DRYING OF PEA BEAN SLURRIES IN A HORIZONTIAL CO-CURRENT SPRAY DRYER

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THESIS

ABSTRACT

DRYING OF PEA BEAN SLURRIES IN A HORIZONTAL
CO-CURRENT SPRAY DRYER

by Madhav Palnitkar

Whole dry pea beans were soaked, cooked, pureed and dried in a horizontal co-current dryer to an instant pre-cooked bean powder. The variables examined were feed pump pressure, types of nozzles, outlet temperature, puree solids content and feed temperature. The test results were evaluated on the basis of dryer capacity, bean powder moisture content, average particle size, bulk density, flowability, solubility index, blue value index, color, viscosity of reconstituted bean powder, reconstitution properties and taste. In addition, the theoretical and experimental capacities and drying times required to dry bean slurry droplets under specific sets of conditions were obtained.

Homogenizing bean puree prior to spray drying was found unacceptable because of excessive amount of cell breakage and free strach in the final product. Bean puree fed to the spray drier with a positive pump in conjunction with the high pressure pump of the spray drier gave satisfactory results. Both high pressure and low pressure nozzles could be

used.

Outlet temperatures over 200$^{\circ}$F were not satisfactory. The cooking methods did not influence the spray drying operation. The characteristics of the bean powder were dependent on the average particle size and the amount of smaller size particles (44  and less).

# DRYING OF PEA BEAN SLURRIES IN A HORIZONTAL CO-CURRENT SPRAY DRYER

by

Madhav Palnitkar

A THESIS

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## SYMBOLS

| | |
|---|---|
| $c_p$ | specific heat at constant pressure, $BTU/lb_m\ ^oF$. |
| $d_d$ | density of bone dried powder, $lb/ft^3$. |
| $d_s$ | density of bean slurry, $lb/ft^3$. |
| $d_t$ | density of outlet air, $lb/ft^3$. |
| $D$ | particle diameter, ft. |
| $D_{max}$ | maximum drop diameter, ft. |
| $D_s$ | orifice diameter, ft. |
| $h$ | average convective heat transfer co-efficient, $BTU/hr\ ft^2\ ^oF$. |
| $k$ | thermal conductivity of film, $BTU/hr\ ft\ ^oF$. |
| $M.C._{in}$ | moisture content of bean puree entering the dryer, lbs of water/lb of dry matter. |
| $M.C._{out}$ | moisture content of bean powder, lbs of water/lb of dry matter. |
| $q$ | rate of heat transfer, BTU/hr. |
| $t$ | time, hr. |
| $T_{ai}$ | inlet air temperature, $^oF$. |
| $T_{ao}$ | outlet air temperature, $^oF$. |
| $T_{wb}$ | wet bulb temperature, $^oF$. |
| $u$ | velocity, ft/sec. |
| $v$ | volume of the dryer, $ft^3$. |
| $W$ | drying rates, lbs of $H_2O$/hr. |

| | |
|---|---|
| $\Delta t$ | temperature difference between outlet air and drop surface, $^{o}F$. |
| $(\Delta t)_{av}$ | Logarithmic mean temperature difference, $^{o}F$ |
| $\lambda$ | heat evaporation, BTU/lb. |
| $\mu$ | dynamic viscosity, units c.p. |
| $\mu$ | particle size, microns. |

Dimensionless Groups

$$Nu = \frac{hD}{k} \quad \text{(Nussult number)}$$

$$Pr = \frac{c_p}{k} \quad \text{(Prandtle number)}$$

$$Re = \frac{Dup}{\mu} \quad \text{(Reynolds number)}$$

# INTRODUCTION

The annual farm value of dry beans in United States is about 125 million dollars. Michigan produces about 40 percent of the nation's total crop and 99.6 percent of the pea beans, about 800 million pounds.

Pea beans are a highly nutrious, low cost food. They contain about 22 percent protein and cost approximately seven cents a pound at the farm. This makes dry beans an economical source of plant protein. Furthermore, they have a pleasant flavor and are well accepted where they are available. However, domestic per capita consumption has been declining in recent years possibly because of the long soaking and cooking time required to prepare beans for serving. Precooked bean powder was first made on a laboratory drum dryer at the Western Regional Research Laboratory, Albany, California (Morris, 1961). Being precooked, the powder is very convenient to use and show promise for use as instant soups, instant dips, meat extender and in a variety of other recipes in manufacturing formulations.

This study was undertaken to determine if instant bean powder could be produced efficiently by spray drying and thus provide potential new uses for dry pea beans.

## REVIEW OF LITERATURE

Spray and drum drying are the two most economical drying methods for the removal of excess moisture from low solid content foods (Anon, 1965). Bakker-Arkema et al., (1966) have described the technique of making instant precooked pea bean powder on a single and double drum dryer.

Spray drying is a process for converting solutions or slurries almost instantly into a dry, free-flowing powder in one operation. It involves atomizing the slurry into small droplets within an enclosed chamber into which heated air is introduced. In the turbulent heated air environment most of the water from the slurry is evaporated instantly, resulting in a rapid drop of the drying gas temperature. The dried particles fall by their own weight to the bottom of the dryer where they are removed by conventional recovery methods.

The distinguishing characteristic of spray drying is the rapid rate of dehydration obtained by the exposure of large surface areas to the heated drying air. The principles of spray drying, with special emphasis on the theory of atomization has been discussed in detail by Marshall (1954).

Spray driers are usually classified according to the relative flow directions of the spray stream and drying air stream. Seltzer and Settlemeyer (1949) listed the following designations:

1) Horizontal co-current,

2) Simple vertical downward co-current,

   a) where air has a straight line flow,

   b) where air has a rotary motion,

3) Complex vertical downward co-current or mixed flow,

4) Vertical upward co-current, and

5) Vertical counter-current.

Seltzer et al., (1949) stated that horizontal co-current driers are used for drying milk, eggs, coffee and other food materials. In addition to the above broad classification, many spray driers are designed or modified according to the requirements of a particular product.

Several types of atomizers are used to spray the slurry into the drying chamber. The three most important types used in the food industry are: pressure spray heads, two fluid nozzles and centrifugal atomizers.

The atomization in pressure nozzles is effected by forcing the spray liquid under high pressure and with a high degree of spin through a small orifice. The spray pressure may range from 100 to 10,000 pounds per square inch. The nozzle orifice may vary from 0.013 to 0.15 inches in diameter. These variables are independent and will affect the capacity, the spray characteristics and the properties of the finished product. Pressure spray nozzles are extensively used in the dairy industry. The most important limitation of pressure spray nozzle is that the larger particles can easily obstruct the nozzle openings.

Perry (1950) reported that two fluid nozzles do not operate effectively at high capacities and consequently are not used widely in plant size spray dryers. The chief advantage of this type nozzles is that they can operate under low pressures (liquid pressure 0-60 psig) while the atomization fluid is under a pressure between 10-100 psig. A two fluid nozzle has been developed especially for dispersion of thick paste and filter cake not previously capable of being handled in an ordinary pressure atomizer.

In centrifugal atomizers the liquid slurry is atomized as it is discharged from the periphery of a rapidly revolving wheel. The number of revolutions may vary from 3,000 to 50,000 rpm depending upon the size of the dryer and particle size desired. The atomizer may be driven by electric motors, steam turbines or compressed air (Van Arsdel et al., 1964). Particle size of any given spray product is determined by the peripheral speed of the disc. Centrifugal disc atomization is particularly advantageous for atomizing suspensions and pastes that erode and plug nozzles (Perry, 1950). Centrifugal atomizers are extensively used for drying of perfumes (Seltzer, 1949). Bower (1931) reported that potato slurries dried with centrifugal atomizers had less starch cell damage. Seltzer et al., (1949) reported that suspensions containing sugar crystals were dried without disintegrating sugar crystals and thick, pasty, malted cereal mixtures containing 60 percent or more solids have been spray dried using a centrifugal atomizer where pressure nozzles would have been unsuitable. Baran (1964) reported on a newly designed nozzle for drying heavy pastes sludges and slurries. The nozzle gave substantial increase in the capacity over conventional drying systems and offered better control of the product quality.

The advantages of spray drying are: (Perry, 1950 and Van Arsdel, et al., 1964) continuous operation, low labor and maintenance cost, simplicity of operation, freedom from contamination, precise control of the final moisture content, elimination of dry particle size reduction or dry milling step, high production rates, favorable heat economies, relatively high quality of product and brief retention time of the product in the dryer, minimum amount of moving or wearing part and production of uniform spherical particles leading to a uniform bulk density.

The disadvantages of spray drying are: (Van Arsdel et al., 1964) low product densities especially at low nozzle pressures, relative inflexibility, high power requirement for pumping high viscosity slurries and high cost due to difficult product recovery and dust collection.

The rate of drying of a liquid drop in a spray dryer is a function of the temperature, the humidity and the velocity of the drying air; in addition, of the diameter of the particle, the dissolved or suspended material, the relative velocity between the drop and the airflow and finally, of the shape of the drying process.

Frossling (1938) used boundary layer theory to develop a set of partial differential equations that describe the constant rate drying process (evaporation from a free water surface) in a spray dryer. The resulting equations, much like the Navier-Stokes equations for fluid flow, are very difficult to solve even for the most simple boundary conditions.

By making a series of simplifying assumptions Gluckert (1962) developed an overall correlation of spray dryer performance. Gluckert's analysis is based on the premise that the capacity of a spray dryer is limited by the maximum amount of heat transferred between the largest droplets and the drying air. The maximum heat transfer rate for a pressure nozzle according to Gluckert, is equal to:

$$q = \frac{10.98 \; k \; v^{2/3} \; \Delta T}{D_{max}^2} \; D_s \sqrt{\frac{d_t}{d_s}} \qquad (1)$$

Kirschbaum (1952) and Marshall (1954) reported that the size of spray dried particles is not substantially different from the parent liquid droplets. If this is the case, a simpler expression than equation (1) for the maximum amount of heat transferred to a spherical droplet is:

$$q = h \, \pi \, D_{max}^2 \; (\Delta T)_{av} \qquad (2)$$

and

$$(\Delta T)_{av} = \frac{T_{ai} - T_{ao}}{\ln \dfrac{T_{ai} - T_{w.b.}}{T_{ao} - T_{w.b.}}} \qquad (3)$$

The value of h has to be found from empirical relationships for the heat transfer from spheres. Dlouhy et al., (1960) reported that in spray drying it can be safely assumed that the simultaneous heat and mass transfer process takes place under stagnant conditions. In this case the Reynolds number is equal to zero. From elementary heat transfer theory the following expression for the Nusselt number can then be developed for spray droplets (Rohsenow et al., 1961):

$$Nu = 2.0 \tag{4}$$

Bose et al., (1964), however, found that for droplet diameters between 40 and 125$\mu$ the relative motion between the particles and the air stream is of significant importance in the determination of heat and mass transfer in the spray drying process. They recommended the use of a correlation developed by Ranz et al., (1952):

$$Nu = 2.0 + 0.6\ Re^{0.5}\ Pr^{0.33} \tag{5}$$

The drying rate of a liquid droplet containing a dissolved material will exhibit two distinct phases: the constant rate period and the falling rate period. During the constant rate period the droplet surface will behave as a free water surface. The vapor pressure of the droplet during this period will be equal to the saturated vapor pressure at the prevailing wet bulb temperature in the dryer. When the internal diffusion in the droplet becomes less than the convective mass transfer, the constant rate drying period ends and the falling rate drying period begins. During this period the vapor pressure at the droplet surface will be less than the saturated vapor pressure. Ranz et al., (1952) developed an empirical relationship for the falling rate drying time. Gluckert (1962), however, showed that no serious error was made by assuming that the full drying process in a spray dryer takes place at a constant rate. The same assumption was made in this study for calculating the evaporation rates and drying time of pea bean droplets.

In calculating the drying time of the droplets produced by an atomizing device in a spray dryer, the distribution of the drop sizes should be considered. The smaller droplets will dry faster than the larger droplets. Uneven drying will thus result. Overdried particles may affect the flavor properties of a food product, while partially dried particles may cause deposition on the drying chamber wall. The drying time, therefore, should be no longer than the time required to dry the largest particle to a non-sticky condition and shorter than the time within which the smaller particles will burn. This last condition can be prevented by decreasing the inlet air temperature. Therefore, the first criterion will be used and the drying rates of the largest particles calculated as the required time to dry bean slurries with a particular nozzle.

The drying rate for drying a droplet can be calculated from equations (2), (3) and (5):

$$W = \frac{k(2.0 + 0.6\ Re^{0.5}\ Pr^{0.33})\pi D_{max}(\Delta T)_{av}}{\lambda} \qquad (6)$$

The total time required to dry a bean droplet is then given by the expression:

$$t = \frac{\lambda d_d\ (M.C._{in} - M.C._{out})\pi D^3_{max}}{6k(2.0 + 0.6\ Re^{0.5}\ Pr^{0.33})\ D_{max}\ (\Delta T)_{av}} \qquad (7)$$

# MATERIALS AND METHODS

Pea beans (variety Sanilac) were obtained from a local bean elevator and were stored at 35°F until used. Representative samples of the beans were soaked and cooked as given in Table 1. Most of the studies on the spray drying variables were made on beans soaked 40 minutes at 210°F and retorted at 250°F for 90 minutes. After soaking and cooking the whole beans which now contained from 55 to 58 percent moisture, were pureed in a Langsenkamp pulper. The beans were put through the pulper twice, first with a 0.065 inch sieve and then with a 0.023 inch sieve. During the pureeing operation, water was added to aid in the pureeing and to adjust the moisture content to the desired level for spray drying.

Two types of spray drying feed systems were investigated. In the first series of tests 15 percent solids content bean slurry was homogenized at 2,000 - 3,000 psig in a Manton Gaulin homogenizer and then fed to the high pressure pump of the spray dryer. In the second series of tests, the bean puree was adjusted to the desired percent solids content (between 15 and 25 percent) and was fed by a positive pump to the high pressure feed pump of the spray dryer.

Table 1. Soaking and cooking procedures for dry pea beans.

| Soaking Time, Minutes at 210°F | Cooking Time, Minutes | Cooking Temperature, °F | Method of Cooking |
|---|---|---|---|
| 40 | 30 | 230 | Retort |
| 40 | 60 | 230 | Retort |
| 40 | 90 | 250 | Retort |
| - | 90 | 210 | Atmosphere |
| - | 120 | 210 | Atmosphere |

A horizontal co-current spray dryer manufactured by the C. E. Rogers Company of Detroit, Michigan, having an evaporation rate of 300 pounds of water per hour at 325$^{o}$F inlet temperature was used. The drying chamber is constructed in the form of an inverted 'tear drop.' The approximate dimensions are 7' 4" width at the widest point by 11' 5" height by 18' in length. A baffle plate is located at 13' 4" from the front (wet) to minimize product loss in the exit air stream. The spray dryer has three individual air inlets, (each inlet for one individual nozzle or bank of nozzles) but only one single nozzle placed in the center air inlet was used. The dryer is provided with a turboblower which delivered 300 cubic feet of air per minute at 3,420 rpm and 13.2 inches of water to the inlet end of the dryer and an exhaust fan operated at 1,790 rpm and 11.5 inch water column, exhausting 4,400 cubic feet of air per minute. The dryer operates under a partial suction draft.

The spray dryer contains a screw conveyer for collecting the dried material. This device was not used due to the loss of powder in the powder collection system. Instead, the bottom of the spray dryer was lined with paper allowing for essentially complete collection of the powder at the bottom of the drying chamber. The walls of the chamber were swept after each trial. The small amount of powder that did not settle in the drying chamber and accumulated in the two dryer cyclones was not recovered. The atomization of the bean slurry was accomplished with pressure type nozzles with a grooved-core insert. The nozzle produced a hollow cone spray pattern. All but one of the test series was performed with high pressure spray nozzles. Flat top cores (No. 20), having two grooves of nominal width and depth of 0.020 inches and 0.031 inches, were employed in the high pressure nozzles. A list of the nozzles used along with their measured water capacities and spray angles is given in Table 2.

The maximum air velocity in the drying chamber was 240 feet per minute. Pal (1959) determined the temperature distribution patterns (Figure 1) at different distances from the spray nozzle during the spray drying of milk for the spray dryer used in this study. Also a typical velocity profile of the dryer as measured by Pal is shown in Figure 2. It should be noted that the direction of airflow in the upper half of the dryer was opposite to that in the lower half. The horizontal co-current spray dryer is shown in Figure 3. Pal concluded: "Ninety percent of the drying process is accomplished

Table 2. Capacity and spray angle of pressure nozzles used for atomizing pea bean slurries.

| Orifice Number | Orifice Dimension Inches | Measured Capacity Gallons $H_2O$/hr | Nozzle Pressure Psig | Spray Angle Degree |
|---|---|---|---|---|
| 76 | 0.020 | 8.53 | 500 | 64 |
| 76 | 0.020 | 11.64 | 1000 | 64 |
| 76 | 0.020 | 15.90 | 2000 | 64 |
| 76 | 0.020 | 17.71 | 2500 | 64 |
| 76 | 0.020 | 19.19 | 3000 | 64 |
| 72 | 0.025 | 11.48 | 500 | 72 |
| 72 | 0.025 | 15.91 | 1000 | 72 |
| 72 | 0.025 | 21.81 | 2000 | 72 |
| 72 | 0.025 | 24.43 | 2500 | 72 |
| 72 | 0.025 | 26.57 | 3000 | 72 |
| 69 | 0.0292 | 13.94 | 500 | 76 |
| 69 | 0.0292 | 19.18 | 1000 | 76 |
| 69 | 0.0292 | 26.40 | 2000 | 76 |
| 69 | 0.0292 | 29.36 | 2500 | 76 |
| 69 | 0.0292 | 31.65 | 3000 | 76 |
| 62 | 0.038 | 17.54 | 500 | 85 |
| 62 | 0.038 | 24.60 | 1000 | 85 |
| 62 | 0.038 | 33.45 | 2000 | 85 |
| 62 | 0.038 | 37.22 | 2500 | 85 |
| 62 | 0.038 | 40.34 | 3000 | 85 |
| 56 | 0.0465 | 27.39 | 500 | 86 |
| 56 | 0.0465 | 37.88 | 1000 | 86 |
| 56 | 0.0465 | 52.15 | 2000 | 86 |
| 56 | 0.0465 | 58.05 | 2500 | 86 |
| 56 | 0.0465 | 62.38 | 3000 | 86 |
| | 0.026* | 12.13 | 250 | 65 |
| | 0.026 | 17.38 | 500 | 65 |
| | 0.026 | 20.66 | 700 | 65 |
| *Low pressure nozzle | 0.026 | 24.60 | 1000 | 65 |

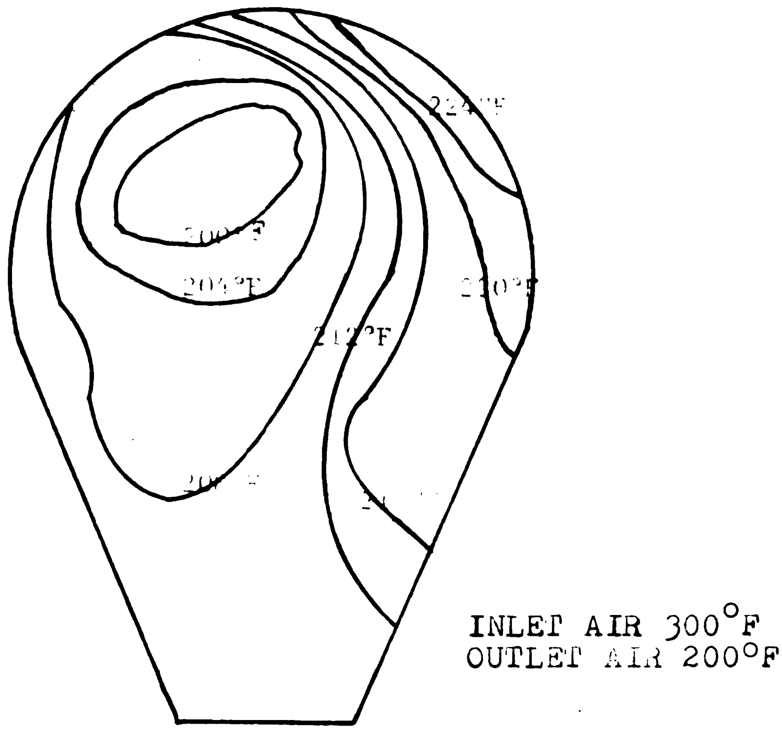



FIGURE 1: TEMPERATURE PROFILE TWELVE FEET FROM FRONT END OF TH DRYER.

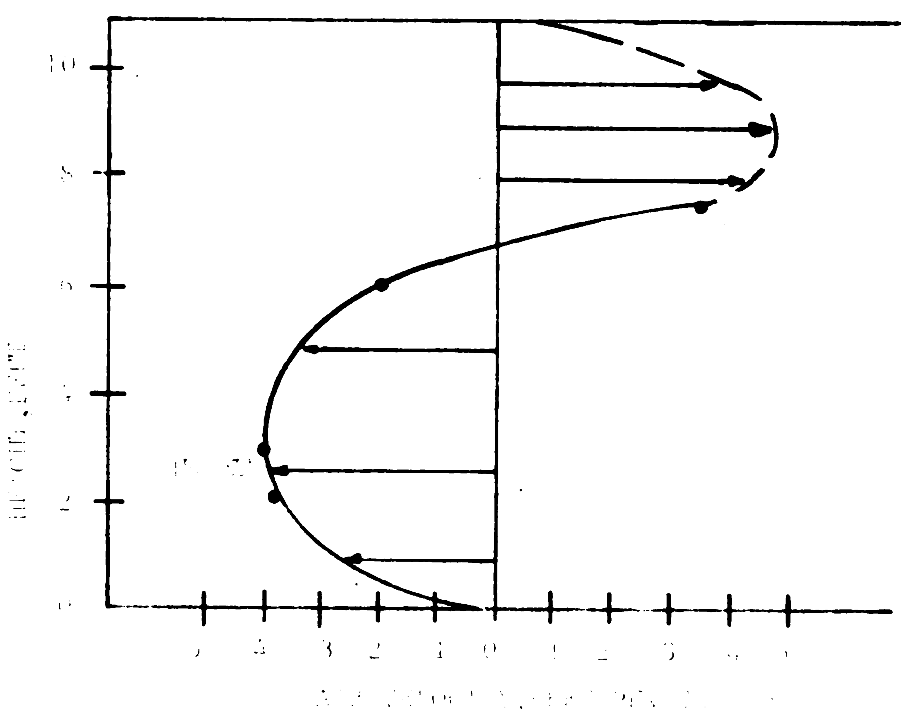


FIGURE 2: AXIAL VELOCITY PROFILE AT TEN FEET FROM FRONT END OF THE DRYER.

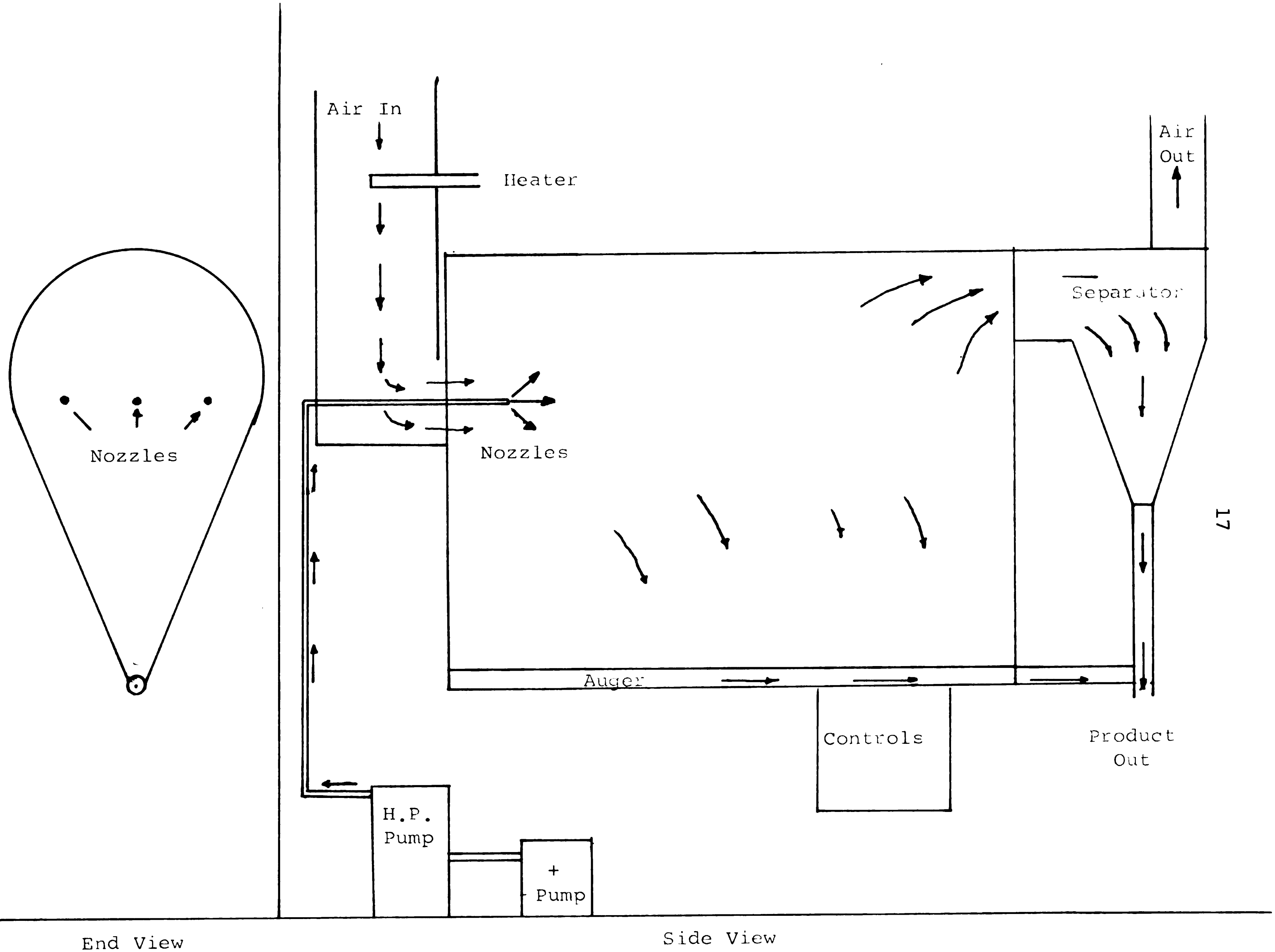



FIGURE 3: COCURRENT HORIZONTAL SPRAY DRYER

within the first five feet of the drying chamber, and the effective utilization of the dryer chamber was limited to the first ten feet of the chamber length."

The percent weight distribution and average particle size distribution of bean powder in the dryer was determined by placing twelve metallic dishes of 9" diameter 6" apart from each other over the cat walk (length) of the dryer. Twenty percent bean slurry was fed through the high pressure nozzle (orifice insert diameter 0.0465") and low pressure nozzle (orifice insert diameter 0.026") at 2,500 and 500 psig, respectively. After completion of the trial the bean powder in each dish was weighed accurately and further analysed for the average particle size.

The following spray drying variables were studied:

1) Type of nozzle

   a) high pressure; b) low pressure

2) Exit air temperature

   a) 160°F; b) 180°F; c) 200°F; d) 220°F

3) Percent solids in the pea beans slurry

   a) 15; b) 20; c) 25

4) Feed temperature

   a) 86°F; b) 122°F; c) 158°F

5) Spray pump pressure

a) homogenized slurry
(1) 500
(2) 1,000
(3) 2,000
(4) 3,000
(5) 4,000 psig

b) unhomogenized slurry
(1) 500
(2) 1,000
(3) 2,000
(4) 3,000 psig

6) Effect of feed pump pressure on outlet temperature keeping inlet air temperature constant

a) 500; b) 1,000; c) 2,000 psig

The following bean powder characteristics were studied:

1) Moisture content - The moisture content was determined by using a calibrated Cenco Infra red moisture meter.

2) Bulk density - A calibrated 250 ml graduated cylinder was slowly filled with 100 g of bean powder and the loose volume was determined. The packed volume was determined by dropping the cylinder from a height of approximately 1 inch fifty times, turning it 15 degrees after each drop. The volume was estimated to $\pm$ 0.2 ml and the weights to $\pm$ 0.1 g. The bulk density was determined by calculating the ratio of weight to volume.

3) Particle size distribution - A Tyler Ro-tap sieve

shaker was used to determine the average particle size. A 20 g sample was placed on the upper sieve of series having successive mesh graduations of 65 (210 $\mu$), 100 (149 $\mu$), 200 (74 $\mu$), 250 (63 $\mu$), 270 (53 $\mu$), and 325 (44 $\mu$). After shaking for 15 minutes the powder retained on each sieve was weighed. The average particle size was estimated on a percent weight basis.

4) <u>Flowability</u> - Tripp et al., (1965) described the static method of measuring the flowability of high fat dried dairy product. The apparatus used by Tripp et al., consisted of a glass funnel and a Petri dish to provide a constant base for measuring the angle of repose. In this study an Adams consistometer (Figure 4) was used for measuring the flowability of the powder. It was observed that more consistant results were obtained with the Adams consistometer than with the static method described by Tripp et al.

Two hundred g of bean powder was added into the cup C resting tightly on the circular plate. The diameter of the heap was measured by the quarter inch marks on the circular plate. The height of the pile was measured by placing a meter ruler across the two 6" plastic rulers E and holding it just above the heap. Flowability is expressed in terms of the angle

A - Stand

B - Circular plate

C - Cup

D - Screw

E - Plastic 6" ruler

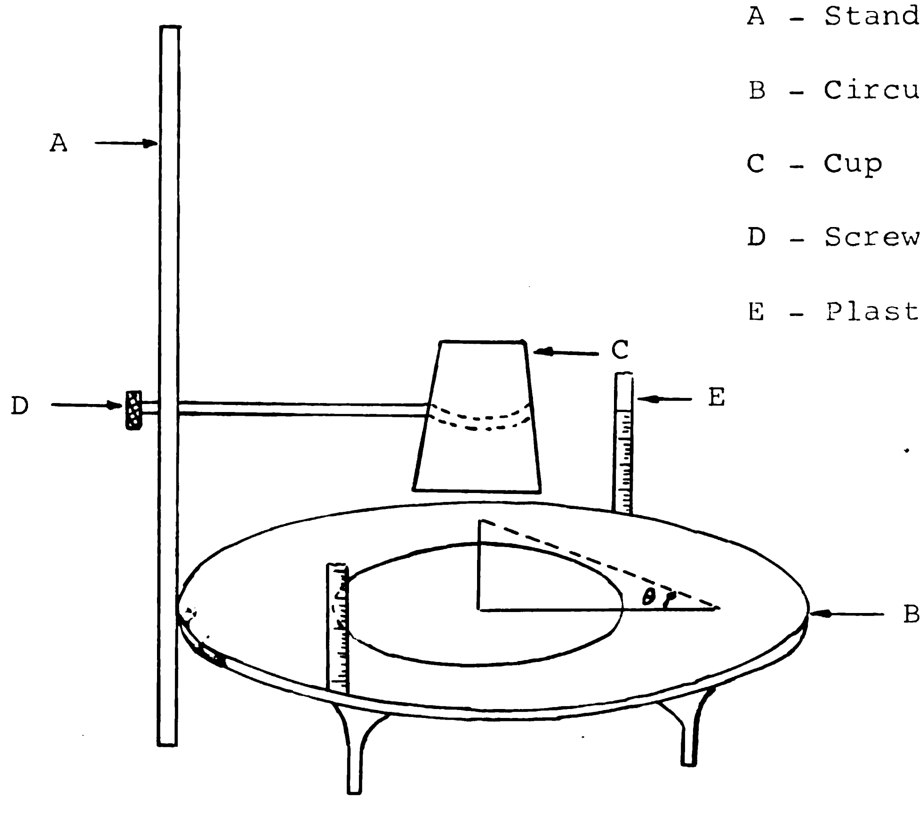



FIGURE 4: APPARATUS USED FOR MEASURING FLOWABILITY OF BEAN POWDER

of repose.

$$\text{Tangent of the angle of repose} = \frac{\text{Height of the pile}}{\text{Radius}}$$

5) Reconstitution - Ten g bean powder was added to 70 ml boiling water in 250 ml beaker. The beaker was placed on a thermostatically controlled hot plate and stirred for 90 seconds. The reconstituted solution was poured in 100 ml graduated cylinder and the rate of settling of solids was measured at five minutes interval for 30 minutes.

6) Solubility index - The procedure given in Bulletin of the American Dry Milk Institute (No. 916) was followed. Thirteen g powder was added to 100 ml distilled water (75°F) in a small Waring blender jar and blended for 90 seconds. The blended sample was allowed to stand until foam separated sufficiently to be removed by a spoon, the time not exceeding 15 minutes. After removal of the foam, the sample was thoroughly mixed by stirring for 5-10 seconds and 40 ml transferred to a graduated conical centrifuge tube. The tube was centrifuged for five minutes at 1,030 rpm in a clinical model centifuge. The supernatant liquid to within 2 ml of the surface of sediment was carefully siphoned off. Twenty-five ml distilled water (75°F) was added and the sediment resuspended by mixing. The tube was again centrifuged for five minutes

at 1,030 rpm and the ml of sediment determined and recorded as solubility index.

7) Color - The color of the bean powder was measured by using both a Gardner Automatic Color Difference meter (Model No. AC-1) and an Agtron meter (Model No. F-2-61). The Gardner was standardized by using a white plate standard having the values of L = 90.5 aL = -2.0 and bL = +2.5. The calibration discs for the Agtron ranged between disc No. 000 (white) and disc No. 95 (black). The spray dried bean powder was found to be in the range of disc No. 33 and disc No. 63. Hence the 0 and 100 on the instrument was adjusted using disc No. 33 and disc No. 63, respectively.

8) Blue value index - Cording et al., (1959) described the procedure for determining the 'blue value index' potato flakes. The same procedure was used to determine the blue value index of spray dried pea bean powder except the bean powder was extracted at 180°F instead of 160°F.

Five g of bean powder was extracted with 500 ml of distilled water at 180°F initial temperature using a magnatic stirrer. The resulting slurry was allowed to settle and then filtered through Whatman No. 1 filter paper. Five ml of filtrate was pipetted in a 100 ml volumetric flask. Two ml of

0.02 N iodine solution was added, and made to volume with distilled water. The color of the resulting solution was determined by measuring the absorbance of the solution at 660 mu with 2 ml of 0.02 N iodine solution diluted to 100 ml as a standard.

9) Viscosity - a) Brookfield Synchro-lectric Viscometer Model LVT. Thirty g of pea bean powder was added to 210 ml distilled water at $80^{\circ}F$ in a Waring blender and blended for 10 minutes at a rheostat setting of 40 volts. The resulting mixture was poured into a 250 ml beaker and allowed to stand for 60 minutes. The viscosity of the reconstituted product was measured using spindle No. 3 at a speed of 12 rpm. Readings were taken after the spindle had rotated for 15 seconds.

b) Brabender Viscoamylograph Model Va-V. Sixty g of bean powder was added to 420 ml boiling tap water in a 500 ml beaker. The beaker was placed on a thermostatically controlled hot plate and stirred for 15 minutes, keeping the temperature of the mixture to approximately $180^{\circ}F$. The reconstituted bean powder was poured into the amylograph bowl. The chart was adjusted to zero. The paste was held in the bowl for five minutes (no heating was carried out during this period).

10) Sensory evaluations - Nine point hedonic system

was used for evaluating the acceptability of the bean powder soup obtained with different spray drying variables. A taste panel of eight to ten was used to make the preliminary evaluations. A 1 to 4.5 ratio of bean powder to water containing one and half percent of salt and 3 percent of fat was used for the preliminary evaluation. Two replications were made for each sample. Finally a small scale consumer taste panel of 47 members evaluated the bean soup which received the highest rating by the small taste panel. The ingredients used to make the soup for this experiment are shown in Table 3.

Table 3. Bean powder soup mixture, list of ingredients

| Ingredients | Percent |
|---|---|
| 1. Powder | 83.63 |
| 2. Fat | 9.4 |
| 3. Salt | 3.0 |
| 4. Monosodium glutamate | 0.8 |
| 5. Onions | 1.0 |
| 6. Beef extract | 2.0 |
| 7. All spice | 0.1 |
| 8. Black pepper | 0.07 |

## RESULTS AND DISCUSSION

### Spray Drying Variables

Feed systems - Homogenizing the bean puree prior to spray drying aided in feeding the bean puree through the high pressure feed pump of the spray dryer. No settling of solids in the feeder trough of the high pressure pump was observed nor did the nozzle clog up. The resulting bean powder reconstituted readily, had a relatively high viscosity, and had good resuspensibility (Table 4). The viscosity of the reconstituted powder, the solubility index, and the blue value index increased with an increase in spray pump pressure. However, the microscopic examination indicated that there was an increase in the amount of broken cells and free starch with an increase of spray pump pressure. The values of viscosity, solubility index and blue value index were much higher than the values obtained with the pean powder without homogenizing the bean slurry (Table 4 and 6). The homogenizing procedure of feeding slurry to the spray dryer was discontinued because sensory evaluations of the powder indicated that these powders were unacceptable due to the excessive pastiness of the reconstituted powder.

Table 4. Effect of homogenizing pea bean puree on the properties of resulting bean powder.*

| Bean Powder Characteristics | Feed Pump Pressure psig | | | | |
|---|---|---|---|---|---|
| | 500 | 1000 | 2000 | 3000 | 4000 |
| Moisture content, percent W.B. | 4.9 | 5.0 | 5.0 | 5.1 | 5.1 |
| Capacity bone dried solids, lbs/hr | 20.8 | 28.7 | 30.6 | 31.5 | 37.4 |
| Bulk density, $lb/ft^3$ | 39.01 | 40.0 | 42.2 | 43.3 | 48.0 |
| Average particle size, $\mu$ | 120.9 | 68.1 | 60.0 | 51.1 | 50.6 |
| Flowability, angle of repose (degree) | 22 | 22.8 | 23.1 | 23.6 | 24.2 |
| Solubility index, ml | 18 | 23.5 | 28.3 | 28.5 | 30.3 |
| Microscopic examination, percent broken cells | 41.7 | 52.7 | 54.8 | 59.4 | 73.3 |
| Viscosity | | | | | |
| a) Brookfield c.p. | 4150 | 6900 | 7100 | 7650 | 8200 |
| b) Brabender B.U. | 97 | 480 | 470 | 488 | 515 |
| Blue value index, absorbancy | 0.30 | 0.92 | 2.0 | $\infty$ | $\infty$ |
| Color | | | | | |
| Agtron | 49.5 | 53.8 | 53.9 | 56.0 | 57.5 |
| Gardner | | | | | |
| L | 70.9 | 74.3 | 74.9 | 75.3 | 76.4 |
| al | 6.5 | 4.7 | 4.6 | 5.2 | 4.4 |
| bl | 20.4 | 17.9 | 17.6 | 18.2 | 16.8 |
| Reconstitution, ml clear liquid | | | | | |
| 10 minutes | 1 | 0 | 0 | 0 | 0 |
| 20 minutes | 1.2 | 2 | 0.5 | 0 | 0 |
| 30 minutes | 1.9 | 3 | 1 | 0.5 | 1.5 |

*Fifteen percent bean slurry homogenized twice through Manton Gaulin homogenizer at 2000 to 3000 psi, high pressure nozzle No. 56 orifice insert (diameter 0.0465"), exit air temperature 180-190°F feed temperature 86°F.

Feeding the bean slurry directly into the spray dryer was found to be satisfactory procedure providing a positive pump was used to maintain a constant supply of puree in order to prevent air from entering the high pressure pump. The positive pump did not affect the bean slurrying capacities of the dryer. In general this procedure was found to be satisfactory in producing the bean powder having less cell damage and free starch.

Powder distribution in the spray dryer - The dry bean powder fell over the length of the dryer. The present weight distribution depended on the nozzle used. With a high pressure nozzle (orifice insert diameter 0.0465", 2500 psig feed pressure, 20 percent bean slurry, and exist air temperature 180$^{o}$F) there was slight decrease in weight of powder unit length from the wet end to the dry end of the drying chamber (Figure 5). The low pressure nozzle (orifice insert diameter 0.026", 500 psig, 20 percent bean slurry, exist air temperature 200$^{o}$F) exhibited the opposite distribution (Figure 6).

The average particle size ranged from 140$\mu$ to 180$\mu$ for the low pressure nozzle and from 90$\mu$ to 120$\mu$ for the high pressure nozzle used. With the high pressure nozzle, the coarse particles were confined to the front and end zones of the dryer while the finer particles were found in a zone of 6

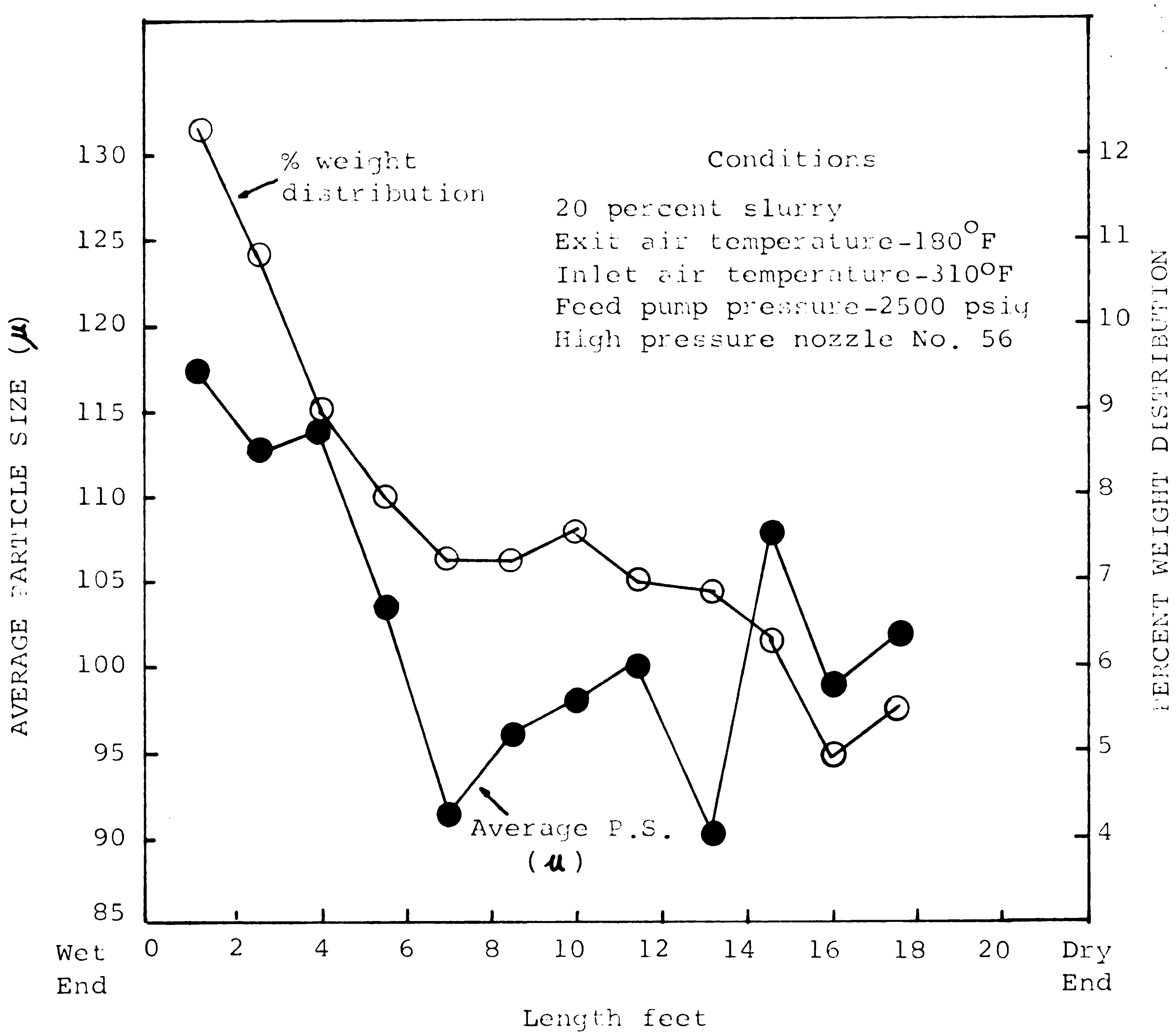



FIGURE 5: PERCENT WEIGHT DISTRIBUTION OF THE DRIED POWDER AND THE AVERAGE PARTICLE SIZE AT VARIOUS POINTS OVER THE LENGTH OF THE SPRAY DRYER USING A HIGH PRESSURE NOZZLE.

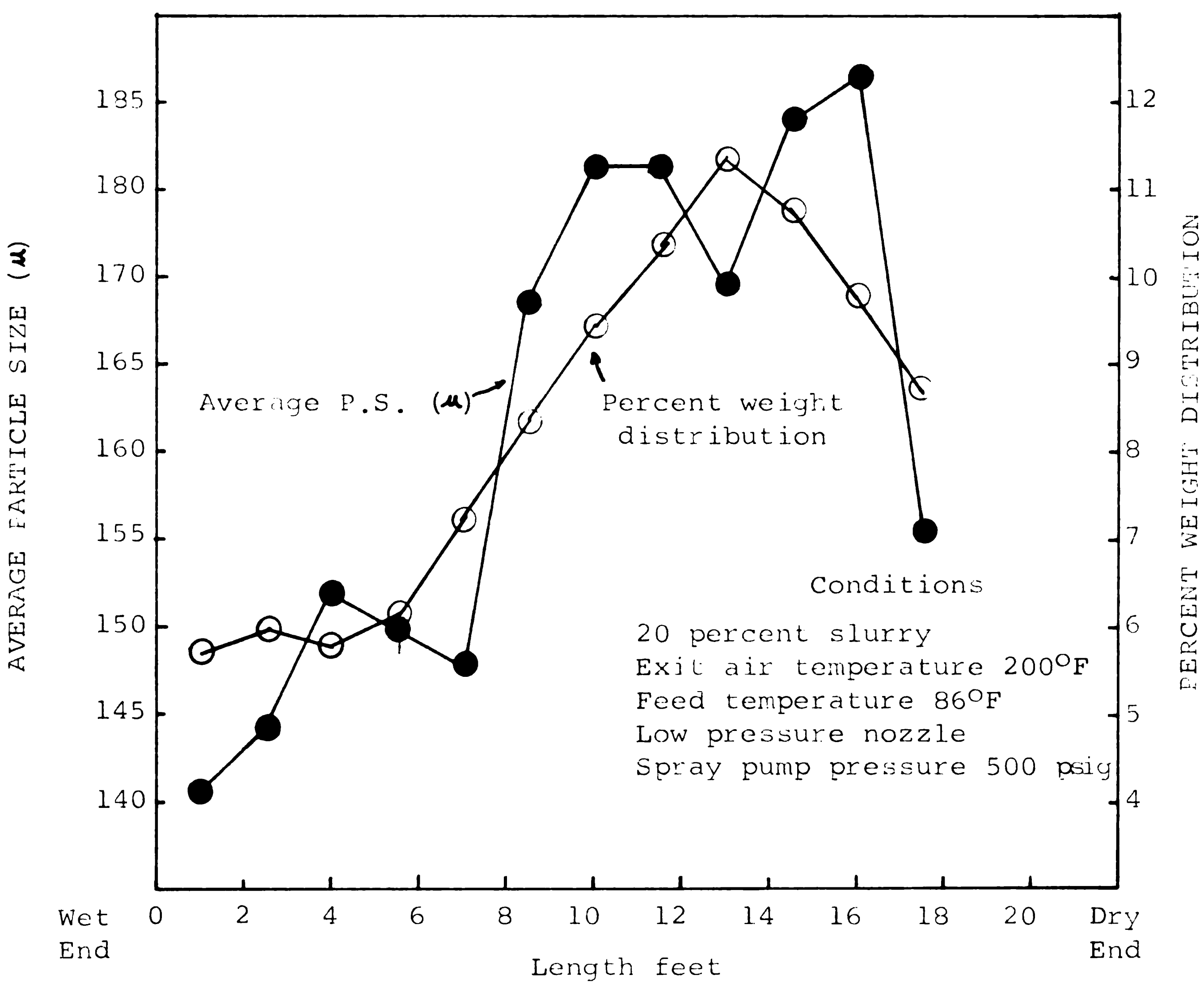



FIGURE 6: PERCENT WEIGHT DISTRIBUTION OF THE DRIED BEAN POWDER AND THE AVERAGE PARTICLE SIZE AT VARIOUS POINTS OVER THE LENGTH OF THE SPRAY DRYER. USING A LOW PRESSURE NOZZLE.

to 13 feet from the wet end (Figure 5). The coarser particles fell within 8 to 17 feet from the wet end and finer particles 0 to 8 feet from the dry end in the case of the low pressure nozzle (Figure 6).

Orifice diameter - The larger the orifice diameter of the high pressure nozzles the greater was the capacity of the spray dryer. The capacity in pounds of dry solids per hour and in gallons of bean puree per hour is plotted versus the orifice diameter in Figure 7. In the same figure the rated or measured capacities in gallons of slurry per hour are also included. The data show that the conversion factor for converting the gallons of water per hour (measured capacity) to gallons of 15, 20 and 25 percent bean puree are 0.65, 0.85 and 0.90, respectively. These data are in agreement with those reported by McIrvine (1952) and Hayashi (1962) who found that the capacity of grooved core nozzles increases with viscosity as long as atomization occurs.

Generally, for most of the substances, as the orifice diameter increased the average particle size increased with a constant nozzle pressure. Low pressure nozzles were reported by their manufacturer to be capable of producing a narrower particle size range, when used at low pressures (100 to 500 psig). Furthermore, it was indicated that the low pressure

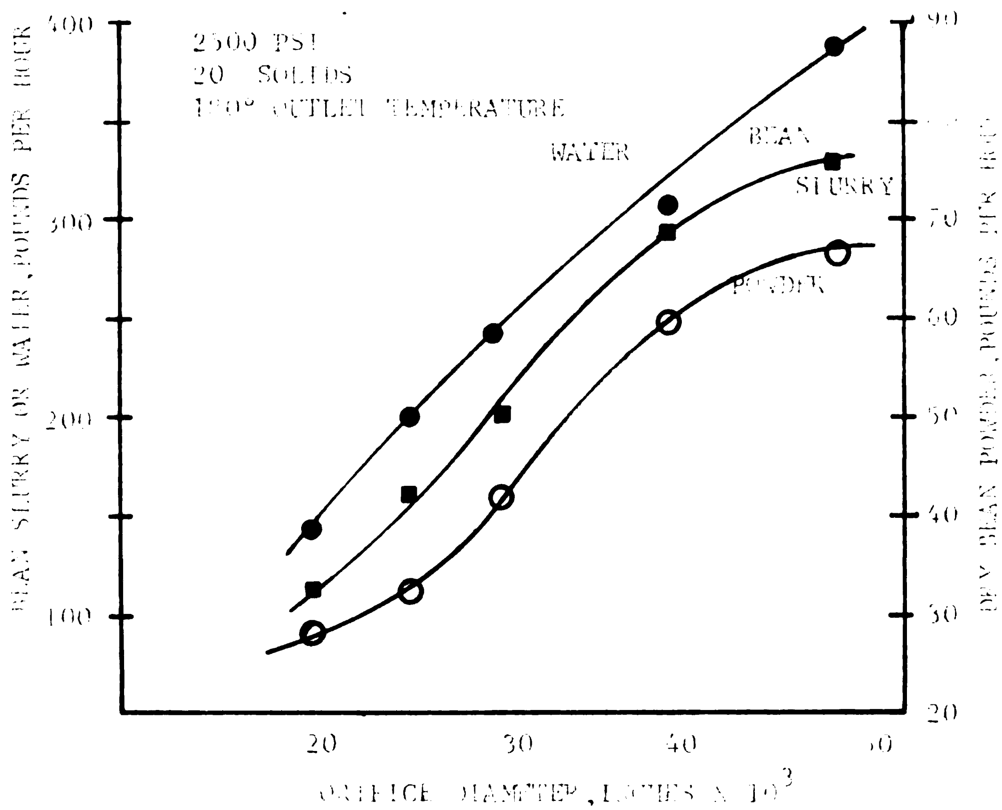
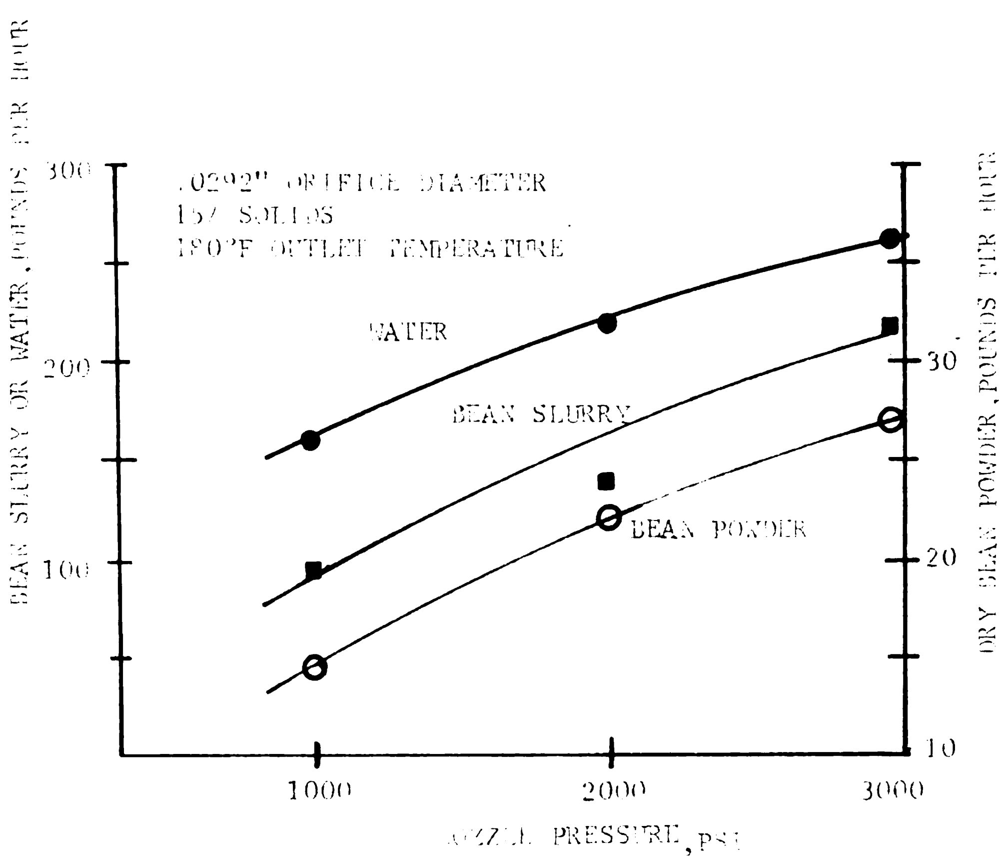



FIGURE 7: SPRAY DRYER CAPACITY OF WATER, BEAN SLURRY AND BEAN POWDER AS A FUNCTION OF ORIFICE DIAMETER.



nozzle eliminated fines, because this type nozzle projects a hollow cone spray with a uniform distribution. The results of this study confirmed that the low pressure nozzle produced a narrower particle size range (Table 6). The coarse particles of pea bean powder, obtained by using low pressure nozzle were agglomerated clusters of small particles when observed under microscope. A coarser slurry could be fed to the spray dryer when a low pressure nozzle was used.

Nozzle pressure - The spray pump pressure of nozzle pressure affected the capacity of the spray dryer more than any other variable. For high pressure nozzles (Figure 8) and for the low pressure nozzle (Table 5) the capacity increased with the nozzle pressure. In Figure 8 the capacity of the spray dryer with nozzle No. 69 (orifice insert diameter 0.0292") and 15 percent bean puree is shown. The measured capacity in gallons of water per hour is included for comparison. The data showed that the capacity in terms of dry solids per hour increased by about a factor of two by increasing the nozzle pressure from 1,000 to 3,000 psig. From a commercial standpoint the higher the spray pressures are, therefore, to be preferred as far as the capacity is concerned.

Solids content of the bean puree - The solids content of the bean puree also affected the capacity of the spray dryer in terms of pounds of dry powder per hour. Increasing the solids content from 15 to 25 percent increased the production of dry powder about 35 percent, from 60 pounds to 82 pounds per hour (Figure 9). This trend could have been predicted since it requires more BTU's to remove the excess water in low solids puree. Although a puree containing more than 25 percent solids would increase the dryer capacity, such concentration could not be used because the nozzles clogged rapidly. Also, excessive amounts of mechanical energy are required for pureeing to higher solids content.

Feed temperature of bean puree - To investigate the effect of this variable bean puree containing 20 percent solids was heated to 86°F, 122°F and 158°F prior to feeding to the spray dryer at 2,500 psig through the high pressure nozzle No. 56 (orifice insert diameter 0.0465") and 180°F outlet air temperature. The moisture content of the bean powder decreased from 4.9 to 4.2 percent, and the average particle size decreased from 102$\mu$ to 82$\mu$ as the feed temperature was increased (Table 6). Van Arsdel et al., (1964) reported that preheating prior to spray drying resulted in more uniform and smaller size particles as well as increasing the thermal efficiency of the dryer.

Sensory evaluations of the powder indicated that feed

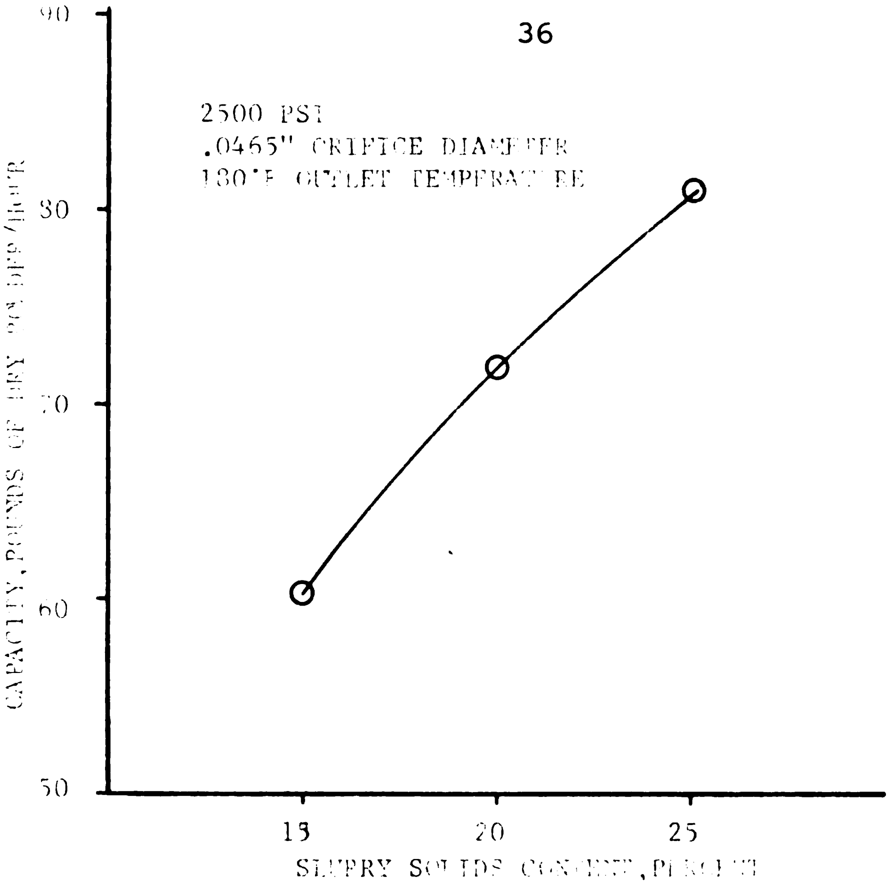



FIGURE 9: CAPACITY VERSUS SLURRY SOLIDS CONTENT.

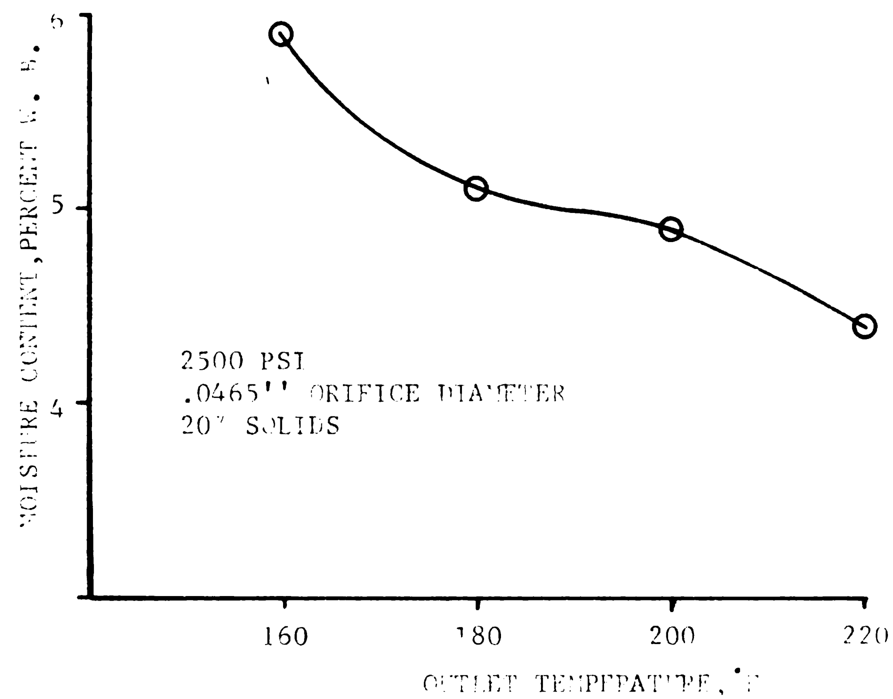



FIGURE 10: THE EFFECT OF OUTLET TEMPERATURE ON MOISTURE CONTENT.

temperature above 86$^{\circ}$F gave the powder an unacceptable flavor apparently due to the excessive heat treatment received by the product.

Air temperatures - The outlet temperature is usually the critical temperature variable in the spray drying of foods. It may be controlled either by varying the nozzle size or nozzle pressure or by increasing the air temperature. When the inlet air temperature was kept constant at 300$^{\circ}$F and the feed pump pressure changed from 500 to 1,000 and 2,000 psig keeping the other conditions constant, the resulting outlet temperatures were 240$^{\circ}$F, 205$^{\circ}$F and 190$^{\circ}$F, respectively (Table 5). Increasing the exit air temperature from 160$^{\circ}$F to 220$^{\circ}$F and using a high pressure nozzle No. 56 reduced the moisture content of the dried powder from 5.8 to 4.4 percent and increased the efficiency of the spray dryer. The sensory evaluation of the product, however, indicated that the powders made with outlet temperatures above 200$^{\circ}$F were slightly less acceptable. The bean powder made using the low pressure nozzle (orifice insert diameter 0.026") in conjunction with an outlet temperature of 200$^{\circ}$F, resulted in an acceptable product. It was necessary to use 200$^{\circ}$F outlet temperature for the low pressure nozzle in order to get the final product with less than 5 percent moisture content. Thus, outlet temperatures of 180$^{\circ}$F to 185°F for high pressure nozzle and 220°F for low pressure nozzle gave an acceptable product

## Capacity of the Spray Dryer

The capacity of the spray dryer was calculated using the Gluckert (1962) equation for the rate of heat transfer. Two terms in the equation k, the thermal conductivity of air and water vapor mixture surrounding the droplet and $D_{max}$, the diameter of the largest particle were difficult to determine with accuracy.

In calculating k, it was assumed that the air - water vapor mixture acted as an ideal gas and the average relative humidity in the boundry layer was 90 percent. On this basis the absolute humidity and the weighted value for k of the moisture at the prevailing wet bulb temperature could be calculated. The same procedure was used to calculate the thermal diffusivity and kinematic viscosity for the Reynolds and Prandtle number.

$D_{max}$ was calculated on the basis that the largest droplet in a spray population is three times the surface per unit volume average size.

The spray dryer capacities measured from actual runs with bean puree were 30 to 60 percent lower than the theoretically calculated values. An example of the calculations can

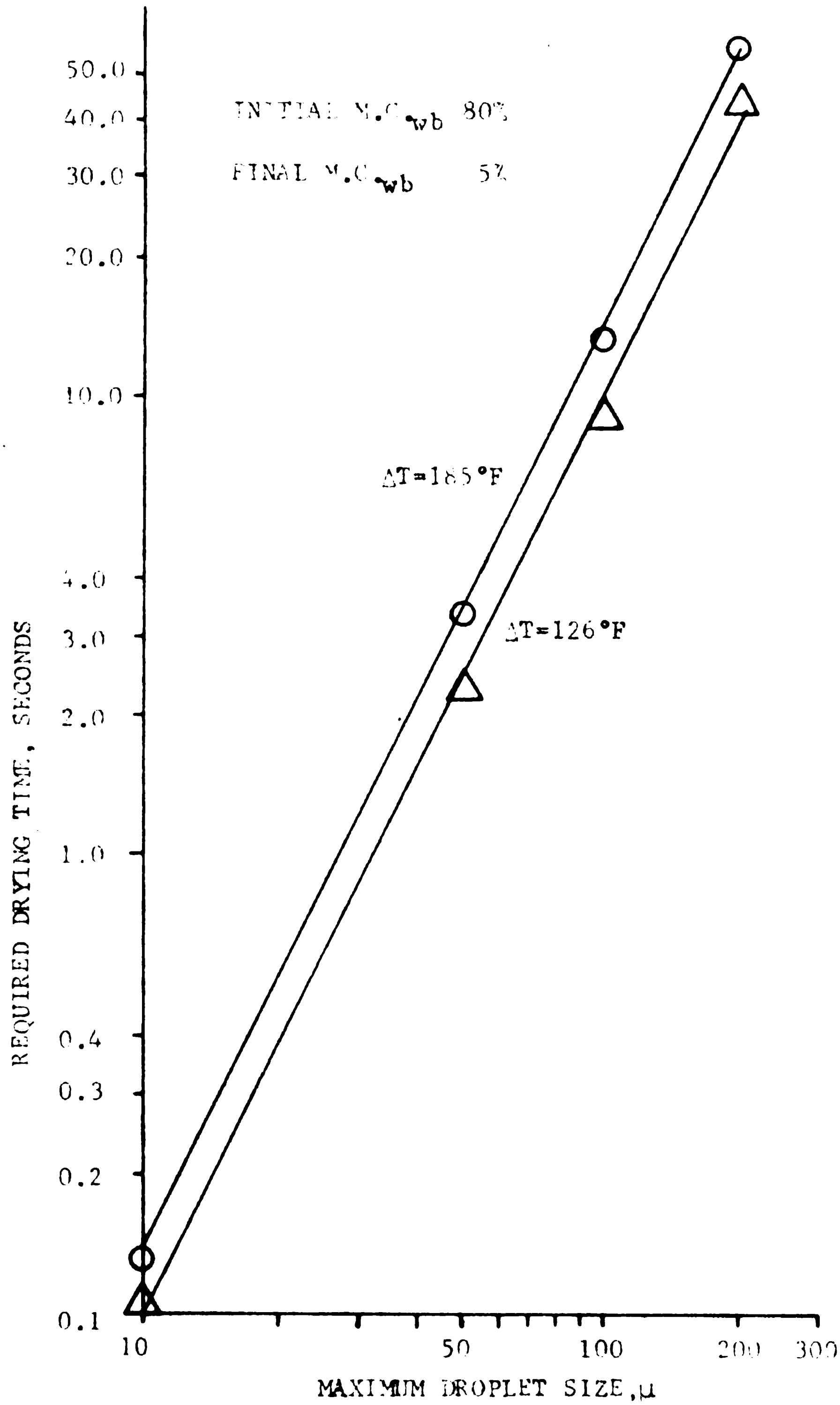



FIGURE 11: THE EFFECT OF MAXIMUM BEAN DROPLET SIZE ON THE REQUIRED DRYING TIME AT TWO DIFFERENT INLET AND OUTLET TEMPERATURE DIFFERENCES.

be found in Appendix. One of the main reasons for the deviation between the theoretical and experimental values is the fact that Gluckert's equation is based on a constant rate of drying and does not take into consideration the falling rate period which may be significant with drying of bean puree.

## Drying Time in the Spray Dryer

The required drying time of a bean droplet being dried from an initial moisture content of 30 percent to a final moisture content of 5 percent using equation (7) was calculated and plotted on a log scale as a function of $D_{max}$ and the difference between the inlet and outlet air temperature (Figure 10). The drying time is approximately proportional to the square root of the maximum bean droplet diameter. For example, at 126°F the required drying time decreased from 13.3 to 3.4 seconds with the decrease in the maximum size of the droplet from 100 $\mu$ to 50 $\mu$ . These results agreed with those of Marshall (1954). Sample calculations are shown in the Appendix.

The importance of equations (1) and (7) is not the fact that exact data can be obtained for the required drying time. The equations allow the researcher or dryer operator to get an idea of what the approximate effect on the capacity and the drying time will be from changing one of the variables such as moisture content, droplet diameter, airflow or drying air temperature.

## Pea Bean Powder Characteristics

The properties of the pea bean powder can be divided into three basic catagories:

1) Engineering or mechanical properties such as bulk density, average particle size and flowability.

2) Physicochemical properties such as reconstitution, solubility index, viscosity, blue value index and color.

3) Sensory properties.

Bulk density and average particle size - the bulk density and average particle size of powder are closely related. The bulk density generally increased as the particle size decreased. Both were influenced by spray drying conditions (Table 5).

The bulk density of bean powder increased from 44.6 to 47.6 pounds per cubic foot and the average particle size decreased from 102.5$\mu$ to 82.4$\mu$ with an increase of feed temperature from 86 to 158$^{o}$F. Marshall (1954) reported that the bulk density may either increase or decrease as the feed temperature was increased. With soap powders and chemicals the bulk density decreases. The increase in bulk density of pea

Table 5. Effect of spray drying variables on moisture content, capacity, bulk density, the average particle size and flowability of dried bean powder.

| Spray Drying Conditions | Variable | Moisture Content Wet Basic Percent | Capacity Bone Dried Solids lbs/hr | Bulk Density lbs/cu ft | Average Particle Size ($\mu$) | Flowability Angle of Repose Degrees |
|---|---|---|---|---|---|---|
| | Exit air °F | | | | | |
| | 160° | 5.9 | 63.00 | 47.3 | 93 | 17.3 |
| A | 180° | 5.0 | 72.50 | 46.9 | 82.4 | 18.0 |
| | 200° | 4.9 | 76.40 | 46.6 | 80.2 | 20.3 |
| | 220° | 4.4 | 79.30 | 45.9 | 73.3 | 22.2 |
| | Feed pump pressure (unhomogenized) | | | | | |
| | 500 psig | 4.5 | 9.91 | 43.7 | 122.4 | 12.3 |
| | 1000 psig | 4.9 | 17.24 | 44.0 | 88.9 | 13.3 |
| B | 2000 psig | 5.3 | 26.38 | 45.9 | 82.3 | 16.4 |
| | 3000 psig | 5.2 | 31.95 | 45.9 | 54.3 | 20.8 |
| | Percent solids in the bean slurry | | | | | |
| | 15 | 4.4 | 60.2 | 45.6 | 59.1 | 16.7 |
| C | 20 | 5.2 | 72.5 | 46.9 | 82.4 | 18 |
| | 25 | 6.1 | 81.4 | 47.6 | 123.8 | 20.7 |
| | Nozzle variation | | | | | |
| | 0.0465" | 5.0 | 68.5 | 46.93 | 82.42 | 18.0 |
| | 0.038" | 5.1 | 60.0 | 46.2 | 80.8 | 21.7 |
| D | 0.0292" | 5.3 | 42.5 | 46.6 | 80.4 | 20.7 |
| | 0.025" | 4.5 | 32.5 | 46.2 | 71.3 | 20.8 |
| | 0.020" | 4.2 | 22.5 | 46.2 | 66.40 | 21.8 |

A - Nozzle diameter 0.0465", feed pump pressure 2500 psig, 20 percent bean slurry, feed temperature 86°F.
B - Nozzle diameter 0.0292", 15 percent bean slurry, exit air temperature 180-185°F, feed temperature 86°F
C - Nozzle diameter 0.0465", feed pump pressure 2500 psig, exit air temperature 180-185°F, feed temperature 86°F.
D - Twenty percent bean slurry, feed pump pressure 2500 psig, exit air temperature 180-185°F, feed temperature 86°F.

Table 5. (continued)

| Spray Drying Conditions | Variable | Moisture Content Wet Basic Percent | Capacity Bone Dried Solids lbs/hr | Bulk Density lbs/cu ft | Average Particle Size ($\mu$) | Flowability Angle of Repose Degrees |
|---|---|---|---|---|---|---|
| | Low pressure nozzle | | | | | |
| | 250-300 psig | 6.3 | 17.0 | 39.0 | 179.7 | 17.3 |
| E | 500 psig | 5.2 | 21.2 | 40.8 | 152.0 | 18.7 |
| | 700 psig | 4.2 | 27.4 | 45.6 | 130.4 | 19.8 |
| | 1000 psig | 4.3 | 31.3 | 46.9 | 108.4 | 20.7 |
| | Method of cooking | | | | | |
| | 230°F 30 min R* | 4.6 | 73.3 | 47.3 | 95.1 | 22.1 |
| | 230°F 60 min R* | 7.0 | 71.0 | 46.8 | 110.8 | 22.0 |
| F | 260°F 90 min R* | 4.9 | 72.5 | 46.9 | 82.4 | 18.0 |
| | 210°F 90 min A** | 5.6 | 72.0 | 47.6 | 94.3 | 19.1 |
| | 210°F 120 min A** | 5.0 | 72.0 | 47.6 | 92.0 | 22.8 |
| | Feed temperature | | | | | |
| | 86°F | 4.4 | 72.5 | 44.6 | 102.5 | 18.0 |
| G | 122°F | 4.6 | 76.3 | 47.3 | 82.4 | 18.3 |
| | 148°F | 3.6 | 73.3 | 47.6 | 98.4 | 17.7 |
| | Feed pump pressure on exit air temperature | | | | | |
| | Feed pump pre / Exit Air °F | | | | | |
| | 500 psig / 240°F | 4.2 | 31.5 | 43.0 | 151.1 | 15.8 |
| H | 1000 psig / 200-210°F | 4.55 | 54.2 | 42.1 | 151.5 | 16.9 |
| | 2000 psig / 180-220°F | 4.8 | 68.1 | 48.9 | 121.9 | 17.4 |

E - Twenty percent bean slurry, low pressure nozzle diameter 0.0262", exit air temperature 200°F, feed temperature 86°F.

F - R* samples were soaked 40 minutes at 210°F, nozzle diameter 0.0465", 20 percent bean slurry, feed pump pressure 2500 psig, exit air temperature 180°F, feed temperature 86°F.

G - Twenty percent bean slurry, nozzle diameter 0.0465", feed pump pressure 2500 psig, exit air temperature 180°F.

H - Twenty percent bean slurry, nozzle diameter 0.0465", feed pump pressure 2500 psig, inlet air temperature 300°F (constant), feed temperature 86°F.

*R - Samples were soaked 40 minutes at 210°F.

**A - Atmospheric cook.

Table 6. Effect of spray drying variables on solubility index, viscosity, blue value index, color and reconstitution properties of the pea bean powder.

| Spray Drying Conditions | Variables | Solubility Index | Viscosity Brabender Units | Viscosity Brookfield Centipoise | Blue Value Index Absorbancy | Agtron | Color (Gardner) L | al | bl | Reconstitution Time, Minutes ml clear liquid 10 | 20 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Exit air $^{o}F$ | | | | | | | | | | | |
| | 160 | 17 | 140 | 2400 | 0.032 | 46.6 | 70.1 | 5.7 | 19.4 | 7 | 11 | 15 |
| A | 180 | 18 | 110 | 2350 | 0.0625 | 47.8 | 70.4 | 6.3 | 20.7 | 4.5 | 7.5 | 10.0 |
| | 200 | 18 | 102 | 2250 | 0.053 | 48.9 | 71.6 | 5.1 | 18.9 | 4 | 9.2 | 12.2 |
| | 220 | 18.5 | 125 | 1900 | 0.076 | 49.7 | 71.7 | 5.3 | 18.5 | 2.7 | 4.5 | 6.0 |
| | Feed pump pressure (unhomogenized) | | | | | | | | | | | |
| | 500 psig | 15 | 103 | 2000 | 0.125 | 44.2 | 67.7 | 5.76 | 18.8 | 9.5 | 12.5 | 14 |
| B | 1000 psig | 17 | 110 | 2100 | 0.015 | 47.6 | 70.4 | 5.27 | 18.2 | 4.5 | 6 | 6.9 |
| | 2000 psig | 18 | 165 | 2350 | 0.1 | 50.3 | 71.6 | 5.26 | 17.0 | 5.7 | 7.6 | 9 |
| | 3000 psig | 17.75 | 210 | 3700 | 0.142 | 51.1 | 72.68 | 4.73 | 17.4 | 6.5 | 9.5 | 10.3 |
| | Percent solids in bean slurry | | | | | | | | | | | |
| | 15 | 17 | 80 | 2150 | 0.11 | 47.4 | 71.3 | 7.2 | 21.5 | 5 | 6.9 | 9.8 |
| C | 20 | 17.25 | 102 | 2350 | 0.06 | 47.8 | 70.4 | 6.3 | 20.7 | 4.5 | 7.5 | 10.9 |
| | 25 | 18 | 105 | 1950 | 0.04 | 49.0 | 70.1 | 6.2 | 19.8 | 5.5 | 8.2 | 11.0 |
| | Nozzle variation | | | | | | | | | | | |
| | 0.0465" | 17.25 | 102 | 2350 | 0.06 | 47.8 | 70.4 | 6.3 | 20.7 | 4.5 | 7.5 | 10.0 |
| D | 0.038" | 17 | 123 | 2350 | 0.06 | 48.8 | 70.9 | 6.5 | 21.3 | 5 | 8 | 11 |
| | 0.0292" | 18 | 182 | 2450 | 0.10 | 51.3 | 71.7 | 6.4 | 21.2 | 4.5 | 6.2 | 9 |
| | 0.025" | 19.5 | 265 | 3100 | 0.112 | 51.5 | 72.3 | 6.2 | 20.9 | 3 | 4.5 | 8 |
| | 0.020" | 21 | 350 | 4400 | 0.145 | 52.9 | 73.7 | 6.1 | 20.1 | 2.2 | 3.2 | 5 |

A - Nozzle diameter 0.0465", feed pump pressure 2500 psig, 20 percent bean slurry, feed temperature 86$^{o}$F.
B - Nozzle diameter 0.0292", 15 percent bean slurry, exit air temperature 180-185$^{o}$F, feed temperature 86$^{o}$F.
C - Nozzle diameter 0.0465", exit air temperature 180-185$^{o}$F, feed pump pressure 2500 psi, feed temperature 86$^{o}$F.
D - Twenty percent bean slurry, feed pump pressure 2500 psig, exit air temperature 180-185$^{o}$F, feed temperature 86$^{o}$F.

Table 6. (continued)

| Spray Drying Conditions | Variables | Solubility Index ml | Brabender B. U. Units | Brookfield C. P. Centipoise | Blue Value Index Absorbancy | Agtron | Color (Gardner) L | al | bl | Reconstitution Time, Minutes ml clear liquid 10 | 20 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low pressure nozzle | | | | | | | | | | | |
| | 250-300 psig | 15.8 | 140 | 2450 | 0.055 | 42.7 | 73.7 | 7.4 | 17.0 | 8 | 11 | 15 |
| E | 500 psig | 16.5 | 150 | 2800 | 0.11 | 46 5 | 74.7 | 6.7 | 16.5 | 7.5 | 10 | 13 |
| | 700 psig | 18 | 250 | 3450 | 0.251 | 48.5 | 77.4 | 6.4 | 16.5 | 4 | 9.2 | 12.2 |
| | 1000 psig | 19 | 300 | 4800 | 0.295 | 49.3 | 77.8 | 6.2 | 16.7 | 2.7 | 4.5 | 6.0 |
| | Method of cooking | | | | | | | | | | | |
| | 230°F 30 min R* | 17.5 | 43 | 1700 | 0.098 | 58.7 | 78.2 | 2.4 | 17.3 | 3.7 | 6.2 | 8.8 |
| F | 230°F 60 min R* | 17 | 65 | 1650 | 0.062 | 56.3 | 77.0 | 2.8 | 17.8 | 3.5 | 5.9 | 8.1 |
| | 250°F 90 min R* | 18 | 102 | 2350 | 0 06 | 48.0 | 70.4 | 6.3 | 20.7 | 4.5 | 7.5 | 10.0 |
| | 210°F 90 min A** | 16.5 | 45 | 1650 | 0.031 | 60.5 | 79.6 | 2.0 | 16.6 | 8.3 | 14.7 | 19.7 |
| | 210°F 120 min A** | 16.5 | 55 | 1700 | 0.074 | 59.4 | 79.6 | 2.7 | 16.6 | 6.5 | 11.3 | 15.3 |
| | Feed temperature | | | | | | | | | | | |
| | 86°F | 18 | 100 | 2350 | 0.052 | 47.8 | 70.4 | 6.3 | 20.7 | 4.5 | 7.5 | 10 |
| G | 122°F | 18.5 | 100 | 2290 | 0.034 | 49.3 | 70.4 | 6.4 | 20.1 | 4 | 8.5 | 11 |
| | 158°F | 18 | 160 | 2300 | 0.07 | 49.6 | 70.1 | 7.5 | 22.3 | 5 | 9.2 | 12 |
| | Feed pump pressure on exit air temperature | | | | | | | | | | | |
| | Feed pump pre / Exit air °F | | | | | | | | | | | |
| | 500 psig / 240°F | 17 | 80 | 2050 | 0.1 | 42.6 | 66.1 | 5.7 | 21.2 | 5.2 | 8 | 11.3 |
| H | 1000 psig / 200-210°F | 18.5 | 100 | 2200 | 0.072 | 43.0 | 67.1 | 5.5 | 21.6 | 4.3 | 6.4 | 10 |
| | 2000 psig / 180-220°F | 18 | 100 | 2000 | 0.09 | 44.2 | 68 | 5.0 | 20.9 | 4.2 | 6.1 | 8.2 |

E - Twenty percent bean slurry, low pressure nozzle diameter 0.026", exit air temperature 200°F, feed temperature 36°F.

F - R samples were soaked 40 minutes at 210°F, nozzle diameter 0.0465", feed pump pressure 2500 psig, exit air temperature 180-185°F, feed temperature 86°F.

G - Twenty percent bean slurry, nozzle diameter 0.0465", feed pump pressure 2500 psig, exit air temperature 180-185°F

H - Twenty percent bean slurry, nozzle diameter 0.0465", feed pump pressure 2500 psig, inlet air temperature 300°F (constant), feed temperature 86°F.

R* Samples were soaked 40 minutes at 210°F.

A** Atmospheric cook.

bean powder with increasing feed temperature may be due to the deaeration of the slurry by heating and the decrease in average particle size resulted from a change in viscosity of the slurry. Hayashi (1962) reported similar results for non fat dried milk powder.

As the outlet drying temperature was increased from 160 to 220°F the bulk density of the powder decreased 47.3 to 45.9 pounds per cubic foot and the average particle size from 93.0$\mu$ to 73.3$\mu$ (Figure 12). Marshall (1954) reported that the decrease in bulk density may be caused by decrease in cell wall thickness of the particles. Van Arsdel et al., (1964) indicated that the residence time in the dryer had more influence on the moisture content than the outlet temperature.

Increasing the solids content of the pea bean slurry from 15 to 25 percent resulted in a slight increase in the bulk density and average particle size (Figure 12) of the dried powder. The effect of feed concentration on bulk density is complicated by the fact that the drop size may be varied due to change in viscosity.

As the feed pump pressure of the high pressure nozzle No. 69 (orifice insert diameter 0.0292") was increased there was a slight increase in the bulk density of the dried unho-

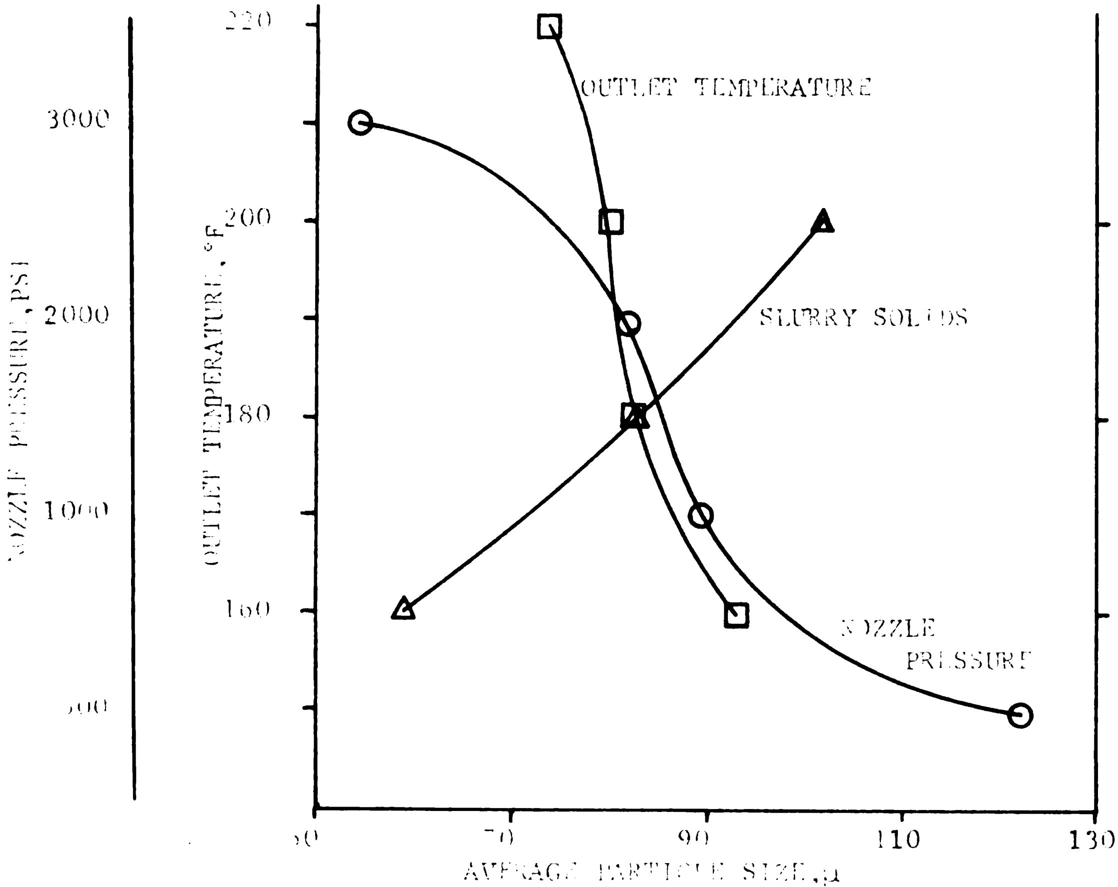



FIGURE 12: THE EFFECT OF OUTLET TEMPERATURE, NOZZLE PRESSURE, AND SLURRY SOLIDS CONTENT ON THE AVERAGE PARTICLE SIZE OF BEAN POWDER DRIED WITH A HIGH PRESSURE NOZZLE.

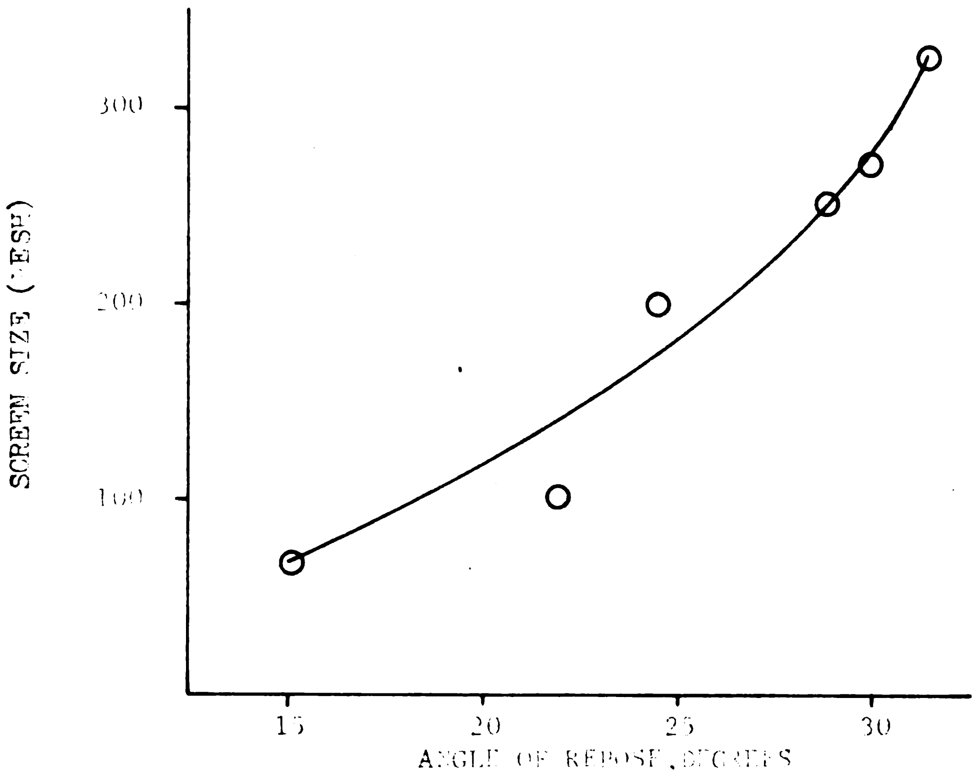



FIGURE 13: THE EFFECT OF AVERAGE PARTICLE SIZE ON THE ANGLE OF REPOSE.

mogenized powder (43.7 to 45.9 lbs/ft$^3$) but a marked increase in that of the homogenized powder (39.0 to 48.0 lbs/ft$^3$). the average particle size decreased as the feed pump pressure was increased from 500 to 3,000 psig (122.4$\mu$ to 54.3$\mu$) and (120.9$\mu$ to 50.6$\mu$) for both unhomogenized and homogenized powders, respectively. At a constant feed pump pressure the size of nozzle used (0.02 to 0.0465 inches) had no effect on the bulk density but the average particle size decreased as the nozzle size decreased (82.4$\mu$ to 66.4$\mu$).

As the pressure of a low pressure nozzle increased from 250 psig to 1,000 psig, the bulk density increased (39.0 to 46.9 lb/ft$^3$) and the average particle size decreased from 179.4$\mu$ to 108$\mu$. The change in bulk density using the low pressure nozzle was similar to that obtained for homogenized bean slurry with the high pressure nozzle.

Tracy et al., (1951) reported that increasing the nozzle size at constant feed pressure decreased the bulk density of whole milk powder. Seltzer et al., (1949) indicated that with high pressure nozzles the particle size range was so wide that the bulk density could not be adjusted. Marshall (1954) reported that particle size was more dependent on the atomizing pressure than on the nozzle size.

The bulk density and average particle size was similar for both atmosphere and report cooked beans. The average particle size tended to decrease with increase cooking time but there was no difference in bulk density.

The packaging and shipping costs of any dry powder are to a large extent determined by its bulk density. A few percent saving in packing and shipping costs may mean the difference between a loss or a profit of the spray drying operation. The results indicated that the bulk density changed from 31.1 to 48 pounds per cubic foot and the average particle from 179.7$\mu$ to 50.6$\mu$ under the different spray drying conditions investigated in this study. Bakker Arkema et al., (1966) reported that the bulk density of drum dried bean powder can be readily changed. The dry milling of drum dried bean flakes makes this flexibility in bulk density possible.

Flowability - the flowability of the dried product is an important mechanical property because it determines the ease with which the powder can be handled. Tripp et al., (1965) have reported that the angle of repose constitutes a good yardstick for measuring the flowability of dry powder. The smaller the angle of repose (Figure 4) the better the flow characteristics of the powder.

The results indicated that the flowability could be decreased by increasing the exit air temperature, the feed pump pressure, the solids content of the bean puree or the nozzle size. The flowability was not affected significantly by the feed temperature of the bean puree or the method of cooling (Table 5).

The flowability of bean powder is related to the particle size. Size grading of one lot of bean powder showed that as the particle size decreased from 210 to 44 microns, the angle of repose increased from $15.3^{\circ}$ to $31.3^{\circ}$ (Table 7). The relationships between flowability and screen size are also plotted in Figure 13. It is suspected that the flowability will also depend on the moisture content of the powder. Some workers have recommended the use of free flowing indgredients to improve the flowability of a powder (Cippola et al., 1961, Sjollema et al., 1963 and Linton Smith, 1961). Tripp et al., (1965) indicated that the flowability of milk powder was improved by 6 to 12 degrees when it was cooled from $74^{\circ}F$ to $36^{\circ}F$.

<u>Reconstitution</u> - Quick solubility and good suspensibility are the first requirements of satisfactory instant precooled bean powder. The results obtained with the spray dried bean powder indicate that their reconstitution properties are related to particle size (Table 7). Generally powders with larger particle sizes suspended more rapidly in water but had a rather short period of suspendibility while powders

Table 7. Relation of particle size to bulk density, flowability, color, viscosity and reconstitution.

| Mesh | Micron | Opening Inches | Percent Retained | Bulk Density gm/cc | Bulk Density lb/cu ft | Flowability Angle of Repose | Color Agtron | Color Gardner L | Viscosity Brabender Units | Reconstitution Time, Minutes ml clear liquid 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65 | 210 | 0.0083 | 1.0 | 0.43 | 26.7 | $15.3^{o}$ | 44.6 | 67.8 | 100 | 5 | 7 | 10 | 13 | 15 | 17 |
| 100 | 149 | 0.0058 | .5 | 0.52 | 32.5 | $22.0^{o}$ | 44.6 | 68.4 | 120 | 5 | 8 | 9 | 11 | 13 | 15 |
| 200 | 74 | 0.0029 | 31.5 | 0.74 | 45.9 | $24.2^{o}$ | 47.4 | 70.9 | 80 | 5 | 7.5 | 9 | 10.5 | 11 | 11 |
| 250 | 63 | 0.0025 | 6.5 | 0.76 | 47.2 | $28.2^{o}$ | 48.1 | 71.1 | 120 | 4 | 7 | 9 | 11 | 11.5 | 12 |
| 270 | 53 | 0.0021 | 22.5 | 0.77 | 48.0 | $28.8^{o}$ | 48.5 | 71.6 | 120 | 4 | 6.8 | 8 | 8.5 | 9 | 10 |
| 325 | 44 | 0.0017 | 13.5 | 0.78 | 48.8 | $30.2^{o}$ | 49.3 | 72 | 240 | 1 | 4 | 6 | 8 | 8 | 10 |
| 325 | <44 | <0.0017 | 24.0 | 0.78 | 48.8 | $31.3^{o}$ | 52.4 | 73.3 | 560 | 0 | 0 | 0 | 2 | 2 | 3 |
| *Cumulative Sample Av. P.S. 82.4 $\mu$ | | | | 0.75 | 46.88 | 18 | 47.8 | 70.4 | 120 | 2.3 | 4.5 | 6.4 | 7.5 | 9.3 | 11 |

*Cumulative Sample - Twenty percent bean slurry, nozzle diameter 0.0465", outlet temperature 180°F, feed pump pressure 2500 psig and 86°F feed temperature.

with smaller particle sizes did not suspend as easily but once in suspension had greater suspendibility. The failure of powders with small particle sizes to resuspend rapidly appeared to be due to a decrease in the ease of wettability.

Solubility index - The solubility index of spray dried pea bean powder made from the unhomogenized slurries ranged from 15 to 18 ml while those made of the homogenized slurry varied between 23 to 31 ml.

The solubility index did not change significantly with increased exit air temperature, nozzle size, percent solids, method of cooking or feed temperature but increased with feed pump pressure especially in the case of homogenized slurries.

Townley (1950) reported that the solubility index increased logarithmically with an increase in exit air temperature above a certain temperature. Hunziker (1949) reported that the solubility index for non-fat dried milk powder lies usually between 0.05 to 1 ml; however, properly processed powder should be less than 0.2 ml. For condensed milk products the solubility index depends upon the preheating conditions prior to spray drying and on the amount of heat received in the later stages of drying (Van Arsdel et al., 1964).

The solubility index for pea bean powder was poor probably because of the high starch content of the product.

Color - The color of the pea bean powder was similar for all methods of spray drying (Table 6). Retort cooking of the beans gave a browner powder than did atmosphere cooking due to carmelization of the sugar present at the higher temperature. The color is also influenced by the particle size (Table 7). The larger the particle size the browner the powder appeared as indicated by lower Agtron values or Gradner color difference meter L values. Also, increasing the outlet temperature from 180 to 220$^{o}$F resulted in a slightly browner powder (Table 6).

Blue value index - Blue value index measurements of the various pea bean powders produced indicated that the value is increased with increase of exit air temperature, increase of nozzle size and feed pump pressure using the low pressure nozzle and homogenizing the pea bean slurry (Table 6). It decreased with increased solids content of the puree and was not affected by the feed pump pressure when unhomogenized slurry was used. Increased time of cooking in the retort decreased the blue value index while increased time of atmosphere cooking increased the value.

The blue value index is an indication of the amount of free soluble starch and, therefore, indicated the amount of cell breakage during the preparation and drying of the powder (Table 4). The index ranged from 0.09 to 0.27 for unhomogenized pea bean powders and was in infinity for homogenized powders spray dried at feed pump pressures over 3,000 psig.

Viscosity - The viscosity of rehydrated pea bean powder increased by increasing the percent solids in the slurry, the feed temperature, the length of cooking time and the outlet temperature (Table 6). As the feed pump pressure increased the viscosity increased for both high pressure nozzle and low pressure nozzle. For unhomogenized bean powder the viscosity ranged between 45 to 350 B.U. and 1650 to 4800 c.p. (Brookfield). Bean powder obtained from homogenized bean puree had viscosities ranging from 97 to 515 B.U. and 4150 to 8200 c.p. Increasing the feed pump pressure increased the viscosity of the rehydrated bean power (Figure 14).

The viscosity was not significantly different for the particle sizes between 53 to 210$\mu$ but increased markedly for smaller particle sizes (Table 7). The viscosity increases paralled the blue value index changes (Figure 14). Thus, the increase in viscosity is related to the amount of free starch in the powder.

Sensory evaluations - The results of the preliminary evaluations indicated that the flavor of the powder at a feed temperature of 86$^{\circ}$F was preferred over that of 150$^{\circ}$F. No

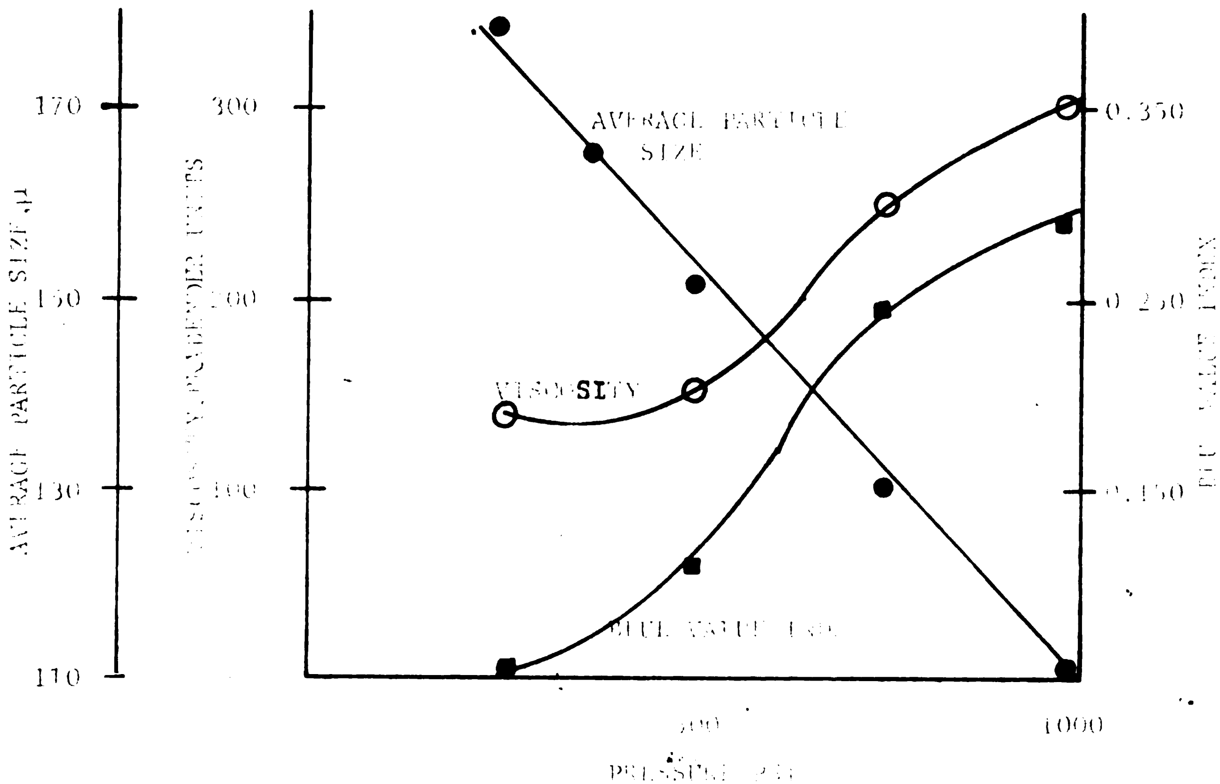



FIGURE 14: THE EFFECT OF PRESSURE OF A LOW PRESSURE NOZZLE ON THE VISCOSITY, BLUE VALUE INDEX AND AVERAGE PARTICLE SIZE OF RECONSTITUTED BEAN POWDER.

significance was obtained between the two feed temperatures on the basis of texture. The sensory evaluation of the 122°F feed temperature was not made because of sample contamination.

No significant difference was found between flavor or texture at the various outlet temperatures. However, there was a tendency to prefer the powder obtained when an outlet temperature below 180°F was used.

Flavor evaluation showed no significant difference between nozzle numbers 56, 62 and 69, indicating that the lower nozzle sizes were preferable. Similar results were obtained for texture. The results of the flavor panel tests were not consistent for nozzle pressure variation but indicated that lower pressures were desirable. Pressures above 2,000 psig were undesirable when nozzle No. 69 was used.

The judges found no significant difference in flavor or texture between the nozzle pressures 500, 700 and 1,000 psig when the low pressure nozzle (orifice diameter 0.026") was used. At 250 psig the flavor was significantly better than either 700 or 1,000 psig.

On the basis of preliminary sensory evaluations the judges showed a preference for the powders dried under the following conditions:

1) <u>High pressure nozzle</u>

| | |
|---|---|
| Nozzle pressure | 2,500 psig |
| Outlet temperature | 180$^{\circ}$F |
| Solids content | 20 percent |
| Feed temperature | 86$^{\circ}$F |
| Nozzle diameter | 0.0465 inches |

2) <u>Low pressure nozzle</u>

| | |
|---|---|
| Nozzle pressure | 250 psig |
| Outlet temperature | 200$^{\circ}$F |
| Solids content | 20 percent |
| Feed temperature | 86$^{\circ}$F |
| Nozzle diameter | 0.026 inches |

When the bean powder sample made by using the high pressure nozzle was evaluated by 47 judges, the results indicated (Table 9) 6.6 average rating on 9 point hedonic scale.

Eighty-two point nine percent people accepted the sample if rating 6 (like slightly) was considered as limit and 61.7 people preferred the sample if rating 7 (like moderately) was considered the consumer preference limit.

Table 8. Sensory Evaluations (Preliminary)

| a) Feed temperature | 86°F | 158°F | | | |
|---|---|---|---|---|---|
| Flavor | 5.6 | 4.7 | | | |
| Texture | 5.3 | 5.0 | | | |

| b) Outlet temperature | 140°F | 160°F | 180°F | 200°F | 220°F |
|---|---|---|---|---|---|
| Flavor | 4.6 | 4.5 | 5.6 | 4.5 | 4.2 |
| Texture | 4.9 | 4.4 | 5.4 | 4.7 | 4.3 |

| c) Nozzle variation<br>Nozzle number | 56 | 62 | 69 | 72 | 76 |
|---|---|---|---|---|---|
| Flavor | 5.6 | 5.0 | 5.1 | 4.2 | 4.2 |
| Texture | 5.8 | 5.1 | 4.7 | 4.2 | 4.1 |

| d) Pressure variation<br>Feed pump pressure psig | 500 | 1000 | 2000 | 3000 |
|---|---|---|---|---|
| Flavor | 5.8 | 4.7 | 4.8 | 4.4 |
| Texture | 5.3 | 4.0 | 4.7 | 3.8 |

| e) Low pressure nozzle (0.026") pressure variation<br>Nozzle pressure psig | 250 | 500 | 700 | 1000 |
|---|---|---|---|---|
| Flavor | 5.8 | 4.7 | 4.8 | 4.4 |
| Texture | 5.3 | 4.0 | 4.7 | 3.8 |

Table 9. Results of the taste panel of 47 judges

| Rating | No. of People Giving Their Rating | Percent |
|---|---|---|
| 9 | 1 | 2.13 |
| 8 | 15 | 31.91 |
| 7 | 13 | 27.66 |
| 6 | 10 | 21.28 |
| 5 | 2 | 4.25 |
| 4 | 2 | 4.25 |
| 3 | 4 | 8.50 |

Average rating 6.6.

Note: Twenty percent solids bean slurry, nozzle diameter 0.0465", feed pump pressure 2500 psig, exit air temperature 180$^{o}$F, feed temperature 86$^{o}$F.

## CONCLUSIONS

1. Homogenizing the bean puree prior spray drying is an unsatisfactory procedure because the powder when reconstituted had excessive pastiness.
2. Both high and low pressure nozzles can be used to produce bean powder which is acceptable.
3. The average particle size and the amount of smaller size particles ($44\mu$ and less) mainly determine the characteristics of bean powder such as solubility index, blue value index, reconstitution properties and viscosity of the rehydrated powder.
4. Outlet air temperatures over $200^{o}$F were unsuitable.
5. The theoretical spray dryer capacities were between 30 and 60 percent above the measured capacities for bean slurry.
6. Different powder distribution patterns were obtained when a low pressure nozzle and high pressure nozzle was used.
7. The drying time for $100\mu$ diameter bean droplets was 13.3 seconds and for $50\mu$ diameter bean droplets 3.4 seconds for a logarithmic mean temperature difference of $126^{o}$F.
8. Sensory evaluations of the reconstituted powder indicated that either low or high pressure nozzle may be used. Pow-

ders produced with 20 percent solids bean slurry fed at $80^{\circ}F$ through high pressure nozzle at 2500 psig and through low pressure nozzle at 250 psig with drying temperatures of $180^{\circ}$ to $200^{\circ}F$ tended to be preferred.

## APPENDIX

### Calculation of Spray Dryer Capacity

Drying conditions of typical spray drying operation:

| | |
|---|---|
| Bean puree initial temperature | $86^{\circ}F$ |
| Solids content of the slurry | 20 percent |
| Final moisture content | 5 percent |
| Nozzle No. 56 orifice insert diameter, | 0.0465 inches |
| Inlet air temperature | $310^{\circ}F$ |
| Exit air temperature | $180^{\circ}F$ |
| Atmospheric temperature | $70^{\circ}F$ |
| Wet bulb temperature of surrounding air | $59^{\circ}F$ |
| Measured product flow rate | 390 lbs of bean puree/hr |

Theoretical capacity was calculated using Gluckert's equation

$$q = \frac{10.98\ k\ v^{2/3}\ \Delta T}{D_{max}^{2}} \cdot D_s \sqrt{\frac{d_t}{d_s}} \qquad (1)$$

where,

k, thermal conductivity of film 0.0157 BTU/hr. ft. $^{\circ}F$ (Holman, 1963).

v, volume of the dryer, $ft^3$.

Assuming the dryer to be circular in cross section and diameter of the dryer 7.0 ft. and length 17 ft.

Total volume $= \pi r^2 l$

$$= 3.1416 . \frac{49}{4} . 17$$

$$= 653.9 \text{ ft}^3.$$

So $$W = \frac{1,150,000}{2000}$$

$$= 575 \text{ lbs of } H_2O/hr$$

The actual rate of drying was 390 lbs of $H_2O$/hr.

Hence, percentage difference $= \frac{575-390}{575} = \frac{185}{575} = 31.8\%$

## Calculation of Drying Time

The total time required to dry a bean droplet was calculated using equation 7.

$$t = \frac{\lambda d_d \; (M.C._{in} - M.C._{out}) \; \pi \; D_{max}^3}{6 \; k \; . \; (2.0 + 0.6 \; Re^{0.5} \; . \; Pr^{0.33}) \; \pi D_{max} (\Delta T)_{av}}$$

$d_d$, density of bone dried powder was assumed to be 100 lb/ft$^3$.

$M.C._{in}$, moisture content of bean puree (20 percent solids) entering the dryer on dry basis.

$$= \frac{80}{100-80} = 4 \text{ lbs of } H_2O/\text{lb of dry matter}$$

and $M.C._{out}$, moisture content of bean powder on dry basis

$$= \frac{5}{100-5} = 0.05 \text{ lbs of } H_2O/\text{lb of dry matter}$$

$$\Delta t_{av} = \frac{T_{ai} - T_{ao}}{\ln \dfrac{T_{ai} - T_{ao}}{T_{ao} - T_{wb}}} = \frac{310 - 180}{\ln \dfrac{310 - 108}{180 - 108}} = 126^{o}F.$$

The value of $Re^{0.5} . Pr^{0.33}$ is negligible since the Reynolds number contains the term diameter of the droplet which is very small (100 $\mu$).

$\Delta t$, temperature difference between outlet air and drop surface is equivalent to $T_{out} - T_{wb}$ ; $T_{out}$ outlet temperature is 180°F.

$T_{wb}$ the wet bulb temperature of drop surface was found out from Psychrometric chart to be 108°F.

Hence, $\Delta t = T_{out} - T_{wb} = 180 - 108 = 72^{o}F$

$D_s$, orifice diameter of nozzle No. 56 is $\frac{0.0465}{12}$ ft.

$D_{max}$, maximum drop diameter was assumed to be 100 microns or

$$D_{max} = \frac{100 \times 10^{-4} \text{ ft}}{30.5}$$

$d_t$, the density of outlet air was found from psychrometric data to be 0.071 lb/cu.ft.

$d_s$, the density of 20 percent bean puree is 62 lb/ft$^3$.

Substituting the values in equation No. 1:

$$q = \frac{10.98 \ . \ 0.015 \ . \ 653.9^{2/3} \ . \ 72}{\left(\frac{100 \times 10^{-4}}{30.5}\right)^2} \cdot \frac{0.0465}{12} \sqrt{\frac{0.071}{62}}$$

$$= 1,150,000 \text{ BTU/hr.}$$

The drying rate, $W = q/\lambda$

$\lambda$, was assumed to be 2,000 BTU/lb. [Hall (1957) in Figure 2.6 page 40 showed that the latent heat of wheat (10 percent moisture) is approximately 1400 BTU/lb. In the case spray drying of bean slurry much energy is lost due to conduction and radiation, hence a higher value was assumed.]

Substituting the values in equation No. 7:

$$t = \frac{2000 \cdot 1000 \cdot (44-0.5) \cdot 3.14\left(\frac{100 \times 10^{-4}}{30.5}\right) \cdot 3600}{6 \cdot 0.015 \cdot 2 \cdot\cdot 3.14 \left(\frac{100 \times 10^{-4}}{30.5}\right) \quad 126}$$

$$= 13.5 \text{ seconds}$$

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