Improving Indirect Heat Transfer to Solids By Better Mixing

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Abstract

This review of literature citations relates how mixing affects the heat transfer rates to solids in a variety of processing units. These units will include pan, horizontal (rotary vacuum), screw conveyor and paddle dryers and/or processors.

The data presented will show that, in all cases, the investigators found that by increasing the speed of mixing the heat transfer rate is enhanced except when the agitator speed produces mechanical fluidization and/or during the constant rate period of a drying cycle.

Some recent work in the area of the paddle processor design will be reported. It shows that agitator shape and the density of the heat transfer surface to process volume improves the heat transfer rate along with the speed of rotation of the processor's agitator.

Introduction

The purpose of this paper is to relate how the rate of heat transfer is often improved by mixing. Reference to other investigators will be used to fortify the conclusion drawn. Mixing can improve heat transfer during heating or cooling cycles. During the drying cycle, mixing will not aid heat transfer during the constant rate drying period. During the rest of the drying cycle, mixing helps the heat transfer rate up to the point that the controlling factor becomes the diffusion rate of the solvent through the individual solid particles.

There are other parameters in the transfer of heat that must be considered including the material's thermal conductivity, flowability, bulk density, particle size and distribution and particle structure. As one might expect, the higher the thermal conductivity of the bed, the less pronounced the effect that mixing will have on the rate of heat transfer. Increasing the moisture content of a solid will increase its thermal conductivity. In a bed having a preponderance of surface moisture, as the bed heats up, the moisture will vaporize thus passing through the interstices of the bed. This moisture will condense on the colder surfaces in the bed. Condensation will transfer heat to the particle, thus causing a rapid heat up of the bed. Since this interaction begins to approach conditions found in a well mixed be, mixing will have little effect on improving the heat transfer.

Particles having low thermal conductivity can be rapidly heated or cooled by increasing the temperature driving force seen by the particle. This can be done by bringing all of the particles to the heat transfer surface by mixing. Dependency on the conductivity of the bed as a whole is minimized; thus indicating that a well mixed bed seems to be the solution.

The particle size, shape and distribution as it applies to a bed of solids also affects the bed's thermal conductivity. A bed of well mixed random size particles probably will have the highest number of contact points for the conductive conveyance of heat. This type of bed has the potential of having a high bulk density.

Materials, such as titanium dioxide, have the capability of plating out on the heat transfer surface. This will act to foul the surface reducing the capacity to exchange heat. These particles are often just a few microns in size.

There is very little in the literature that helps us to practically classify materials. An empirical approach to calculate a heat transfer rate to a material is almost impossible. This requires us to resort to testing with the particular solids to be processed in the piece of machinery to be used in the production scheme.

The specific design of the processor will affect the rate of heat transfer. The degree of mixing of the bed particles around the heat transfer surface will control the number of exposures of a specific particle to a heat transfer surface as well as the contact time. The better mixed the bed is the nearer it reaches an isotherm. This improves the temperature of driving force. The way in which the heating surface –vessel wall, agitator shaft, agitator arms, agitator flights, agitator blades – is presented to the bed influences the heat transfer rate.

Other factors unrelated to mixing would be the operating temperature and operating pressure. In the case where heat transfer is to change the sensible heat, then only operating temperature is important. When drying is being carried out both play almost an equal part in the process. By varying the operation pressure, one can also change the temperature driving force by lowering the boiling point and equilibrium pressures of the solvent. Economic reasons somewhat dictate the proper selection here, although physical characteristic of the material may set certain limits.

Pan Dryers

Very little work of any depth that was found in the literature on the interrelationship of mixing and heat transfer rates. Most of the literature resources, that provide an inkling of data, involved the pan dryers, properly the oldest style of dryer. Loughlin (1) using a 350-gallon (1325 liter) grease kettle with vertically mounted, double motion positive scraping agitation as a crystallizer dryer observed that "this (overall heat transfer) coefficient may vary considerably with the nature of the material, the moisture content, the effectiveness of agitation, and the total weight of the material bearing on the surface". In concluding he states, "Regarding the effects of agitation, one run was made without operating the agitator for the first 5 hours of the cycle … the drying cycle required 8-1/2 hours compared with the usual 7 hours with agitation throughout the cycle."

Rosenbluth (2) using a flat bottom 10.25 inch (260 mm) pan dryer reports his observation of how agitator speed affects the heat transfer coefficient. This is in line with Laughlin's statement about effectiveness of agitator enhancing the coefficient. Figure 1 plots the data Rosenbluth reported and confirmed the theory that agitation improved the heat transfer rate in pan-type dryers. It was concluded from his work that the rate of drying was proportional to the speed of rotation raised to the 0.4 power. A discussion of this and further data tying the conclusion to other investigators was reported by Uhl & Root (3).

More recently, work has been done by Schlunder and other associates in the area of contact drying. The data was collected using an electrically heated plate as the heat source. Gunes and Schlunder (4) developed a model to describe the contact drying of an agitated bed of particles (magnesium and aluminum silicates). They concluded that "when the packing (bed) has a high moisture content, the rate of stirring had no observable influence on the drying rate; whereas, towards the end of drying, i.e. when the moisture content of the packing is low, the drying rate can be increased by increasing the stirring rate." During the period of high moisture level, the bed is kept as an isotherm due to the evaporating liquid (vapor) passing at a fairly high rate up through the bed. Only as the moisture level drops off does the bed begin to develop temperature gradients. At this time, efforts to produce a well mixed bed by stirring eliminates or diminishes this possibility of developing many small gradients. This, therefore, increases the temperature driving force from the heat transfer surface to the particles in the bed.

Gunes and Schlunder refer to earlier studies attempting to use an equation of the form

$$\dot{n} = C\,Z^{-m}$$

to describe the fact that the drying rate $\dot{n}$, in a rotary dryer can be improved by increasing the revolution rate, Z. They found that the exponent, m, must necessarily depend on the moisture content of the material (bed). The exponent, m, was reported to have a value between 0 and –0.5.

Schlunder (5) suggests the existence of a formula that would correlate laboratory and full-scale test for the heat transfer coefficient between the bed and heat transfer surface. The thing noteworthy in this is that he uses a different constant to characterize each particular type of dryer.

Schlunder (6) plots data collected while studying contact drying under vacuum as shown in Figure 2. One observed from this family of curves that only a small amount of agitation produces a quantum increase in the heat transfer rate. As speed increases further, the percentage of the increase begins to diminish rapidly. While the results were obtained while drying under vacuum, the same results will exist under atmospheric conditions if the vapors are removed as they are formed.

Forthruber (7) observed the same phenomenon occurring in the plate-type dryer (a multi-tiered pan dryer). He makes the comment, 'A thin product layer on large heat exchange surface together and a high product turnover number (mixing) improve the heat and mass transfer.'

The above mentioned investigators using pan-type dryers, which are batch processors except for the plate dryer, all found agitation improved the heat transfer rates to some extent. Unfortunately, no mathematical correlation can be made of the percentage of improvement one may anticipate with a specific material with an increase in the rate of mixing in a specific processor. Piloting seems to be the only way to get the specifics.

Horizontal Processor

Porter (8) using a pilot-sized horizontal processor handling washed foundry sand observed that the sensible heat transfer rate was influenced by agitator speed and residence time. Figure 3 shows the results from testing using the unit as a batch processor and then with varying residence time and agitator speeds. The data shows a marked improvement with increased speed of agitation while operating in a batch mode. With the shortening of the residency time to less than 0.5-1 hour and an increase in agitation speed, the heat transfer rate improves over that found in a batch process.

Screw Conveyor Type Processor

The pan and horizontal types equipment had the disadvantage of providing limited heat transfer surfaces to process volume ratios. As the sizes grow larger, the ratio diminishes. About twenty (20) years ago, a screw conveyor with hollow heated flights operating in a jacketed trough came on the market. It provided a high ratio of heat transfer surface to process volume. Also as the size increased, the ratio did not decay as rapidly as with other dryers available then.

Horzella (9) provides a plot of the effect on agitation on the rate of heat transfer. He also found that the type of material processed does have an effect on the rate of heat transfer (Figure 4). On some materials, he found that too much speed could be detrimental. He furthered reports an increase of 20-40% in the heat transfer rate if two screws were used rather than one screw per trough. The use of multiple screws eliminated roping by making the units more self-cleaning, as a result of better mixing.

Mulcahey (10), using a single-shafted, heated screw type unit, noted "agitation is increased by the use of internal lifters between the flights of the screw, external ribbons on the periphery of the flights, or mixing paddles mounted on the shafts." He stated this improved the heat transfer rates by 1.5 to 5 times over that of alternative equipment.

Kasatkin, et al (11) found the rate of heat transfer was almost a linear function of the feed rate. They used a double shafted hollow screw conveyor with jacket. This somewhat follows the data presented by Porter. Figure 5 presents the work of Kasatkin, et al.

Paddle Processors

More recently, the paddle processor was developed. Possibly, it can best be categorized as a discontinuous flight, hollow screw conveyor. The cut flights provide better mixing without lowering the ratio of heat transfer surface to process volume too drastically. Basically, there are two (2) different styles of paddle processors, those having a wedge-shaped type blade; the other a parallel sided blade. This type equipment is not to be confused with some units having an European origin called paddle dryers, which for the purpose of this paper are called horizontal units.

Even within the equipment category of paddle dryers, the blade design, pitch, etc., can cause variations in the heat transfer ratio of as much as 30%. This data was confirmed in actual field performance involving the heat treatment of starch.

Data showing the effect of speed on drying solvent wetted coal ash is plotted in Figure 6. The effect of agitator speed and feed rate while drying water-wetted methionine is shown in Figure 7. As one can readily see, the thesis that agitation will improve the rate of heat transfer continues to run through the paddle processor. An increase in feed rate or reduction in residence time improves heat transfer. This again can be related to the renewal rate of the material laying next to the heat transfer surface.

Other field work where comparisons can be made between a paddle processor and a hollow heated, screw conveyor show almost a ten-fold improvement in the rate of heat transfer while heating carbon in a paddle processor over the screw type. This can be attributed to better mixing of the carbon bed. The screw flight operated at about 3-5 rpm while the paddle processor ran at 20 rpm. While cooling instant coffee, the rate was 3 to 5 times better in favor of the paddle processor. Again, mixing was the major factor producing the higher heat transfer rates.

Conclusions

In all cases reported, the degree of mixing had a considerable effect on the rate of heat transfer. The exceptions were in the constant rate drying period or when diffusion of vapors became the controlling factor during the drying cycle.

Since there is little data available to aid in the development of an empirical formula for calculating heat transfer rates, the best method of equipment selection is by running a test with the specific material to be processed in the specific machine most likely to succeed. The specific material to be processed in the production unit should be used so that physical variations of the bed are not a part of the evaluation. A pilot machine of the 'same' design as the production unit will eliminate mechanical differences in the final scale up.

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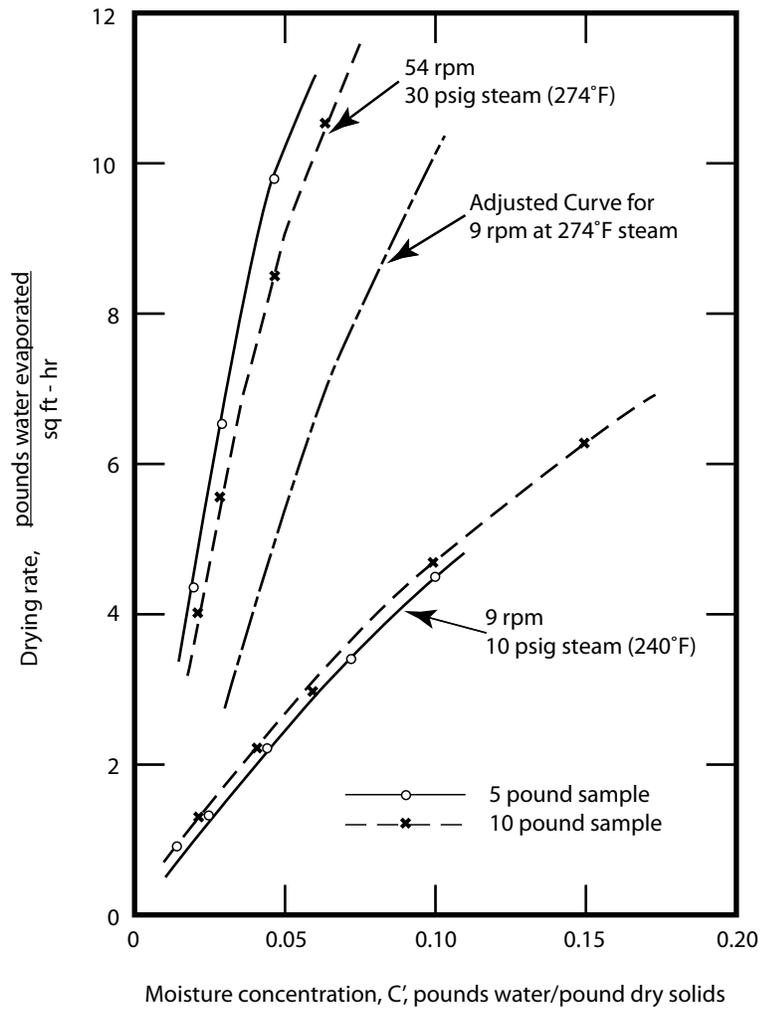
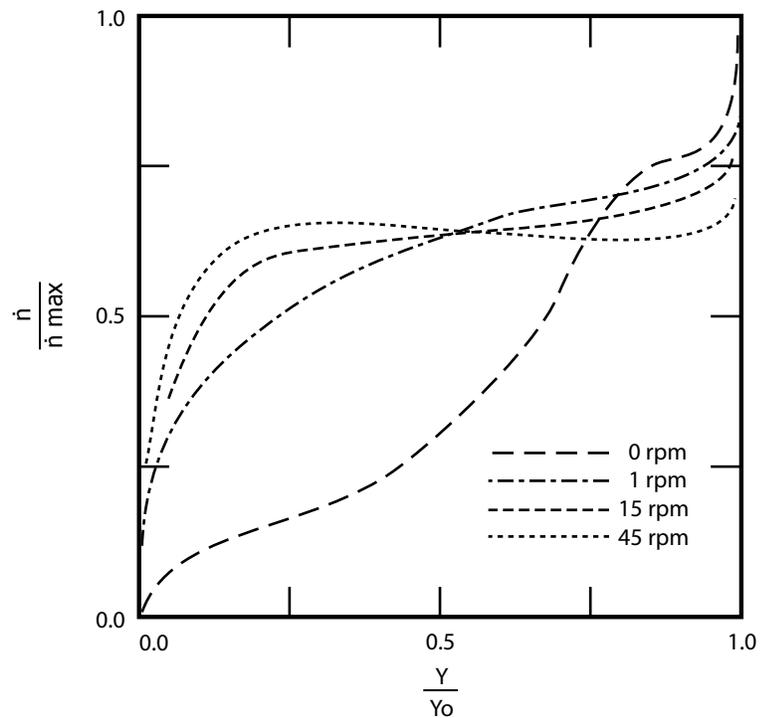Figure 1 - Drying rates for sand vs agitator speed in 10.25 inch diameter pan dryer

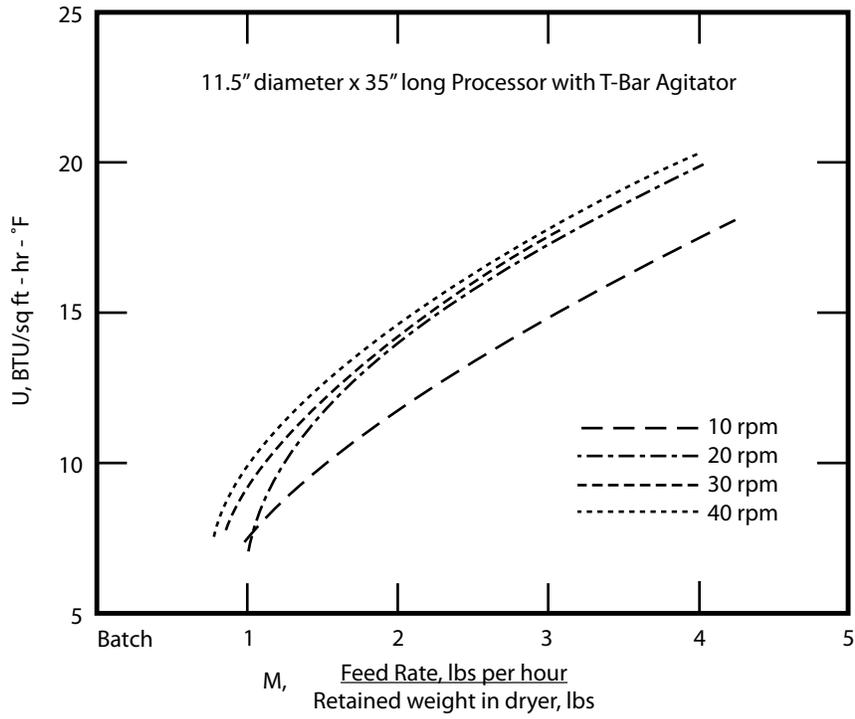Figure 2 - Drying curve of magnesium silicate particles at different agitator speeds

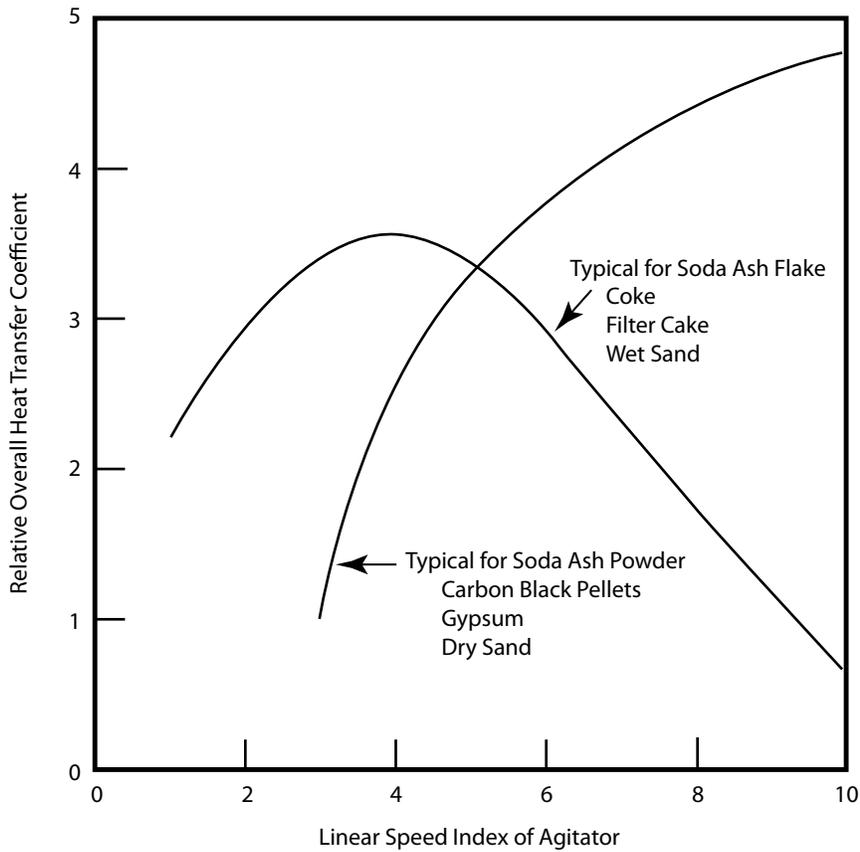Figure 3 - Plot of heat transfer coefficient, U, vs reciprocal of residence time, M

11.5" diameter x 35" long Processor with T-Bar Agitator

— — 10 rpm
—·—·— 20 rpm
— — — 30 rpm
········ 40 rpm

U, BTU/sq ft - hr - °F

Batch

M, $\dfrac{\text{Feed Rate, lbs per hour}}{\text{Retained weight in dryer, lbs}}$

Figure 4 - Effect of Agitator Speed on rate of heat transfer in a
heated screw type jacketed conveyor

Relative Overall Heat Transfer Coefficient

Typical for Soda Ash Flake
    Coke
    Filter Cake
    Wet Sand

Typical for Soda Ash Powder
Carbon Black Pellets
Gypsum
Dry Sand
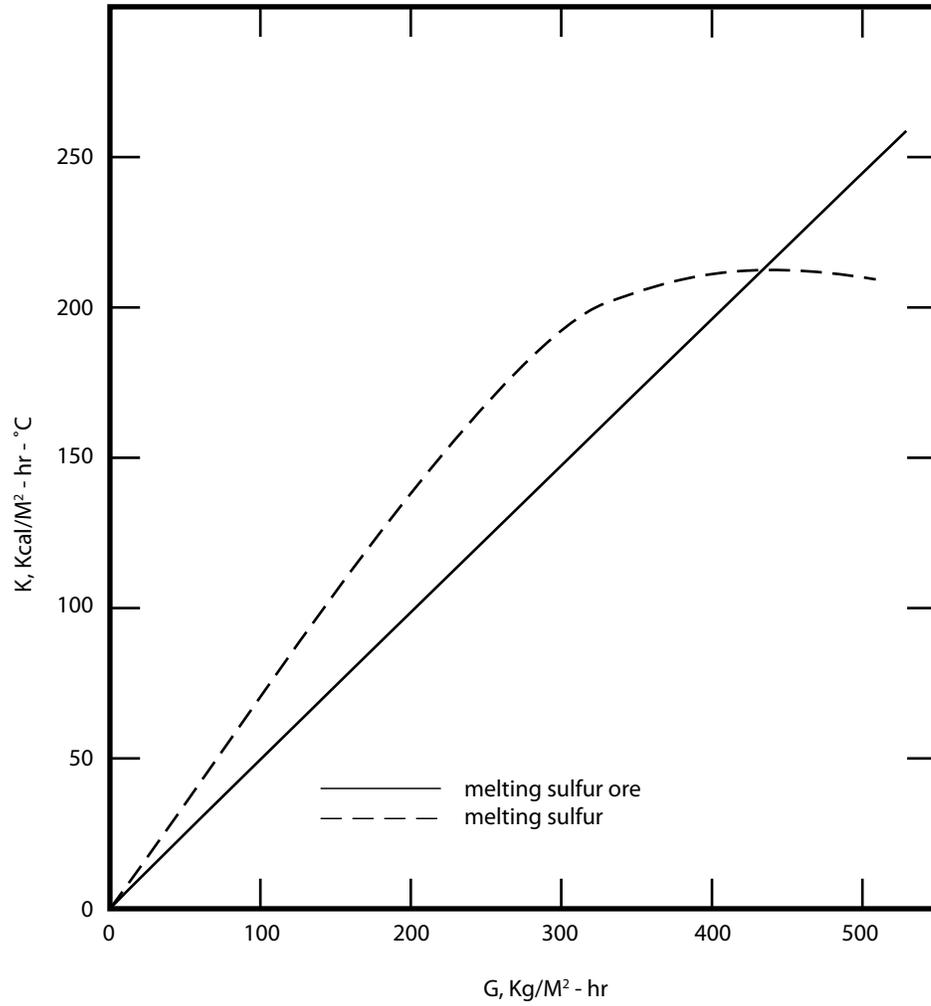
Linear Speed Index of Agitator

Figure 5 - Variation of heat transfer coefficient as a function of axial velocity of feed in a conveyor with heated screw and jacket.
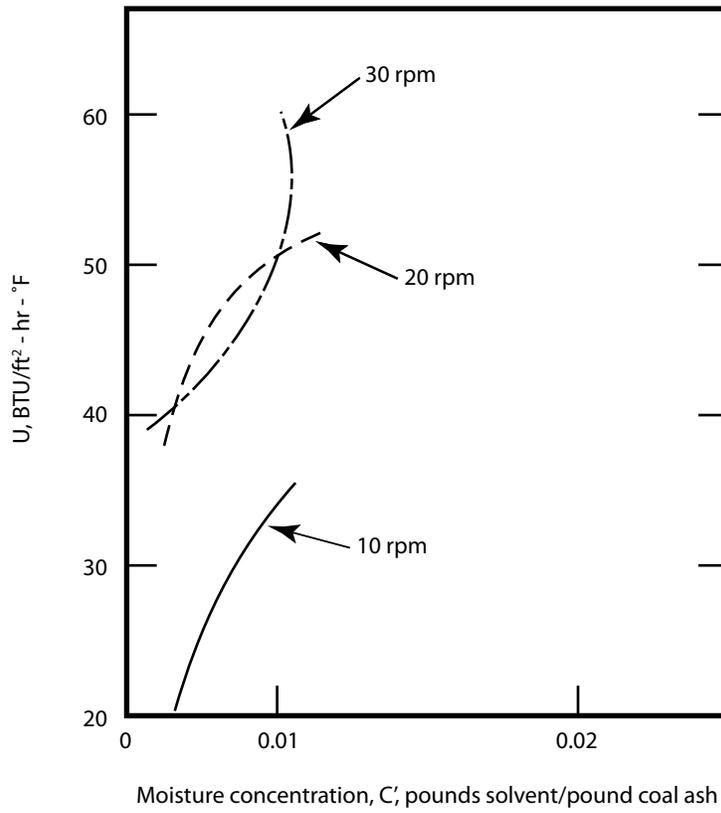
Figure 6 - Plot of U vs Moisture Concentration for solvent wetted coal ash
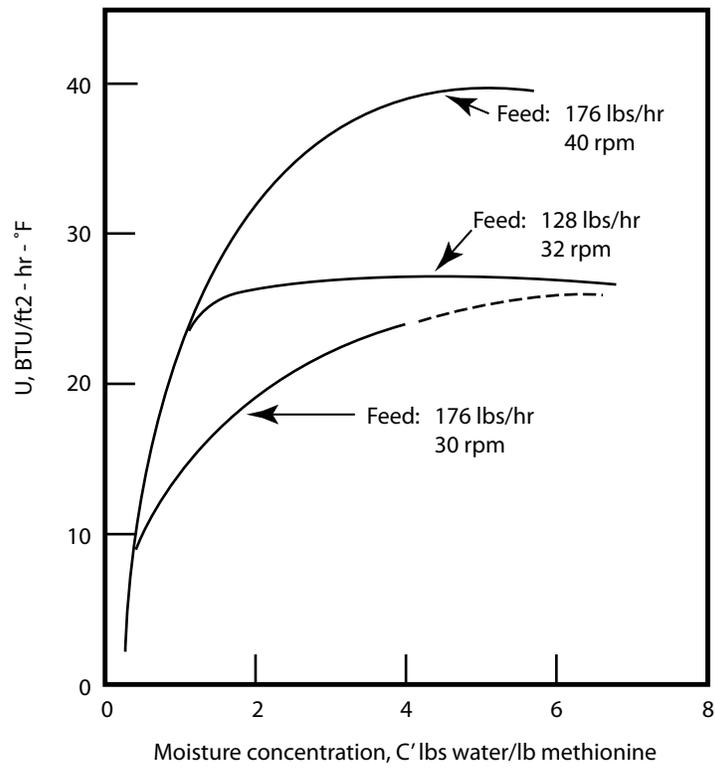showing effect of agitator speed

Figure 7 - Effect of Feed and Agitator speed on drying of
water wetted methionine