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Dwight H. Bergquist
Iowa State College

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FUNCTIONAL PROPERTIES OF EGG WHITE AS INFLUENCED BY ATOMIZATION AND DRYING

by

Dwight H. Bergquist

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The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Food Technology

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State College
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TABLE OF CONTENTS

Page

I. INTRODUCTION

In recent years dried egg white has been finding wide application in the food industry. The advantages it possesses over fresh and frozen egg white include reduced cost of transportation, smaller storage space requirements and longer storage life (without refrigeration). Dried egg white is widely used in prepared mixes, cake frostings, meringue powders, candies (creams, nougats, and marshmallow whips) and elsewhere. Nonetheless, its use is limited by changes brought about during the drying process. For example, spray dried egg white does not appear to be satisfactory for the making of angel cakes where high whipping power and good meringue stability are essential.

Commercial methods for preparing dried egg white vary considerably. In practically all cases, the egg white is fermented prior to drying in order to remove glucose; this process increases the stability of the dried product. The most common methods of dehydration are tray drying and spray drying. The first of these is a noncontinuous process requiring considerable labor. On the other hand, the latter method is a continuous process capable of high production with a minimum amount of labor required. In spray drying, the liquid is atomized into hot air. With the very large surface created, evaporation is so rapid that the particles are dried almost instantaneously; there is no chance for bacteriological spoilage such as can take place in tray drying. Since the temperature of the atomized egg white does not rise above the wet bulb temperature of the drying air until it becomes quite dry, and since methods are employed for removing the dried product while it is relatively cool, the effect of heat is minimized. In spite of this, marked changes occur in the functional properties of egg white during spray drying.

The objective of the work reported herein was to determine the limitations of spray drying as applied to egg white and to develop a spray drying process wherein the functional properties of the egg white would be retained to a greater extent than is possible at present.

II. REVIEW OF LITERATURE

In the spray drying of egg white, two distinct aspects must be considered: (1) the effect of atomizing liquid egg white, and (2) the effect of dehydration on the atomized egg white. The pertinent literature related to these aspects under consideration in this study are reviewed below.

A. The Effect of Atomizing Liquid Egg White

1. General

The operation and theory of atomization have been discussed by several authors (22, 33, 46, 48, 49, 69). The various devices used for atomization of liquids can be classified under one of the following types: (1) the pressure nozzle, (2) the centrifugal atomizer, and (3) the gas atomizing nozzle. The pressure nozzle and centrifugal atomizer subject the liquid to severe shear and homogenizing forces which were considered by Seltzer and Settelmeyer (69) to be destructive to the colloidal properties of egg white. These authors suggested the use of an external mixing gas atomizing nozzle in which the gas impinges upon the liquid outside of the nozzle itself. In another type of gas atomizing nozzle, the gas and liquid are mixed within the nozzle before emerging through a common channel or orifice. No work directly related to the effect of atomization on egg white was found by the present author.

A few investigations concerning the effect of atomization on proteinaceous products have been reported. Conrad, et al. (27) found that atomization alone by either a high pressure spray nozzle at 5000 psi or a gas atomizing nozzle had no significant effect on the performance of liquid whole egg in sponge cakes, custards, and cream puffs. Wilkinson, et al. (82) described a small spray drier operated at low inlet temperatures (70-80°C.) and using an internal mixing, two-fluid type nozzle with a capacity of only 1½-2 liters per hour. They were able to dry human blood serum and plasma; the resultant products were very readily soluble in cold water. In addition, they were able to spray dry pepsin so that it lost none of its activity and muscle extract so that it showed no loss of its sensitive glycolytic enzymic system activity. Greaves (37, p. 6) reported that plasma dried on this apparatus, when reconstituted, contained numerous "motes, presumably of denatured protein." This worker pointed out that any factor which tends to increase the aggregation of the molecules of a protein solution (such as the formation of a large surface area in atomization) also tends to hasten denaturation.

Sharp (70) reported that the whipping quality of tray dried egg white is destroyed by fine grinding. Whether this is a result of heat produced during grinding or of comminution alone was not stated.

2. Effect of high pressure and homogenization on egg white

During atomization liquid egg white is subjected to static pressures and shear forces, the severity of which are dependent upon the type of atomizing device used. In the case of the pressure type nozzle, pressures from 2,000 to 6,500 psi (140-475 atmospheres) are necessary to properly atomize egg white. Bridgman (12) reported that a slight stiffening occurred when egg white was subjected to a pressure of 3,000 atmospheres for 16 hours at room temperature. Complete coagulation took place when a pressure of 7,000 atmospheres was applied for 30 minutes. Grant, *et al.* (36) exposed egg white to pressures from 1,000 to 7,500 kg. per cu. cm. (approximately 1,000 to 7,500 atmospheres). Coagulation and the appearance of sulfhydryl groups were noted in every case. Coagulation was greater at the higher pressures. On the other hand, MacDonnell, *et al.* (53) found that egg white subjected to pressures up to 5,000 psi (340 atmospheres) showed no change in viscosity, foam stability and angel cake performance. It would seem, therefore, that the highest static pressures ordinarily used in atomization would have little effect on the properties of egg white.

The shear forces imposed upon egg white during atomization would appear to be similar to those produced by homogenization where the liquid is passed very rapidly under high pressure through a small opening. The effects of homogenization on the functional properties of egg white have been observed by Slosberg (71). Beating power and angel cake volume were found to decrease considerably as homogenization pressure increased to 4,000 psi. MacDonnell, *et al.* (*loc. cit.*) demonstrated that homogenization causes a decrease in viscosity, a reduction in foam stability, and a decrease in angel cake volume. The effects were roughly proportional to the pressure used. Damage was attributed to mechanical disruption of the physical structure and to the liquid-liquid or liquid-metal shear effect.

Bernard, *et al.* (8) reported that mild physical disintegration (in a Waring blender) greatly accelerated the beating rate of egg white. Forsythe and Bergquist (34) demonstrated that this treatment causes a breakdown of the thick portion of egg white into short, disconnected fibers. As fiber length decreased (longer blending), beating rate and angel cake volume increased.

3. Effect of surface formation on egg white

Lewis (48) pointed out that in spray drying substances which exert very marked lowering of surface tension in solution produce an increased concentration of solids at the liquid-gas interface of the atomized droplets and a resulting precipitation or coagulation of solids. Certain proteins are known to be quite surface active; thus, this phenomenon may be encountered in spray drying of egg white.

Little effort has been made to investigate directly the surface characteristics of egg white. However, surfaces of solutions of ovalbumin (which makes up 70 per cent of the egg white protein) have been studied extensively. The surface tension of egg albumin solutions has been measured by several methods (40, 41, 43, 63, 79). It was found to be influenced by age of the surface, concentration of protein, and pH. Hauser and Swearingen (41), using the pendant drop method for measuring surface tension, found that surface tension decreased with increase in the age of the surface. Solutions containing from 0.005 to 2 per cent albumin approached the same limiting surface tension values after extensive aging. Solutions with higher or lower concentrations than these approached different limiting values. The fall of surface tension with time was sharper as concentration was increased. Surfaces of all ages showed a minimum surface tension near the isoelectric point. In slightly aged solutions maximum surface tensions were obtained at pH 8.5 and 2.5. The effect of pH was attributed to the influence of the ionic state of the solution. These authors state:

> The extended aging effect is best explained by the slow accumulation of native or partially denatured albumin molecules in the multilayers. Since these albumin molecules in the secondary surface layers will remain at least partially soluble, they may return to the solution phase if they remain soluble, thus delaying and retarding the tendency toward establishing of an equilibrium. Some denaturation and coagulation will undoubtedly occur and this, together with the indirect influence of the native albumin in the multilayers, may be responsible for the extended changes in surface tension with time. (41, p. 648)

Harvey and Danielli (40) demonstrated the elastic properties of protein films by the bubble method. Bubbles of egg white showed very marked elasticity and hysteresis. Doubling the surface area produced a tension increase of approximately 9.0 dynes.

Surface denaturation of proteins has been studied by several workers (2, 13, 14, 15, 16, 17, 61, 80, 83). Wu and Ling (84) produced surface denaturation and coagulation in ovalbumin solutions by shaking; on the other hand, conalbumin was not coagulated. Surface denaturation was reported to be independent of concentration. The rate of coagulation was found to be reduced by surface-active substances and increased by salts and non-electrolytes known not to have a marked influence on surface tension. Maximum rate of coagulation occurred near the isoelectric point. (This is in marked contrast to heat denaturation where the minimum rate is at the isoelectric point.) The temperature coefficient for surface coagulation of albumin between 25-38°C. was only 1.09. These workers explained that the albumin solution is covered by a layer of denatured protein and shaking causes the layer to "roll up" and be removed. Surface coagulation was stated to be irreversible.

Bull and Neurath (16) made a study of surface denaturation similar to that reported above. They found that a change of pH resulted from surface denaturation and that this change was a function of pH similar to that experienced in heat denaturation. Sucrose and certain salts, such as potassium chloride and potassium sulfate, increased the rate of denaturation slightly whereas potassium thiocyanate decreased it. Two tenths (0.2) per cent n-heptyl alcohol was shown to completely inhibit coagulation in a 1.05 per cent albumin solution with 12 hours of shaking.

Wang and Wu (80) found that surface coagulation was prevented by saponin; however, surface denaturation still occurred. They stated that if the molecule unfolded at the surface is insoluble in the bulk of solution it is said to be coagulated. If it is still soluble in the bulk of solution it is denatured.

Neurath (61) described surface denaturation as being an irreversible unfolding of protein molecules at the solution surface. Bull and Neurath (17) stated that the rate of surface denaturation is governed by (1) the rate of diffusion of protein molecules to the surface from the bulk of the solution, (2) the rate of spreading at the solution surface, (3) the rate of new surface formation, and (4) the rate of precipitation of denatured protein. They claim that once denatured, the protein should have only a small tendency to leave the surface since this represents a point of low energy content. Thus, in a quiescent solution protein does not progressively denature on the surface.

Bull (13) made a more quantitative study of surface denaturation by rotating a porcelain drum through a solution of albumin. A piece of cotton was placed against the drum in the solution in order to remove the coagulated protein. The amount of albumin removed was followed by measuring the refractive index of the solution. By this method the amount of denatured protein obtained per unit area (as a function of speed of rotation and concentration) was calculated. At 0.1, 1.0 and 1.5 per cent protein, the amount of coagulation per revolution was found to be independent of speed of rotation. For concentrations of 0.2, 0.5 and 0.75 per cent, the amount of denaturation per revolution was found to be greater at the lower speeds. At the latter concentrations, extrapolation to zero speed gave the same quantity as at 1.0 and 1.5 per cent concentrations. Irregularities found with the 2 per cent solution were not explained. Here coagulation in one instance was much less at a lower speed than at a higher speed.

Evidence was found in these experiments that the amount of denaturation is independent of concentration. In tests with 1.5 per cent albumin, 68.1 per cent of the protein removed by surface coagulation was found soluble; however, with a 0.1 per cent solution only 6.5 per cent remained soluble. It was explained that at the latter level or lower the surface film consisted of a monomolecular layer of denatured protein (about 10 Å thick). As the concentration increased above 0.1 per cent, additional protein was absorbed under this 10 Å layer. This second layer of protein had as a limit 3.5 times the amount of protein in the first layer; thus, a large fraction of the second layer was undenatured.

An interesting observation made by Bull (13) was that the rate of evaporation from the protein solution surface during rotation of the drum was greater than from free water surface similarly treated. The difference in rate of evaporation from a quiescent protein solution and pure water was zero. Thus, it was thought that the higher evaporation from a denaturing protein solution surface is related to denaturation itself. However, the quantity of water evaporated from the protein solution surface was much greater than could be accounted for on the basis of the difference in hydration between surface-denatured and native protein.

Comparisons between surface and heat denatured proteins have shown more similarities than dissimilarities. Neurath and Bull (62) found that heat-coagulated and surface-coagulated protein do not have identical densities when using xylene as a displacement liquid. They stated that the denser structure found in surface-coagulated protein probably indicates more orientation of peptide chains. Later Bull (15) reported that the densities determined in hydrogen do not differ significantly from each other.

Mirsky and Anson (56) stated that when native albumin (which contains no detectable sulfhydryl groups) is coagulated at the air-liquid interface all of the sulfhydryl groups in the molecule become detectable. Mirsky (55) reported that the same number of sulfhydryl groups reduced ferricyanide in surface films of egg albumin as in albumin denatured by urea, guanidine-hydrochloride, Duponol or heat, provided the reaction takes place with films while they are at the surface and with denatured protein while denaturing agent is present.

Bull (14) studied films of native and urea- and heat-denatured albumin with a Langmuir surface balance. The properties of urea- and heat-denatured films were very similar to those of spread, native film. It was suggested that surface-denatured and urea- and heat-denatured proteins are structurally very similar. Each represents an unfolding of the native protein molecule in an asymetric polar form.

Bull (15) stated that the temperature coefficient of heat denaturation is very large while that of urea and surface denaturation was less than 1.0. If the energy of activation is calculated for surface denaturation, a negative value is found. This might possibly be due to the fact that the strength of surface field falls off as temperature is raised.

Studies of the surface characteristics of the egg white have been of a more indirect nature, being confined mainly to investigations of its foaming properties (3, 7, 20, 24, 29, 30, 42, 47, 67, 68, 78). Barmore (7) made an extensive study of the chemical and physical factors influencing egg white foam. He found that the amount of insoluble protein remaining in the foam after extensive drainage and washing was roughly proportional to the surface area of the foam. By using the dimensions of albumin molecules given by DuNouy and assuming that the molecules at the surface of the bubbles were so crowded as to stand on end, he estimated the weight of the molecules to be similar to the weight of insoluble protein in the foam obtained experimentally. This worker reported that changes of as much as 14°C. in temperature of egg white on beating produced no apparent effect on foam stability. Egg white to which acid had been added produced a more stable foam than the control. Not all acids had the same effect.

Bailey (3) found that untreated egg white had higher foaming power than egg white adjusted to pH 5, 6, 7, or 9.5 by phosphoric acid and sodium carbonate. Foams from egg white adjusted to pH 6 and 7 were, for the most part, more stable than those made from untreated egg white. At pH 5 it took longer to produce an increase in foam volume; however, leakage diminished markedly with the increase in volume. LeClerc and Bailey (47) stated that the addition of cream of tartar to egg white during whipping toughens the protein making it more elastic and capable of building up a stronger structure. Barmore (loc. cit.) measured surface tension using the DuNouy apparatus over the range pH 5.0 to 8.6 and found it to vary from 54.0 to 58.4 dynes per cm. This variation was not considered to be enough to account for differences in foam stability.

St. John and Flor (78) reported that yolk has a detrimental effect on the foaming power of egg white. Henry and Barbour (42) found that egg white diluted with water (up to 40 per cent) showed a beating power (foam volume) equal to the control. With 60 to 80 per cent water, stability was greatly reduced. Barmore (loc. cit.) concluded that the increase in stability of foam might be due to: (1) greater adsorption at the surface producing a thicker film, (2) better structural properties of film-building materials, or (3) increase of apparent viscosity.

Hanning (38) reported that since it required longer beating to produce a measurable amount of insoluble foam, sugar retarded the coagulation of egg white protein at the air-liquid interface. It required about four times as long a beating period to reach a maximum stability with sugar present; however, the amount of liquid drained in one hour was about one-fourth to one-third as much as the control. This worker assessed denaturation during beating by determining the reducing groups exposed. Her data suggest that a large portion of the denaturation occurs in the early part of the beating period. It was postulated that the sugar might retard an extension of the globular structure of the native protein in the denatured form or that the sugar might block the intermingling and clumping of the denatured protein structure into a coagulum.

Epstein (29) considered mucin to be an important factor in egg white foam stability. He stated that when air is whipped into the egg white the mucin collects at the surface of the air bubbles to form a rigid network. Hanson (39) precipitated the mucin in egg white by acidification; the pH was then restored to normal. With the mucin precipitated and/or removed, the egg white did not produce an acceptable angel cake.

Slosberg (71) has produced evidence that mucin plays a part in the angel-cake-making properties of egg white. He found that the acidification brought about by fermentation does not destroy angel cake performance appreciably until a pH of 6.5 is reached.

4. Effect of sound waves on egg white

Fogler and Kleinschmidt (33) noted that gas atomizing nozzles produce a hissing sound caused by very high frequency sound vibrations. These vibrations may in some way affect the properties of egg white. Wu and Liu (85) studied the coagulation of ovalbumin by ultrasonic waves. Coagulation proceeded actively in the presence of hydrogen or oxygen where bubbles formed but not in hydrogen sulfide or carbon dioxide or under vacuum where no bubbles formed. It was concluded that bubbles are essential in the coagulation of the albumin; the change was apparently due to surface denaturation. Chambers and Flosdorf (23) found that audible sound waves at frequencies of between 1,000 and 15,000 coagulated solutions of egg albumin. Only sonic vibrations intense enough to promote vigorous cavitation in the solution produced denaturation. The solubility of this product was reported to be similar to heat-denatured protein.

B. Effect of Dehydration on Egg White

1. General

Since water is an integral part of the protein molecule (83), its removal may cause certain changes to occur in the properties of egg white. Parsons and Mink (65) claimed that egg white can be concentrated to 60 per cent solids, but not to dryness, and still retain angel-cake-making properties. On the other hand, Hanson (39) concentrated egg white by lyophilization to 92 per cent solids without causing significant changes in the angel-cake-making ability of the reconstituted product. By this same method Slosberg (71) concentrated egg white to 95 per cent solids and found little change in its beating power. However, a definite effect was noted in egg white concentrated to 90 per cent solids at temperatures of 40.5 to 46°C. by the air-film method of drying. Bollenback (11) dried thin films of egg white below 40°C. with little effect on the functional properties of the reconstituted product.

Smith (73) dried egg white over phosphorus pentoxide (which would presumably reduce the moisture content to a very low level). He found that the reconstituted product obtained by adding back the amount of water lost appeared similar to fresh white, with the thick and thin parts reappearing in almost their initial proportions.

Bumzahnov (18) reported that rate of evaporation from a motionless surface of egg white is the same as from a free water surface until a solids content of 64 to 68 per cent is attained. Removal of water beyond this critical point results in a sharp reduction in evaporation rate, apparently due to a skin formation (74) and lack of free water at the surface.

Bull (13) indicated that evaporation from a protein solution would be affected by atomization. He reported that the rate of evaporation from newly formed protein solution surfaces was even greater than that from a free-water surface.

Water which is chemically bound with the proteins of egg white is conceivably more difficult to remove than free water. It has been reported to constitute from 6.5 to 30 per cent of the liquid egg white (21, 44, 57, 58, 60, 64, 76, 77). This large range of values is due to the variation in methods as well as to the basic inaccuracy of the measurements. The relationship between bound water and protein in concentrated or dried egg white and the actual effect of removal of bound water are not clearly stated in the literature.

Studies of the relationship between water content and vapor pressure have been made (6, 10, 18, 35). Gane (35) found that denaturation of protein by heating prior to drying had little effect on the water relationships of the dried product. Egg white dried from the frozen state did not differ from the spray dried product.

2. Effect of heat on egg white

In considering the effects of drying, the effect of heat on egg white of all concentrations needs to be kept in mind. In liquid egg white, Payawal (66) found by viscosity measurements that denaturation occurs in a range of 58 to 62°C. Above 62°C. fractional coagulation of the proteins occurred.

Slosberg (71) demonstrated that the momentary heating of liquid egg white to temperatures above 57.5°C. and then cooling resulted in a loss of whipping power and angel-cake-making properties. It was also found that a loss in leavening power resulted from heating egg white below these temperatures if held for sufficient time. Holding egg white at 49°C. for 1 hour or at 40.5°C. for 6 hours or more caused a loss in whipping properties. Clinger, *et al.* (26) found that egg white heated to 57°C. for 4 minutes produced an undesirable angel cake.

pH is known to be important in affecting denaturation of protein solutions. Lewis (50) found that the rate of heat denaturation of albumin had a minimum at pH 6.76. Slosberg (71) showed that lowering the pH from its normal value of approximately 8.5 to values as low as 6.5 increased the stability of liquid egg white to heat.

Certain substances help stabilize liquid egg white against heat denaturation. Ball, et al. (4) studied the influence of sugars on formation of sulfhydryl groups on heat treatment of egg albumin. They found that sucrose, d-glucose, d-fructose, l-arabinose, d-mannitol, and d-zylose inhibit denaturation. Slosberg (71) also found that sugars have a marked influence on the stability of egg white to heat. For example, with 20 per cent sucrose, egg white could be heated to 65°C. before a change in whipping power resulted. He reported that reducing sugars have a greater stabilizing effect than the non-reducing type.

Slosberg (71) indicated that natural egg white (with mucin intact) was more sensitive to heat than egg white with mucin removed. He showed that heat treatment of the thick portion of egg white had a greater effect on whipping power than heat treatment of the thin portion.

As water is removed from egg white, its susceptibility to heat is changed. Chick and Martin (25) stated that denaturation is essentially a reaction between protein and water. Barker (6) reported that denaturation rate of partially dried egg white is greatly reduced by decrease in water content. At any given temperature the rate was found to be an exponential function of relative humidity in equilibrium with the egg white. Bumzahnov (18) stated that the presence of a given amount of moisture is absolutely necessary for denaturation to take place. This investigator showed that when the moisture content of egg white is less than 30 per cent the danger of denaturation is not so great as at higher moisture contents. He reported that egg white powder at 5 per cent moisture heated to a temperature of 80°C. for 1 hour lowered the solubility only 8 per cent.

Bernhart (9) studied the kinetics of heat denaturation at different moisture levels. He heated dried egg albumin (presumably of a very low moisture level) to temperatures between 111 and 176°C. and determined the proportion insoluble in water. He found the kinetics to be those of an autocatalytic reaction (the heat coagulation of egg albumin in aqueous solution is a first order reaction).

Mecham and Olcott (54) heated dried egg white in boiling inert hydrocarbons and found that solubility together with equilibrium moisture content decreased markedly with increase of heating temperature up to 153°C. Above 153°C. an increase in solubility was noted and was attributed to the degradation of the product.

In dried egg white the presence of naturally occurring free glucose is known to play an important role in the deterioration of this product (45). The reaction is one which apparently occurs between the reducing group of glucose and the amino group of the proteins and results in development of color (browning) and fluorescence and a reduction in solubility. Stewart and Kline (75) showed that low moisture content and pH minimize the rate of the reaction. Glucose concentration was found to be an important factor. With the glucose content reduced to 0.02 per cent, changes in solubility were almost completely prevented.

3. Effect of pretreatment of egg white before drying

Egg white consists of both thick and thin portions. The structure of the thick portion is due to ovomucin. Balls and Swenson (5) described the thick portion as jelly-like mass and the thin portion as mobile liquid. These authors stated that the thick portion is very difficult to dry and when once dried the protein remains insoluble in water. Bumzahnov (18) stated that the lowered whipping quality of untreated egg white during drying is caused by the high viscosity of the liquid. The viscosity and characteristic structure of egg white were claimed to inhibit diffusion of moisture to the liquid surface. This, he explained, results in a rise in temperature which leads to the destruction of functional properties of protein. On the other hand, Hanson (39) found that egg white which had been mixed in a Waring blender took approximately the same length of time to concentrate as did egg white with mucin removed.

The condition and pretreatment of the liquid egg white prior to spray drying apparently have considerable effect upon the susceptibility of the egg white to damage (28, 31, 32, 51, 52, 81). Watts and Elliot (81) presented evidence indicating that the performance of commercial dried whites was affected by the various treatments to which the liquid white was subjected before drying. These workers compared fresh egg white, dried fresh egg white (dried for 6 to 10 hours at 45°C. in a partial vacuum), fermented flake albumen (from China) and acid-treated spray dried albumen. The flake albumen and the spray dried albumen were found to whip better and to be more stable in meringues than the fresh or vacuum dried products. Maximum foam volumes were greater, whipping time was less, and foams were more stable as evidenced by the amount of drainage. The increased foaming ability was thought to be due to partial hydrolysis by the acid treatment before drying. In all batter and dough products, the flake albumen and spray dried albumen were inferior.

Mulvany (59) claimed that a product with excellent whipping properties was obtained by acidifying egg white to pH 5.8, agitating in a vacuum at 57°C. until the pH reached

7.0, repeating acidification to pH 5.8 and agitating to pH 7.0, and then spray drying this product.

III. EXPERIMENTAL PROCEDURE AND APPARATUS

A. Preparation of Liquid Egg White

1. Source of egg white

Most of the egg white used in the experiments reported herein was the commercial frozen product. Uniformity was assured by obtaining, from one firm, a large quantity of the product from one churn. The egg white had been passed through a Tranin mill* before freezing in 30 pound cans. In certain studies fresh eggs were obtained from the Iowa State College poultry farm, broken, separated, the whites blended with a Waring blender and frozen for future use. In one study the thick portion was separated from the thin portion by passing the egg white through 8-mesh screen. Each of the portions was blended with the Waring blender and frozen for future use.

2. Fermentation

Fermentation of the egg white was carried out by the

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*This mill is thought to have an action similar to a Waring blender since the liquid egg white passed continuously through a channel containing rapidly rotating blades which break down the structure of thick egg white and produce a homogeneous product.

method of Bollenback (11) using pure cultures of *Aerobacter aerogenes*. In most cases, an inoculum of 0.5 per cent and an incubation temperature of 34°C. were used. A fermentation time (to the sugar-free point) of approximately 12 to 13 hours was required. The end point was determined by placing 0.1 ml. of egg white on a preheated petri dish and heating for 15 minutes under an infrared lamp (250 watts, General Electric reflector drying lamp) placed 4 inches above the plate. No color development during the heating period indicated that the egg white was sugar-free. A few fermentations were carried out with yeast using the method described by Carlin and Ayres (19).

3. pH adjustment

The pH of egg white was lowered by the dropwise addition of normal hydrochloric acid with continual agitation. The pH was raised by adding 28 per cent ammonium hydroxide.

4. Incorporation of added substances

The various substances which were added to egg white were incorporated directly or first dissolved in water before addition, depending upon convenience.

5. Concentration

Concentrating of egg white before spray drying was accomplished by one of two methods. In one case the egg white was concentrated by lyophilization. In the other case, egg white was concentrated by the air-film technique. In the latter case, egg white was placed in aluminum pans to a depth of approximately 1/4 inch and heated with several infrared lamps placed at a sufficient distance above the pans to maintain a liquid temperature below 40°C. Evaporation was aided by passing a current of air over the surface of the egg white using an electric fan. In this case the egg white was continually stirred during concentration.

B. Surface Formation

Egg white surface formation studies were conducted using the apparatus shown in Figure 1. It consists of a porcelain cylinder postage stamp moistener. The cylinder was 7.3 cm. in diameter and 5.5 cm. wide. Allowing for contact between the sides of the cylinder and the liquid, the total area of surface formed per revolution was 132 sq. cm. The cylinder was turned by a rubber wheel pressed against its side and attached to a Cenco No. 18805 variable speed motor.

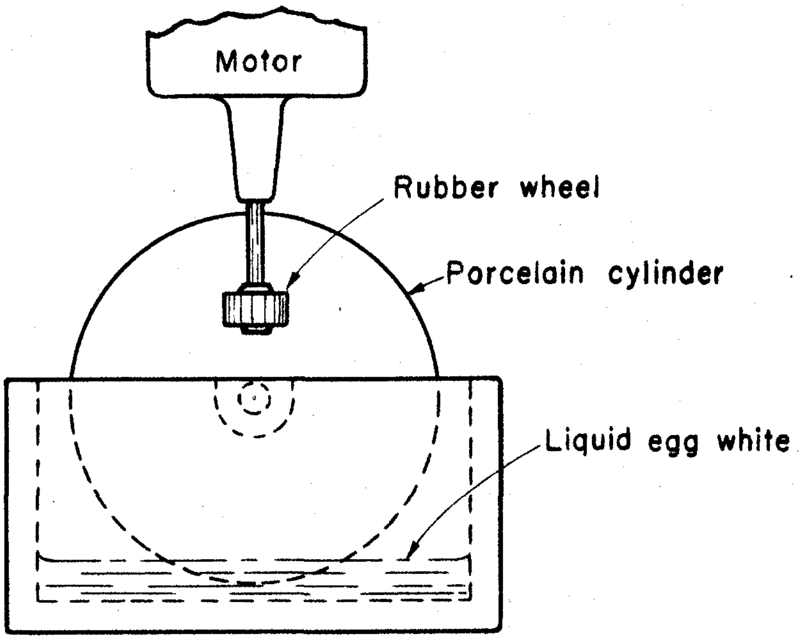

Figure 1. Surface Formation Apparatus

C. Atomization Devices

Three atomization devices were employed in this study: (1) an external mixing, two-fluid nozzle, (2) an internal mixing, two-fluid nozzle, and (3) a special external mixing, two-fluid nozzle. The first external mixing, two-fluid nozzle was a Type 1/4 J pneumatic atomizing nozzle, setup No. 1A, manufactured by Spraying Systems Company, Chicago, Illinois. The internal mixing nozzle was a Spraco two-fluid nozzle, size 4BM, manufactured by Spray Engineering Company, Summerville, Mass. The special atomizing nozzle was designed especially for spray drying egg white foam; it is shown in Figure 2. This device effected the mechanical mixing of egg white with air to produce a free-flowing foam. Liquid egg white passed through small orifices (a) into a round chamber (b) where it was mixed with air coming in at right angles from an annular air supply chamber (c). The air-egg mixture was then passed through screens (d) which provided further subdivision and aided in producing a more uniform foam. The foam was then atomized by a stream of air impinging on the foam at right angles.

D. Spray Drying

The spray drier designed for use in these tests is shown

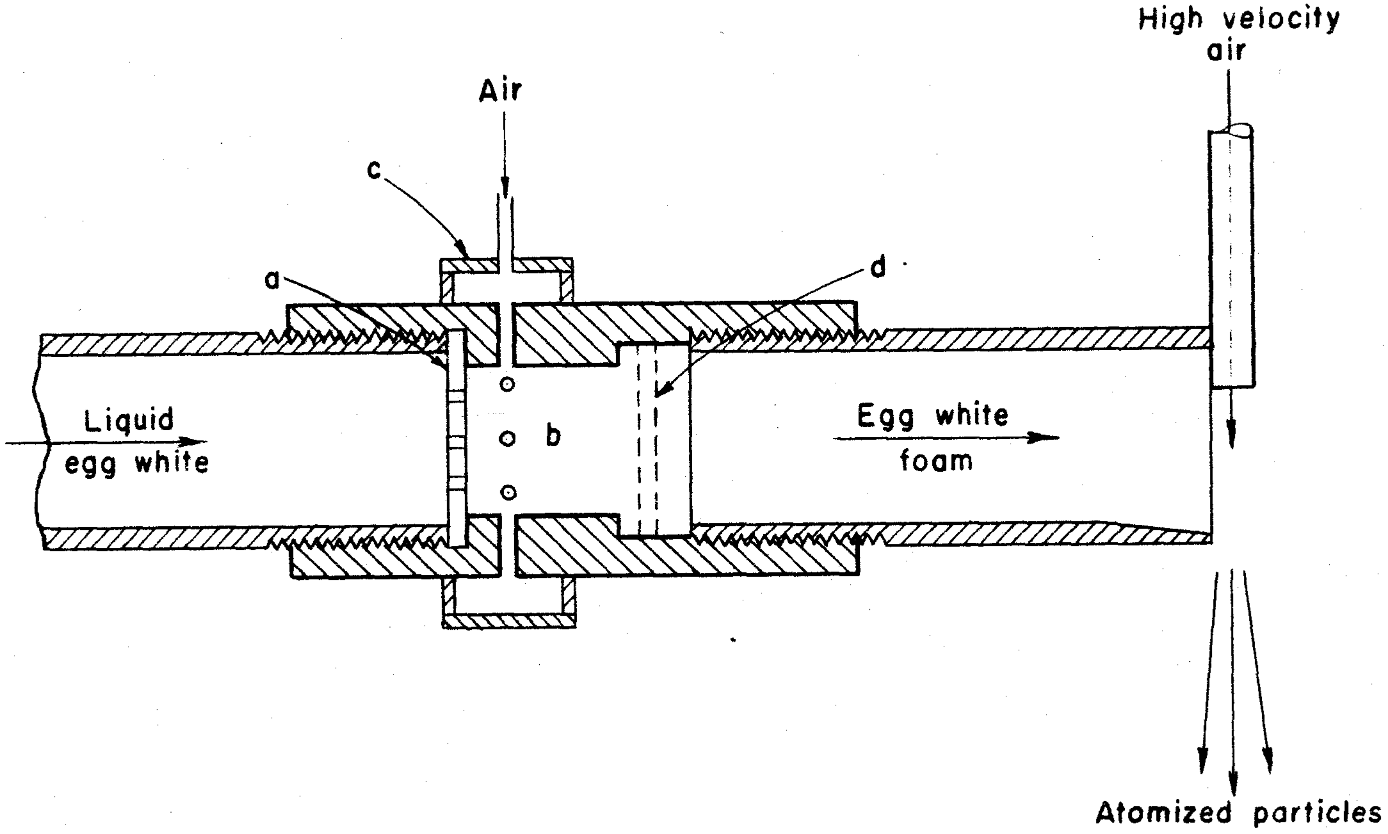

Figure 2. Special Atomizing Nozzle

in Figure 3. It consisted of a horizontal cylindrical drying chamber 22 inches in diameter and approximately 20 feet long. A fan (Allen Billmyre Corporation, Model 15SG27, Type SG) at the exhaust end pulled air through the chamber at a velocity from 5 to 6 feet per second. The air was heated by a unit heater at the inlet to a temperature of 85 to 90°C. The liquid egg white was atomized in the direction of air flow and the resulting dried particles were collected in a bag filter immediately upstream from the fan. The liquid was fed to the atomizer from a pressure tank. Compressed air adjusted to the desired pressure by a regulator was used to force the egg white through to the nozzle. Compressed air was also used as the atomizing fluid. The entire liquid feed system was placed on wheels such that the atomization device could be rolled into the spray drying chamber or the atomization device could be used outside the chamber (to study the effect of atomization alone).

In operation, the steam was first turned on and the fan was started. When the inlet temperature reached approximately 75°C. atomization was begun. Liquid pressure and atomizing air pressure were then adjusted to the desired level. Exhaust temperatures ranged between 55 and 65°C. depending upon the rate of feed of liquid, relative humidity of the air, etc. As soon as all of the liquid had been fed

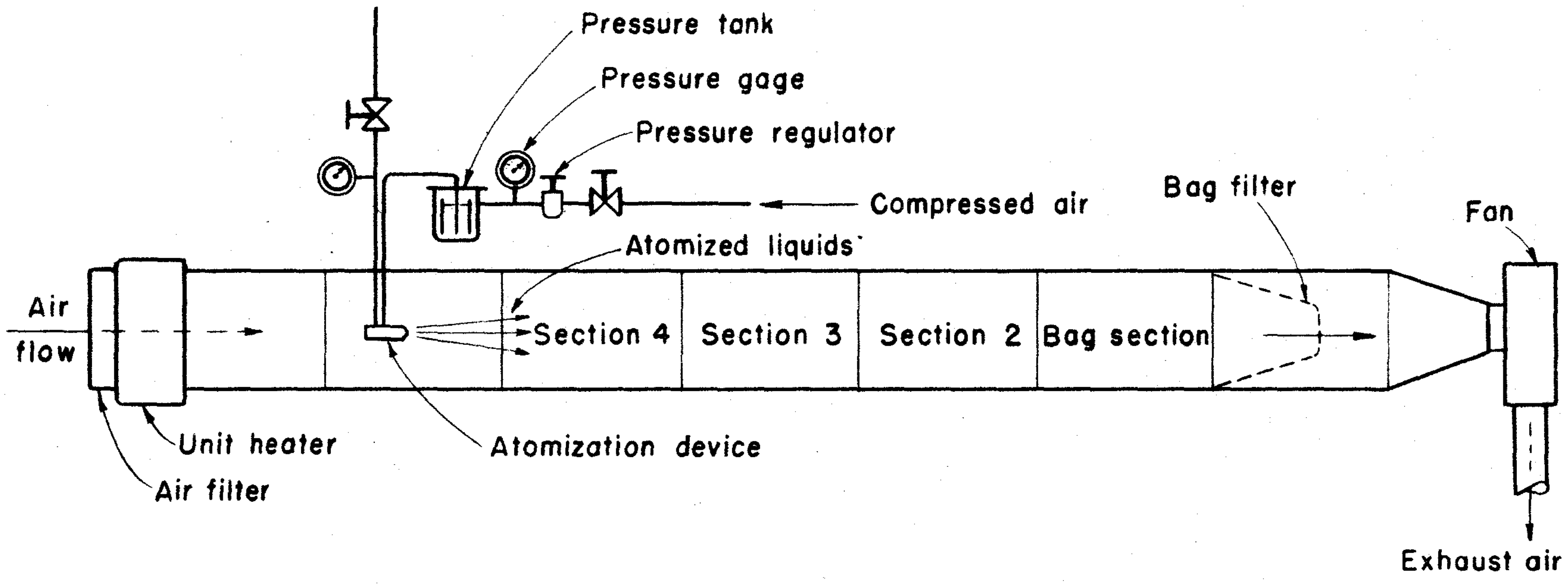

Figure 3. Laboratory Spray Drier

to the atomizer, the steam and fan were turned off.

E. Measurement of Particle Size

A small portion of the spray dried product was spread on a slide coated with castor oil, which effected excellent separation of particles. Atomized liquid was caught on a slide similarly coated. In this case, the liquid particles collected on the surface of the oil and there they dried, giving particles comparable to spray dried material. Samples of the atomized droplets were obtained by holding a sampler (Figure 4) in the path of the spray. A slide coated with castor oil was placed on the platform within the rotating hollow cylinder. When the cylinder was revolved, a lengthwise 3/8 inch slit in its side afforded a passage for the droplets whenever the slit faced the atomizing device. The cylinder was turned 5-15 times at 50-150 rpm, depending on rate of atomization.

Particle counts were made under a microscope at 100x. A sufficient number of particles were counted such that additional counting did not alter the mean diameter obtained. A count of 300 particles was found to be sufficient in most cases.

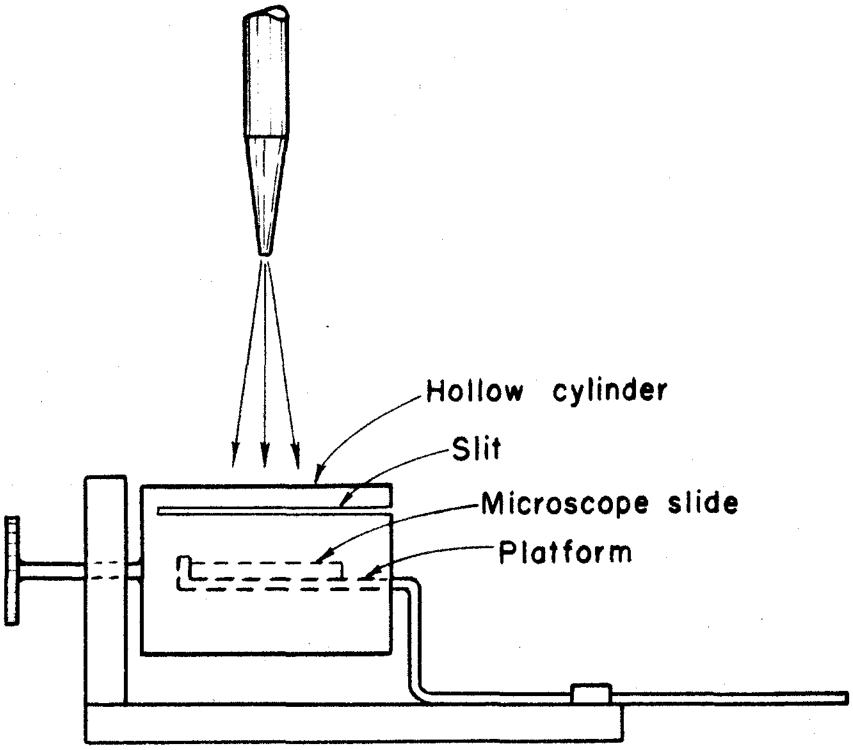

Figure 4. Sampler for Collecting Atomized Liquid

F. Moisture Determination

The moisture content of the dried products was determined by the vacuum oven method (Association of Official Agricultural Chemists, 1).

G. Reconstitution of the Dried Products

The dried egg white was reconstituted to a solids content of 12.5 per cent by the addition of distilled water. The powder-water mixture was thoroughly mixed with a glass stirring rod and then allowed to stand overnight at 5°C. It was then stirred to form a homogeneous mixture before testing.

H. Meringue Test

The test used was that devised by Slosberg, *et al.* (72) to measure the beating rate of egg white in an angel cake meringue. Sixty one grams of egg white were measured into a mixing bowl and adjusted to a temperature of 21.5°C. This was then beaten at speed 3 on a Hobart "KitchenAid" electric mixer (Model 4) using the wire whip. After 10 seconds, and while still beating, 0.9 gram of cream of tartar and 0.3 gram of salt were added; 47 grams of sugar were next added (in four equal portions) after 20, 30, 37, and 45 seconds. Beating was continued for a total of 75 seconds. At this time the density of the meringue was determined by weighing 1/4 cup (60 ml.). The beating rate was determined by dividing the increase in volume of the meringue by the weight of the foam by the total beating time.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Effect of Surface Formation

When liquid is atomized in spray drying, an enormous surface area is produced. For example, several samples of commercial spray dried egg white were examined and found to have an average mean particle diameter* of 44.0 microns. This is equivalent to a surface-volume ratio of 1360 sq. cm. per ml. Early in this study the effect of creating such large surfaces was determined by beating egg white into a foam, allowing this foam to break down completely, then measuring the beating power of the resultant liquid.

It is seen in Table 1 that the beating power of the liquid obtained by breaking down egg white foam was not reduced much below that of the control until a foam of fairly high specific volume was first produced. The foams formed by beating the egg white for 60 seconds at speed 3 were quite stable and showed very little drainage even after standing 1 hour. It was estimated that the mean bubble diameter of these foams was 0.01 mm. The total surface area of the bubbles was 5,200 sq. cm. per gram of egg white, which

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*Mean diameter is the diameter of a single particle with the same surface-volume ratio as the total sum of drops.

Table 1

Effect of Beating Egg White on Subsequent Beating Power of Disintegrated Foam

		Trial #1[a]		Trial #2[a]		Trial #3[b]	
Speed of mixer	Time of initial beating (sec)	Spec.vol. of foam (ml/g)	Beating rate of disintegrated foam (ml/g/min)	Spec.vol. of foam (ml/g)	Beating rate of disintegrated foam (ml/g/min)	Spec.vol. of foam (ml/g)	Beating rate of disintegrated foam (ml/g/min)
Control	-	-	4.25	-	4.10	-	3.52
1 (low)	120	5.32	4.30	5.52	4.48	-	-
	180	5.65	4.36	5.91	4.30	-	-
	240	5.99	4.36	6.05	4.05	-	-
2 (medium)	30	7.80	4.42	8.33	4.42	5.98	3.38
	60	9.10	4.36	8.85	4.42	6.25	3.56
	90	9.44	4.10	9.00	3.56	6.58	3.10
3 (high)	20	9.51	4.25	9.10	4.30	7.15	3.52
	40	10.20	3.86	9.90	3.42	9.90	3.04
	60	10.52	3.14	10.52	2.95	11.75	2.36

[a] Commercial frozen egg white, unfermented.

[b] Commercial frozen egg white, Aerobacter fermented.

is a much greater surface than is obtained on spray drying. The average rate of surface formation was estimated to be 86 sq. cm. per second per gram.

A more quantitative study of the effect of surface formation on egg white properties was made by rotating a porcelain cylinder through the liquid. In this way the exact quantity of surface formed as well as the rate of its formation could be controlled very accurately. The results of this study are shown in Figure 5 and Table 2. It can be seen that beating rate of egg white is very definitely affected by surface formation and that not only is it a function of amount of surface formed but also it is related to the rate of surface formation. It is interesting to note that the beating power was little affected by forming a surface of 1,713 sq. cm. per gram. (This is slightly greater than that achieved in commercial spray dried egg white.) However, with a surface formation of 30,000 sq. cm. per gram the beating power was considerably reduced. For the same number of rotations of the cylinder, beating power was found to be less with the greater speeds of rotation. This would indicate that although a surface formation equivalent to that obtained on atomization in spray drying produced at a relatively slow rate has little effect on beating power, a much higher rate of surface formation (which would be expected on atomization)

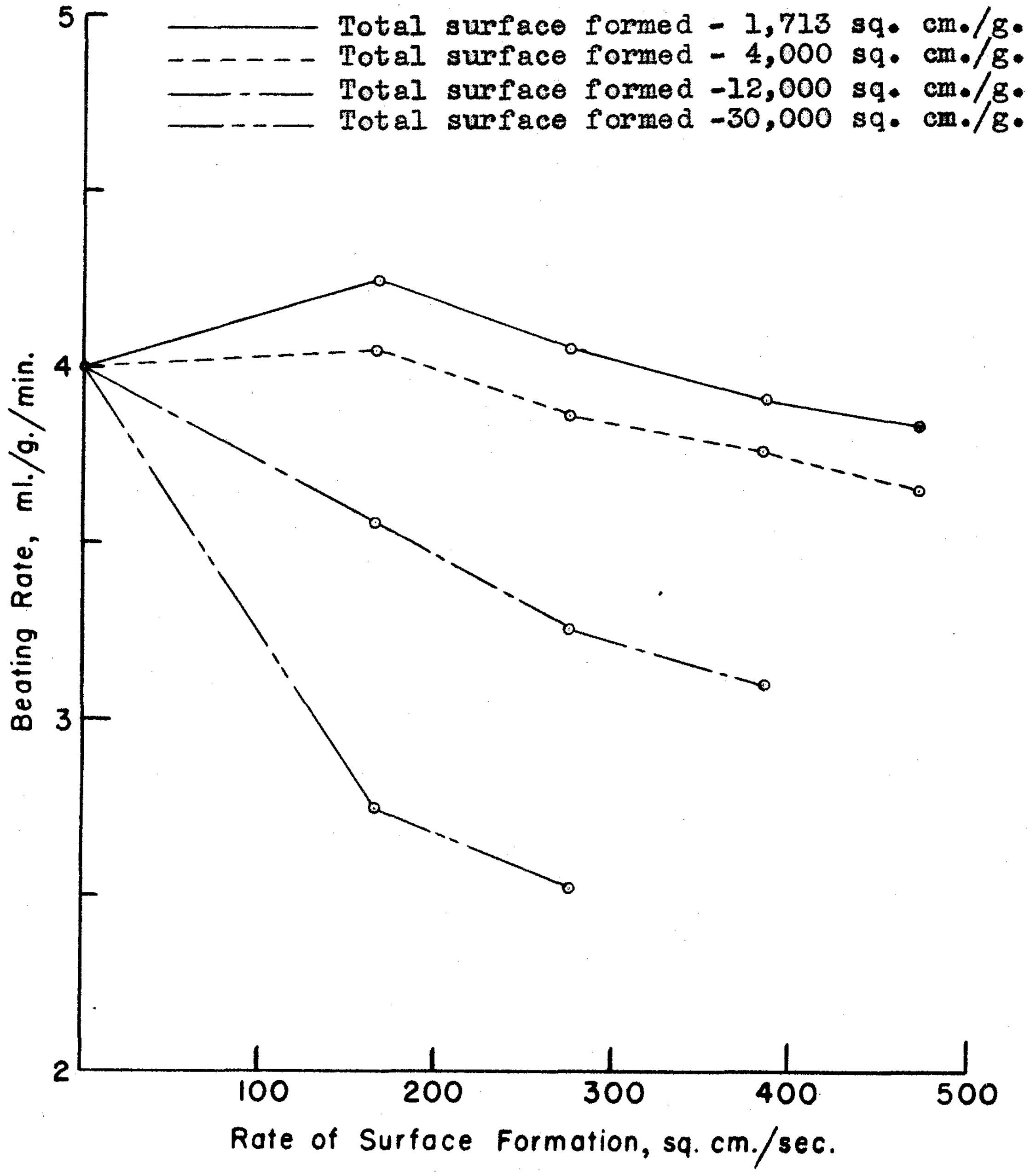


Figure 5. Effect of Forming Surfaces on Beating Power of Egg White

Table 2

Effect of Surface Formation on Beating Power of Egg White

Surface formed (sq.cm/g)	Rate of surface formation (sq.cm/sec)	Beating power (ml/g/sec)		
		Trial #1[a]	Trial #2[b]	Trial #3[a]
Control		4.00	3.95	4.60
1,713	167	4.25	-	4.85
	277	4.05	-	4.66
	385	3.90	-	4.48
	471	3.86	-	4.48
4,000	167	4.05	-	4.92
	277	3.86	-	4.36
	385	3.77	-	3.95
	471	3.65	-	-
12,000	167	3.56	4.10	3.90
	277	3.27	3.73	3.56
	385	3.10	3.38	3.14
30,000	167	2.73	2.63	3.07
	277	2.52	2.54	2.81
	385	-	2.38	-

[a] Commercial frozen egg white, unfermented.

[b] Commercial frozen egg white, Aerobacter fermented.

has considerable effect. The reason for the slight increase in beating rate over the control noted at slower rates of surface formation and smaller surface areas is not clear. The effect may be similar to that obtained by blending, where beating rate is increased by breaking down the structure of egg white (34).

It was not possible to study still higher rates of surface formation by this method since the egg white showed a tendency to foam badly at the higher cylinder speeds. In the tests mentioned earlier where the egg white was beaten to obtain the surface exposure, the surface formation rates were considerably higher. In this case, however, the rate of surface formation would be expected to vary with time. In the case where egg white was beaten at speed 3 for 60 seconds, the average rate of surface formation was estimated to be 2,000 sq. cm. per second for 23 grams. The highest rate achieved with the porcelain cylinder was 471 sq. cm. per second for the 23 grams used in each trial. For the same amount of surface formation, beating produced greater destruction in properties than surface formation on the cylinder. This again indicates that high rate of surface formation is detrimental.

In the studies using the rotating cylinder, an insoluble mass of material built up on the liquid surface where the cylinder entered the liquid. Apparently this was surface-coagulated protein. Before making the whip test on the treated liquid the sample was thoroughly stirred so as to completely disperse this insoluble mass. In a few cases the whip tests were run on liquid separated from the insoluble portion; it was found to give results similar to those where the insoluble material had been dispersed. In each case there was a certain amount of evaporation from the liquid on the cylinder. This quantity of water lost was determined by measuring weight loss of the entire apparatus and was added back to the egg white before testing. No measurable change in the refractive index of the egg white was brought about by surface formation. Apparently the small influence of the insoluble portion on properties of the treated egg white indicates that the greater portion of surface denatured protein remains soluble in the liquid egg white.

The possibility of solid-to-liquid shear forces in the surface formation apparatus which might affect beating rate of the egg white was investigated. A test tube 2.5 cm. in diameter was placed into egg white and rotated at 223 rpm for 224 minutes. This gave a peripheral speed equal to that of the cylinder when rotated at 167 rpm and gave a solid-to-liquid shear area of 30,000 sq. cm. per gram liquid. No change was noted in the beating power of egg white treated in this manner. It was assumed, therefore, that the changes produced by the apparatus were caused entirely by surface formation.

B. Effect of Atomization and Spray Drying

1. Effect of atomization without drying

The results of these tests are shown in Figure 6 and Table 3. Considerable change in the egg white resulted from atomization. The atomized egg white was quite turbid and possessed a lowered beating power. The pH was unchanged. The three types of nozzles tested exhibited different amounts of degradation to the beating power of egg white.

For each device, egg white was atomized to different degrees by varying the rate of the liquid feed as well as the air pressure. It can be seen that, with each nozzle, the greater the surface-volume ratio the greater was the reduction in whipping power of the treated egg white. The internal type, two-fluid atomizer was more detrimental than the external type and the foam atomizing nozzle. The latter was the least destructive of all. In the case of the internal type, there may be forces which are not in effect in the other types. For example, the liquid is forced through

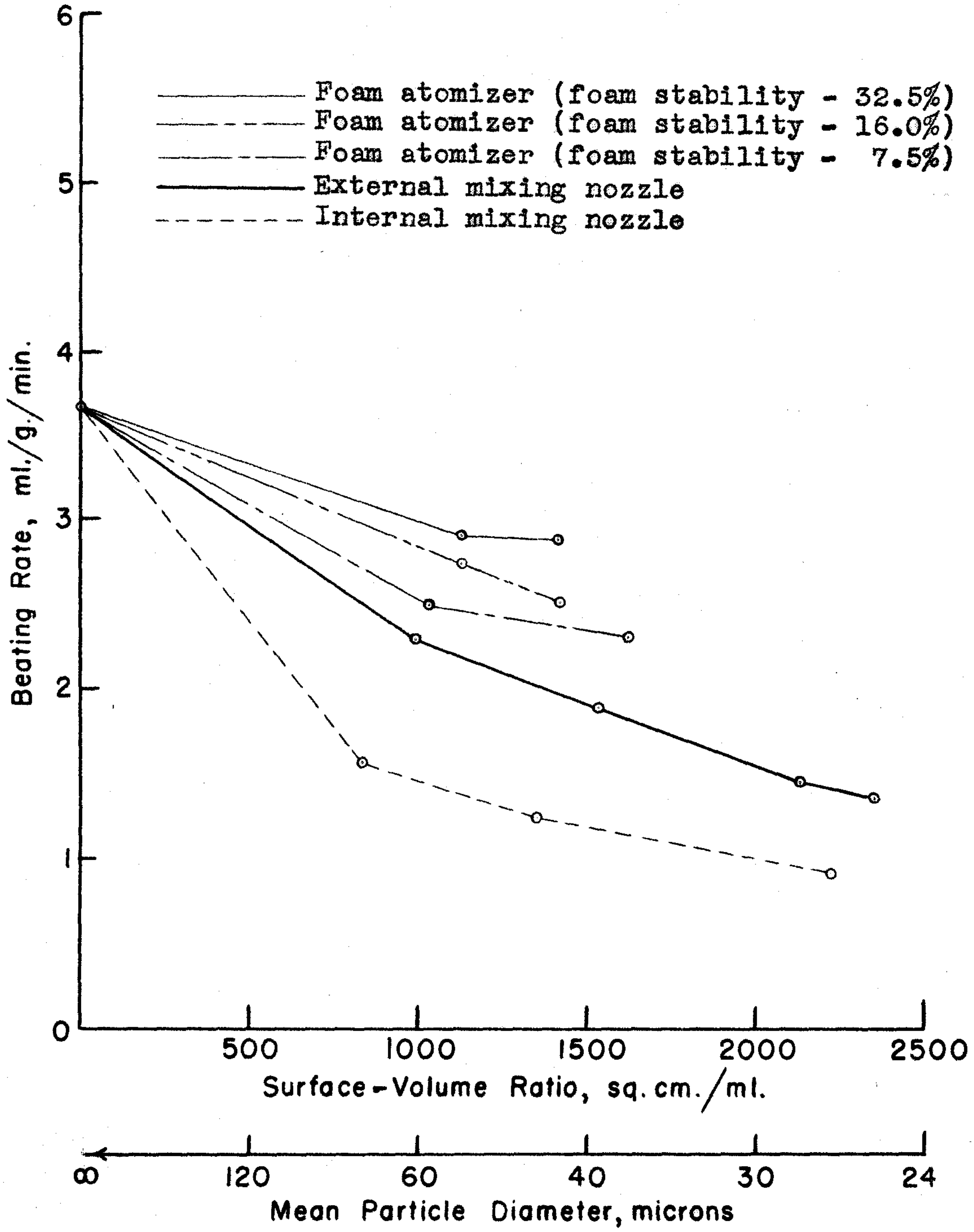


Figure 6. Effect of Atomization on Beating Power of Egg White

Table 3

Effect of Some Selected Atomization Devices on Beating Power of Egg White[a]

	Type nozzle	Liquid pressure	Atomizing air pressure (psi)	Mean diameter of particles (microns)	Surface-volume ratio (sq.cm/ml)	Beating rate (ml/g/min)
Fermented	Control	-	-	-	-	3.65
	External	-26" H_2O	50	25.6	2340	1.36
	"	-7" "	25	28.0	2140	1.44
	"	24" "	20	39.3	1530	1.87
	"	24" "	10	59.7	1000	2.28
	Internal	1 psi	45	27.0	2220	0.94
	"	1 "	26	44.3	1355	1.22
	"	1 "	10	71.8	840	1.55
	Foam atomizer (10% stable foam)	4 psi	20	37.0	1620	2.30
		4 "	13	57.7	1040	2.46
	Foam atomizer (16% stable foam)	5 psi	20	42.2	1420	2.49
		5 "	13	52.4	1150	2.76
	Foam atomizer (32.5% stable foam)	5 psi	25	42.5	1410	2.87
		5 "	20	52.8	1135	2.89
Unfermented	Control	-	-	-	-	4.00
	External	-7" H_2O	25	24.1	2490	1.54
	"	6 psi	25	29.9	2000	1.46
	"	6 "	10	38.5	1560	1.77
	"	10 "	10	47.7	1260	2.28
	Internal	-7" H_2O	50	26.4	2270	1.49
	"	-7" "	35	48.7	1230	1.63
	"	-7" "	20	62.5	960	2.22
	Foam atomizer (20% stable foam)	5 psi	60	30.3	1980	2.76
		5 "	30	52.5	1140	2.95

[a] Commercial frozen egg white.

an orifice after it has absorbed energy from the compressed air. Thus, there would seem to be more likelihood of greater liquid-to-metal and liquid-to-liquid shear forces than with the other atomizers where the liquid or foam, as the case may be, is caught up by the air after it has passed through its discharging channel. Air traveling in the same direction carries the liquid or foam out into fine threads, which become unstable and break into droplets. There is, without doubt, a certain amount of shear. However, forcing egg white through the liquid channel of the external nozzle under pressure of 50 psi (higher than used in any trial) was found to cause no change in its properties.

In the atomization of the foam, rate of surface formation was conceivably much less than with the other two atomizing devices. This may account for the smaller loss in beating power. Egg white showed less degradation when foams with greater stability (per cent of egg white retained in foam after draining 5 minutes) were atomized. This indicates that the foam was partially reunited into a liquid before dispersing into fine droplets; such an effect is more pronounced with less stable foams.

Figures 7 and 8 and Tables 4 and 5 show the effect of variations in atomizing air pressures on the beating power of liquid atomized with the internal and external nozzles. In these cases, varying degrees of atomization were attained

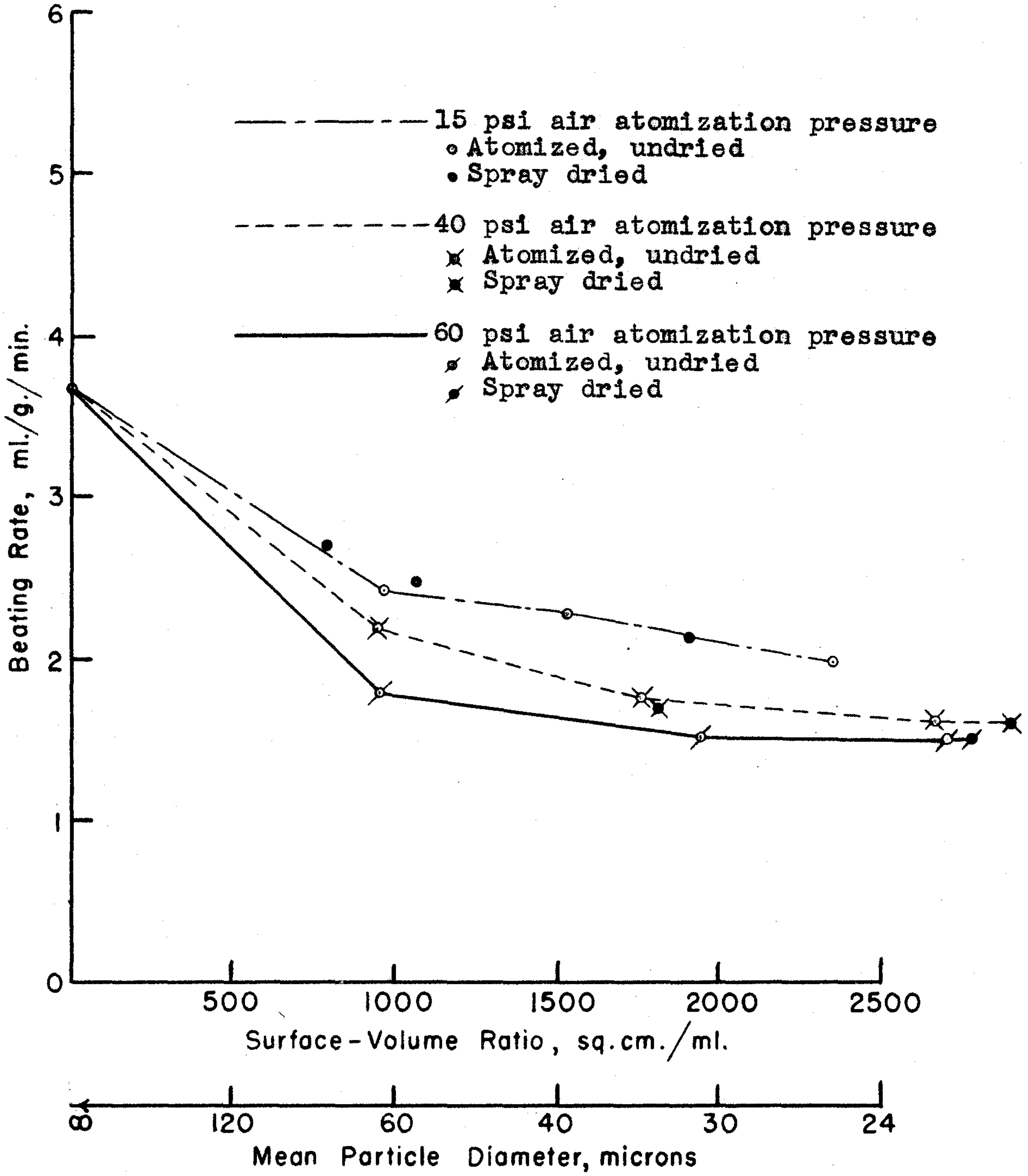


Figure 7. Effect of Atomization and Spray Drying on Beating Power of Egg White Using External Mixing Nozzle

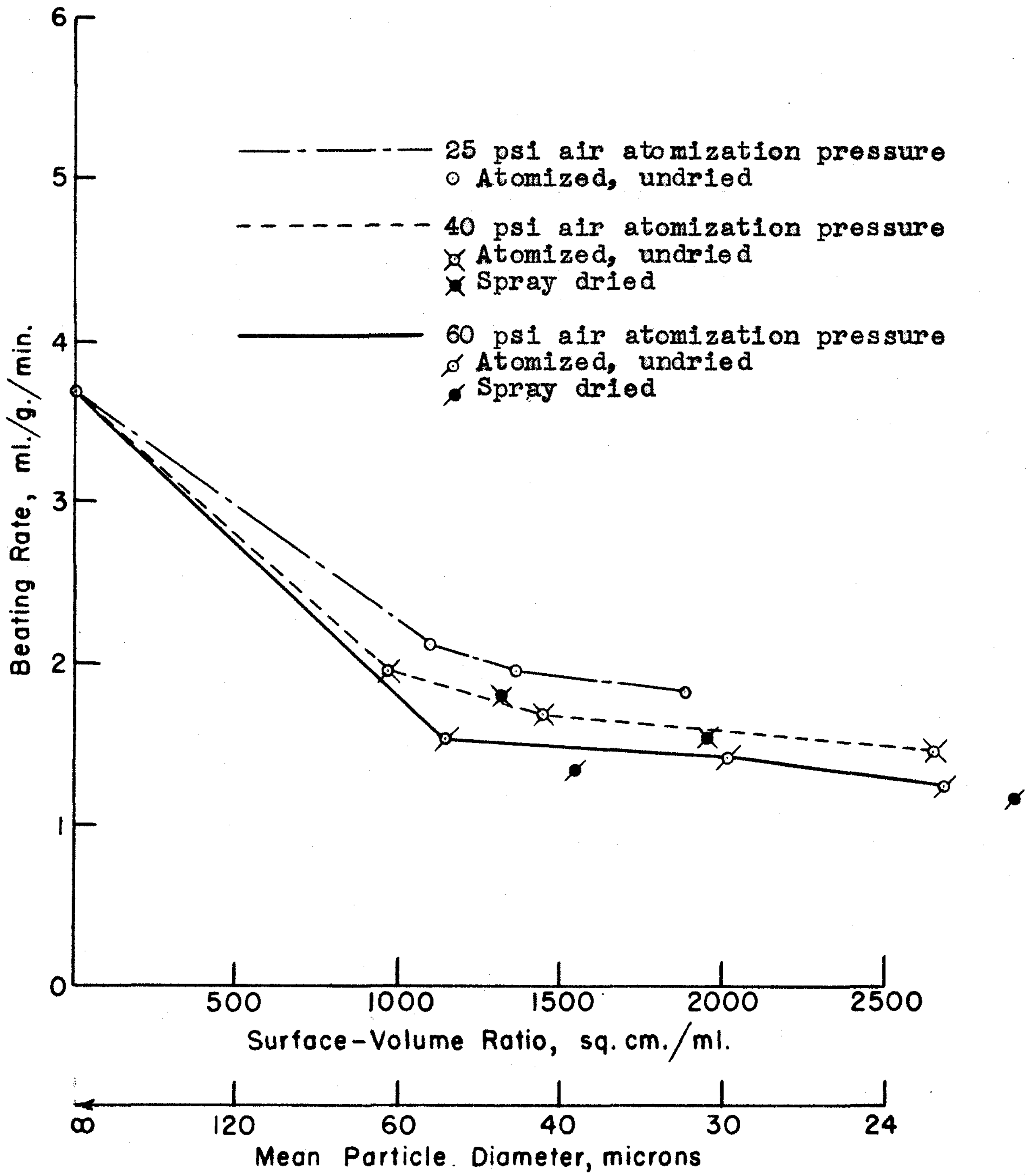


Figure 8. Effect of Atomization and Spray Drying on Beating Power of Egg White Using Internal Mixing Nozzle

Table 4

Effect of Atomization and Spray Drying on Beating Power of Egg White[a]

	Liquid pressure	Atomizing air pressure (psi)	Collection	Mean diameter of collected particles (microns)	Surface-volume ratio (sq.cm/ml)	Beating rate (ml/g/min)
	Control	-	-	-	-	3.65
Atomized, undried	1 psi	60	Entire spray	22.2	2700	1.51
	10 "	60	"	30.0	1940	1.51
	30 "	60	"	63.2	950	1.78
	-7" H_2O	40	Entire spray	22.6	2660	1.59
	10 psi	40	"	34.3	1750	1.74
	25 "	40	"	64.0	940	2.18
	-7" H_2O	15	Entire spray	25.6	2340	1.96
	7.5 psi	15	"	39.4	1520	2.24
	20.0 "	15	"	61.1	970	2.36
Spray dried	5 psi	60	Bag section	18.2	3300	1.50
	10 psi	40	Bag section	20.7	2900	1.53
			2nd section	35.1	1710	1.66
	14 psi	15	Bag section	31.5	1900	2.13
			2nd section	56.2	1070	2.46
			3rd section	75.0	800	2.70

[a] Commercial frozen egg white, Aerobacter fermented; external mixing nozzle.

Table 5

Effect of Atomization and Spray Drying on Beating Power of Egg White[a]

	Liquid pressure	Atomizing air pressure (psi)	Collection	Mean diameter of collected particles (microns)	Surface-volume ratio (sq.cm/ml)	Beating rate (ml/g/min)
	Control	-	-	-	-	3.65
-Atomized, undried -	1.5 psi	60	Entire spray	22.3	2690	1.25
	5.0 "	60	"	29.7	2020	1.45
	10.0 "	60	"	52.2	1150	1.57
	-7" H_2O	40	Entire spray	22.6	2650	1.45
	2.5 psi	40	"	41.7	1440	1.66
	5.0 "	40	"	62.0	968	1.84
	-7" H_2O	25	Entire spray	31.7	1890	1.81
	0.5 psi	25	"	44.0	1360	1.95
	1.5 "	25	"	54.7	1100	2.10
Spray dried	10 psi	60	Bag section	19.6	3060	1.11
			2nd section	39.4	1520	1.24
	10 psi	40	Bag section	30.6	1960	1.57
			2nd section	45.4	1320	1.83

[a] Commercial frozen egg white, Aerobacter fermented; internal mixing nozzle.

at each air pressure by varying the rate of liquid feed. It is seen that for the same degree of atomization damage was less at the lower pressures. It would seem that at the lower pressures the liquid is drawn out more slowly and into longer threads before breaking into droplets. Thus, the rate of surface formation would be less at low atomizing pressures and this might contribute to the smaller amount of damage. Another contributing factor might be the reduced amount of liquid-to-liquid shear at low pressures.

2. Effect of drying

Drying of the atomized egg white was found to produce certain additional changes. Table 6 shows the effect of drying on particle size. The mean diameter of the atomized droplets was estimated to decrease about 75 per cent on drying. This was determined by measuring the mean diameter of the droplets which had been caught simultaneously on a magnesium oxide film and on castor oil. Those caught on the magnesium oxide made an impression where they cut through the surface of the film before drying, and represented the undried droplets. Those caught on the castor oil remained on the surface and dried, retaining their spherical shape; these represented the dried particles.

The pH of egg white was found to change considerably on

Table 6

Effect of Drying on Particle Size of Sprayed Egg White

Trial No.	Mean diameter of undried particles (microns)[a]	Mean diameter of dried particles (microns)[a]	Reduction in diameter (per cent)
1	42.9	31.8	74
2	37.6	26.3	69

[a] Based on a count of 4500 particles.

drying. Table 7 shows these changes when different types of egg white were spray dried. The pH of unfermented, fermented, and fermented egg white adjusted to a pH below 8 all were found to increase as a result of drying, apparently due to the loss of carbon dioxide. The pH of fermented egg white adjusted to a pH above 8 was found to decrease. This was probably due to a loss of ammonia.

The beating power of the egg white was not affected to any great extent by drying. This is indicated in Figures 7 and 8 showing studies made with the external and internal types of nozzles. With these two atomization devices it was quite easy to obtain size separation of the spray dried particles within the horizontal drying chamber. These were compared with undried liquid atomized to varying degrees at the air pressures used in spray drying. For similar degrees of atomization at the same pressure it was found that there was very little difference in beating power between the atomized, undried egg white and the spray dried, reconstituted egg white. The moisture content of the spray dried egg white products varied between 4 and 7 per cent.

In succeeding studies the following air atomization pressures were used since they represent conditions at which each nozzle operated most efficiently with relatively good uniformity of particles and maximum recovery of powder (in

Table 7

Effect of Spray Drying on pH of Egg White

Type of egg white	pH before spray drying	pH of reconstituted product
Unfermented	9.0	9.9
Aerobacter fermented, pH unadjusted	6.0	7.9
Aerobacter fermented, pH adjusted with ammonium hydroxide to 7.2	7.2	8.2
Aerobacter fermented, pH adjusted with ammonium hydroxide to 9.0	9.0	8.4
Yeast fermented, pH unadjusted	6.9	9.8

the bag section): external mixing nozzle, 40 psi; internal mixing nozzle, 60 psi; foam atomizer, 40 psi. Using these pressures, recovery in the bag section was approximately as follows: external mixing nozzle, 80-90 per cent; internal mixing nozzle, 80-90 per cent; foam atomizer, 50-70 per cent. The angle of spray of the foam atomizer was wide in comparison to the other two atomizers. Thus, considerable accumulation of powder occurred in the section near the atomizer.

C. Condition of Egg White Before Spray Drying

1. Fresh egg white compared with commercial frozen egg white

Commercial frozen egg white was used in most of the studies reported herein since it was felt that this represented quite closely the type of egg white which would generally be available in industry. However, it was noted that this product was much more affected by atomization and spray drying than was egg white freshly broken out and separated from the yolk. The results are shown in Table 8. It may be seen that egg white obtained from fresh shell eggs retained its beating power much better than did the commercial frozen egg white. The whites from 2 day old shell eggs were less affected by spray drying than were whites from 7 day old eggs. The susceptibility of commercial frozen

Table 8

Effect of Spray Drying on Beating Power of Egg White[a]

	Beating rate (ml/g/min)			
Source	Control	External mixing nozzle[b]	Internal mixing nozzle[c]	Foam atomizer[d]
Eggs 2 days old	5.05	3.42	3.07	4.10
Eggs 7 days old	5.60	1.95	1.73	2.81
Commercial frozen egg white	4.36	1.53	1.11	1.81

[a] Aerobacter fermented.

[b] Atomization conditions: 20 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 10 psi liquid pressure; 60 psi air atomization pressure.

[d] Atomization conditions: 14 psi liquid pressure; 10-15" water air foaming pressure; 40 psi air atomization pressure.

egg white to spray drying may be influenced by the following factors: age of the eggs, physical treatment of the whites before freezing (such as the use of the Tranin mill), freezing and storage. These points need further investigation.

2. Effect of fermentation of egg white

Fermentation had very little effect on the susceptibility of egg white to damage by atomization (Table 9). Yeast fermented egg white seemed to be slightly more susceptible to damage than the bacteria fermented product.

3. Effect of spray drying thick and thin egg white

Results of this study are shown in Tables 10 and 11. In atomization and spray drying, the thick egg white was not reduced in beating power to any greater extent than was thin egg white. The thick white, which had been liquified by blending, showed greater beating power before treatment. In the case of every atomized and spray dried product where thick and thin egg white had been subjected to similar treatments the product obtained from thick white had proportionately better beating power than that obtained from thin white.

Table 9

Effect of Spray Drying on Beating Power of Egg White

		Beating rate (ml/g/min)		
Source	Control	External mixing nozzle[a]	Internal mixing nozzle[b]	Foam atomizer[c]
Commercial frozen, unfermented	4.10	1.13	0.97	1.38
Commercial frozen, Aerobacter fermented	4.00	1.53	1.11	1.81
Commercial frozen, yeast fermented	4.48	1.12	1.00	1.66
Eggs (7 days old), Unfermented	4.36	2.05	1.42	2.78
Eggs, (7 days old), Aerobacter fermented	5.60	1.95	1.73	2.81

[a] Atomization conditions: 20 psi liquid pressure; 40 psi air atomization pressure.

[b] Atomization conditions: 10 psi liquid pressure; 60 psi air atomization pressure.

[c] Atomization conditions: 14 psi liquid pressure; 10-15" water air foaming pressure; 40 psi air atomization pressure.

Table 10

Effect of Spray Drying on Beating Power of Thick and Thin Egg White[a]

	Beating rate (ml/g/min)			
	Control	External mixing nozzle[b]	Internal mixing nozzle[c]	Foam atomizer[d]
Thick	5.05	3.42	3.07	4.10
Thin	4.66	3.17	2.58	3.68

[a] From fresh eggs, Aerobacter fermented.

[b] Atomization conditions: 20 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 10 psi liquid pressure; 60 psi air atomization pressure.

[d] Atomization conditions: 14 psi liquid pressure; 10-15" water air foaming pressure; 40 psi air atomization pressure.

Table 11

Effect of Atomization and Surface Formation on Beating Power of Thick and Thin Egg White[a]

Type of egg white	Beating rate (ml/g/min)			
	No treatment	External mixing nozzle[b]	Internal mixing nozzle[c]	Surface formation[d]
Thick, unfermented	5.05	3.73	3.73	4.00
Thin, unfermented	4.66	3.42	3.24	3.86
Thick, Aerobacter fermented	5.20	4.20	4.10	4.00
Thin, Aerobacter fermented	4.60	3.77	3.27	3.71

[a] From fresh eggs.

[b] Atomization conditions: 15 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 7.5 psi liquid pressure; 60 psi air atomization pressure.

[d] 30,000 sq. cm. per gram at 277 sq. cm. per second.

4. Temperature of liquid being spray dried

Results of this study are shown in Table 12. Although differences were not great, the tendency in the case of the external mixing nozzle was for the product to have better whipping properties when the temperature of the liquid fed to the atomization device was low. Indications were that viscosity of liquid at lower temperatures caused rate of surface formation to be less; thus, less reduction in beating power resulted. The reverse was true in the case of the internal mixing nozzle. Higher viscosities at the lower temperatures were apparently more detrimental in the case of the internal nozzle where shear forces would seem to play a larger part. Differences in surface denaturation at the two temperatures would not be expected to be great since the temperature coefficient of surface denaturation has been shown to be small (7, 16, 84).

5. Effect of pH on whipping power of spray dried egg white

In this study the lowest pH used was 6.0 since below this level certain proteins of the egg white begin to precipitate. Table 13 shows the effect of pH on atomized, undried egg white; Table 14 shows the effect of pH on spray dried egg white. The trend of the results indicates that

Table 12

Effect of Egg Temperature During Spray Drying on Beating Power of Egg White[a]

Temperature of feed (°C.)	Beating rate (ml/g/min)		
	Control	External mixing nozzle[b]	Internal mixing nozzle[c]
4	4.00	1.90	1.13
43	4.00	1.60	1.55

[a] Aerobacter fermented.

[b] Atomization conditions: 20 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 10 psi liquid pressure; 60 psi air atomization pressure.

Table 13

Effect of pH in Spray Drying Egg White on Beating Power[a]

Initial pH	Final pH	Beating rate (ml/g/min)			
		Control	External mixing nozzle[b]	Internal mixing nozzle[c]	Foam atomizer[d]
6.05	7.90	2.89	1.52	1.19	1.55
7.20	8.20	4.00	2.26	1.48	2.76
9.00	8.40	3.90	1.53	1.11	1.81

[a] Commercial frozen egg white, Aerobacter fermented.

[b] Atomization conditions: 20 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 10 psi liquid pressure; 60 psi air atomization pressure.

[d] Atomization conditions: 14 psi liquid pressure; 10-15" water air foaming pressure; 40 psi air atomization pressure.

Table 14

Effect of pH of Egg White in Atomizing and Forming Surfaces on Beating Power

Type of egg white	pH	Beating rate (ml/g/min) No treatment	External mixing nozzle[a]	Internal mixing nozzle[b]	Surface formation[c]
Commercial frozen egg white, unfermented	9.0	4.71	2.24	1.65	2.60
	7.6	4.25	2.87	2.38	3.30
	6.2	3.81	2.73	2.04	2.73
Commercial frozen egg white, fermented	9.0	4.36	2.17	1.72	2.58
	7.2	4.71	2.52	2.22	2.89
	6.0	3.42	2.36	1.69	2.65

[a] Atomization conditions: 15 psi liquid pressure; 40 psi air atomization pressure.

[b] Atomization conditions: 7.5 psi liquid pressure; 60 psi air atomization pressure.

[c] 30,000 sq. cm. per gram at 277 sq. cm. per second.

there is less destruction of egg white at a lower pH than at the natural pH of 9.0. The tendency was for minimum degradation to take place near pH 7.2. Whipping itself might be affected by the pH of the product. However, the pH of all reconstituted spray dried products prepared from Aerobacter fermented egg white approached the same pH value (approximately 8.0) regardless of initial pH. (Table 7)

6. Effect of concentration

It seems that there would be less surface denaturation in the atomization of concentrated egg white solutions since less surface is formed per gram of dried protein. However, little advantage was found in concentrating egg white before spray drying (Table 15). It was noted that concentration by itself had degradating influence on the beating power of egg white. Even lyophilization seemed to be detrimental to the commercial frozen egg white. Although the initial beating power of the egg white concentrated to 29 per cent solids was less than that concentrated to 17 per cent solids, the spray dried products had slightly better beating power in every case. The results obtained by concentrating liquid by the surface film method were similar to those by lyophilization.

Table 15

Effect of Concentration Prior to Spray Drying on Beating Power of Egg White[a]

Method of concentration	Solids (%)	Beating rate (ml/g/min)		
		Control	External mixing nozzle[b]	Internal mixing nozzle[c]
Lyophilization	12.5(Control)	3.27	1.00	0.90
	17.0	3.27	1.05	0.93
	29.0	2.76	1.37	1.22
Film evaporation	12.5(Control)	3.86	1.42	1.16
	18.0	3.86	1.42	1.18

[a] Commercial frozen egg white, Aerobacter fermented.

[b] Atomization conditions: 20 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 10 psi liquid pressure; 60 psi air atomization pressure.

7. Effect of added substances

Added substances might have some effect on the surface characteristics of egg white. Therefore, it seemed advisable to investigate the addition of certain sugars, salts and surface-active agents on the quality of egg white after atomization and surface formation.

(a) Sugars. The effects of adding sucrose, glucose, and glycerol to egg white before spray drying, atomization and surface formation are shown in Tables 16 and 17. Addition of sucrose (up to 20 per cent) did not prevent the reduction in whipping power of spray dried egg white. In atomization and surface formation studies, 10 per cent sucrose and 10 per cent glucose were without effect whereas 10 per cent glycerol seemed to inhibit denaturation. Apparently neither sucrose nor glucose influenced the characteristics of the protein solution surface whereas glycerol may have modified the surface in some way. The reason for this is not clear. In heat coagulation, all three compounds effectively reduce susceptibility of egg white to damage.

(b) Salts. The results of adding different salts to egg white before atomization and surface formation are shown in Table 18. None of the salts tested, except calcium chloride, were effective. The positive influence of calcium

Table 16

Effect of Adding Sucrose Before Spray Drying on Beating Power of Egg White[a]

Sucrose concentration (%)	Beating rate (ml/g/min)			
	Control	External mixing nozzle[b]	Internal mixing nozzle[c]	Foam atomizer[d]
0	4.00	1.50	1.07	2.10
1	3.90	1.53	0.83	2.11
5	3.90	1.49	0.75	2.13
10	4.00	1.05	0.77	2.28
20	3.95	1.37	0.99	2.52

[a] Commercial frozen egg white, Aerobacter fermented.

[b] Atomization conditions: 20 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 10 psi liquid pressure; 60 psi air atomization pressure.

[d] Atomization conditions: 14 psi liquid pressure; 10-15" water air foaming pressure; 40 psi air atomization pressure.

Table 17

Effect of Adding Sugars and Glycerol Before Atomization and Surface Formation on Beating Power of Egg White[a]

Substance added	Beating rate (ml/g/min)			
	No treatment	External mixing nozzle[b]	Internal mixing nozzle[c]	Surface formation[d]
Control	4.05	1.95	1.49	2.70
10% Sucrose	4.00	1.98	1.57	2.76
10% Glucose	4.15	1.90	1.51	2.76
10% Glycerol	4.20	2.56	2.20	3.60

[a] Commercial frozen egg white, unfermented.

[b] Atomization conditions: 15 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 7.5 psi liquid pressure; 60 psi air atomization pressure.

[d] 30,000 sq. cm. per gram at 277 sq. cm. per second.

Table 18

Effect of Adding Certain Salts Before Atomization and Surface Formation on Beating Power of Egg White[a]

Salt	Beating rate (ml/g/min) No treatment	External mixing nozzle[b]	Internal mixing nozzle[c]	Surface formation[d]
Control	4.06	1.63	1.16	2.46
0.2N Sodium Chloride	4.30	1.73	1.25	2.81
0.2N Potassium Chloride	4.48	1.58	0.95	2.81
0.2N Calcium Chloride	4.00	2.89	2.36	3.65
0.2N Potassium Thiocyanate	4.00	2.08	1.70	2.68
0.05N Potassium Sodium tartrate	4.10	1.51	1.12	2.56
0.2N Mono-Sodium Phosphate	4.10	2.03	1.33	2.58

[a] Commercial frozen egg white, unfermented.

[b] Atomization conditions: 15 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 7.5 psi liquid pressure; 60 psi air atomization pressure.

[d] 30,000 sq. cm. per gram at 277 sq. cm. per second.

chloride in reducing the damage caused by atomization and surface formation may have been due to the change in pH. The pH of the egg white to which calcium chloride was added was 7.4; all other salts gave a pH of 9.0

(c) Surface-active agents. The results for three selected agents are shown in Table 19. Tween 80 and D-C 200 were without effect in reducing the degradating influence of atomization and surface formation. Tween 80 by itself was found to lower the beating power of egg white. Sodium lauryl sulfate inhibited the change in beating power brought about by atomization. However, the foaming power of sodium lauryl sulfate itself may have influenced the beating rate of the egg white even though the protein may have been affected.

D. Effect of Holding Reconstituted Egg White on Beating Power

MacDonnell, *et al.* (53) noted a reversion in the properties of egg white which had been homogenized and allowed to stand at 2°C. for 6 days. This phenomenom was tested on reconstituted spray dried products in order to determine if there is any reversibility of the denaturation brought about by atomization and spray drying. Several samples of spray dried egg white with different beating powers were tested.

Table 19

Effect of Adding Surface-Active Agents Before Atomization and Surface Formation on Beating Power of Egg White[a]

Surface active agent	Beating rate (ml/g/min)			
	No treatment	External mixing nozzle[b]	Internal mixing nozzle[c]	Surface formation[d]
Control	4.05	1.63	1.16	2.46
Tween 80[e] (0.2%)	2.63	1.40	1.12	2.18
Sodium lauryl sulfate (0.2%)	4.48	3.81	3.60	3.27
D-C 200[f] (0.05%)	4.25	1.93	1.80	2.87

[a] Commercial frozen egg white, unfermented.

[b] Atomization conditions: 15 psi liquid pressure; 40 psi air atomization pressure.

[c] Atomization conditions: 7.5 psi liquid pressure; 60 psi air atomization pressure.

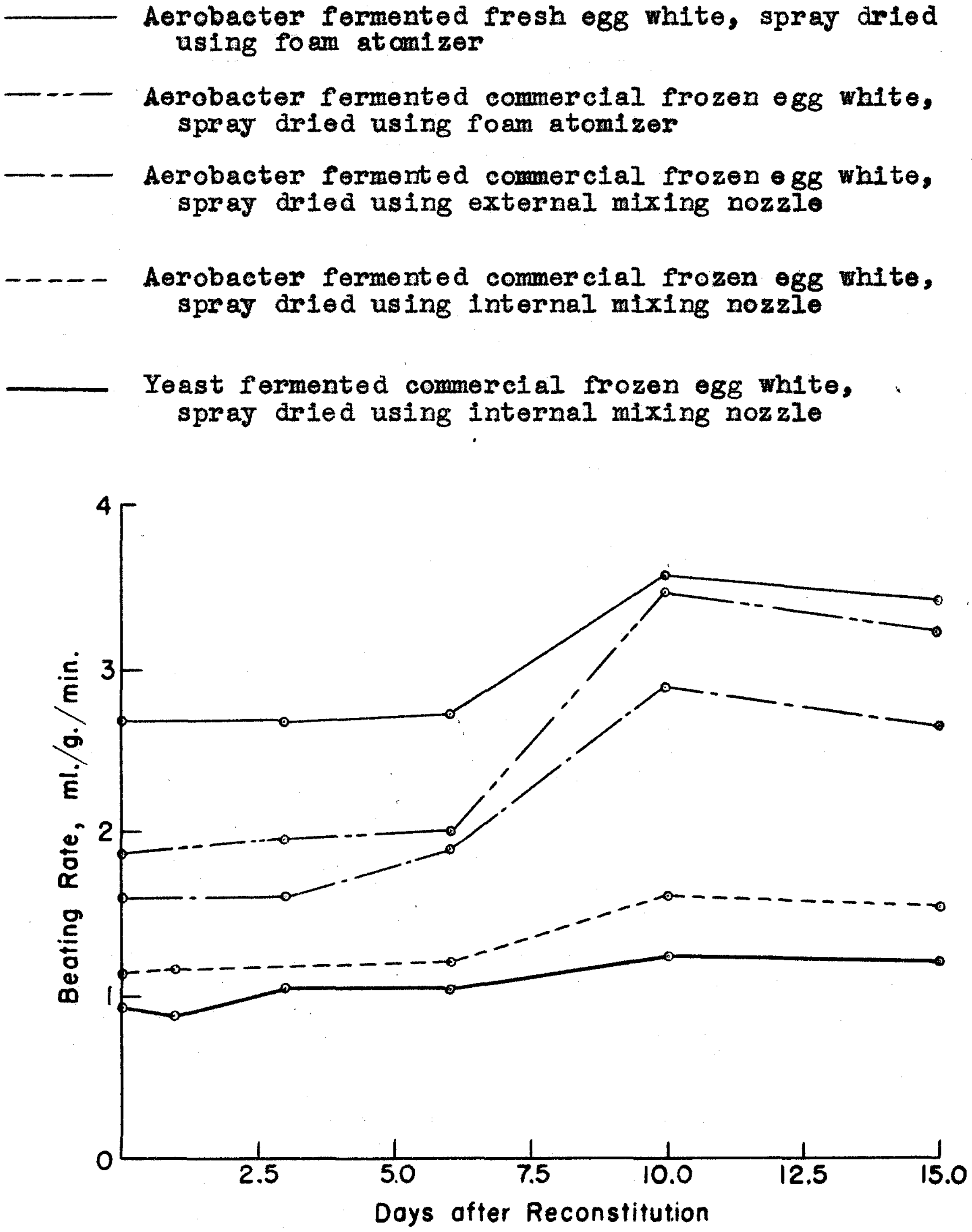
[d] 30,000 sq. cm. per gram at 277 sq. cm. per second.

[e] Polyoxyethylene sorbitan monooleate.

[f] A Dow-Corning silicone product.

The data obtained in this study are shown in Figure 9 and Table 20. The samples were reconstituted and stored at 2°C. for varying lengths of time. No change in beating power of egg white was noted after 6 days of storage. However, considerable increase was noted after 10 days at which time the beating power reached a maximum. This effect was more pronounced for spray dried products with better beating power.

There is the possibility that bacterial action was the cause of the changes brought about on holding the reconstituted products. However, no change in pH resulted after 10 days of holding at 2°C.; after 15 days holding, a slight reduction in pH was noted in every case, indicating some bacterial activity. No changes in odor were observed. The author feels that the effects noted in this study were over and above those possible by bacterial action and that the changes were due to spontaneous rearrangement of denatured protein which favored better beating properties.



——— Aerobacter fermented fresh egg white, spray dried using foam atomizer

— - - — Aerobacter fermented commercial frozen egg white, spray dried using foam atomizer

— - — Aerobacter fermented commercial frozen egg white, spray dried using external mixing nozzle

- - - - - Aerobacter fermented commercial frozen egg white, spray dried using internal mixing nozzle

——— Yeast fermented commercial frozen egg white, spray dried using internal mixing nozzle

Figure 9. Effect of Holding Time on Beating Power of Reconstituted Spray Dried Egg White

Table 20

Effect of Holding Time on Beating Power of Reconstituted Spray Dried Egg White[a]

Sample No.	Days after reconstitution					
	0	1	3	6	10	15
1[b]	0.95	0.90	1.05	1.01	1.24	1.22
2[c]	1.13	1.19	-	1.20	-	1.57
3[d]	1.60	-	1.60	1.91	2.92	2.65
4[e]	1.86	--	1.99	1.98	3.49	3.27
5[f]	2.70	-	2.70	2.76	3.56	3.42
6[g]	1.34	-	-	1.44	-	-
7	1.42	-	-	1.42	-	-
8	1.77	-	-	1.64	-	-
9	1.89	-	-	1.81	-	-
10	1.73	-	-	1.63	-	-
11	2.65	-	-	3.01	-	-
12	2.18	-	-	2.38	-	-
13	1.74	-	-	1.86	-	-
14	1.66	-	-	1.53	-	-
15	1.64	-	-	1.53	-	-
16	1.26	-	-	1.14	-	-
17	0.97	-	-	0.96	-	-
18	1.74	-	-	1.74	-	-
19	1.28	-	-	1.28	-	-
20	1.59	-	-	1.72	-	-
21	1.24	-	-	1.24	-	-
22	1.20	-	-	1.29	-	-
23	1.44	-	-	1.49	-	-
24	1.52	-	-	1.52	-	-

[a] Beating rate ml/g/min.

[b] Yeast fermented, spray dried using internal mixing nozzle.

[c] Aerobacter fermented, spray dried using internal mixing nozzle.

[d] Aerobacter fermented, spray dried using external mixing nozzle.

[e] Aerobacter fermented, spray dried using foam atomizer.

[f] Aerobacter fermented from fresh egg white, spray dried using foam atomizer.

[g] Numbers 6 through 24 are miscellaneous spray dried samples.

V. CONCLUSIONS

From the results of the experiments reported in this study the following conclusions are made:

1. Spray drying egg white results in a definite loss of beating power.

2. The loss in beating power of egg white imposed by spray drying is caused primarily by the dispersion of egg white into fine droplets. Very little, if any, additional loss results from drying of the atomized droplets.

3. Egg white is subject to surface denaturation during the formation of new surfaces. Its beating power is reduced more the greater the rate of surface formation.

4. In spray drying, egg white is affected to different degrees depending upon the type of atomizing device and the conditions of atomization. The internal mixing, two-fluid nozzle is more destructive to beating power of egg white than is the external mixing, two-fluid nozzle; atomization of foam is less detrimental than either of these. For the same degree of atomization, use of low air atomization pressures are less detrimental than high pressures.

5. Egg white obtained from fresh eggs is less susceptible to damage by spray drying than is commercial frozen or egg white from older eggs.

6. Thick egg white which has been thinned by blending is no more susceptible to damage by atomization and spray drying than is thin egg white.

7. The optimum pH for atomization is between 7 and 8, in which pH range beating power is reduced to the least extent.

8. Addition of 10 per cent glycerol reduces susceptibility of egg white to damage by atomization while the addition of sucrose or glucose does not. The addition of the surface active agent sodium lauryl sulfate minimizes reduction of beating power while Tween 80 and D-C 200 have little effect. Certain salts (sodium chloride, potassium chloride, potassium thiocyanate, potassium sodium tartrate, and monosodium phosphate) do not influence susceptibility of egg white. However, calcium chloride affected the egg white favorably. This effect may be due to pH.

9. Denaturation of egg white caused by spray drying is partially reversible. Increase in beating power takes place when egg white powder is reconstituted and allowed to stand for 10 days at 2°C.

VI. SUMMARY

A study was made to determine the limitations of spray drying as applied to egg white. A meringue-type whip test was employed in following the changes in functional properties brought about by spray drying.

New surface formation which takes place in the atomization of egg white was studied by forming surfaces on a porcelain cylinder revolving through the liquid product. Formation of new surfaces was found to be detrimental to beating power of egg white. For the same quantity of surface formed, more damage was caused when high rates of surface formation were used.

A horizontal type spray drier was used to study the effects of atomization and spray drying. Three different types of atomizing devices were used: (1) internal mixing, two-fluid nozzle, (2) external mixing, two-fluid nozzle, and (3) special external mixing, two-fluid nozzle which effected the formation and atomization of foam. The former (1) was found to be the most detrimental, and the latter (3) the least detrimental to the beating properties of egg white. The differences found between the atomization devices are thought to be related to the rate of surface formation.

For the internal and external nozzles, less destruction was imparted at lower air atomization pressures. Little, if any, additional deterioration was found to be caused by drying at the temperatures (55-65°C. exhaust) used in this investigation.

Differences were noted in the type of egg white atomized and spray dried. Fresh egg white was less susceptible to deterioration than the commercial frozen egg white used in this study.

Fermentation by Aerobacter aerogenes did not alter changes brought about by atomization and spray drying. Blended thick white showed no more susceptibility to damage by spray drying and surface formation than did thin egg white. A higher beating power was noted in products produced from egg white atomized or spray dried at a pH between 7 and 8 than at a higher or lower pH.

Most of the added substances studied (sugars, salts, and surface-active agents) showed little promise in reducing the deterioration in egg white caused by spray drying.

Reconstituted spray dried egg white which had stood at 2°C. for 10 days showed improvement in beating power.

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