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THE PHYSICAL CHEMISTRY OF BREAD MAKING[1]

THE art of making leavened bread has been so long perfected that the experience upon which present practise rests is now forgotten. Meanwhile the science of bread making, involving physical, chemical and physiological problems of a certain complexity, and only recently promoted by a great organized industry, has hardly kept pace with the advance of biological chemistry. But at length war time necesssity has imposed new conditions, and the use of flours other than wheat has brought about changes from the best practise of the past.

It seems desirable, therefore, to review the physical and chemical processes involved in the fermentation of dough and the baking of bread, and make suggestions which may facilitate the use of wheat substitutes.

GLUTEN

When wheat flour is made into dough the proteins, after absorbing water, hold together to a much greater extent than do the proteins of any other grain. This property makes it possible to separate from the other constitutents of wheat flour the two proteins, gliadin and glutenin,[2] which are insoluble in water. The material which can in this way be washed free contains about ten per cent. of the flour[3] and includes about nine tenths of all the protein material.[4] It is called gluten.

[1] From the Wolcott Gibbs Memorial Laboratory of Harvard University, in collaboration with the Division of Food and Nutrition, Medical Department, U. S. Army.

[2] Osborn, T. B., "The Proteins of the Wheat Kernel." Washington, 1907.

[3] Bulletin 13, part 9, Division of Chemistry, United States Department of Agriculture.

[4] Jago, William, "Science and Art of Bread-making," pp. 288–303, London, 1895.

Proteins, unlike starches, combine with acids and alkalis. Such combinations differ in their properties according to the quantity of acid or alkali which they contain. Similar differences are also produced in the properties of proteins by the action of salts. Among the most important of the effects of acids, alkalis and salts upon proteins is the modification of the swelling in water, and partly as a result of this, of elasticity, tenacity and cohesiveness. Another important effect is a change in the solubility of the proteins.

As the amount of acid or alkali combined with gluten varies, the amount of water which can be absorbed varies from 2½ to 3½ times the weight of the gluten itself.[5, 6, 7] Certain salts also have an important effect upon the swelling of gluten.[8]

In spite of the fact that such phenomena are more or less similar to those which may be observed with other proteins, there are many properties of gluten which are very different from those of other known protein substances. The unique properties of gluten make possible the manufacture of good leavened bread.

DOUGH

The swollen, coherent gluten imparts to wheat-flour dough the properties of tenacity and elasticity that are peculiar to it. It permits the stretching and distending of the mass in bread-making. As a result the volume may increase four or five fold. Dough made from other grains, even though containing more protein and possessing a greater capacity to absorb water, is both less elastic and less coherent. When stretched such doughs break. The baker calls them "short."

The extent to which dough can be distended varies with the quantity and with the physical condition of the gluten. Within certain limits the baker can therefore improve the rising of dough by modifying the physical condition of gluten. Thus, for instance, increasing the acidity of dough will increase its elasticity[9] and certain salts, such as calcium sulphate, may have a similar effect.

THE FERMENTATION OF SUGAR

Bread is leavened by the formation of carbon dioxide within the dough through the fermentation of sugar by yeast. Yeast can freely utilize either cane sugar or glucose for the production of carbon dioxide. In American baking practise, where a short fermentation is usually preferred, sugar is therefore added to dough. The proper amount of sugar depends upon the conditions of the fermentation. It is, however, as the present practise of certain nations and the early history of baking prove, not necessary to add any sugar at all, for a small amount of sugar is present in flour,[10, 11] and more is slowly produced from starch during fermentation by the action of enzymes. But sugar can not be left out unless the whole practise of the baker differs from that now followed in America.

THE PRODUCTION OF CARBON DIOXIDE BY YEAST

Yeast is very sensitive to slight changes in the dough batch. For instance, activity at 30° C. (86° F.) is about twice as great as 20° C. (68° F). The production of carbon dioxide is, however, much decreased by the large quantity of salt which is added to the dough with the water, sugar and shortening. By means of this effect of salt on the activity of yeast the baker commonly controls the

5 Wood, T. B., "The Chemistry of Strength of Wheat Flour," *Jour. Agricultural Science*, Vol. 2, Part 3, pp. 267–277, 1907.

6 Wood, T. B., and Hardy, W. B., "Electrolytes and Colloids: The Physical State of Gluten," *Proceedings Roy. Soc. B*, LXXI., pp. 31–43, 1909.

7 Unpublished observations.

8 Wood, T. B., "The Chemistry of Strength of Wheat Flour," *Jour. Agricultural Science*, Vol. 2, Part 2, pp. 139–160, 1907.

9 Henderson, L. J., Fenn, W. O., Cohn, E. J., "The Influence of Electrolytes upon the Viscosity of Dough" *Journal of General Physiology*.

10 Wood, T. B., "The Chemistry of Strength of Wheat Flour," *Jour. Agricultural Science*, Vol. 2, Part 2, pp. 267–277, 1907.

11 Maurizio, *Landwirtschaftliche Jahrbücher*, XXXI., 1902.

length of fermentation. Another method is to vary the quantity of yeast.

But the rate of carbon dioxide production by yeast is also greatly influenced by the products of its own activity. During fermentation there is a continual increase in the acidity of dough and as a result, up to a certain point (reached only in very old and very acid dough), the activity of the yeast steadily becomes greater. The activity of the yeast will, nevertheless, diminish when the supply of sugar is no longer sufficient.

THE PRODUCTION OF ACID BY YEAST

The increasing acidity of dough both improves the condition of the dough and increases the production of carbon dioxide by the yeast. Accordingly, the dough rises more and more rapidly as the fermentation progresses.

The baker usually prolongs fermentation by "knocking down" the dough. By thus prolonging the process the products of the fermentation and the acidity of the dough are increased and therefore the volume of the dough, when it rises again, is greater.

THE ADDITION OF ACID TO DOUGH

The addition of such weak acids as lactic or acetic acid (vinegar) to dough has much the same effect. The amount of acid that may be added will vary with the amount of yeast and the length of fermentation. It can best be judged by determining the acidity of the baked loaf.[12] This can be done by judging the color when a few drops of methyl red are added to a slice of bread. The amount of acid which can favorably be added in ordinary bread making is discussed below in connection with the prevention of rope. It must be remembered that the desirable amount of acid varies with the quantity of yeast, with the quality of the wheat flour, with the quantity and variety of substitute and with the habits of the baker.

In the first place the desirable length of the fermentation is determined by the acidity of the dough. Increase in acidity increases the activity of the yeast and shortens the fermentation. Consequently the amount of sugar required by the yeast is diminished.[13] Beside the rate of carbon dioxide production of the yeast within the dough, the tenacity and elasticity of the dough, and the escape of gas from the dough are dependent upon acidity. Experience in this and other laboratories has shown that the best acidity for the baking of bread is indicated by the turning of methyl red from orange to red.[14, 15, 16] *In sum, the acidity of the dough at the time of baking seems to be the most important variable factor in bread making.*

THE ESCAPE OF GAS FROM THE DOUGH

The volume of the baked loaf is not completely determined by the volume of the risen dough. For not all of the carbon dioxide produced is retained within the dough: a large part escapes into the air. As a dough expands more and more the loss of gas increases, because the surface of a distended dough becomes greater, while the walls of the batch grow thin and more leaky. When, during the last rise, loss of gas from the dough becomes nearly as great as the production of carbon dioxide, the loaf *must* be baked regardless of its size. But the more tenacious and elastic the dough, the larger will be its volume before the losses from the batch reach this point. The "age" or "ripeness" of the dough is always best determined by the baker who through long practise has learned to judge it accurately.

BAKING

It has been suggested that dough must be baked before the loss of gas is equal to the

12 Henderson, L. J., "The Prevention of Rope in Bread," SCIENCE, N. S., Vol. 48, No. 1236, pp. 247–248, 1918.

13 Unpublished observations.

14 Cohn, E. J., Cathcart, P. H., and Henderson, L. J., "The Measurement of the Acidity of Bread," *Jour. Biological Chemistry*, 1918.

15 Jessen-Hansen, *Comptes Rendus Trav. Lab. Carlsberg*, Vol. 5, No. 10, 1911.

16 Landenberger, L. L., "Barley Bread Optimum Reaction and Salt Effect," SCIENCE, N. S., Vol. 48, No. 1237, pp. 269–270, 1918.

production of carbon dioxide, or, in other words, before the rise ceases. Such doughs are "ripe" for the oven. The baker says their "proof" is complete.

The less elastic and tenacious doughs of the present emergency have little "spring" in the oven and if ripe are very liable to fall during the early stages of the baking. To guard against this it is a common practise to shorten the fermentation, which involves baking at a lower acidity.

"Overproved" doughs usually fall in the oven before the crust is formed by drying and coagulation of the proteins of the dough. In them the loss of carbon dioxide is not even compensated by the expansion of the gas at the higher temperature of the oven. Doughs that are not "ripe" for the oven are in the opposite condition and are termed "underproved." The leakage of carbon dioxide from such doughs is not sufficient to permit the escape of the expanded gas and the loaf is "ripped."

WHEAT SUBSTITUTES

Although corn, barley and wheat flour contain nearly equal amounts of similar proteins, the properties of their doughs are markedly different. Rye is more tenacious than barley, and barley than corn, but in comparison with doughs made of wheat flour all others are "short." They do not hold together and are not distensible. Therefore—with the possible exception of rye—they can not retain the carbon dioxide that is produced within them. To whatever extent such flours are substituted for wheat the same effects are observed in due proportion. For the "body" of the dough is supplied by the wheat gluten alone. The degree to which the dough can be distended therefore depends upon the amount and the hydration of the gluten. But in the presence of substitutes the hydration of gluten is complicated in two ways: first because water is absorbed by the proteins of corn and of barley as well as by the proteins of wheat, but nevertheless without the resulting elasticity;[17] secondly because corn and barley combine with larger quantities of acid than does wheat.[18] The increasing acidity of the fermenting dough is thus partially neutralized. As a result neither the activity of the yeast nor the elasticity of the dough increases so rapidly in the presence of substitutes. If the smaller amount of gluten that is present is to swell to the same extent as in ordinary bread the same acidity must be reached. Therefore if the amount of yeast or the length of the fermentation is not to be increased, acid must be added to the dough.

But if the volume of the loaf is in this way increased, other dangers beset the baker when using a high percentage of substitute flours, for the leakage of carbon dioxide from the dough is also increased. As above mentioned the dough has little "spring" and falls more easily in the oven. This is another reason why the cautious baker has made his bread less acid during war time. He prefers baking dough that is "younger." The frequent occurrence of "ripped" bread is in this way accounted for.

Moreover, the popularity of starch in the larger bake shops of the country during the last year, and the facility with which it was used, depend upon the fact that unlike all flours, starch absorbs only about half its weight of water and combines with acid to an inappreciable extent.

SERUM PROTEINS

Although skillful control of the fermentation and of the acidity of dough (and sometimes the addition of salts like calcium sulphate) can improve leavened bread of any kind, it can not make up for the lack of gluten in wheat substitutes. Therefore, when wheat substitutes are employed it is desirable to add a small amount of a substitute for gluten.

The proteins of serum are such a substitute. The addition to flour containing 20 to 25 per cent. wheat substitutes of two or three per cent. of dry powdered serum (which must be

17 Unpublished observations.

18 Unpublished observations.

freely soluble)[19] yields a dough quite as easy to handle as that produced from pure wheat flour. Such a dough does not, like ordinary doughs containing substitutes, easily become "overproved." The loaves do not fall in the oven, for the serum proteins decrease the leakage of carbon dioxide from the dough.[20] The danger of the loss of a whole batch from excessive fermentation is therefore minimized.

The use of serum proteins in this way materially lessens the very real difficulties which now exist. Moreover the resulting loaf is larger and more elastic, of better color and texture, and in all respects superior to loaves containing equal amounts of wheat substitutes but lacking serum. If it is inferior to bread made of pure wheat flour, it possesses certain important qualities of its own, and its use seems to be in all respects quite unexceptionable.

ROPE

Ropy bread is produced by the action of certain microorganisms whose spores survive the heat of the oven and later, when the conditions are favorable, attack the center of the loaf. At a temperature of about 26° C. (80° F.) their growth is rapid. For this reason epidemics of rope occur in summer. The principle organisms which cause rope belong to the *B. mesentericus* group.

Another condition which is necessary for the development of the rope organism is low acidity.[21] Bread which is sufficiently acid is quite immune. It is therefore possible absolutely to prevent rope by sufficiently increasing the acidity of dough. It has been found that the degree of acidity which is otherwise most favorable in ordinary bread making, at least as practised both in America[14, 16] and in Denmark[15] is sufficient for this purpose. This acidity is indicated by a full red color when a few drops of a solution (0.02 per cent. in 60 per cent. alcohol) of the indicator methyl red are placed upon a slice of bread. Bread should be adjusted to this acidity, especially when there is danger of an epidemic of rope. This is best done by the addition of increasing amounts of acid to the dough of successive batches until the baked loaf gives the desired color. Generally the right amount of lactic acid is between one and two pounds of the commercial product (22 per cent.–25 per cent.) per barrel of flour. (This corresponds to 1.25 c.c. normal lactic acid in 100 g. flour.)

It has been pointed out that wheat substitutes usually combine with more acid than wheat flour itself. In this way they neutralize the acidity of the dough and as a result the greater the amount of substitute the greater is the amount of acid that must be added to bring bread to the acidity indicated by a red color of methyl red. The preference of the baker for "young" doughs and the greater capacity of the substitutes to neutralize acids is the reason why rope has caused so much trouble during war time.

We are indebted to the Carnegie Institution of Washington and to Professor Theodore W. Richards for the use of much valuable and indispensable apparatus, without which our researches could hardly have been carried out. It is a great pleasure to express our thanks for this aid.

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[19] Burrows, G. H., and Cohn, E. J., "A Quantitative Study of the Evaporation of Serum Proteins," *Jour. Biological Chemistry*, 1918.

[20] Unpublished observations.

[21] Cohn, E. J., Wolbach, S. B., and Henderson, L. J., "The Control of Rope," *Jour. of General Physiology*, Vol. 1, No. 2, 1918.

INDUSTRIAL RESEARCH AND NATIONAL WELFARE[1]

AT the outbreak of the war the average statesman of the Allied powers was but little concerned with the interest of research. Necessity, however, soon opened his eyes. He began to perceive the enormous advantages derived by Germany from the utilization of sci-

[1] From an address delivered by Dr. George E. Hale under the auspices of Engineering Foundation in the Engineering Societies Building, New York, May 28, 1918.