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EXPERIMENTAL COATING AND HEAT TRANSFER STUDIES IN A VIBRATING FLUIDIZED BED

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Abstract—This work presents an experimental study of the heat transfer in a vibrofluidized bed and an investigation of the vibrofluidized bed coating process of thin copper plates.

At superficial velocities close to that of minimum fluidization the heat transfer coefficient increases with the air flow rate and also with the immersion depth in the bed. It is independent of the initial object temperature.

For different experimental conditions the obtained vibrofluidized bed coating thicknesses increase with the initial object temperature and immersion time. When compared with the theoretical predictions calculated for a regular fluidized bed, they show a good agreement. The temperature–time histories of the coated object are also recorded and compared to theoretical results.

1. INTRODUCTION

One of the widely used powder coating techniques is the fluidized bed coating (Pettigrew 1966; Toth 1970; Conte 1969). In this method the metallic object to be coated is first heated to a temperature which is higher than the melting temperature of the fluidized plastic powder. Then the hot object is immersed in the fluidized bed. The plastic particles in contact with the body melt and adhere to it, forming a coating layer on the object. When the required coating thickness is obtained the body is removed from the fluidized bed. In order to obtain pit free coatings, the object is sometimes reheated in an oven.

The coating thickness obtained by this technique depends on the initial temperature of the object, the melting temperature of the plastic powder, the immersion time, the physical properties of the object and the powder and the heat transfer coefficient between the object and the fluidized bed. If the heat capacity of the object is very large or the proper amount of heat is supplied to the body during the coating process, the temperature of the object may be considered as constant. In this case the coating thickness increases until at steady state the heat conducted from the object through the coating is equal to the heat convected to the fluidized bed (Gutfinger & Chen 1969). If the object possesses a finite heat capacity, then its temperature decreases during the coating process with the coating thickness depending strongly upon the rate at which heat is convected to the surroundings (Abuaf & Gutfinger 1973).

One of the essential characteristics of the fluidized bed is its fluid like behavior (Kunii & Levenspiel 1969). The object to be coated can be immersed easily. As the gas velocity is increased above the minimum fluidization velocity, the fluidity of the bed is enhanced. But at high gas flow rates the fluidized bed becomes unstable and discontinuities or bubbles appear.

The heat transfer coefficient between a fluidized bed and a surface is very high and increases with the fluidization gas velocity (Gelperin & Einstein 1971: Gutfinger & Abuaf 1974). For a body of finite heat capacity a very large heat transfer coefficient implies a limitation of the final coating thickness obtainable. Thus, one would like to keep the heat transfer coefficient as low as possible while still retaining high bed fluidity required for easy dipping of the object into the bed. Bubbles present during operation of the fluidized bed have an adverse effect on the uniformity of the coating. A reduction in bubble formation is, therefore, very desirable.

One way of maintaining a low heat transfer coefficient with a fairly high fluidity, while at the same time reducing the amount of bubbles is by operating the fluidized bed close to minimum fluidization velocity and vibrating it simultaneously.

The vibrofluidized bed has a higher fluidity at minimum fluidization and also has a tendency to reduce the discontinuities while keeping the heat transfer rate almost constant.

In this investigation first the variation of the heat transfer coefficient in a vibrating fluidized bed is studied in order to determine the operating conditions for the coating experiments. Then, based on the obtained results, the vibrofluidized bed coating experiments are performed and the data compared to the theoretical calculations.

2. HEAT TRANSFER STUDIES IN A VIBRATING FLUIDIZED BED

In the first part of this study the heat transfer coefficient between a vibrating fluidized bed and a surface was determined experimentally and its variation with the different parameters was investigated. The experimental conditions were adjusted such that no coating of the object would take place.

2.1 *Characteristics of the fluidized plastic powder*

The plastic powder which was fluidized consisted of Nylon particles, available commercially under the name RILSAN 11. A size distribution analysis of the commercial powder was accomplished by means of a simple sieving experiment. The apparatus consisted of an Endecott test sieve shaker and a series of sieves with standard mesh sizes. Two hundred grams of the plastic powder was put on the upper sieve and vibrated for a period of 20 min. Then the weight of the particles remaining on each sieve was recorded and a weight size distribution of the particles obtained. The results of the sieve analysis are presented in figure 1. The volume mean diameter of the nylon powder as calculated from this graph is 125 μm. The physical properties of the nylon powder were reported by Landrock (1964):

$$\rho_c = 1.07\ \text{g/cm}^3; \qquad c_c = 2.43\ \text{J/g°C}; \qquad k_c = 2.62 \times 10^{-3}\ \text{W/cm°C}$$

where ρ_c, c_c, and k_c are the density, specific heat and thermal conductivity, respectively, of the coating material. These properties were assumed to be independent of temperature, e.g. constant during the experiments. The nylon polymer has a softening range 200–240°C. The assumption of temperature independent physical properties is not too good especially close to, or within the softening range. In the theoretical solution we assume a melting point

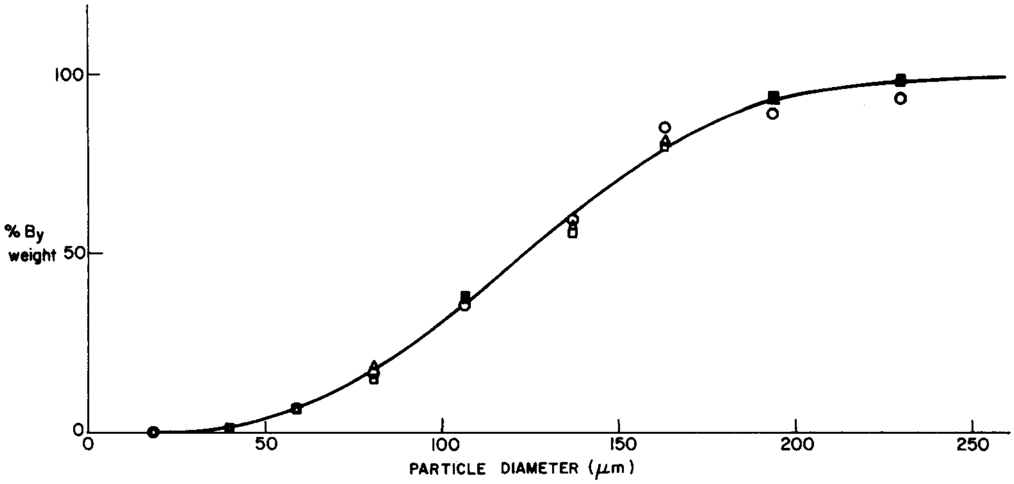

Figure 1. The cumulative percentage frequency curve for particle size distribution.

of 220°C instead of the softening range 200–240°C. Some deviations between theory and experiments may be attributed to these assumptions.

In the heat transfer studies the object was heated up to 175°C so that no coating of the object took place. In the second part of this investigation the body was heated up to 350°C and the coating thicknesses obtained were compared to the theoretical predictions.

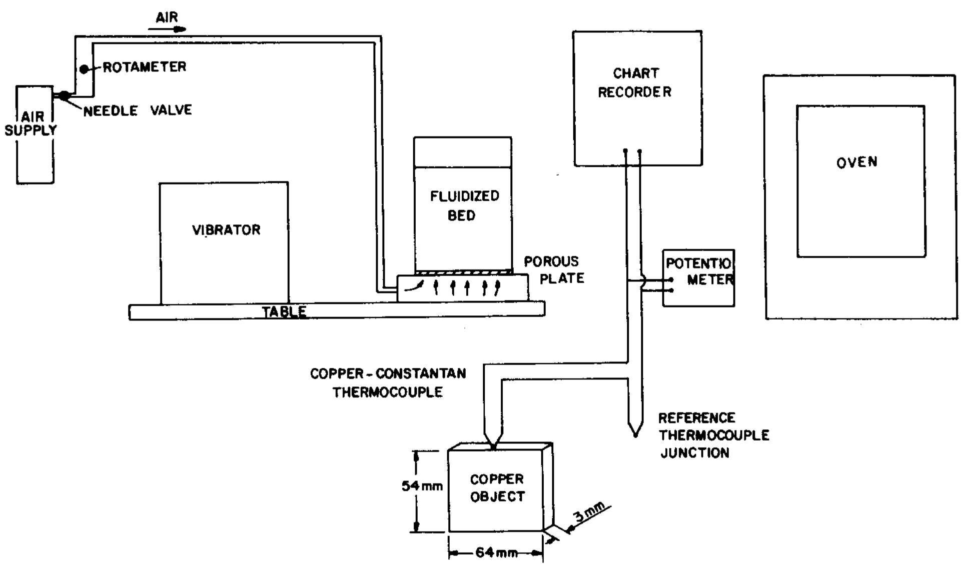

Figure 2. Schematic representation of the experimental set-up.

2.2 *Description of the experimental set-up and procedure*

A schematic of the experimental set-up is presented in figure 2. It consists of a 11.4 cm diameter and 26.5 cm high fluidized bed filled with powder to a height of L_o = 15.5 cm attached rigidly to a table together with a 50-Hz vibrator. The porosity of the bed at rest was 0.4 while during the experiments it increased to 0.45. During operation the vibrator induced a vibrating motion in the vertical direction to the fluidized bed. The nylon powder was fluidized by means of an air stream entering the fluidized bed through a 0.8 cm thick sintered bronze porous plate located at the bottom of the bed. Due to its high hydraulic resistance the plate insured an even distribution of the incoming air as checked by measurements of air velocities above the plate taken with a hot wire anemometer.

The heat transfer and the coating experiments were all performed with identical copper plates of dimensions 6.4 × 5.4 × 0.3 cm^3 in which copper–constantan thermocouples were embedded. The readings of the thermocouples were recorded by means of a potentiometer calibrated strip chart recorder, thus providing a continuous temperature history. The copper objects were heated inside an electric resistance oven whose temperature could be thermostatically controlled to within 2°C accuracy.

The procedure of measurement of the heat transfer coefficient consisted of heating the copper plate to a given temperature in the oven and then immersing it in the fluidized bed and letting it cool while its temperature–time history was recorded. This provided the necessary data for determining the heat transfer coefficient. The copper plate was taken as a

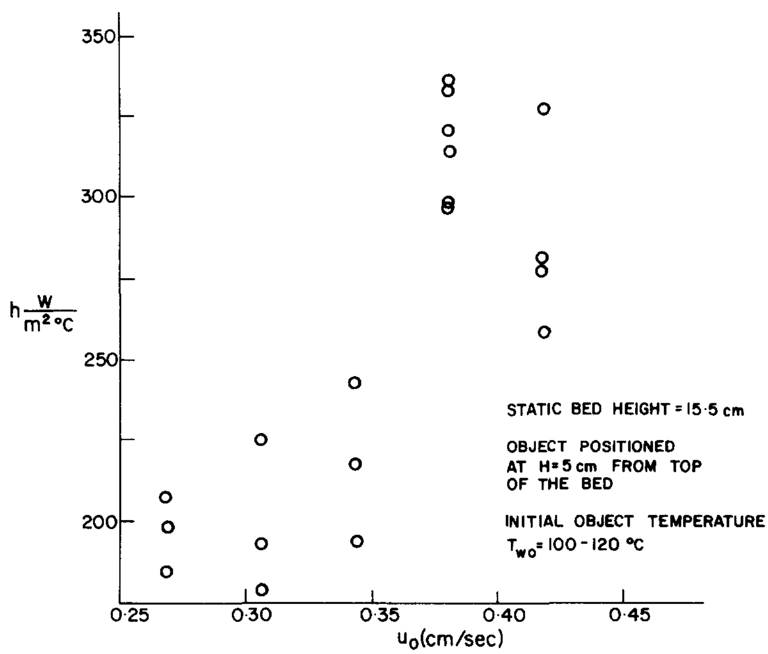

Figure 3. Variation of heat transfer coefficient with air velocity.

lumped parameter system of uniform temperature. Preliminary experiments were performed in still air and in front of an operating fan with the purpose of checking the reproducibility of the results. The procedure and apparatus were accepted as satisfactory after reproducible results were obtained in different experiments. The heat transfer experiments with the operating fan were also performed during the fluidized bed heat transfer studies. Their consistent reproducibility as compared to the high scatter of data obtained with the fluidized bed, serve to maintain our confidence in the reliability of the measuring system.

2.3 *Heat transfer results*

The heat transfer coefficient in a fluidized bed is a function of many variables. Several investigators have studied this problem experimentally and a large number of heat transfer correlations have been proposed (Gutfinger & Abuaf 1974). In the present study we have looked at the effect of several variables on the heat transfer coefficient in a vibrofluidized bed in order to be able to describe quantitatively the coating process.

Figure 3 presents the variation in heat transfer coefficient with the air flow rate through the vibrofluidized bed. The static bed height was L_o = 15.5 cm, while the copper plate heated to 100–120°C was immersed in the bed to a depth of 10.5 cm from the bottom. We decided to dispense with ordinary practice of plotting heat transfer coefficients on log–log graph paper in order to emphasize the difficulties in obtaining reproducible heat transfer data in fluidized bed studies. It should be noted that the spread is entirely due to the dynamic conditions of the fluidized bed and not due to the instrumentation which was found to give

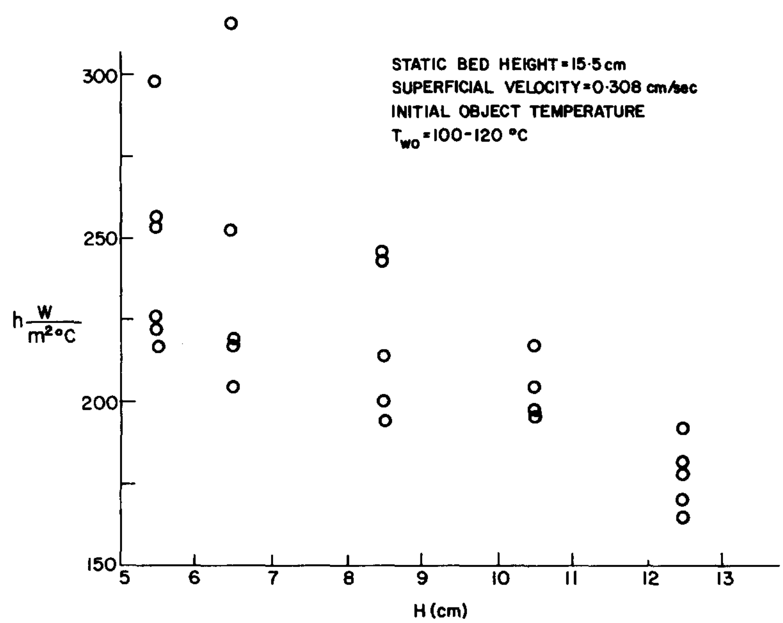

Figure 4. Variation of heat transfer coefficient with distance of the object from the bottom of the bed.

reproducible results in runs performed in air. The increase in the heat transfer coefficient with the air flow rate follows typical heat transfer results obtained in the literature (Gutfinger and Abuaf 1974) in the range close to the minimum fluidization velocity. A superficial gas velocity $u_o = 0.308$ cm/s, corresponding to the lowest velocity of stable fluidization, minimum fluidization velocity, of the vibrofluidized bed, was chosen for the rest of the experiments.

Figure 4 presents the variation of heat transfer coefficient with distance from the bottom of the bed at a superficial air velocity of $u_o = 0.308$ cm/s. In spite of the spread of the results, it is fairly apparent that the heat transfer coefficient increases with immersion depth until it reaches a distance of 3–4 cm from the bottom of the bed where entrance effects become apparent resulting in wide spread of the results. The monotonous increase in heat transfer coefficient with immersion depth is contrary to accepted views on this matter (Gutfinger and Abuaf 1974), according to which the heat transfer coefficient should be independent of the object's position in most of the bed, but close to the active entrance region at the very bottom. We have decided to perform our coating experiments at a distance of 10.5 cm from the bottom (an immersion depth of 5 cm), in order to standardize the experimental conditions.

The heat transfer coefficient in a fluidized bed is said not to be dependent on the object temperature. We have checked whether this is true also in a vibrofluidized bed. As seen in figure 5, the effect of initial temperature (up to 175°C) on the heat transfer coefficient, was found to be negligible.

3. THEORY OF FLUIDIZED BED COATING

The problem of fluidized bed coating may be viewed as a variation of the well known Stephan problem (Kyner 1959). Here a hot object immersed in a fluidized bed loses part of its internal energy as heat to the bed, while another part is being used to melt the plastic powder forming the coating layer. This heat transfer process can be described by the simultaneous solution of the heat conduction equation in the coated object and the conduction equation in the growing coating layer with the proper matching boundary conditions.

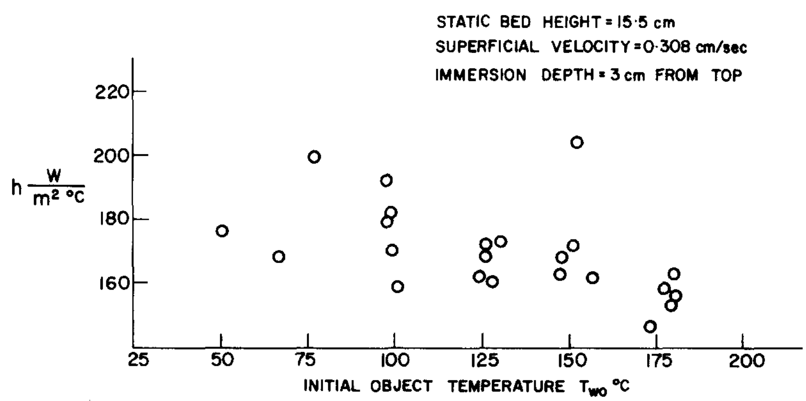

Figure 5. Variation of heat transfer coefficient with initial object temperature.

If the coated object possesses a very large heat content, its temperature could be taken as constant during the coating process. The case of constant-wall-temperature fluidized bed coating was solved by Gutfinger and Chen (1969). The more general case is that of the variable object temperature. Typically one coats metallic objects of high thermal conductivity with a plastic coating of relatively high thermal resistivity. Here the object temperature, although dropping with time, will remain fairly constant throughout the body at any time; thus the object may be represented as a lumped parameter system. The solution for the case of variable object temperature, which is applicable to fluidized bed coating of thin plates was obtained by Abuaf and Gutfinger (1973) and Elmas (1970). All these solutions were developed for a regular fluidized bed under the assumption of a known, constant heat transfer coefficient between the object, or coating, and the bed. In the present paper we have attempted to find out firstly whether this condition applies also to a vibrofluidized bed, and secondly whether the fluidized bed coating theory as a whole holds also in the case of vibrofluidized bed coating. As seen in the first part of this paper dealing with heat transfer to a vibrofluidized bed, the heat transfer coefficient at given gas flow and vibration conditions is independent of initial object temperature. Thus we decided to apply the fluidized bed theory to vibrofluidized bed coating without any modifications.

We now summarize shortly the theoretical approach presented previously (Abuaf & Gutfinger 1973). The heat transfer within the coating is given by the one-dimensional heat conduction equation:

$$\rho_c c_c \frac{\partial T}{\partial t} = k_c \frac{\partial^2 T}{\partial x^2} \qquad [1]$$

with the initial and boundary conditions:

$$T(0,0) = T_{wo} \qquad [2]$$

$$T(0,t) = T_w(t) \qquad [3]$$

$$T(\delta,t) = T_m \qquad [4]$$

$$\frac{m_w c_w}{A_w}(T_{wo} - T_w(t)) = ht(T_m - T_\infty) + \rho_c c_c \int_0^{\delta(t)} (T - T_\infty)dx \qquad [5]$$

$$-k_c \left.\frac{\partial T}{\partial x}\right|_{x=\delta} = h(T_m - T_\infty) + \rho_c c_c (T_m - T_\infty)\frac{\mathrm{d}\delta}{\mathrm{d}t} \qquad [6]$$

$$\delta(0) = 0. \qquad [7]$$

Here δ denotes the coating thickness, h the heat transfer coefficient, m_w, c_w, and A_w the mass, specific heat and surface area of the coated object, respectively, while T_m denotes the coating melting temperature and T_∞ the temperature of the bed. The initial object temperature is denoted as T_{wo} while that at time t as $T_w(t)$.

Equation [5] provides the integral heat balance for the time interval $(0, t)$ for the coated object while [6] is the local balance at the bed to coating surface. The problem was redefined in terms of a dimensionless coordinate ξ, time τ, temperature θ, and coating thickness Δ, respectively.

$$\xi = \frac{x}{\delta}; \qquad \tau = \frac{k_c t}{\rho_c c_c}\left(\frac{h}{k_c}\frac{(T_m - T_\infty)}{(T_{wo} - T_\infty)}\right)^2$$

$$\theta = \frac{T - T_\infty}{T_{wo} - T_\infty}; \qquad \Delta = \frac{h}{k_c}\left(\frac{T_m - T_\infty}{T_{wo} - T_\infty}\right)$$

and solved by a heat balance integral technique similar to the one used by Goodman (1958). The solution resulted in plots of dimensionless coating thickness, Δ, as a function of dimensionless time, τ, dimensionless melting temperature θ_m, and a coating parameter, Z:

$$\Delta = \Delta(\tau : \theta_m, Z)$$

where

$$\theta_m = \frac{T_m - T_\infty}{T_{wo} - T_\infty}; \qquad Z = \frac{\rho_c c_c}{\rho_w c_w}\frac{k_c}{hL}\frac{T_{wo} - T_m}{T_m - T_\infty}.$$

Here L denotes half the thickness of the object. Figure 6 is typical of the numerical results obtained for $\theta_m = 0.8$.

For a given object and coating material, e.g. for constant ρ_c, c_c, k_c, ρ_w, c_w and T_m, the parameter Z expresses the coating conditions for a certain experiment as defined by the thickness of the coated object ($2L$), the dynamics of the fluidized bed as reflected by the heat transfer coefficient, h, and the temperature to which the object is heated (T_{wo}) before immersion into the bed.

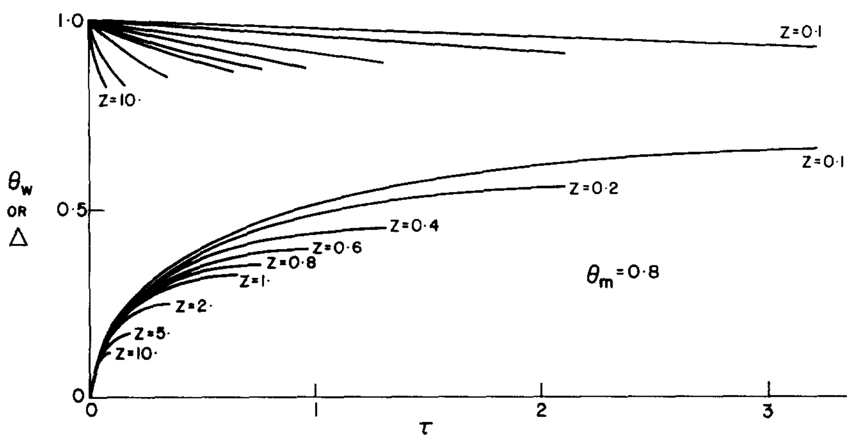

Figure 6. Theoretical predictions for dimensionless coating thickness and dimensionless object temperature as a function of dimensionless time.

4. COATING EXPERIMENTS

The procedure followed in the coating experiments was similar to the one in the heat transfer studies, the only difference being the higher initial temperature of the object (250–350°C). In order to facilitate coating, the object was heated above the softening temperature of the plastic powder. The experiments were performed by immersing the hot object into the vibrofluidized bed and removing it from the bed after a given time. The coating thickness was computed from the object weight gain divided by its exposed area and the powder density. The thickness obtained in this way is an average thickness. Micrometric pointwise measurements were performed on several samples and showed that the variation of these thicknesses from the average one is within ± 5 per cent, on all of the exposed surfaces but the edges.

Figure 7 presents plots of coating thicknesses versus immersion time for copper plates being coated by nylon powder, the characteristics of which were described above. In these experiments the initial temperature and the immersion time were varied. As seen, the coating thickness increases with initial temperature and immersion time, as it should. However, contrary to the theoretical predictions we observed a slight but consistent decrease in the thickness for the last stages of the coating process. It seems like this decrease is due to the fact that at prolonged immersion times the outer layer formed consists of partially softened particles forming a fairly rough surface. These particles may be transferred back to the bed due to the abrasive action of the vibrofluidizing process. In practice the coated object should be removed from the bed somewhere before the maximum thickness is reached, in order to ensure a smooth surface finish.

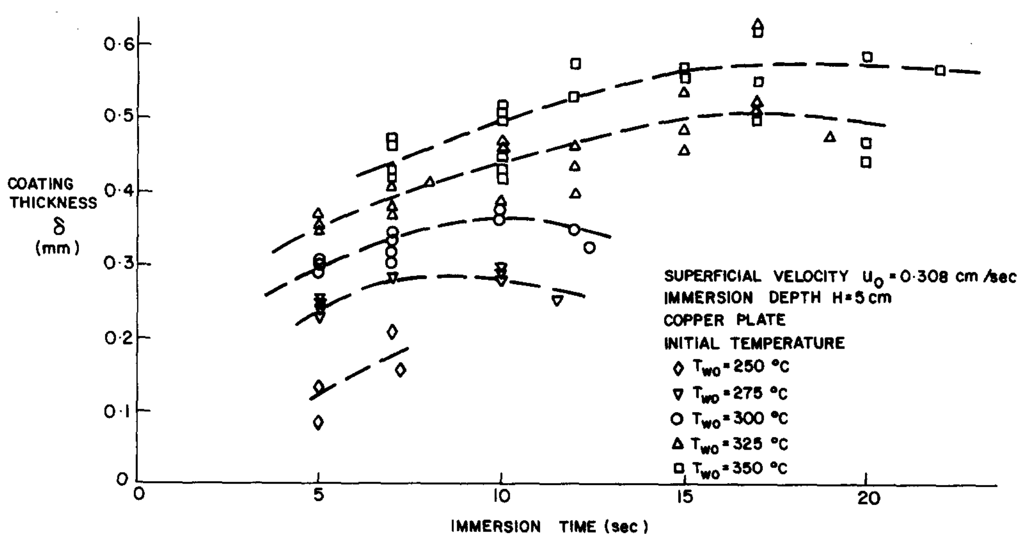

Figure 7. Plot of coating thickness versus immersion time for various initial object temperatures.

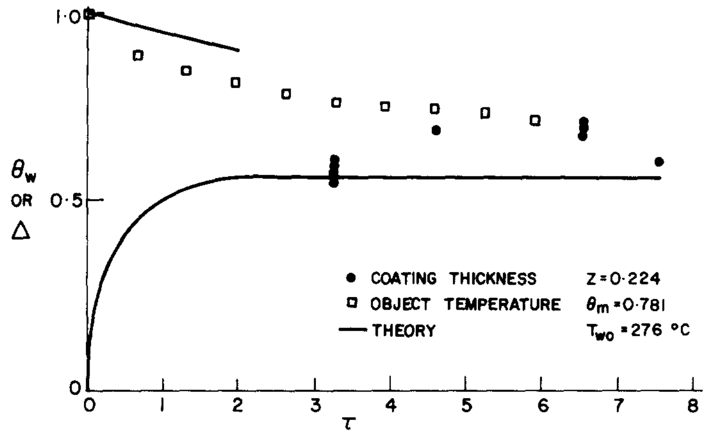

Figure 8. Dimensionless coating thickness and object temperature as a function of dimensionless time. Comparison between theory and experimental data.

In order to check the applicability of the fluidized bed theory to the vibrofluidized bed coating process, the solution obtained previously by the present authors was compared with the experimental results presented here in figures 8–11. On the average the fit between experimental and theoretical coating thicknesses seems quite good (maximum deviation of 20 per cent) with a spread being not more pronounced than the one observed above in ordinary heat transfer coefficient measurements.

As these data are based on the above measured heat transfer coefficients, the present authors are quite satisfied with the results. Still there is a visible deviation between the theoretical and experimental thicknesses for very short values of dimensionless time, τ: with the experimental ones being on the lower side. This deviation is not due to a possible systematic error in time measurement, therefore, it may indicate experimental conditions under which some of the assumptions underlying the theory may not hold. It is suspected that the assumption of a uniform object temperature does not hold for very short times.

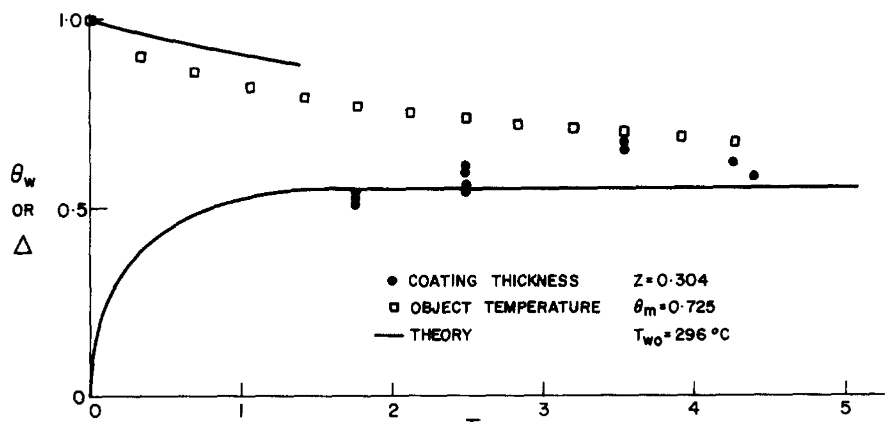

Figure 9. Dimensionless coating thickness and object temperature as a function of dimensionless time. Comparison between theory and experimental data.

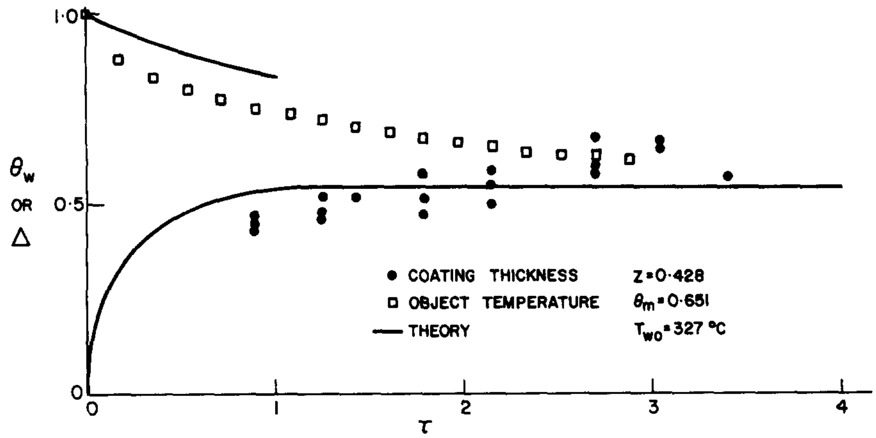

Figure 10. Dimensionless coating thickness and object temperature as a function of dimensionless time. Comparison between theory and experimental data.

For short times, the outer surface of the object which is in contact with the coating will be markedly lower in temperature than the rest of the body, resulting in a lower coating thickness as observed in reality.

The theoretical and experimental dimensionless object temperatures, θ_w, are also plotted in figures 8–11 as a function of the dimensionless time, τ. The theoretical temperatures were calculated only for the time period between the immersion of the object into the fluidized bed and the time at which the final coating thickness was obtained. After final thickness is attained, the boundary condition of constant temperature at the coating surface does not hold any more and thus the present numerical solution cannot be continued. As the object temperature is of secondary importance in the coating study, the authors did not feel it worthwhile to reformulate the heat transfer problem for the constant thickness cooling period. The experimental dimensionless object temperatures are about 10 per cent lower than the theoretical ones. This deviation may be attributed to the assumption of constant

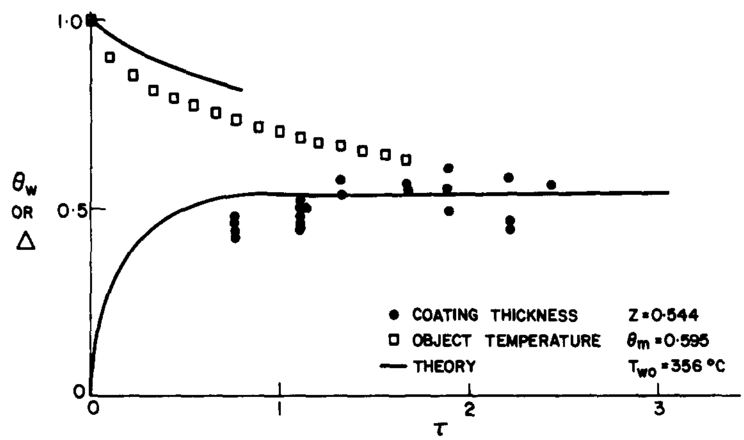

Figure 11. Dimensionless coating thickness and object temperature as a function of dimensionless time. Comparison between theory and experimental data.

physical properties of the coating material, especially that of constant heat capacity. It is known that in amorphous polymers the heat capacity changes markedly in the vicinity of the softening range.

5. SUMMARY AND CONCLUSIONS

The purpose of the present study was to investigate experimentally the vibrofluidized bed coating process in comparison with existing theories. This study was divided into two parts. The first part dealt with heat transfer in a vibrofluidized bed. The second part described coating experiments performed, and compared with results obtained with a coating theory derived previously for ordinary fluidized beds. The heat transfer data obtained in the first part were used in the theoretical computations needed for the coating study.

The following conclusions may be drawn from the heat transfer study:

(1) The heat transfer coefficient measured close to the minimum fluidization velocity, a range used in coating practice, shows a strong increase with the superficial air velocity (figure 3).

(2) The heat transfer coefficient shows an increase with immersion depth not only in the active region close to the bottom of the bed but throughout the bed as well (figure 4).

(3) It was found that the heat transfer coefficient is independent of the initial temperature of the immersed object corroborating the results from the literature for non vibrating fluidized beds (figure 5).

The results of the coating studies may be summarized as follows:

(1) The coating thickness increases with the initial object temperature as well as with immersion time (figure 7).

(2) Contrary to theoretical predictions the coating thickness vs. immersion time plot shows a slight decrease for long immersion times probably accounting for the abrasive behavior of the fluidized bed.

(3) In general there is good agreement between the theoretical solution for fluidized bed coating thicknesses and those found by experiments in vibrofluidized beds for varied experimental conditions. However, the theory seems to give higher predictions for thickness at very short immersion times.

(4) The temperature drop of the coated object is higher than the one predicted by the numerical solution, possibly reflecting effects of variable properties that were not taken into account.

(5) In general one may sum up that the theoretical model developed for coating in an ordinary fluidized bed can also be applied satisfactorily in predicting coating thicknesses in vibrofluidized bed coating process.

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Résumé—Dans ce travail, on présente une étude expérimentale du transfert de chaleur dans un bain fluidisé, par vibrations et une investigation du processus de revêtement, dans un bain fluidisé par vibrations, de plaques minces de cuivre.

A des vitesses surfaciques proches de celle de la fluidisation minimum, le coefficient de transfert de chaleur augmente avec le débit d'air ainsi qu' avec la profondeur d'immersion dans le bain. Il est indépendant de la température initiale de l'objet.

Dans des conditions expérimentales différentes, les épaisseurs de revêtement obtenues dans un bain fluidisé par vibrations augmentent avec la température initiale de l'objet et le temps d'immersion. Les épaisseurs expérimentales sont en bon accord avec les résultats de calculs théoriques dans le cas d'un bain fluidisé régulier. Les évolutions en fonction du temps de la température de l'objet qui est revêtu sont aussi mesurées et comparées aux résultats théoriques.

Auszug—Diese Arbeit stellt eine experimentelle Studie des Waermeuebergangs in einen vibrierenden Fliessbett dar, und eine Untersuchung des Ueberziehprozesses duenner Kupferplatten in einemvibrierenden Fliessbett.

Solange die Oberflaechengeschwindigkeiten in der Naehe der minimalen bleiben, die fuer das Fliessbarmachen erforderlich sind, waechst der Waermeuebergangskoeffizient mit dem Luftdurchsatz, und ebenso mit der Eintauchtiefe im Fliessbett. Er ist von der Anfangstemperatur der Objekte unabhaengig.

Unter verschiedenen Versuchsbedingungen waechst die im vibrierenden Fliessbett erhaltene Ueberzugsdicke mit der Anfangstemperatur der Objekte und der Eintauchzeit. Die Versuchsergebnisse stimmen gut mit den theoretischen Voraussagen ueberein, die unter Annahme eines regelmaessigen Fliessbettes berechnet wurden. Die Aenderung der Temperatur der ueberzogenen Objekte mit der Zeit wurde ebenfalls aufgezeichnet und mit den Ergebnissen der Theorie verglichen.

Резюме—Настоящая работа представляет собой экспериментальное исследование теплопереноса в псев доожиженном вибраценном слое и процесса покрытия тонкой медной пластины с помощью такового.

При скоростях на поверхности, близких к значениям минимального ожижения, коэффициент теплопереноса возрастает с увеличением скорости воздушного потока, а также с увеличением глубины погружения в слой, но не зависит от начальной температуры объекта.

При разнообразных условиях эксперимента толщины покрытия, долученного с помощью ожиженного вибрацией слоя, возрастали с начальной температурой объекта и глубиной погружения. Сравнение с предсказанным на основе теоретического расчета для обычного жидкого слоя показывают хорошее соответствие. Наряду с этим учтено температурнои временное прошлое покрываемого объекта и сравнено с теоретическимн результатами.