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SUBJECT: Development of Optimum Conditions for Drying Ion Exchange Resin in a Fluidized Bed Dryer

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ABSTRACT

Drying of Amberlite IRC-72 ion exchange resin in a fluidized bed dryer was investigated. Resin water content was measured as a function of drying time for various drying temperatures, bed loadings, and air flow rates. An incomplete equation for the induction period and complete model for constant rate drying were developed. Further development of an induction period model requires installation of an accurate air flow measurement device. A drying temperature of 200°F results in the shortest drying time with no resin damage. Optimization of the process with regard to other process parameters requires development of a complete drying model.

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1. SUMMARY

Amberlite IRC-72 cation exchange resin was dried in a fluidized bed dryer to determine conditions required for drying the resin to the desired state for particle shape separation. The dried resin should show no evidence of agglomeration caused either by static charge or by high resin water content. In experiments, resin water content, inlet and outlet air temperatures, and humidities were measured at regular intervals for different drying temperatures, air flow rates, and bed loadings.

Three drying regimes, an induction period, a constant rate period and a falling rate period, were observed. An incomplete model was developed for the induction period because of lack of accurate air flow measurements. A complete constant rate period model was developed and verified with experimental data. However, use of this model depends on the development of a complete induction period model. The dried resin had the desired characteristics throughout the falling rate period as long as the bed temperature did not exceed 200°F. Therefore, this regime was not modeled.

Installation of an accurate flow measuring device is necessary for development of a complete drying model. A drying temperature of 200°F will result in the shortest drying time with no damage to the resin.

Optimization of the process with regard to other process parameters requires a complete drying model. Finally, to automate the dryer, a control might be installed to turn off the dryer when the outlet air temperature approaches the inlet air temperature within 10°F.

2. INTRODUCTION

2.1 Background

In the manufacture of fuel for the High Temperature Gas-Cooled Reactor, ²³³U is loaded onto ion exchange resin beads as indicated in Fig. 1. Before loading, the resin particles must be uniform in size and spherical in shape. Size separation is accomplished by wet-sieving the resin. Spherical particles are separated from non-spherical particles by a vibrating plate, a process which requires that the resin be dry. After shape-separation, the resin is re-wet, converted from sodium to hydrogen form, and loaded with uranium (1).

The water-saturated resin is dried in a fluidized bed dryer before it can be shape-separated. The dried resin must have a low water content to avoid sticking. However, the resin must not be dried to the point that either static charge is induced in the resin, or that cracking of the resin occurs. To develop the optimum conditions for drying Rohm and Haas Amberlite IRC-72 resin, experiments were performed for various values of resin mass, inlet air temperature, air flow rate, and inlet air water content.

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RESIN PROCESS STEPS

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2.2 Experimental Approach

The water content of resin was measured as a function of drying time for different charge sizes, temperatures, and air flow rates. From the data, the three regimes of drying: induction period, constant rate period, and falling rate period, were identified, and equations to explain resin drying behavior were developed. In addition, a set of operating conditions were derived for production of dried resin with the desired properties.

3. APPARATUS AND PROCEDURE

The dryer was a Fitz-Mill Model 75, Fluid Bed Dryer equipped as shown in Figs. 2 and 3. The bed is removable and can be wheeled elsewhere for filling and emptying. Amberlite IRC-72 cation exchange resin was loaded into the dryer bed, and excess water was drained through a screen in the bed bottom before placing the bed in the dryer. Conditions for the drying experiments are shown in Table 1. The water content of the resin was

Table 1. Conditions for Drying Experiments

Run No.	Drying Period Studied	Drying Temperature (°F)	Resin Charge (lb)	Air Flow Rate (lb/min)
1	constant rate	250	86	65
2	constant rate	250	143	56
3	constant rate	250	108	48
4	constant rate	250	60	44
5	constant rate	194	110	51
6	constant rate	194	90	45
7	constant rate	194	60	72
8	constant rate	194	140	53
9	constant rate	136	132	72
10	constant rate	250	136	52
11	induction	136	131	51
12	induction	250	137	52
13	induction	225	128	56
14	induction	195	137	28
15	induction	250	120	43
16	induction	225	100	58
17	induction	225	60	57
18	induction	225	80	44

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FLUID BED DRYER FLOW SHEET

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measured by taking resin samples at 5-, 10-, or 15-min intervals during drying. Exhaust air water content was measured at the same times with a psychrometer. Air flow rate was computed from a mass balance on water. To obtain data during the induction period, exhaust air water content and exhaust air temperature were measured at 0.5-, 1-, or 2-min intervals for different values of resin charge, air flow rate, and inlet temperature. Samples for measurement of resin water content were taken before and after the induction period. Drying was continued into the constant rate period, when resin water content was measured for calculation of air flow rate.

To measure the resin water content, resin samples were weighed wet and then dried in an oven at 110°C for at least eight hours. Dry sample weights were subtracted from wet sample weights to determine the water loss. To test the dried resin for static charge, samples were shaken in a jar to see if the resin stuck to the glass. Finally, cracking of the resin was investigated by comparing a dried sample with a sample of new, undried resin under an optical microscope.

4. THEORY

4.1 General Drying Curve

A typical plot of resin water content as a function of drying time is shown in Fig. 4. There are three drying regions characterized by the conditions shown in Fig. 5. An induction period occurs first, during which the dryer approaches a steady drying rate. The second regime is characterized by a constant rate of drying and occupies most of the drying time. A falling rate of drying is representative of the final regime.

4.2 Induction Period

Unsteady state response of fluid beds to step changes in inlet temperature or concentration has been described mathematically by Pfafflin et al. (4). However, their model cannot be adequately applied to drying, in which simultaneous heat and mass transfer occur. To describe the response of the drying resin as the bed is heated, an exponential equation was assumed of the form

$$(N_{out} - N_{in}) = (N_{out} - N_{in})_{oc} [1 - \exp(-At)] \quad (1)$$

The time constant, A , should be related to the ratio of air flow rate to the mass of dry resin in the bed, which also has the units of inverse time.

Q_0 = initial water content
 Q_{oc} = resin water content at start of
 constant rate period (time = t_{oc})
 Q_c = critical water content at time t_c

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GENERAL DRYING CURVE			
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INDUCTION RATE PERIOD

CONSTANT RATE PERIOD

FALLING RATE PERIOD

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DRYING REGIME CONDITIONS

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A mass balance on water around the fluid bed would then provide values for the resin water content,

$$Q_0 - Q = \frac{F(N_{out} - N_{in})_{oc}}{M_r} \left[t - \frac{1}{A}(1 - e^{-At}) \right] \quad (2)$$

A major limitation of this equation is that it predicts an induction period of infinite length. However, if the magnitude of the time constant could be predicted from experimental conditions, the length of the induction period could be approximated.

4.3 Constant Rate Period

Behavior of a fluid bed dryer in the constant-rate regime has been described by Kunii and Levenspiel (3). Since heat transfer for evaporation limits the drying rate during this period, an enthalpy balance around the bed yields the following equation:

$$Q_{oc} - Q = \frac{FC}{M_r L} (T_{in} - T_{out})(t - t_{oc}) \quad (3)$$

which predicts a linear decrease of resin water content with time.

5. RESULTS AND DISCUSSION

5.1 Measured Characteristics of Resin

Amberlite IRC-72 resin had a water content of 3.8 lb water/lb dry resin as received from the manufacturer. After drying and resaturating the resin with water, the water content varied from 3.6 to 4.0 lb water/lb dry resin. The resin critical water content, which was measured when the outlet air temperature began to rise from the constant drying rate period, was 0.71 lb water/lb dry resin. This water content is attained at the start of the falling rate period. The manufacturer recommended a maximum temperature of 250°F for the resin (5). However, when dried above 200-220°F, the resin particles were partially damaged by melting.

5.2 Induction Period

During the induction period, the resin is heated from room temperature to the adiabatic saturation temperature of the inlet air. Simultaneously, water is evaporated from the resin, and the water content of the outlet air increases as the temperature of the outlet air increases.

To compare the experimental data with the equation for the induction period, the water content difference between outlet and inlet air on a dry air basis was plotted as a function of time in Figs. 6 through 8. The observation of an exponential response led to plotting the data on a semilogarithmic scale. The difference in water content between outlet and inlet air minus the difference in water content of air during the constant drying period was plotted as a function of time in Figs. 9 through 11.

From these figures, the time constant, A , for each run was calculated, and a correlation of these constants with the ratio of air flow rate to the dry mass of the bed was attempted. Relating the time constants to the ratio of air flow rate to dry bed mass was not successful as shown in Fig. 12. For this reason the parameters included in the time constant were not determined.

For the bulk of the experiments performed, there was no air flow metering device available, and the air flow rate had to be calculated from a water mass balance during the constant rate drying period which yielded an average value. The flow rate obtained did not satisfy a water mass balance during the induction period as shown in Appendix 9.3.3. As an example of the flow measurement problem, the flow rate obtained by the material balance in Run 14, 28 lb/min, did not agree with the flow rate obtained by a vane anemometer placed in the air intake stream which measured 41 lb/min, nor with the flow rate obtained by a pitot tube placed in the exhaust vent which indicated 49 lb/min. Not having accurate air flow rate measurements made it impossible to apply the data to the expression derived for the moisture content of the resin and prevented prediction of the magnitude of the exponential time constant A .

Before any additional modeling of the induction period is attempted, a calibrated air flow meter must be installed on the dryer to measure the air flow rate accurately.

The fluidization characteristics of initially wet resin vary from one batch to the next depending on the amount of water in the resin bed above the 3.8 lb water/lb dry resin required to saturate the resin. The amount of additional water depends on the amount of time that water is allowed to drain out of the bed after loading. The bed should be allowed to drain until water is no longer observed dripping through the bed bottom which may take up to 20 min. During the induction period, because of the drainage problem, the bed was not uniform. Parts of the bed were observed to be very turbulent, while other parts appeared to be insufficiently fluidized. The non-uniform behavior prevents the measurement of consistent data from

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INDUCTION PERIOD DATA
FOR RUNS 12, 13, AND 15

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FIG.
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- Run 18
□ Run 17
△ Run 16

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INDUCTION PERIOD DATA
FOR RUNS 16, 17, AND 18

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Run numbers are indicated below points.

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ATTEMPT TO CORRELATE A WITH F/M_r

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one run to another. For example, two drying runs with 140 lb of wet resin at 250°F and air flow rates of 56 and 52 lb/min calculated from a water mass balance had induction periods of 20 and 40 min. This large difference in induction time illustrates the problem in obtaining reproducible induction period data.

Finally, although an exponential equation for the induction period was derived, it cannot be included in a general drying model since it does not predict a finite length for the induction period, and thus prevents computation of the time and resin water content at the start of the constant drying rate period. Development of a complete drying model will require further study of the induction period.

5.3 Constant Rate Period

In the constant rate period, inlet air temperature, wet and dry bulb temperatures of the outlet air, and bed temperature remain constant. When the water content of the resin reaches the critical water content of 0.71, the constant rate period ends. A plot of water content of the resin as a function of time gave a straight line as shown in Figs. 13 through 18, which indicates that drying was constant.

The enthalpy balance around the bed gives

$$Q_{oc} - Q = \frac{FC_p}{M_r L} (T_{in} - T_{out})(t - t_{oc}) \quad (3)$$

the water content as a function of time in the constant rate period. This calculation requires the water content and inlet and outlet air temperatures at the end of the induction period. The inlet air temperature can be fixed arbitrarily by deciding to what temperature the air is heated before passing through the bed. The drying time and water content at the end of the induction period can be obtained either by experimental measurement or from the induction period model if it can be developed fully.

The increase in air humidity was found to be 80% of the increase that can be achieved by saturating the air adiabatically. This fact can be employed to predict the temperature of the outlet air. From the inlet air humidity and dry bulb temperatures, a point can be located on the psychrometric chart. Then moving along the adiabatic saturation line, which is the same as the wet bulb line, the humidity at the 100% saturation can be found. Hence, the increase that can be achieved by saturating the air adiabatically can be obtained. The humidity of the outlet air can be calculated by adding 80% of this increase to the inlet air humidity. With this humidity a point is located on the same wet bulb line used for finding humidity of the saturated air. The dry bulb

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CONSTANT RATE PERIOD DATA
FOR RUNS 1, 2, 3, 4, AND 10

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FIG.
13

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CONSTANT RATE PERIOD DATA FOR RUN 9

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FIG.
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CONSTANT RATE PERIOD DATA
FOR RUNS 13 AND 16

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CONSTANT RATE PERIOD DATA
FOR RUNS 17 AND 18

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temperature corresponding to this point can be taken as the temperature of the outlet air, T_{out} .

The experimentally measured decrease in water content from the start of the constant rate period was plotted as a function of the value predicted by Eq. (3). From this equation, temperature of the outlet air was calculated with the observed time and water content at the end of the induction period. A straight line of slope 1.0 was obtained (Fig. 19). Thus Eq. (3) can be used for predicting the water content as a function of time, where temperature of the outlet air is predicted as indicated previously.

5.4 Falling Rate Period

The falling rate period begins when the outlet air temperature starts to rise from the constant rate period value. At the end of the drying procedure, the outlet and inlet air temperatures are equal. For inlet air temperatures to 200°F, the dried resin had the desired characteristics for separation of particles by shape. For these conditions, the resin water content in this period varied from $Q_c = 0.71$ to 0.080 lb water/lb resin. In this range, there was no sticking of particles caused either by water on the surfaces or by static charge. In addition, there was no cracking of the resin particles caused by heating, even after the particles were resaturated with water and dried a second time. However, resin dried in the sample oven at 230°F appeared to have melted, so the temperature of the resin in the fluid bed was always kept below 200°F. Thus, for inlet air temperatures over 200°F, drying was terminated when the outlet air temperature reached 200°F.

No equation for the falling rate period was developed because the resin has the desired properties at any time during this period as long as the temperature of the outlet air is below 200°F. The resin can be removed any time after the outlet air temperature begins to rise from the constant rate period value.

Finally, the drying process could be automated by installing a controller which would shut off the dryer when the outlet air temperature approached the inlet air temperature within 10°F. On the controller, a margin of at least 5-10°F should be allowed since it is possible that because of heat losses in the exhaust vent, the outlet air temperature may never equal the inlet air temperature.

6. CONCLUSIONS

1. A complete induction period model could not be developed for lack of accurate air flow rate measurements.
2. The constant rate drying equation was developed and verified with data. The time at which the induction period ends and water content at

that time are needed to predict the water content at any time in the constant rate period. The temperature of the outlet air was found from the fact that the increase in the humidity is 80% of the increase corresponding to 100% saturation.

3. The resin will have the desired properties for the shape separation if it is removed any time during the falling rate period. The outlet air temperature should be below 200°F since it may melt above 200°F.

4. Minimum drying times for all bed charge sizes are obtained at 200°F. Optimization of the process with regard to other parameters will require the development of the complete drying model.

7. RECOMMENDATIONS

1. Further study of the induction period is necessary for development of a complete drying model. This will require installation of an accurate air flow measurement device on the dryer.

2. The resin should be dried at 200°F for minimum drying times, but drying temperatures above 200°F are not recommended. If time is not a criteria, temperatures below 200°F to room temperature are also satisfactory for producing dried resin for shape separation.

3. Automation of the drying process can be accomplished if a temperature control is installed to shut off the dryer when the outlet air temperature approaches within 10°F of the inlet air temperature.

8. ACKNOWLEDGMENTS

We wish to thank P.A. Haas and D.L. Million for their continued aid and advice through the project.

9. APPENDIX

9.1 Sample Calculations and Error Analysis

Data for sample calculations were taken from Run 3 except for the induction period (Appendix 9.1.3) where data from Run 14 were used. Errors in computing the values of different quantities are caused by uncertainty in measurement of time, temperature, and mass. The minimum increment of time that can be measured was one second. The minimum increment of mass on the analytical balance was 1×10^{-4} g, and on the large scale balance was 0.25 lb. The minimum increment of temperature was 1°F . The error analysis is provided along with the sample calculations.

9.1.1 Resin Water Content

By drying a sample in the oven, the water content of the resin is calculated. From Sample 2,

$$Q = \frac{S_{\text{wet}} - S_{\text{dry}}}{S_{\text{dry}}} = \frac{8.6874 - 2.1651}{2.1651} = 3.0125 \frac{\text{lb water}}{\text{lb resin}}$$

The percentage error in computing water content is

$$\begin{aligned} \frac{\Delta Q}{Q}(100) &= \left[\frac{\Delta(S_{\text{wet}} - S_{\text{dry}})}{S_{\text{wet}} - S_{\text{dry}}} + \frac{\Delta S_{\text{dry}}}{S_{\text{dry}}} \right] (100) \\ &= \left(\frac{0.0002}{6.5223} + \frac{0.0002}{2.1651} \right) (100) = \pm 0.012\% \end{aligned}$$

9.1.2 Bed Dry Mass

From the initial total mass and the water content of the sample at $t=0$,

$$\text{mass of dry bed} = \frac{M_{\text{rw}}}{Q_0 + 1.0} = \frac{108.2}{3.4655 + 1.0} = 24.33 \text{ lb}$$

The percentage error in measurement of mass of dry bed is

$$\begin{aligned}
 \frac{\Delta M_r}{M_r}(100) &= \left[\frac{\Delta M_{rw}}{M_{rw}} + \frac{\Delta Q_0}{Q_0} \right] [100] \\
 &= \left[\frac{\Delta M_{rw}}{M_{rw}} + \frac{\Delta(S_{wet} - S_{dry})_{t=0}}{S_{wet} - S_{dry}} + \frac{\Delta S_{dry}}{S_{dry}} \right] [100] \\
 &= \left[\frac{0.5}{108.2} + \frac{0.0002}{6.4920} + \frac{0.0002}{1.8733} \right] [100] = \pm 0.61\%
 \end{aligned}$$

9.1.3 Induction Period

To verify the water mass balance during the induction period, the predicted resin water content is compared with the measured water content. The decrease in water content up to any time is predicted by

$$\begin{aligned}
 (Q_0 - Q)_{\text{predicted}} &= \frac{(N_{\text{out}} - N_{\text{in}})_{\text{oc}} F}{M_r} \left[t - \frac{1}{A} (1 - e^{-At}) \right] \\
 &= 0.018 \times 0.93 \left[17 - \frac{1}{0.35} [1 - \exp(-0.35 \times 17)] \right] \\
 &= 0.24
 \end{aligned}$$

For $Q_0 = 3.55$ lb water/lb dry air, $F/M_r = 0.93$, $(N_{\text{out}} - N_{\text{in}})_{\text{oc}} = 0.018$ lb water/lb dry air, $A = 0.35 \text{ min}^{-1}$, and $t = 17 \text{ min}$,

$$(Q_0 - Q)_{\text{actual}} = 3.55 - 3.21 = 0.34$$

The percent error between the actual and predicted values is $\pm 29\%$.

9.1.4 Predicted Outlet Temperature

Referring to a standard psychrometric chart, the wet bulb temperature lines are the lines of adiabatic saturation (2). If it is known that $T_{\text{in}} = 250^\circ\text{F}$ and $N_{\text{in}} = 0.0045$ lb water/lb dry air, then $N = 0.040$ lb water/lb dry air and $T = 98^\circ$ at adiabatic saturation. Eighty percent of this value is $0.80 \times 0.040 = 0.032$ lb water/lb dry air. On the 98°F wet bulb temperature line at 0.032 lb water/lb dry air, the dry bulb temperature is $T_{\text{out}} = 112^\circ\text{F}$.

9.1.5 Constant Rate Period Model

Water gained by the air is calculated from inlet temperature and relative humidity, outlet air wet and dry bulb temperatures, and psychrometric charts. The rate of water content change per pound of dry resin for constant rate regime is obtained from the slope of the graph of resin water content as a function of time. With this information and the mass of the dry bed calculated above, the air flow rate is calculated.

$$F = \frac{-\frac{dQ}{dt}(M_r)}{N_{out} - N_{in}} = \frac{(0.054)(24.23)}{0.027} = 48.46 \text{ lb/min}$$

The percentage error in calculating air mass flow rate is

$$\begin{aligned} \frac{\Delta F}{F} &= \left[\frac{\Delta\left(\frac{dQ}{dt}\right)}{\frac{dQ}{dt}} + \frac{\Delta M_r}{M_r} + \frac{\Delta(N_{in} - N_{out})}{N_{in} - N_{out}} \right] (100) \\ &= \left[\frac{\Delta Q}{Q} + \frac{\Delta t}{t} + \frac{\Delta M_r}{M_r} + \frac{\Delta N_{in} + \Delta N_{out}}{N_{in} - N_{out}} \right] (100) \end{aligned}$$

To calculate the maximum error, substitute the minimum time measured (300 sec) and minimum humidity (0.0005 lb water/lb dry air).

$$\frac{\Delta F}{F} = (0.00012 + \frac{2}{300} + 0.0061 + \frac{0.001}{0.077})(100) = 4.92\%$$

Now we check the value $(N_{out} - N_{in})$.

$$\frac{C_p}{L}(T_{in} - T_{out}) = 0.03$$

which is higher by 11.1% than $(N_{out} - N_{in}) = 0.027$ experimentally measured. To test the accuracy of the constant rate model,

$$Q_{oc} - Q = \frac{F}{M_r} \left(\frac{C_p}{L} \right) (T_{in} - T_{out}) (t - t_{oc})$$

where t_{oc} is the time at which constant rate period starts. T_{out} was calculated from the inlet air temperature and inlet air humidity.

From the experiments it was found that an increase in the humidity of the outlet air was on an average 80% of the increase adiabatically obtained by saturating the air corresponding to the inlet air temperature and inlet air humidity. This fact was utilized in finding temperature of the outlet air. For example,

$$N_{in} = 0.0045 \text{ lb water/lb dry air}$$

$$N_{saturated} = 0.045 \text{ lb water/lb dry air}$$

$$N_{saturated} - N_{in} = 0.0405 \text{ lb water/lb dry air}$$

$$0.8(N_{saturated} - N_{in}) = 0.0324 \text{ lb water/lb dry air}$$

$$N_{out} = (0.0324 + 0.0045) = 0.0369 \text{ lb water/lb dry air}$$

The dry bulb temperature of the air corresponding to this humidity and the same wet bulb temperature line used for finding the water content of the saturated air is 112°F. Thus, $T_{out} = 112^\circ\text{F}$. Substituting the values $T_{in} = 250^\circ\text{F}$, $T_{out} = 112^\circ\text{F}$, and $t - t_{oc} = 12 \text{ min}$ in the equation gives

$$\begin{aligned} Q_{oc} - Q &= \frac{F}{M_r} \left(\frac{C_p}{L} \right) (T_{in} - T_{out})(t - t_{oc}) \\ &= \frac{48}{24.2} \left(\frac{0.236}{1039} \right) (138)(12) = 0.746 \end{aligned}$$

while the value obtained experimentally is 0.750. The % error in determining the value of the loss in the water content from the beginning of the constant rate period for this calculation is 0.53.

The percent error in calculated $(Q_{oc} - Q)$ is

$$\begin{aligned} \left[\frac{\Delta \left[\frac{F}{M_r} \left(\frac{C_p}{L} \right) (T_{in} - T_{out})(t - t_{oc}) \right]}{\left[\frac{F}{M_r} \left(\frac{C_p}{L} \right) (T_{in} - T_{out})(t - t_{oc}) \right]} \right] (100) &= \left[\frac{\Delta F}{F} + \frac{\Delta M_r}{M_r} \right. \\ &+ \frac{\Delta T_{in} + \Delta T_{out}}{T_{in} - T_{out}} + \frac{\Delta(t - t_{oc})}{t - t_{oc}} \left. \right] (100) = [0.0492 + 0.0061 \\ &+ 0.015 + 0.0027] (100) = 7.3\% \end{aligned}$$

9.2 Nomenclature

A	induction period time constant, min^{-1}
C_p	heat capacity of air, $\text{Btu/lb-}^\circ\text{F}$
F	air mass flow rate, dry basis, lb/min
L	enthalpy of vaporization of water, Btu/lb
M	mass, lb
N	water content of air, dry basis, $\text{lb water/lb dry air}$
Q	water content of resin, dry basis, $\text{lb water/lb dry resin}$
Q_0	initial water content of undried resin, dry basis, $\text{lb water/lb dry resin}$
Q_{0c}	water content of resin at beginning of constant rate period, dry basis, $\text{lb water/lb dry resin}$
Q_c	critical water content of resin, dry basis, $\text{lb water/lb dry resin}$
S	resin sample mass, lb
T	temperature, $^\circ\text{F}$
t	time, min
t_{0c}	time at beginning of constant rate period, min
ρ	density, lb/ft^3

Subscripts:

a	air
r	resin
rw	resin, wet basis
w	water
in	at inlet to bed
bed	in fluid bed
out	at exhaust vent

9.3 Location of Original Data

The original data are located in ORNL Databook A-7549-G, pp. 58-79, on file at the MIT School of Chemical Engineering Practice, Bldg. 3001, ORNL.

9.4 References

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