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AQUEOUS FILM-COATING VAPORIZATION EFFICIENCY

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ABSTRACT

A steady-state condition is achieved during most of an aqueous film-coating cycle, i.e., the rate of application of moisture to the tablet bed is equal to its rate of evaporation. A mathematical model was developed for the steady-state condition to describe the efficiency of evaporation of the aqueous solvent for any set of drying conditions (inlet air flow rate, temperature, and humidity) and spray rate of coating suspension. The model was tested utilizing a series of different coating conditions and coating compositions. A vaporization efficiency, E_s, was defined as a means to assess a reproducible coating end point. E_s values for each coating formula fell within a narrow range. The hydroxypropyl cellulose coating system had a significantly lower E_s value due to the higher tackiness that occurs with this polymer during film formation.

INTRODUCTION

The first film-coated tablet was marketed by Abbott Laboratories in 1953. An impressive list of advantages of film-coating was enumerated for this tablet coating process[1]. While the original film-coating work was exclusively with organic solvent systems, there is currently a shift underway to aqueous tablet coating. The impetus for the transition to an aqueous solvent for coating formulas comes from the flammability, environmental toxicity, and escalating cost of organic solvents. Aqueous tablet

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coating is not without its drawbacks, however. The stability of the active ingredients in the presence of moisture is of obvious concern. Aqueous coating suspensions may also support bacterial growth which is not a consideration when organic solvents are used. From a process point of view, one of the greatest difficulties presented by the shift to aqueous coating is the greatly increased energy requirements to evaporate the water in the formation of the film on the tablet surface. This, of course, is a result of the very high latent heat of vaporization for water relative to the commonly used organic solvents.

At present, the approach used in the pharmaceutical industry towards the film-coating of tablets is primarily empirical. The purpose of this report is to describe a drying theory for the vaporization of aqueous solvent during a film-coating process. It can be used to examine the effect of coating formula application rate and in determining the influence of the air temperature, air flow rate, and humidity of the drying air in the aqueous film-coating of tablets.

THEORETICAL

During most of the aqueous coating operation in an air-suspension or perforated pan type coater a steady-state is maintained between the rate of application of water in the coating composition and its rate of evaporation. The drying theory developed is aimed at describing the steady-state situation only. At steady-state the drying rate must equal the application rate of the coating suspension. That is, the rate of evaporation of water is exactly the same as the rate of spraying of water onto the tablet bed. A moisture balance for this steady-state condition, assuming a closed system, is

$$GH_1 + 15.432RX = GH_2 \qquad (1)$$

where

R = coating formula application rate (g./min.)

X = aqueous fraction of the coating formula

G = mass flow of air through the system (lb. dry air/min.)
H_1, H_2 = humidity in the inlet and exhaust air ducts respectively (gr./lb. dry air)

The mass flow of air through the system is obtained from the standard cubic feet per minute (SCFM) of air flow divided by the specific volume of the air. Solving for R

$$R = \frac{G(H_2-H_1)}{15.432X} \tag{2}$$

Under a given set of drying conditions (fixed inlet temperature, humidity, and air flow rate) there will be a maximum possible application rate, R_{max}, at which a steady-state condition can be achieved and it will be given by

$$R_{max} = \frac{G(H_s-H_1)}{15.432X} \tag{3}$$

where H_s is the saturation humidity of the exhaust air (gr./lb. dry air). Spray or evaporative cooling follows the wet-bulb line on a psychrometric chart[2]. This means that the temperature of the exhaust air at R_{max} will be the wet-bulb temperature of the inlet air. To obtain a wet-bulb temperature on a temperature probe in the exhaust duct would require a water surface reaching a dynamic equilibrium between the rate of heat transfer by convection and the rate of mass transfer by evaporation. For this to occur, the entire tablet bed surface would have to be saturated with water. This is not a condition of practical interest in film-coating, but is useful theoretically as a reference point.

Using the application rate and the theoretical maximum application rate under the given drying conditions, a vaporization efficiency, E, can be expressed

$$E = \frac{R}{R_{max}} \tag{4}$$

This is similar to the vaporization efficiency described for through-circulation batch drying[3]. The exhaust humidity, H_2, is calculated from the following rearrangement of equation (1):

$$H_2 = \frac{15.432RX}{G} + H_1 \quad (5)$$

The exhaust temperature, T_2, can be estimated by subtracting from the heat input the heat loss due to evaporation of the aqueous solvent and loss to the environment.

$$T_2 = T_1 - \frac{RX\lambda}{Gs} - 0.05T_1 \quad (6)$$

T_1 is the inlet temperature (°C), λ is the latent heat of vaporization (cal./g.) at the wet-bulb temperature, and s is the humid heat (cal./lb.°C) of the drying air. A 5% heat loss to the environment is assumed based on experience in a 24" Accela-Cota. Substituting equations (2) and (3) into equation (4) yields

$$E = \frac{(H_2-H_1)}{(H_s-H_1)} \quad (7)$$

Substituting for H_2 in equation (7) gives

$$E = \frac{15.432RX}{G(H_s-H_1)} \quad (8)$$

The independent variables in the film-coating process are X, T_1, H_1, R and G. Equation (8) expresses the vaporization efficiency in terms of the independent variables except that the saturation humidity, H_s, is included. Since H_s is a nonlinear function of humidity and temperature, further simplification is difficult.

Presumably acceptable film-coating can be made over a range of vaporization efficiency as calculated using equation (8). With a specific coating formula and drying conditions there will be a maximum coating application rate compatible with the formation of an acceptable film-coating. The vaporization efficiency calculated with this maximum coating application rate and the specific drying conditions will be a critical value above which successful coating will not generally be possible. The critical vaporization efficiency for a specific coating formula is not a single value, but falls within a narrow range under various drying conditions. Different coating formulas may produce a range of critical vaporization efficiencies. This is primarily dependent on the physical properties of the films obtained from the coating formulas. The tackiness of the film during drying is particularly relevant to this assessment.

Using the vaporization efficiency as expressed in equation (8), the influence of the coating spray rate, the solids content of the formula and the temperature, humidity, and flow rate of the drying air can be examined and quantified. Only the quantity of water in the coating composition is important in the derivation of this mathematical model. However, the actual composition of the coating liquid is significant in determining the quality of the film-coated tablets under specified conditions. At the higher vaporization efficiencies the coating system is operating closer to saturation conditions in the exhaust air and the difficulty in obtaining acceptable film-coated tablets is significantly increased.

The influence of changing any of the variables defining the vaporization efficiency in a given set of coating conditions can be examined by evaluation of the partial derivatives of equation (8) with respect to each variable. They can be utilized to describe the magnitude of change in each of the coating variables necessary to affect a desired change in the vaporization efficiency. The following derivatives can be obtained:

$$\frac{\partial E}{\partial R} = \frac{15.432X}{G(H_s-H_1)} = \frac{1}{R_{max}} \qquad (9)$$

$$\frac{\partial E}{\partial X} = \frac{15.432R}{G(H_s-H_1)} = \frac{E}{X} \qquad (10)$$

$$\frac{\partial E}{\partial G} = \frac{-15.432RX}{G^2(H_s-H_1)} = \frac{-E}{G} \qquad (11)$$

The vaporization efficiency in equation (8) is a complicated function of inlet humidity since H_s is a function of inlet humidity as well as inlet temperature. The evaluation of the effect of changing inlet humidity can be examined by looking at the effect of changing the humidity driving force, (H_s-H_1). The partial derivative of equation (8) with respect to the humidity driving force is

$$\frac{\partial E}{\partial (H_s - H_1)} = \frac{-15.432RX}{G(H_s - H_1)} = \frac{-E}{(H_s - H_1)} \qquad (12)$$

The humidity driving force is increased by increasing T_1 or decreasing H_1. At constant T_1, increasing H_1 also increases H_s, but not as rapidly. This results in the humidity driving force, $(H_s - H_1)$, decreasing.

At constant inlet humidity, increasing the inlet air temperature increases the saturation humidity, H_s. The saturation humidity can empirically be precisely and accurately represented by a polynomial, P, in terms of the wet-bulb temperature, T_w, of the inlet air

$$H_s = P(T_w) = a_0 + a_1 T_w + a_2 T_w^2 + \ldots + a_n T_w^n \qquad (13)$$

This allows evaluation of the partial derivative, $\partial E/\partial T_w$, using the chain rule

$$\frac{\partial E}{\partial T_w} = \frac{\partial E}{\partial H_s} \times \frac{\partial H_s}{\partial T_w} \qquad (14)$$

Thus, at constant inlet humidity, the evaluation of $\partial E/\partial T_w$ can be used to estimate the *influence of a change in inlet temperature* on the vaporization efficiency. From a psychrometric chart, at 50 gr./lb. dry air humidity (approximately 40% relative humidity at 24°C), the wet-bulb temperature changes about 1°C for every 3°C change in T_1.

EXPERIMENTAL

All aqueous film-coating of tablets was performed in a 24" Accela-Cota modified to produce air flow rates up to 700 SCFM at an inlet air temperature setting up to 90°C. The inlet air humidity was monitored by an EG&G Model 911 Dew-All humidity analyzer. The coating liquid spray rate was followed with a Micro-Motion Model C12 mass-flow meter. Coating trials were performed at a fixed pan speed of 12 RPM using 60 PSI atomizing air pressure. A Spraying Systems Co. spray-gun Model 1/4JAU was equipped with a Model 2850 fluid cap and a Model 67228-45° air cap.

Nonabsorbent polystyrene beads 7/16" in diameter were used in a preliminary trial where distilled water (with 0.2% sodium lauryl sulfate) was sprayed at increasing rates until the bead bed was saturated. This pure aqueous system was used to demonstrate the validity of the basic mathematical model. Lactose placeboes were used as the tablet substrate in all the film-coating trials. Twelve kilograms was the tablet load in each case.

The basic coating formula is given in Table 1. Hydroxypropyl methylcellulose 6 cps (Pharmacoat Type 606, Shin-Etsu Chem. Co.), hydroxypropyl methylcellulose 15 cps (Pharmacoat Type 615), and hydroxypropyl cellulose (Klucel LF, Hercules Inc.) were the film-formers investigated.

TABLE 1

Aqueous Film-coating Formula

Film-Former	4.0% (w/v)
Propylene Glycol	2.0
Titanium Dioxide	1.0
Dye, Yellow, FD&C #6	0.1
Distilled Water	q.s.

To adequately test the drying theory, film-coating was performed at extremes of inlet air temperature, humidity, and air flow. Inlet temperature settings of 55°C and 85°C were used in combination with ambient room humidity and the equivalent of greater than 60% relative humidity in the room air (achieved by the introduction of steam in the inlet air supply). The air flow settings were either approximately 300 SCFM or 650 SCFM. All runs were repeated at as close as possible to identical conditions.

RESULTS AND DISCUSSION

The mathmatical model describes the drying efficiency of the aqueous solvent in the tablet film-coating process. Convection drying is assumed as the sole method of moisture evaporation. The effect of different film-formers and drying conditions on vaporization efficiency at a defined coating end point was examined as well as the effects of changing coating conditions.

The applicability of the drying model based only on convection drying was shown by spraying water on the polystyrene beads as illustrated in Figure 1. The recorded inlet temperature was constant around 60°C. The exhaust temperature, measured in the duct immediately outside the Accela-Cota, was seen to drop as the spray rate of water was incremented until 250 g./min. was reached. At this point the temperature probe in the exhaust duct was visibly wet. A spray-rate of 300 g./min. did not produce any further change in the exhaust temperature. The inlet humidity was measured to be 36 gr./lb. dry air (± 2 gr./lb. fluctuation during the trial). The wet-bulb temperature from a psychrometric chart for air at 60°C and 36 gr./lb. dry air is 25°C, which is in excellent agreement with the minimum exhaust temperature value from Figure 1. This is evidence that as the rate of spraying water increases the T_2 value approaches the wet-bulb temperature of the inlet air. Comparison of the experimentally measured values of T_2 based on the evaporation of water present in the formula were in very good agreement. Thus, the presence of polymer, plasticizer and pigments did not significantly change the results expected from pure convection drying of water. Good agreement between the values for the wet-bulb temperature of the inlet air and the temperature of a probe placed directly in the spray during the coating process is further evidence of the primary role of convection drying. The spray probe temperature was generally about 1°C less than the calculated T_w of the inlet air. This small difference could be the result of the temperature of the air at the point where the spray probe was placed being slightly less than the value of T_1 measured further upstream in the inlet air supply duct.

Acceptable film-coating can be made over a range of vaporization efficiency up to a critical value dependent on the coating formula and coating conditions. The critical vaporization effi-

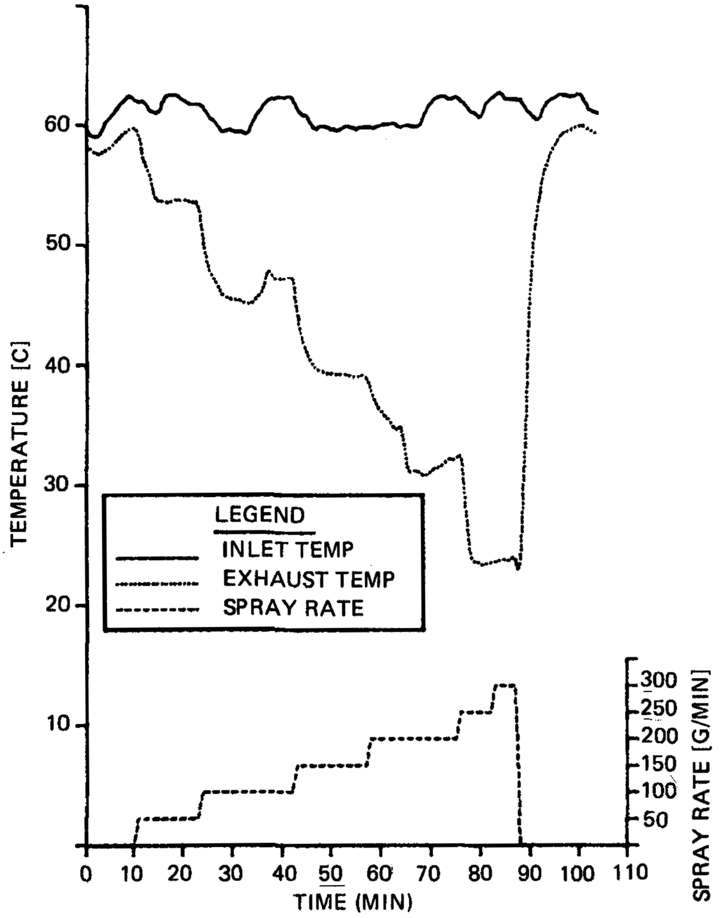

FIGURE 1. Spraying of Water on Polystrene Beads.

ciency is a coating end point dependent on the subjective evaluation of the quality of the coating. To attempt to reduce the subjectivity in the determination of the coating end point, a vaporization efficiency, E_s, at which sticking to the coating pan occurs, was defined. This is the vaporization efficiency calculated from the drying conditions and coating spray rate that produced 2 or more tablets sticking to the coating pan for a complete revolution during a 1 minute observation period. The end point defined in this manner proved quite reproducible. The E_s value will be slightly higher than the upper limit for vaporization efficiency compatible with good quality film-coating. Elegant film-coating can be obtained at E values below E_s.

The effect of the 3 different film-formers on the coating vaporization efficiency at which sticking occurred, under the very best drying conditions studied, is shown in Table 2. Two trials at approximately the same conditions are reported in all cases. The most striking observation was the dramatically lower E_s value for hydroxypropyl cellulose when compared with the two viscosity grades of hydroxypropyl methylcellulose studied. The hydroxypropyl cellulose films were quite tacky during film formation and this was reflected in the much lower E_s values. Coating with the two viscosity grades of hydroxypropyl methylcellulose could be performed at much higher vaporization efficiencies before sticking occurred. The lowest viscosity grade of hydroxypropyl methylcellulose could be applied slightly faster. With the same film-former the tackiness of the coating composition would be expected to decrease with decreasing molecular weight[4]. The average viscosity of the hydroxypropyl cellulose coating suspension was 87 cps. which is intermediate between the 6 cps. and 15 cps. viscosity grades of hydroxypropyl methylcellulose (56 cps. and 145 cps. respectively). The reproducibility of the E_s values was good.

At lower temperatures or air flows no acceptable film-coating could be produced with the hydroxypropyl cellulose coating composition, i.e., severe picking, chipping, or edge peeling occurred up to the point where tablets started sticking to the coating pan. Further coating trials were limited to formulas employing hydroxypropyl methylcellulose as the film-former. The effect of air flow at low and high inlet temperatures is illustrated in Table 3 for the hydroxypropyl methylcellulose coating liquids. Ambient humidity was used in all trials and ranged from 10 to 40 gr./lb. dry air. Again the E_s values for each coating formula fell within a narrow range. Sticking to the coating pan occurred at the same vaporization efficiency under the various coating

TABLE 2

VAPORIZATION EFFICIENCIES (E_s) FOR 4% FILM-FORMER COATING COMPOSITIONS AT MAXIMUM DRYING CONDITIONS

Film-former	T_1(°C)	H_1(gr/#)	SCFM	R_s(g/min)	E_s
Hydroxypropyl methylcellulose - 6 cps	84	41	673	145	0.26
	85	15	655	165	0.29
Hydroxypropyl methylcellulose - 15 cps	84	15	622	120	0.23
	87	25	646	115	0.20
Hydroxypropyl cellulose	87	38	649	80	0.14
	86	41	663	80	0.14

conditions. This indicates that given a set of coating conditions that produce film-coated tablets of acceptable quality, it is possible to predict the spray rate of coating suspension under other conditions that would result in the same vaporization efficiency and a similar appearing product.

The effect of inlet humidity on the vaporization efficiency is shown in Table 4. Only the low temperature of the inlet air is reported because 60% relative humidity air at 21°C heated to 85°C reduces the relative humidity to less than 3% which is obviously not going to affect the drying significantly. Even after heating to only 55°C the relative humidity of the original air is reduced to about 10%. The results in Table 4 verify that no major influence of the inlet humidity is seen in the E_s values, although greater scatter was observed. Low temperatures and low air flows are necessary before any significant affect of humidity on coating rates will become evident.

The evaluation of the partial derivatives of the vaporization efficiency with respect to the independent variables in a set of

TABLE 3

VAPORIZATION EFFICIENCIES (E_s) for 4% HYDROXYPROPYL METHYLCELLULOSE AT AMBIENT HUMIDITY

	Coating Conditions[a]			
Viscosity Grade	T_1(°C)	SCFM	R_s (g./min.)	E_s
6 cps.	87	316	70	0.25
	85	260	65	0.29
15 cps.	87	316	65	0.23
	86	283	65	0.27
6 cps.	58	659	90	0.27
	58	682	95	0.27
15 cps.	57	638	70	0.21
	56	672	70	0.21
6 cps.	54	306	45	0.29
	55	338	45	0.26
15 cps.	59	361	45	0.24
	56	338	40	0.23

[a] Results for high temperature and high air flow of both the 6 and 15 cps. viscosity grades appear in Table 2.

coating conditions quantifies the influence of each of the variables under the given coating conditions. The results obtained can be used to linearly estimate the magnitude of a change in one of the coating conditions necessary to achieve a specific new vaporization efficiency desired. For example, sticking occurred at E_s = 0.27 for 4% hydroxypropyl methylcellulose - 6 cps at an inlet temperature of 58°C with 38 gr./lb. dry air inlet humidity and an air flow of 659 SCFM. The spray rate was 90 g./min. The following partial derivatives are obtained using this data:

$$\frac{\partial E}{\partial R} = 0.0033 \text{ per g./min.}$$

TABLE 4

VAPORIZATION EFFICIENCIES (E_s) FOR HYDROXYPROPYL METHYLCELLULOSE AT HIGH HUMIDITY[a]

	Coating Conditions[b]			
Viscosity Grade	H_1(gr./lb.)	SCFM	R_s (g./min.)	E_s
6 cps.	73	682	100	0.32
	75	700	105	0.36
15 cps.	97	711	80	0.28
	70	672	70	0.24
6 cps.	61	337	40	0.28
	64	337	35	0.23
15 cps.	62	290	40	0.32
	64	337	35	0.23

[a] Equivalent to greater than 60% relative humidity in the inlet air.

[b] An inlet temperature setting of 55°C was used in all cases.

$$\frac{\partial E}{\partial (H_s - H_1)} = -0.0028 \text{ per gr./lb. dry air}$$

$$\frac{\partial E}{\partial G} = -0.0004 \text{ per SCFM}$$

$$\frac{\partial E}{\partial X} = 0.0029 \text{ per 1\% change in X}$$

$$\frac{\partial E}{\partial T_w} = -0.0135 \text{ per °C wet-bulb}$$

The largest change is seen to occur with an increase in T_w at constant humidity, i.e., an increase in T_1. The negative signs shown indicate that the vaporization efficiency decreases with an increase in humidity driving force, air flow and inlet temperature.

To obtain good quality film-coating the vaporization efficiency must be reduced from 0.27 where sticking of tablets to the coating pan occurred. If a vaporization efficiency, E_2, equal to 0.22 was desired this could be estimated to be achieved by reducing the spray rate to 75 g./min., increasing the humidity driving force by 18 gr./lb. dry air, increasing air flow by 125 SCFM, increasing the total solids content from 7.1% to 25%, or increasing T_1 to 69°C. In many cases the difficulty in achieving each of these changes will dictate the approach to be used. An increase in solids content to 25% will obviously change the viscosity greatly as well as many other important film properties. It may indeed be impossible to reduce the humidity in the inlet air sufficiently to achieve the desired increase in the humidity driving force. Air flow rates may already be limited by the capacity of the delivery system. The choice will often then be reduced to increasing the temperature of the drying air or coating slower. Product thermal stability is obviously going to be a primary concern.

The calculation of the vaporization efficiency can be an easy and convenient method of quantifying variables in the coating process. It provides for the assessment of the influence of changing any of the coating variables on the film-coating process.

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