

# A vacuum microbalance technique for studies on the wettability of powders

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A vacuum microbalance technique has been used to evaluate the wettability of powders. The rate of uptake, and equilibrium weight of uptake, of water vapour onto outgassed powder samples, of differing wettabilities, were determined at different known temperatures. Standard techniques of data analysis were used to establish the enthalpy, entropy and Gibb's free energy of the activation and adsorption processes. The values obtained appeared to be in the correct order of magnitude and those for activation clearly reflected the relative wettability of the powders. Tests for compensation demonstrated that with the exception of phenobarbitone, there was probably a common mechanism producing the adsorption.

The bringing of water and a solid into intimate contact is an important aspect in both the processing of pharmaceutical materials and also their use as solid oral dosage forms. The extent to which a liquid spreads over a solid surface, 'wetting', is associated with the relative magnitude of the surface energies between the phases of gas, liquid and solid. There are difficulties associated with the determination of the liquid/solid and the gas/solid surface energies. Methods to determine the surface energy of a solid which can form smooth flat surfaces have been proposed, these involve the measurement of the angle of contact formed between the solid surface and a liquid drop (the contact angle,  $\theta$ ) for a series of liquids of known surface energy (Fox & Zisman 1950; Neumann et al 1974; Good 1980). Most pharmaceutical powders do not exist as smooth flat surfaces, and hence there are practical and theoretical problems associated with the determination of a contact angle, especially if the powders are hydrophobic.

There are three techniques reportedly capable of determining the wettability of powders, two of which determine a contact angle and one of which measures the enthalpy of immersion. Liquid penetration experiments generally require the use of binary liquid mixtures to obtain an extrapolation to an estimated penetration rate for water when dealing with materials whose contact angles exceed  $90^\circ$  (Buckton & Newton 1985a); the results obtained do

reflect the powders wettability but the theoretical basis of such results is by no means certain. The use of sessile drops on compressed discs, as advocated by Heertjes & Kossen (1967) and Zografi & Tam (1976), has been criticized by Buckton & Newton (1985b, 1986a) because the process of forming the powder compacts can alter the surface energy of the powder. Measurements of enthalpies of immersion have a sound theoretical basis, however, hydrophobic powders will not spontaneously immerse in water (Buckton 1985). Previous workers (Hansford et al 1980) have applied extrapolation techniques from ethanol/water mixtures to obtain a value for the enthalpy of immersion into water, but the theoretical basis for this cannot be relied upon, owing to preferential adsorption of solvents. There is, therefore, a need for an alternative approach to the assessment of the wettability of hydrophobic powders. For this purpose, the study of a vapour phase wetting by means of gravimetric adsorption, a technique not previously used for such determinations, has been applied.

The underlying principles have long been established, and the review by Casanderna & Vasofsky (1979) demonstrates the versatility of the technique. Those authors noted that information could be gained on surface area, porosity, enthalpies of adsorption, and activation energies of adsorption. Schroder (1984) demonstrated how the thermodynamic functions obtained from gravimetric adsorption studies could be related to immersionsal wetting.

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Vacuum microbalance systems have been used to study interfacial phenomena (Casanderna & Vasofsky 1979) and many studies of water vapour adsorption have been carried out, for example that of the affinity of fibre forming polymers for water (Jacobasch 1979). However, there are no reports of the technique having been applied to the study of the wetting by water of hydrophobic powders of pharmaceutical interest.

Most adsorption studies in the literature are generally designed to study a range of adsorbates and one adsorbent, as for example adsorption of alcohols onto magnesium maillanite (Anielshi et al 1979). The current study differs in approach in that the adsorbate is constant (water) and the adsorbent is changed.

#### MATERIALS AND METHODS

##### Materials

Studies were carried out on four powders (BP quality): amylobarbitone, butobarbitone, phenobarbitone and pentobarbitone. A standard range of surface areas for the samples was obtained by sieving (45–63  $\mu\text{m}$  size fraction). These powders were selected to ensure a range of wettabilities and because data existed from techniques for assessing contact angles, such as liquid penetration and sessile drops on compressed powder discs (Buckton 1985; Buckton & Newton 1985a, b).

##### System construction

A vacuum microbalance system was constructed using a Robal microbalance with a vacuum head (CI Electronics). A diagrammatic representation of the system is presented in Fig. 1. Construction of the bulk of the system was from metal (copper and stainless steel with brass flanges) and glass, with each

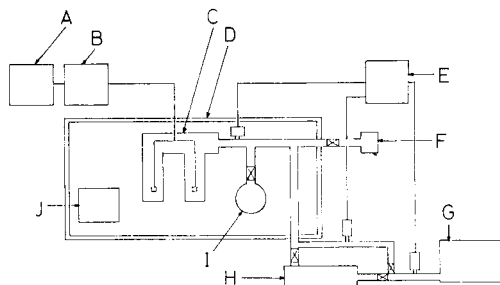


Fig. 1. Diagrammatic representation of the vacuum microbalance system. Key: A, chart recorder; B, Robal control unit; C, microbalance head; D, thermostatically controlled cabinet; E, vacuum gauge; F, manometer; G, rotary pump; H, diffusion pump; I, water reservoir; J, heater unit; X, valves.

individual section being sealed with solder or epoxy-resin as appropriate. The various sections were coupled with co-seals (Edwards) which provide a strong and effective joint. The vacuum was obtained using a Diffstak 63/150 oil diffusion pump (Edwards) with a pumping speed of 135 litres  $\text{s}^{-1}$  and an ultimate vacuum capability of  $3 \times 10^{-8}$  mbar. The Diffstak was backed and the system 'roughed out' with an E2M5 double stage rotary pump (Edwards) with a maximum water vapour pumping rate of 0.06  $\text{kg h}^{-1}$ . Two pirani gauge heads (Edwards, PRL 10) were mounted in the system, one to measure the vacuum obtained during 'roughing' and one to monitor the backing vacuum for the Diffstak. A penning gauge head (Edwards, CP25K) was used to measure the ultimate vacuum obtained. All three of the gauge heads were connected to a microprocessor based digital pirani/penning gauge (Edwards, 1005).

A water reservoir and a manometer were connected into the system, and the relevant sections were thermostatically controlled. Temperature control was achieved by making an air thermostat connected to a heating element in a fan unit. This instrument when mounted in a Perspex cabinet was found to control the temperature  $\pm 0.05$  K when operated in the range from  $5^\circ$  above room temperature to 318 K. Temperatures of ambient values and below could not be used.

The connection to the manometer, which was outside of the temperature-controlled chamber, was heavily lagged to prevent water condensation producing false readings.

##### Method

One pan of the balance was covered with a thin layer of powder, the weight of which was recorded. The use of a two pan balance allowed the empty pan to compensate for any buoyancy effects and any adsorption onto the pans or suspensions rods. The upper surface of the empty pan was coated with a thin layer of high vacuum silicon grease to ensure the same surface area was available for adsorption as on the powder covered pan.

Once a suitable quantity of powder (about 10 mg) had been weighed onto one pan of the balance, the Robal was zeroed. The range was set so that full scale deflection on the chart recorder was 0.500 mg. The system was then maintained at a vacuum in the region of  $10^{-6}$  mbar for 24 h. The Robal unit was once again tared to zero, which corresponded to the reproducibly cleanest state of the powder, i.e. the state of constant weight, where no further desorption of impurities from the surface occurs. This is

regarded as a clean surface for the purpose of this work.

The clean sample was isolated from the vacuum pump, and water (which had previously been out-gassed by ultrasonic and vacuum treatment) was allowed to equilibrate with the powder to produce a saturated vapour pressure at that particular temperature. The rate of uptake and the equilibrium uptake were recorded. Six replicate determinations were undertaken, after each of which vacuum treatment of the powder resulted in a return to the previously tared zero reading of the balance. This demonstrates that the original surface is as clean as can possibly be obtained with this system. The process was then repeated with the water vapour being admitted in small amounts; again equilibrium was established, and the pressures were noted from the manometer.

### Theory

*Equilibrium uptake.* Considering the equilibrium clean dry powder + water vapour  $\rightleftharpoons$  adsorbed water on powder (1)

the activity of the powder is taken as unity (Atkins 1982), the concentration of the water vapour is taken as the vapour pressure and the weight of uptake at equilibrium is the measure of the adsorbed water on the powder. Throughout this work, the standard state corresponding to unit activity is defined as the equilibrium uptake (mg) onto 10.000 mg of powder (b) at the saturated vapour pressure of water at the temperature of the experiment ( $P_o$ ). It follows that the Gibb's free energy and entropy terms will not be absolute values, but will be relative to the choice of standard state. If a different standard state had been chosen the values would be simply altered by a factor. The equilibrium constant  $K_{ad}$  for this particular standard state can be obtained thus:

$$K_{ad} = \frac{b}{P_o} \quad (2)$$

Considering the equilibrium at different temperatures (T), and by use of the van't Hoff isochore, the value of the enthalpy of adsorption ( $\Delta H^*_{ads}$ ) can be obtained. The value of  $\Delta H^*_{ads}$  observed experimentally is the sum of the initial monolayer formation ( $\Delta H_{mon}$ ) and the subsequent multilayer formation, which can be regarded as analogous to condensation ( $\Delta H_{cond}$ ). Brunauer et al (1938) (BET) first described multilayer adsorption by means of those two steps when extending the Langmuir equation to form the BET equation. The BET equation assumes that

only the first layer of multilayer adsorption can be ascribed a special value indicative of the solid ( $\Delta H_{mon}$ ). Subsequent layers are related only to the evaporation and condensation of the adsorbate ( $\Delta H_{cond}$ ).

The Gibbs function,  $\Delta G^*$  is given by

$$q\Delta G^*_{ads} = -RT \ln K_{ad} \quad (3)$$

and hence  $\Delta S^*_{ads}$  can be obtained from

$$\Delta G^*_{ads} = \Delta H^*_{ads} - T\Delta S^*_{ads} \quad (4)$$

The entropy of adsorption ( $\Delta S^*_{ads}$ ) again consists of two components, the entropy change due to the ordered formation of a monolayer ( $\Delta S_{mon}$ ) and the entropy change due to multilayer formation, which is not necessarily ascribed to any property of the solid surface, and is taken as analogous to condensation ( $\Delta S_{cond}$ ) (Brunauer et al 1938). By consideration of the entropy of water vapour ( $S_{WV}$ ) and liquid ( $S_{WL}$ ), it is possible to assess the entropy change due to condensation ( $\Delta S_{cond}$ ).

$$S_{WL} - S_{WV} = \Delta S_{cond} \quad (5)$$

the entropy change due to monolayer formation is thus

$$\Delta S^*_{ads} - \Delta S_{cond} = \Delta S_{mon} \quad (6)$$

*Rate of uptake.* A representative plot of uptake as a function of time (t) is shown in Fig. 2. Transformation of these data via plots of  $-\ln(b-x)$  as a

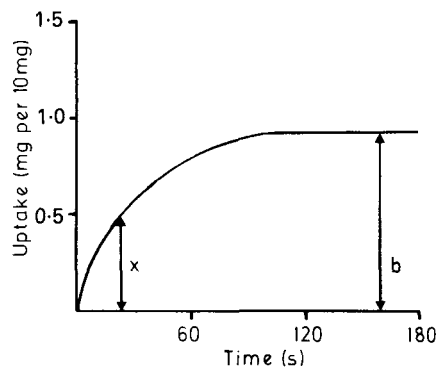


FIG. 2. A typical trace of uptake as a function of time, for butobarbitone, showing the equilibrium uptake (b) and an example of the pre-equilibrium uptake (x).

function of time, yields straight lines the slopes of which are the apparent first order rate constant ( $k_1$ ). Plots of  $\ln k_1$  as a function of  $1/T$ , yield values of the activation energy ( $E_a$ ) for the overall uptake process. This value of  $E_a$  can be used to calculate  $\Delta H^\ddagger$  and  $\Delta S^\ddagger$  and subsequently  $\Delta G^\ddagger$  can be determined by standard procedures (Atkins 1982).

Rouquerol (1985) and Galway (1985) have discussed the complex reaction sequences describing solid state reaction systems. These general accounts make it clear that there is no simple relationship between the thermodynamic parameters for activation and those for reaction, in this case an adsorption reaction.

Having obtained data for  $\Delta G^\ddagger$ ,  $\Delta H^\ddagger$  and  $\Delta S^\ddagger$  for the process, it is possible to test for enthalpy-entropy compensation. A review by Tomlinson (1983) stressed the importance of this 'little used' method of data analysis. Compensation testing does not arise from the principles of classical thermodynamics, but from relationships between thermodynamic quantities, this concept is termed extrathermodynamics. The two possible tests for compensation are to obtain a linear relationship for (i)  $\Delta H$  as a function of  $\Delta S$ , (ii)  $\Delta H$  as a function of  $\Delta G$ . Krug et al (1976a, b) noted that  $\Delta S$  is obtained using  $\Delta H$  and  $\Delta G$  values; non-compensated series can show high correlation between  $\Delta H$  and  $\Delta S$  due to propagation of errors. Those workers concluded that  $\Delta H$  as a function of  $\Delta G$  was thus the reliable test for compensation. A linear relationship between  $\Delta H$  and  $\Delta G$  can be taken to imply a structure-activity relationship, indicating that the mechanism of the process is the same throughout, the relationship being due to chemical causality.

## RESULTS AND DISCUSSION

### Adsorption isotherms

Figs 3 to 6 show the adsorption isotherms of water vapour, at various temperatures, onto amylobarbitone, butobarbitone, pentobarbitone, and phenobarbitone, respectively. The general trend is as expected, whereby a Type I Van der Waals (physical) adsorption isotherm (Brunauer 1945) is exhibited at high temperatures. This corresponds to the formation of a unimolecular layer, the volume of

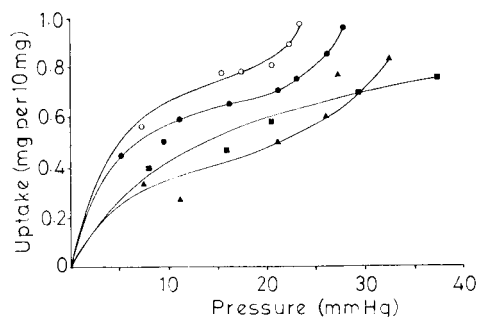


Fig. 3. Adsorption isotherms for amylobarbitone. Key: ○, 25.0; ●, 27.3; ▲, 30.2; ■, 32.8 °C.

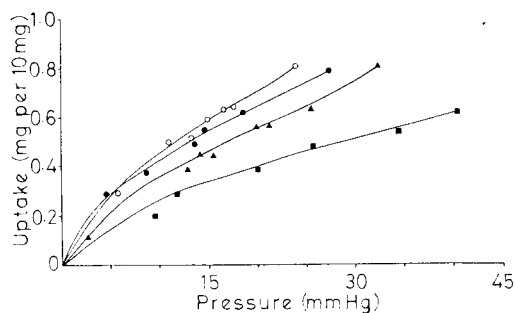


Fig. 4. Adsorption isotherms for butobarbitone. Key: ○, 25.0; ●, 27.3; ▲, 30.2; ■, 34.4 °C.

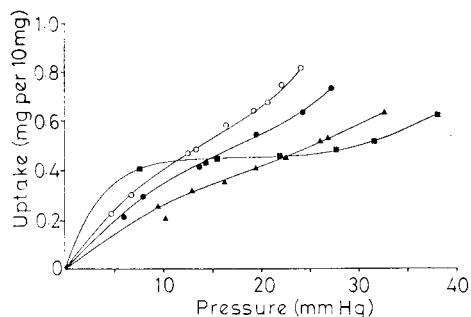


Fig. 5. Adsorption isotherms for pentobarbitone. Key: ○, 25.0; ●, 27.4; ▲, 30.4; ■, 33.4 °C.

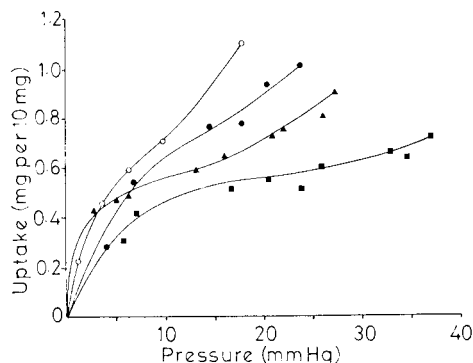


Fig. 6. Adsorption isotherms for phenobarbitone. Key: ○, 20.0; ●, 25.0; ▲, 27.3; ■, 32.8 °C.

gas adsorbed reaching a limiting amount as the vapour pressure increases. At lower temperatures, the general trend is to a type II (Brunauer 1945) isotherm indicating multilayer adsorption; this isotherm shows rapid adsorption initially until a monolayer is obtained, then slow coverage as multilayers begin to form, followed by a further period of rapid adsorption as the multilayers facilitate further bonding.

The condensed film isotherm was proposed by Harkins & Jura (1944), who derived an equation relating pressure to the reciprocal of the square of the quantity of gas adsorbed ( $b$ ),

$$\log \frac{P}{P_0} = B - \frac{U}{b^2} \quad (7)$$

where  $B$  and  $U$  are constants and  $P_0$  is the saturated vapour pressure. Many type II isotherms do produce a straight line plot for  $\log P/P_0$  as a function of  $1/b^2$  (Adamson 1967), and the isotherms obtained in this work show good correlation to such a relationship; correlation coefficients ranging from 0.929 to 0.992. Adamson (1967) noted that the model of a uniform condensed monolayer used by Harkins & Jura (1944) does not adequately represent the process, as type II isotherms almost certainly do involve multilayer adsorption. The use of such isotherms are thus descriptive of the process but can offer no theoretical explanation.

#### Rate of uptake

The results in Fig. 7. show the relationship  $-\ln(b-x)$  as a function of time ( $t$ ) at various temperatures for butobarbitone, which is representative of all four powders. Straight lines with correlation coefficients in the region of 0.99 were obtained in every case, from which the apparent first

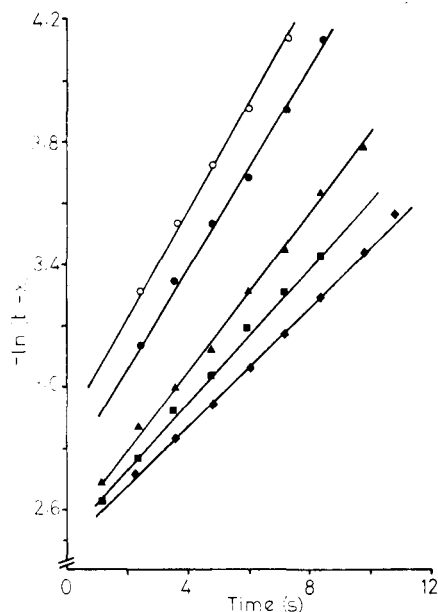


Fig. 7.  $-\ln(b-x)$  as a function of time, for butobarbitone. Key:  $\circ$ , 310.0 K;  $\bullet$ , 307.4 K;  $\blacktriangle$ , 303.2 K;  $\blacksquare$ , 300.3 K;  $\blacklozenge$ , 298.0 K.

order rate constants ( $k_1$ ) were obtained. Fig. 8 shows the values of  $k_1$  obtained from Fig. 7 presented as  $\ln k_1$  as a function of  $1/T$ . The correlation coefficient obtained from Fig. 8, and those obtained from similar plots on the other three powders are presented in Table 1, together with the derived enthalpy of

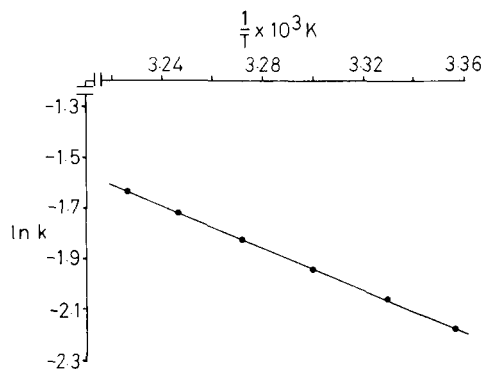


Fig. 8.  $\ln k_1$  as a function of  $1/T$ , for butobarbitone.

activation ( $\Delta H^\ddagger$ ), the entropy of activation ( $\Delta S^\ddagger$ ) and the Gibb's free energy ( $\Delta G^\ddagger$ ) of the process. The possible error in  $\Delta H^\ddagger$  has been calculated by adjustment of one end of the straight line of  $-\ln k$  as a function of  $1/T$  by the mean standard deviation of  $\ln k$ ; the maximum error that could be introduced into  $\Delta S^\ddagger$  and  $\Delta G^\ddagger$  has also been assessed (Table 1). The average error for each thermodynamic quantity is about 10%. Considering the practical difficulties inherent in this system, such as problems with measuring the pressure in the system due to a possible temperature and pressure gradient leading to the manometer, and the problem of accurately reproducing uptakes in the order of 0.800 mg of water, such errors are remarkably low. It clearly is encouraging that the differences between the thermodynamic functions (shown in Table 1) for the powders are greater than that which could be caused by experimental error. The mean values of  $\Delta G^\ddagger$ , and  $\Delta H^\ddagger$  do fit a logical pattern, reflecting the rank order of wettability as assessed by apparent contact

Table 1. The mean values of the thermodynamic functions of the activation process ( $\pm$  error), together with the correlation coefficient of  $\ln k_1$  as a function of  $1/T$ .

Powder	Correlation coefficient	$\Delta H^\ddagger$ (kJ mol <sup>-1</sup> )	$\Delta S^\ddagger$ (J mol <sup>-1</sup> K <sup>-1</sup> )	$\Delta G^\ddagger$ (kJ mol <sup>-1</sup> )
Amylobarbitone	0.998	33.4 $\pm$ 2.4	-431.3 $\pm$ 9.8	161.9 $\pm$ 5.8
Butobarbitone	0.994	29.1 $\pm$ 1.5	-421.6 $\pm$ 5.5	154.7 $\pm$ 3.4
Pentobarbitone	0.995	33.2 $\pm$ 5.5	-434.8 $\pm$ 20.4	162.8 $\pm$ 12.3
Phenobarbitone	0.996	32.3 $\pm$ 3.7	-432.0 $\pm$ 14.4	161.1 $\pm$ 8.6

angles obtained from liquid penetration results (Buckton & Newton 1986b), that is amylobarbitone 101°, pentobarbitone 100°, phenobarbitone 89°, butobarbitone 88°. The values obtained for the activation energy, and the Gibb's free energy term, are of the correct order to indicate that the process is not favoured; these findings are compatible with the hydrophobic nature of the solids. The negative value of the entropy term suggests an imposition of order in the system. This is to be expected as water molecules are changing from a gas phase to a more ordered condensed phase. The mean values of  $\Delta G^\ddagger$ ,  $\Delta S^\ddagger$  and  $\Delta H^\ddagger$ , are descriptive of the processes involved, and are clearly indicative of the wettability of the powders. The comparatively low activation energy of butobarbitone (29.1 kJ mol<sup>-1</sup>), even after addition of the maximum error for this powder, will be less than the mean value for amylobarbitone (33.4 kJ mol<sup>-1</sup>).

In Fig. 9, the values of  $\Delta G^\ddagger$  are presented as a function of  $\Delta H^\ddagger$  as a test for compensation. The correlation coefficient for the line shown, which

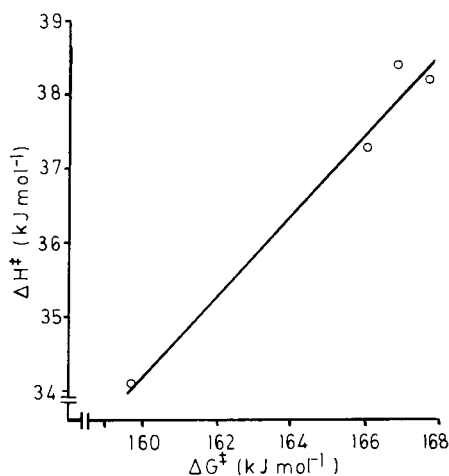


Fig. 9.  $\Delta H^\ddagger$  as a function of  $\Delta G^\ddagger$  as a test for compensation.

includes all four powders, is 0.9871, and if phenobarbitone is excluded (see below) the correlation becomes 0.9898. The values of the correlation coefficients are surprisingly high given the problems associated with the measuring technique, and data analysis, and do indicate chemical causality. It is not unexpected that the correlation should improve (albeit slightly) after the exclusion of phenobarbitone, which, of the four powders, is chemically distinct due to the substitution of a benzene ring. The

original selection of powders was intended to represent a range of wettabilities and this necessitated significantly different substituents on the barbituric acid. It is encouraging therefore that such structurally diverse compounds should indicate clear correlation, and the possibility of exploring structure-activity relationships clearly exists by application of the method to other systems (homologous series).

#### Equilibrium uptake

The thermodynamic functions  $\Delta G^\circ_{\text{ads}}$ ,  $\Delta H^\circ_{\text{ads}}$ , and  $\Delta S^\circ_{\text{ads}}$  calculated from the data which are presented in Table 2, are shown in Table 3.

Table 2. The equilibrium uptake (b) onto 10.000 mg of powder, at the saturated vapour pressure of water ( $P_o$ ) at various temperatures (T) together with the correlation coefficients for  $\ln(b/P_o)$  as a function of  $1/T$ , from the gradient of which  $\Delta H_{\text{ads}}$  was calculated.

Powder	T (K)	b (mg/10 mg)	$P_o$ (mm Hg)	$\ln b/P_o$	Correlation coefficient
Amylobarbitone	298.0	0.080	23.756	-5.69	0.998
	300.3	0.079	27.16	-5.84	
	303.2	0.068	32.19	-6.15	
	305.8	0.062	37.31	-6.40	
	309.5	0.058	45.70	-6.67	
	312.6	0.053	54.15	-6.93	
Butobarbitone	298.0	0.080	23.76	-5.69	0.988
	300.3	0.079	27.16	-5.83	
	303.2	0.081	32.19	-5.98	
	307.4	0.063	40.80	-6.47	
	310.0	0.064	47.08	-6.60	
Pentobarbitone	298.0	0.080	23.76	-5.69	0.9862
	300.4	0.073	27.37	-5.93	
	303.4	0.063	32.56	-6.25	
	306.4	0.063	38.59	-6.42	
Phenobarbitone	293.0	0.080	17.54	-5.39	0.990
	298.0	0.074	23.76	-5.77	
	300.3	0.066	27.16	-6.02	
	303.2	0.052	32.19	-6.43	
	305.8	0.052	37.3	-6.58	
	309.5	0.052	45.7	-6.78	

Table 3. The thermodynamic functions of the adsorption process, calculated starting from  $\ln K$  as a function of  $1/T$ , where  $K = b/P_o$  as defined in equation 2.

Powder	$\Delta H^\circ_{\text{ads}}$ (kJ mol <sup>-1</sup> )	$\Delta H_{\text{mon}}$ (kJ mol <sup>-1</sup> )	$\Delta G^\circ_{\text{ads}}$ (kJ mol <sup>-1</sup> )	$\Delta G_{\text{mon}}$ (kJ mol <sup>-1</sup> )	$\Delta S^\circ_{\text{ads}}$ (J mol <sup>-1</sup> K <sup>-1</sup> )	$\Delta S^\circ_{\text{ads}}$ (J mol <sup>-1</sup> K <sup>-1</sup> )
Amylobarbitone	-66.8	-22.8	14.1	22.6	-271.6	-152.5
Butobarbitone	-61.4	-17.4	14.0	22.5	-253.0	-133.9
Pentobarbitone	-67.5	-23.5	14.2	22.7	-274.0	-154.9
Phenobarbitone	-65.2	-21.2	14.5	22.9	-267.2	-148.1

The enthalpy of adsorption ( $\Delta H^\circ_{\text{ads}}$ ) consists of two components,  $\Delta H_{\text{cond}}$  and  $\Delta H_{\text{mon}}$ ;  $\Delta H_{\text{cond}}$  may be regarded as the difference between the enthalpies of formation of liquid water (-286 kJ mol<sup>-1</sup>) and of

water vapour ( $-242 \text{ kJ mol}^{-1}$ ) (data from Stark & Wallis 1978), thus  $\Delta H_{\text{cond}}$  equals  $-44 \text{ kJ mol}^{-1}$ . The enthalpy of monolayer formation ( $\Delta H_{\text{mon}}$ ) can be calculated from equation 8.

$$\Delta H_{\text{ads}}^{\circ} - \Delta H_{\text{cond}} = \Delta H_{\text{mon}} \quad (8)$$

Similarly the entropy of monolayer formation can be calculated from equations 5 and 6. Using data for  $S_{\text{WL}}$  and  $S_{\text{WV}}$  provided by Stark & Wallis (1978),  $\Delta S_{\text{cond}}$  equals  $-119.1 \text{ J mol}^{-1} \text{ K}^{-1}$ .

The values of  $\Delta H_{\text{mon}}$  and  $\Delta S_{\text{mon}}$  together with the value of  $\Delta G$  calculated from them ( $\Delta G_{\text{mon}}$ ) are also presented in Table 2. If the views of Brunauer et al (1938) are correct in that multilayer adsorption can be considered as monolayer formation and condensation, the values of  $\Delta H_{\text{mon}}$  may identify the sort of adsorption process involved. The range of values obtained for  $\Delta H_{\text{mon}}$  is  $-17.4$  to  $-23.5 \text{ kJ mol}^{-1}$ , and this is the order of magnitude found for physical adsorption and hydrogen bonding ( $5$ – $20 \text{ kJ mol}^{-1}$ ). The adsorption process under consideration here is therefore likely to be physical adsorption rather than chemisorption, where values would be considerably greater.

The possible order of magnitude of error for  $\Delta G_{\text{ads}}^{\circ}$  has been obtained by reference to the work on propagation of errors when using Van't Hoff analysis, reported by King (1965); the error in  $\ln k$  is  $\pm 0.02$ , thus these errors are the likely range of variance:  $\Delta H_{\text{ads}}^{\circ} = 4.1 \text{ kJ mol}^{-1}$ ,  $\Delta S_{\text{ads}}^{\circ} = 13.8 \text{ J mol}^{-1} \text{ K}^{-1}$ ,  $\Delta G_{\text{ads}}^{\circ} = 2.8 \text{ kJ mol}^{-1}$ . It follows, from Table 3, that the thermodynamic functions cannot be regarded as significantly different.

### General discussion

Current methods of assessing the wettability of powders suffer from theoretical or practical limitations. The ideal situation is to be able to determine experimentally a complete set of thermodynamic functions for the wetting process. The relevant functions can be considered, in practice, as being those related to adsorption, adhesion and immersion. The wetting process can either be considered as a single step, or as involving many steps with one particular intermediate equilibrium and by application of Hess's law

$$\Delta H_{\text{ads}} + \Delta H_{\text{imm}}(x = b) = \Delta H_{\text{imm}}(x = 0) \quad (9)$$

where the subscript imm refers to immersion, and  $x$  is the degree of coverage of the original surface.

Similarly, Schroder (1984) describes the interrelation between adsorption and immersion in the manner of Harkins (1952) where:

$$\Delta H_{\text{imm}}(x = 0) - \Delta H_{\text{imm}}(\text{mon}) = \frac{1}{b} (\Delta H_{\text{mon}} - \Delta H_{\text{cond}}) \quad (10)$$

whereby the immersion of a sample loaded to one monolayer capacity is considered ( $\Delta H_{\text{imm}}(\text{mon})$ ). It follows that having obtained the enthalpy of adsorption, it is only necessary to overcome the practical difficulties for the immersion of the vapour covered powder in order to obtain  $\Delta H_{\text{imm}}(x = 0)$ . It is then possible to relate immersion to adhesion and indeed immersion to contact angle and surface tension as described by Schroder (1984).

The value of data obtained from adsorption studies is that it provides a possible method of overcoming the practical difficulties of measuring the enthalpy of immersion of a clean hydrophobic powder in water by application of Hess's law. The practical difficulties being that hydrophobic powders will not spontaneously immerse in water (Buckton 1985).

### Conclusion

Gravimetric studies of vapour phase adsorption can be used to obtain thermodynamic functions for the mechanism of the adsorption of water vapour onto hydrophobic pharmaceutical powders, as well as for the final equilibrium adsorption state. All the thermodynamic quantities obtained for the activated state, appeared to be in the correct order of magnitude (Schroder 1984) and generally reflected the rank order of wettability suggested from the results of liquid penetration experiments (Buckton 1985; Buckton & Newton 1986b).

The tests for compensation demonstrated that with the possible exception of phenobarbitone, there was probably a common mechanism producing the adsorption. This relationship could be studied by future work on more closely related compounds, however, the results may become indistinguishable within the limits of experimental error with such determinations.

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