carman equation (Eriksson et al., 1990). All presented values are mean values of three determinations.

For a bed of particles packed in a cylindrical container, the porosity of the bed will vary across the cross-sectional area, i.e., it gives rise to the wall effect. Such wall effects will affect the bed permeability but it has been suggested (Coulson, 1949) that it could be neglected if the ratio between particle diameter and container diameter equals or exceeds 10. This ratio was chosen in this study to avoid the wall effect but to keep the container dimensions as low as possible in order to be able to use the smallest possible amounts of material.

Surface area by steady-state permeametry The granules or the steel balls were poured manually into the container to a height of approx. 40 cm. The container was tapped 10 times and the height and weight were carefully recorded. The container is connected to a Blaine apparatus (Blaine, 1943) which was used as a manometer to detect the pressure drops over the bed of granules. With the aid of a pump the pressure was reduced under the bed and the resulting pressure difference over the bed of granules was determined on the manometer. The manometer was filled with either water or mercury, i.e., a wide measurable range of pressure differences was accomplished with these two manometers. The velocity of the air through the bed of granules was measured and controlled by a flow meter (Brook model 5850E, Brook Instruments B.V., The Netherlands).

Permeability plots were constructed by plotting the air velocity as a function of the pressure difference per unit length of the bed of granules, the slope of this line giving the permeability coefficient for the bed of granules according to Eqn 1.

$$u = P_c \cdot (\Delta P/L) \qquad (1)$$

The permeametry surface area was then calculated from the permeability coefficient and the bed porosity (Eqn 2).

$$S_v^2 = \left(\epsilon^3/(1-\epsilon)^2\right) \cdot 1/(k \cdot \eta \cdot P_c) \qquad (2)$$

In addition, the Reynolds number was calculated for each experimental system, for the transient permeameter according to an equation presented earlier (Eriksson et al., 1990) and for the steady-state permeameter according to Eqn 3:

$$\mathrm{Re} = \left(u \cdot 4 \cdot \rho_g \cdot (L_e/L)\right)/(S_v \cdot \eta \cdot (1-\epsilon)) \qquad (3)$$

All presented results are mean values of three determinations.

Surface area by microscopy With the aid of the surface to volume diameters by number, based on the projected area measurements, and the surface to volume shape coefficients estimated as described above, the specific surface area of the granules was calculated (Heywood, 1954; Nyström, 1978).

Shape from permeametry and microscopy measurements With the aid of the surface to volume diameters by number, based on the projected area measurements by microscopy, and the volume specific surface areas from steady-state permeability measurements, the surface to volume shape coefficients were calculated for all granules (Allen, 1981a).

Results and Discussion

Densities of granules

The densities and porosity of the granules and the voidage of the beds of granules are given in Table 1. The effective particle density of the granules varied slightly among the granule masses. It appears that an increased spheronization time and plate speed increased the effective particle density.

The bulk density of the granule beds increased slightly, similarly to the effective particle density. However, the voidage of the beds of granules (calculated from the effective particle density val-

ues) was similar for all granules. This indicates that the packing of the granules was similar for all the masses, and that it was not, therefore, significantly affected by possible differences in shape characteristics.

Particle size and shape characteristics of granules assessed by microscopy

A qualitative estimate of the shape and surface texture of the granules was obtained by SEM. The photomicrographs (one representative example is given in Fig. 1) indicated that all granule masses consisted of almost spherical granules, but a slight shape variation was observed. In the presentation of the results, the granules are denoted A–F and the denomination is based on the visual estmation of the shape, i.e., increasing sphericity from A to F. The surface texture of the granules was considered to be smooth and similar for all granule masses.

The size fraction of the granules used in the study was obtained by sieving. Sieving tends to sort particles by their breadth (Nyström and Stanley-Wood, 1977) which means that the breadth ought to be similar between the different size qualities. Although a variation in granule breadth was obtained, both the absolute and the relative variations were less compared to the variations in granule length and thickness (Table 2). The projected area diameter, determined from microscopy measurements, is a measure of the mean size of the granules based on a two-dimensional analysis, i.e., the length and breadth. In this case, the variations in granule breadth were relatively limited and the variation in projected area diameter is therefore governed by variations in granule length.

The granule thickness, as measured by the ring gap sizer, is generally lower than the granule breadth. It seems therefore that the preparation procedure produced granules which were slightly flaky (Table 3). A reduced flakiness correlated with a reduction in elongation. The Heywood surface to volume shape coefficients for the different granule qualities were generally near the lowest theoretical value of 6, i.e., the shape coefficient for a perfect sphere. If this size fraction is representative for the overall shape characteristics of the granules, it seems that during the spheronization an increase in relative density occurred simultaneously with a rounding-off of the agglomerates. From the size and shape characteristics, the external surface area of the granules was calculated (Table 4).

External surface area of granules

Determination of aspect factor The Kozeny-Carman equation has been successful for the calculation of the external particle surface area from permeability measurements of beds of the particles. However, the equation is semi-emperical in the respect that it contains a factor, i.e., the

TABLE 2

Size characteristics of granules as measured by microscopy and ring gap sizing

Granule mass (−)	Projected area diameter [a]		Length [b] (L) (μm)	Breadth [b] (B) (μm)	Thickness [c] (T) (μm)
	Median (μm)	Surface to volume [d] (μm)			
A	1024	1037	1132	930	786
B	1028	1045	1161	936	808
C	1025	1042	1120	959	798
D	1005	1021	1056	944	822
E	998	1008	1042	940	845
F	1000	1011	1030	952	859

[a] Values from size distributions by number.
[b] Median values from size distributions by number.
[c] Measured by the ring gap sizer, median values from number distribution.
[d] Equivalent with harmonic mean diameter by weight (Herdan, 1960).

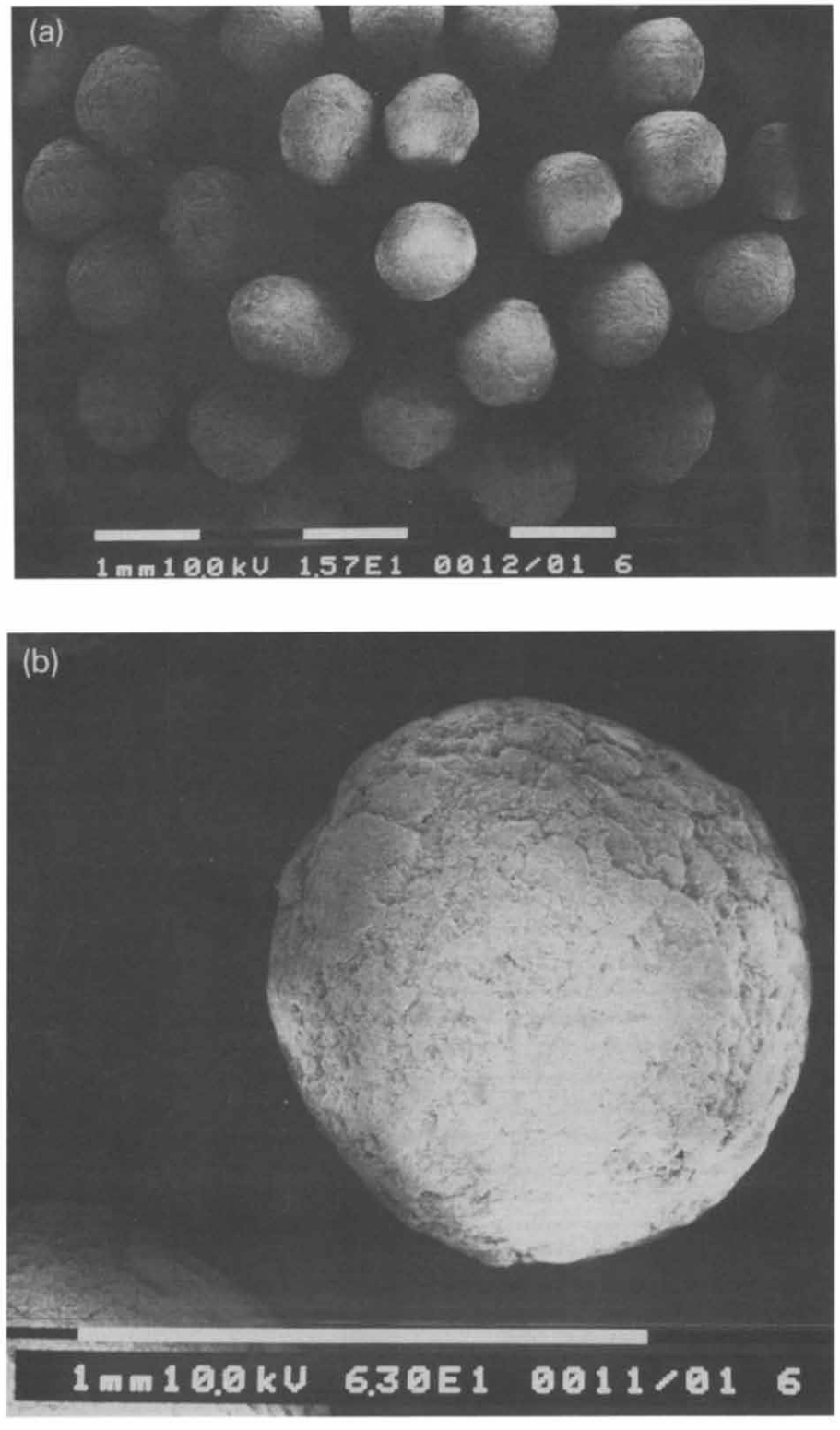

Fig. 1. SEM photomicrographs of one representative example of the granules.

TABLE 3

Shape characteristics of granules as measured by microscopy and ring gap sizing

Granule mass (−)	Elongation (−)	Flakiness (−)	Surface to volume shape coefficient [a] (−)
A	1.22	1.18	7.44
B	1.24	1.16	7.46
C	1.17	1.20	7.30
D	1.12	1.15	7.02
E	1.11	1.11	6.90
F	1.08	1.11	6.80

[a] Calculated according to Heywood (1945) using the elongation and flakiness data and assuming rounded particles with $\alpha_e = 0.54$ and $C = 2.1$.

aspect factor, which can be physically defined but has been numerically determined by a calibration procedure. Thus, the aspect factor can be described as a correlation factor (Kaye, 1967) of which the significance is to correlate the permeametry surface area with the external surface area obtained by another method, i.e., ideally the accurate external surface area. The aspect factor was determined to be 5 by Carman (1937) by liquid permeability measurements on fairly coarse particulate materials. Although it has been pointed out that the aspect factor is dependent on, e.g., the shape characteristics of the particles (Wasan et al., 1976) and the porosity of the bed of particles during the permeability analysis (Wasan et al., 1976), the traditional use of the permeability equation is to use the value of the aspect factor proposed by Carman on more or less all types of particles. There seem to be very few attempts in the literature to actually determine the aspect factor for a specific type of particles. In the following paper, the application of the method to a special type of particles, i.e., pelletized granules, is discussed. An accurate determination of the external surface area with the permeability method is required to ensure a good consistency with other methods for the assessment of the external particle surface area.

Pelletized granules represent comparatively well-defined materials concerning the shape characteristics of the granules, i.e., rounded or nearly spherical granules with a smooth surface texture, and also represent comparatively coarse particles with respect to the use of air permeability methods. In a previous work (Eriksson et al., 1990) on the measurement of the external surface area of coarse particles it was found that the permeametry surface area values generally were slightly higher than the microscopy surface areas. The meaning and thereby the chosen value of the aspect factor in the Kozeny-Carman equation have been discussed as one probable reason for

TABLE 4

Specific surface areas of granules estimated by permeametry and microscopy

Granule mass (−)	Transient permeameter				Steady-state permeameter			Microscopy surface area (cm^{-1})
	Permeametry surface area [a] (cm^{-1})	Permeability coefficient ($\times 10^{-5}$) (m^4/Ns)	Reynolds number Max [b] (−)	Reynolds number Mean [b] (−)	Permeametry surface area [a] (cm^{-1})	Permeability coefficient ($\times 10^{-5}$) (m^4/Ns)	Reynolds number Max [c] (−)	
A	73.0 (0.42)	3.28	17.9	8.19	72.2 (0.92)	3.39	9.25	71.7
B	73.8 (0.34)	3.51	19.3	8.80	72.2 (0.80)	3.48	9.26	71.4
C	74.4 (0.40)	3.46	18.9	8.62	73.2 (0.82)	3.45	9.57	70.1
D	69.5 (0.22)	3.59	20.6	9.42	68.0 (0.60)	3.65	9.59	68.8
E	70.8 (0.45)	3.75	24.3	11.1	65.7 (0.98)	3.93	9.69	68.5
F	69.1 (0.73)	3.72	30.0	13.7	70.3 (0.48)	3.75	9.87	67.3

[a] Calculated with an aspect factor of 5.8.
[b] Maximun and mean pressure head.
[c] Maximum pressure head.
Relative standard deviations in percent, for surface area values, in parentheses.

the surface area discrepancy. Thus, it was considerd of interest to determine a suitable value of the aspect factor for such particles. A suitable particle for this calibration procedure is steel balls which are perfectly spherical with an extremly smooth surface texture, i.e., the steel balls resemble the granules concerning granule size and shape.

The steel balls represent such coarse particles that the risk for turbulent air flow is obvious which is not consistent with the use of the Kozeny-Carman equation. To ascertain that laminar air flow is at hand during the permeability analysis, the air velocity as a function of pressure difference over the bed of particles at steady-state was determined.

In Fig. 2a, such a permeability profile in a range up to the maximum air velocity obtained by the flow meter is presented for two heights of the bed of steel balls. It was not possible to use a bed of the steel balls of lower height due to the very low obtained pressure difference over the bed. The permeability profile deviated considerably from a straight line due to an increased incidence of turbulent air flow with increasing air velocity. There is also a tendency that the profiles for the respective bed height diverged with increasing air velocity. A similar observation was also made for permeability profiles of the granules. It seems that an increased height of the bed of steel balls or granules decreased the assessed permeability probably due to an increased incidence of turbulence in the flow pattern. A possible explanation is that the number of sites in the bed of granules where turbulence occurs increases with increasing height of the bed.

In a restricted air velocity range (Fig. 2b), permeability profiles consisting of almost straight lines were obtained, indicating laminar flow in the bed of steel balls. From these profiles, the permeability coefficent (Eqn 1) was calculated. The transformation of this permeability coefficient into a surface area equal to the surface area calculated from microscopy data required an aspect factor of 5.8, i.e., the aspect factor was calculated from Eqn 2 where S_v was equal to the microscopy surface area and P_c was obtained from Fig. 2b. This aspect factor was subsequently

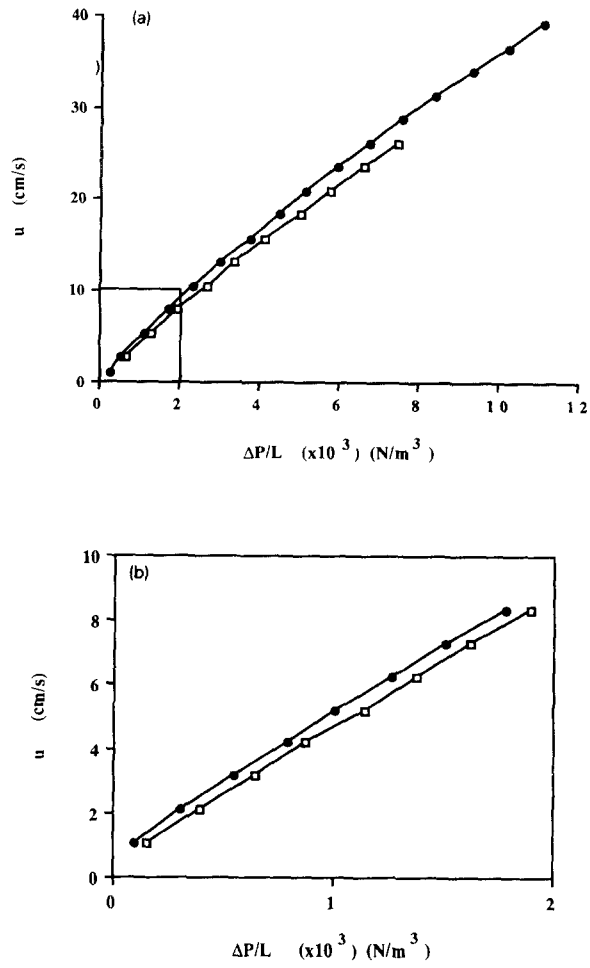

Fig. 2. (a) Permeability profiles for beds of steel balls in the maximum air velocity (u) range through the bed as a function of the pressure difference over the bed of steel balls per unit length ($\Delta P/L$). Height of the bed of steel balls: (●) 20 cm and (□) 30 cm. (b) Permeability profiles for the restricted air velocity (u) range through the bed of steel balls as a function of the pressure difference over the bed per unit length ($\Delta P/L$). Height of the bed of steel balls: (●) 20 cm and (□) 30 cm.

used in the calculations of the permeametry surface area for the granules.

It should be pointed out that the aspect factor has been reported (Wasan et al., 1976) to vary with the voidage of a bed of particles. This relationship is not possible to evaluate for coarse particulate solids as they pack spontaneously at relatively low porosities and a forced further packing will probably change the appearance of

the particles, i.e., deformation and fracturing. It is thereby reasonable to apply the obtained aspect factor to beds of other particles with similar particulate characteristics. Furthermore, one explanation (Wasan et al., 1976) for the relationship between aspect factor and bed voidage is changes in particle-particle contact area as a result of a reduced bed voidage. If this is valid, the porosity effect ought to be limited for packed beds of spheres compared to beds of particles of other shapes, e.g., cubes.

Comparison between permeametry and microscopy surface area

In Table 4, air permeability data and permeametry surface areas are presented for all granules. Although the packing density of the beds of granules was similar for all granules, the permeability coefficient varied and there was a tendency for the permeability of the bed to increase from granule A to F. This means that, although the overall intergranular voidage of the bed of granules was similar between the beds, a slight variation in the characteristics of the pore system of the beds of the different granules was obtained. It seems thus reasonable that this variation in pore characteristics was related to the observed variations in size and shape characteristics of the granules as discussed above.

It has been suggested that for a Reynolds number between 2 and 2000 (Allen, 1981b) there is a gradual change from laminar to turbulent air flow. The Reynolds numbers (Table 4), calculated from the permeability measurements, are found at the lower part of this interval which suggests that the flow can be described as mainly laminar.

The surface areas, calculated from air permeability data, also varied among the granules. There is a tendency that the surface areas obtained for granules A–C were slightly higher than the surface areas of granules D–F. There is also a tendency that the transient permeameter gives surface areas slightly higher than the steady-state permeameter. This can be explained by an uncertainty in the experimentally calibrated apparatus constant (Eriksson et al., 1990) for the calculation of surface area for the transient permeameter. However, it is also possible that the assessed

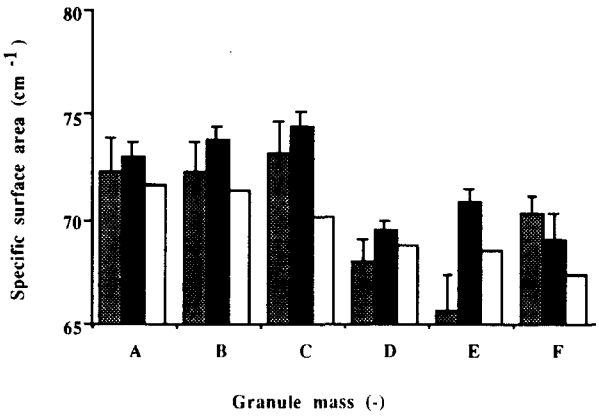

Fig. 3. Specific surface area and 95% confidence interval for the different granules measured by (■) transient permeameter, (▩) steady-state permeameter and (□) microscopy.

permeability for the transient permeameter is affected by some incidence of turbulent air flow in the initial phase of the permeability measurement when the air velocity is comparatively high.

Generally, for both permeameters, the variability in surface area is very low. Hence, although the absolute difference in surface area is small, both permeameters deliver surface area results which in some cases differ significantly (Fig. 3), e.g., for the steady-state permeameter, the external surface areas for granules A–C are significantly higher ($P < 0.05$) than for granules D and E. This surface area difference is probably governed by the small differences in geomerical shape, as assessed both visually and quantitatively from the main dimensions of the granules (Fig. 4). Thus, the air permeability measuring principle is capable of distinguishing between particles which are characterized by only small differences in shape characteristics, which are smaller than those manifested as differences in packing density. This supports the suitability of the method for the assessment of external surface areas of pelletized granules provided laminar flow can be obtained.

Calculation of the external surface area from the size and shape analysis from microscopy measurements was used as a reference technique to evaluate the permeametry surface areas (Table 4). Also here, small absolute differences in sur-

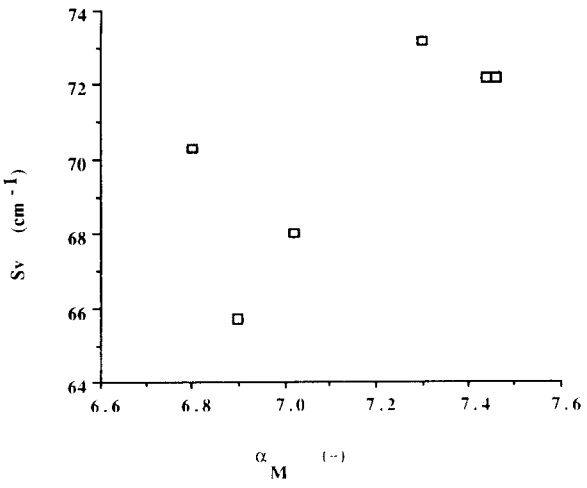

Fig. 4. Specific surface area (S_v) for the different granules calculated from permeametry measurements by steady-state permeametry as a function of surface to volume shape coefficient (α_M) calculated from microscopy measurements.

face areas were obtained but a positive correlation between the surface areas obtained by permeametry and microscopy was found (Fig. 3). Furthermore, the absolute surface area values are generally similar. It can thus be concluded that the permeability procedure utilized in this study results in surface area values which represent reasonably accurate external surface areas of the pelletized granules.

The comparison between surface areas obtained by permeametry and microscopy thus indicates that the aspect factor of 5.8, determined with the aid of steel balls, seems to be relevant for the type of material which pelletized granules represent. It can also be concluded that the effective voidage for beds of porous granules should be estimated with the aid of the effective particle density. The pore system of a bed of particles consisting of porous particles is dualistic and consists of intra- and inter-particulate pores. When the particles are coarse aggregates of small primary particles, e.g., the granules used in this study, it is reasonable to assume that the air prefers to flow in the comparatively large interparticulate pores. The porosity of this part of the pore system thus represents the effective porosity (voidage) and can be estimated by the effective particle density of the granules. There is a small tendency that the permeametry methods gave larger surface areas than the microscopy method. One possible explanation can be difficulties in assessing the effective particle density. In this study, the most common approach, i.e., mercury pycnometry, has been utilized.

Comparison between surface to volume shape coefficients

The good correlation between the surface areas obtained by microscopy and permeametry also indicates that the measurement of the surface area by permeametry can be utilized for the quantitative description of the shape of the granules based on all three main dimensions. A good correlation between the surface to volume shape coefficients, calculated by the two different procedures described above, was obtained (Fig. 5). This suggests that the surface to volume shape coefficient calculated from permeametry surface area data is a suitable procedure for estimating the sphericity of granules. By this approach, the sphericity value describes the three dimensions of a granule in contrast to sphericity values based on projected images of particles. A limitation of the procedure might be related to the characterization of very rough particles. For such particles, it

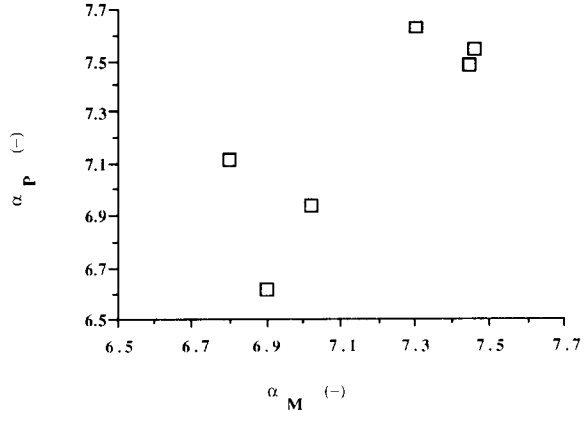

Fig. 5. Surface to volume shape coefficient (α_P) for the different granules calculated from steady-state permeametry measurements and microscopy measurements as a function of surface to volume shape coefficient (α_M) calculated from microscopy measurements.

cannot be excluded that the calculated permeametry surface area will increase (Eriksson et al., 1990) and thus, the determined surface to volume shape coefficient does not correspond entirely to the geometrical shape of a particle.

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Glossary

Symbol	Meaning
C	constant related to particle geometry
k	aspect factor (−)
L	length of bed of particles (m)
L_e	length of capillaries in the bed of particles (m)
L_e/L	$\sqrt{2}$, given by Carman (1937)
P_c	permeability coefficient ($m^4\ N^{-1}\ s^{-1}$)
ΔP	pressure difference across the bed of particles ($N\ m^{-2}$)
Re	Reynolds number (−)
S_v	specific surface area from steady-state permeametry (m^2/m^3)
α_e	constant related to particle geometry
α_M	surface to volume shape coefficient from microscopy (−)
α_P	surface to volume shape coefficient from steady-state permeametry (−)
ρ_g	density of air (1.2047 $kg\ m^{-3}$)
ϵ	porosity of bed of particles (−)
η	viscosity of air ($1.81 \times 10^{-5}\ N\ s\ m^{-2}$)
u	air velocity (m/s)

References

Allen, T., *Particle Size Measurements*, 3rd Edn, Chapman and Hall, London, 1981a, pp. 121–122.

Allen, T., *Particle Size Measurements*, 3rd Edn, Chapman and Hall, London, 1981b, p 436.

Beddow, J.K., Vetter, A.F. and Sisson, K., Particle shape analysis. Part 1. *Powder Metall. Int.*, 8 (1976) 69–70; 75–76.

Blaine, R.L., A simplified air permeability fineness apparatus. *A.S.T.M. Bull.*, No. 12B (1943) 51–55.

Carman, P.C., Fluid flow through granular beds. *Trans. Inst. Chem. Eng.*, 23 (1937) 150–166.

Chapman, S.R., Rowe, R.C. and Newton, J.M., Characterization of the sphericity of particles by the one plane critical stability. *J. Pharm. Pharmacol.*, 40 (1988) 503–505.

Coulson, J.M., The flow of fluids through granular beds: effect of particle shape and voids in streamline flow. *Trans. Inst. Chem. Eng.*, 27 (1949) 237–257.

Eriksson, M., Nyström, C. and Alderborn, G., Evaluation of a permeametry technique for surface area measurements of coarse particulate materials. *Int. J. Pharm.*, 63 (1990) 189–199.

Herdan, G., *Small Particle Statistics*, 2nd Edn, Butterworths, London, 1960, p. 35.

Heywood, H., Particle shape coefficients. *J. Imp. Coll. Chem. Eng. Soc.*, 8 (1954) 25–33.

Kaye, B.H., Permeability techniques for characterizing fine powders. *Powder Technol.*, 1 (1967) 11–22.

Nyström, C. and Stanley-Wood, N., Measurement of the minimum dimension of particles by a ring gap sizer. *Acta Pharm. Suec.*, 14 (1977) 181–190.

Nyström, C., The use of the ring gap sizer for characterization of particle shape in the sieve range. *Powder Technol.*, 20 (1978) 83–87.

Ridgway, K. and Rupp R., The effect of particle shape on powder properties. *J. Pharm. Pharmacol.*, 21 (1969) 30S–39S.

Strickland, W.A., Busse, L.W. and Higuchi, T., The physics of tablet compression XI. Determination of porosity of tablet granulations. *J. Am. Pharm. Assoc.*, 45 (1956) 482–486.

Wasan, D.T., Wnek, W., Davies, R., Jackson, M. and Kaye, B., Analysis and evaluation of permeability techniques for characterizing fine particles. Part 1. Diffusion and flow through porous media. *Powder Technol.*, 14 (1976) 209–228.

Wikberg, M. and Alderborn, G., Compression characteristics of granulated materials: II. Evaluation of granule fragmentation during compression by tablet permeability and porosity measurements. *Int. J. Pharm.*, 62 (1990) 229–241.