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The Drying of Plasticized Pasta

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可塑化된 파스타의 乾燥

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요 약

삶은 스파게티를 10%, 20%와 40% 글리세린 수용액에 10분간 담가둔결과 차후의 건조과정에서 가소화(可塑化)시키는데 충분한 글리세린을 흡수했다. 글리세린의 가소화작용으로 높은 건조온도와 건습구온도의 큰차에서도 스파게티가 균열되고 표면에 주름지는 것이 방지되었다. 그러한 보호가 가능한 건조온도와 건습구온도차는 글리세린의 농도가 높을수록 높아졌다. 건조속도의 감소에도 불구하고 스파게티의 수분활성도를 0.65로(저장안정성에 필요한 수준) 내리는데 필요한 건조시간은 글리세린양이 증가함에 따라 짧아졌다. 글리세린의 첨가로 높은 건조온도에서 스파게티의 갈변화 정도가 심해졌고 갈변화를 유도하는 기간이 짧아졌으나 갈 변화는 모든 경우에 스파게티의 수분활성 가 건조완성에 필요한 0.65에 도달한 훨씬 후에 시작되었다. 글리세린의 첨가로 건조시간을 단축하고 더 높은 온도에서 건조할 수 있기 때문에 약간의 글리세린을 (0.15 kg glycerine/ kg dry spaghetti) 첨가함으로써 스파게티의 건조시간을 약 80%에서 93%까지 단축시킬 수 있다.

Introduction

Spaghetti drying exemplifies a recurrent characteristic of many food drying processes. Special drying conditions, which frequently are relatively uneconomical; or expensive, specially constructed dryers are used in order to provide organoleptically desirable product attributes. In the case of spaghetti drying times on the order of 18 hours and very mild drying conditions are used to prevent "checking", the formation of a multiplicity of lateral fissures in the strands of spaghetti. These fissures are not only unsightly but they lead to strand breakage which interferes with efficient conveying and packaging. Breakage may occur during drying or after some induction period, so that breakage may occur after the spaghetti is packaged, particularly if the packaged spaghetti is exposed to changes in relative humidity.

Checking is thought to be due to stresses caused by localized contraction as moisture concentration and temperature gradients develop during drying and product cooling. Under normal production conditions spaghetti shrinks roughly 30% in volume (10% linearly) while drying. Keey[1] has presented a method for calculating the stresses which develop due to the moisture concentration gradients produced by drying. Luikov[2] has determined the modulus of elasticity for elasticplastic behaviors, the elastic limit, the limiting yield stress and the ultimate breaking stress for spaghetti as a function of moisture content. The value of each of these properties increases markedly as moisture content decreases.

Cooked spaghetti is less susceptible to fissuring during drying than freshly extruded spaghetti. This reduced susceptibility is apparently due to cooking induced gelatinization of the spaghetti's starch. The gelatinized starch is more plastic than ungelatinized starch and thus more capable of yielding without fissuring as stresses develop during drying. The moisture content of cooked spaghetti varies with cooking time and with soaking time after cooking. For eight to ten minutes immersion in boiling water the moisture content will be 63.6% and for fourteen to twenty minutes immersion 72%[3]. If spaghetti cooked in boiling water for 10 minutes is soaked in cold water for an additional ten minutes its water content increases to 71%. Thus, any reduction in fissuring achieved by virtue of cooking is also attended by a marked increase in water removal load.

Glycerine addition has been used to plasticize meat to facilitate compression after freeze drying[4]. Glycerine and/or propylene glycol addition prior to drying has been used to minimize breakage of leafy vegetables which become frangible after drying; or to improve the softness of dried fruits[5]. and to improve crispness of dried vegetables upon rehydration[6]. Presumably, in fruits and vegetables glycerine acts in the same manner as it does when it is used to plasticize cellophane; hydrogen bonding between the glycerine and cellulose and between adjacent glycerine molecules provides a more flexible bonding structure than the rigid cellulose-to-cellulose hydrogen bonding which develops as water is removed during drying. It was reasoned that glycerine would act in the same manner with respect to starch and thus might be used to plasticize spaghetti and other pasta products. Such plasticizing should minimize stress development during drying and thus facilitate more rapid drying by permitting the use of higher drying temperatures and lower relative humidities. It was also felt that by providing a fluid-like path for moisture migration, glycerine might facilitate moisture diffusion through the solid during the drying. In addition, since glycerine acts to supress water activity, dried glycerine plasticized spaghetti should be stable in storage at higher residual moisture contents than unplasticized spaghetti. Lastly it appeared possible that glycerine plasticization might facilitate the rehydration of spaghetti and yield an "instant" or quick-cooking product.

Materials and Methods

An eighty-five strand batch of spaghetti (Prince No. 3, 1.8mm diameter) was weighed, placed in boiling water for ten minutes, decanted into a colander, rinsed with cold water and reweighed. Two, fifteen-strand batches of the cooked spaghetti were soaked in cold water for 10 minutes, and individual fifteen-strand batches were respectively soaked for 10 minutes in pools of 10% glycerine-water solution, 20% glycerine-water solution, and 40% glycerine-water solution. The weights and refractive indices (% Brix) of the glycerine-water solutions and the weights of the batches of spaghetti were checked before and after soaking. The concentration of the glycerine as determined from the refractive index measurements were used to determine the glycerine pickup and the water gain or loss by the spaghetti batches.

The strands of spaghetti in each batch were draped over 9mm diameter, 0.38m long wooden dowels and placed in the rack shown in Figure 1. The rack was then placed on the shelf of a Proctor and Schwartz steam-heated hot-air dryer so that the air passed perpendicular to the support rods and hanging strands of spaghetti, (see Fig. 2). Unloaded rods were also put in the rack to permit measurement of drying induced weight loss from the rods themselves. The rack was periodically removed from the dryer and the individual rods and associated spaghetti were weighed using the yoke-balance arrangement shown in Figure 3. The rack was reinserted in the dryer as soon as the weighing was finished. The samples were weighed every five minutes at the start of each run, at ten minute intervals in the middle of a run and at still longer intervals in the latter part of a run. Runs were carried out at the drying conditions listed in Table 1. In all cases, air velocities of 3.3 to 3.5 m/s were used. The wet bulb and dry bulb temperatures were controlled by means of dry-bulb and wet-bulb actuated feedback control of heating coil steam pressure, and spray water and steam injection into the drying air stream. Runs were continued until constant or near-constant product weights were achieved.

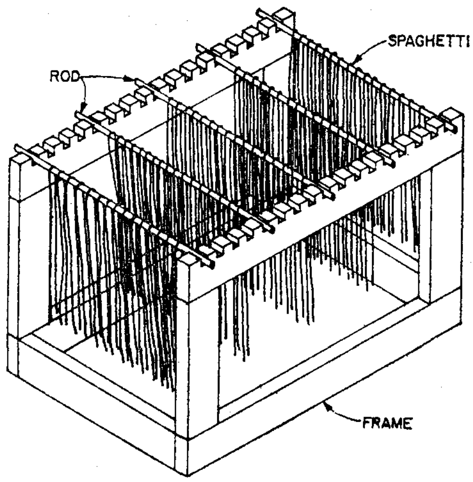

Fig. 1. Drying frame

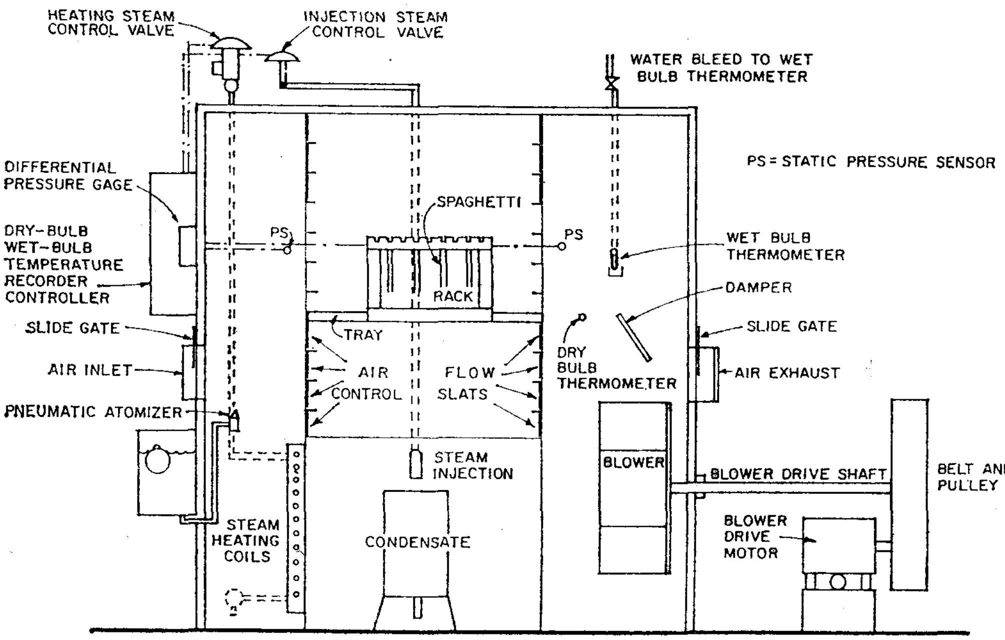

Fig. 2. Dryer arrangement

The dried spaghetti was examined visually both without magnification and 30X magnification to determine whether fissures and/or other surface irregularites were present. Samples of the dried spaghetti were immersed in 25°C water, in 75°C water and in boiling water to measure the rate of rehydration. The samples were periodically withdrawn from the water, weighed and reimmersed.

Table 1. Drying times (D.T.) to a_w equivalent to 12%(wet-basis) moisture content in glycerine free spaghetti, and times of onset of browning Times (B.T. in hours)

Glycerine concentration in soaking liquid		0 %		10 %		20 %		40 %	
kg glycerine	By glycerine balance	0		.15		.31		.67	
kg dry spaghetti	By dried weight comparison	0		.16		.30		.44	
Air temperatures (°C)		D.T.	B.T.	D.T.	B.T.	D.T.	B.T.	D.T.	B.T.
Dry bulb	Wet bulb								
54.4	43.3	3.99	—	3.17	—	2.05	—	1.00	—
71.1	43.3	1.87	—	1.19	—	0.82	—	0.44	—
87.8	43.3	0.72	—	0.58	—	0.38	2.5—3.5	0.24	2.0—2.9
104.4	43.3	0.57	—	0.39	1.2—1.4	0.25	1.0—1.2	0.17	0.8—1.0
121.1	43.3	0.41	—	0.30	0.8—1.0	0.23	0.6—0.8	0.16	0.5—0.7

—A dash indicate no browning was observed during drying.

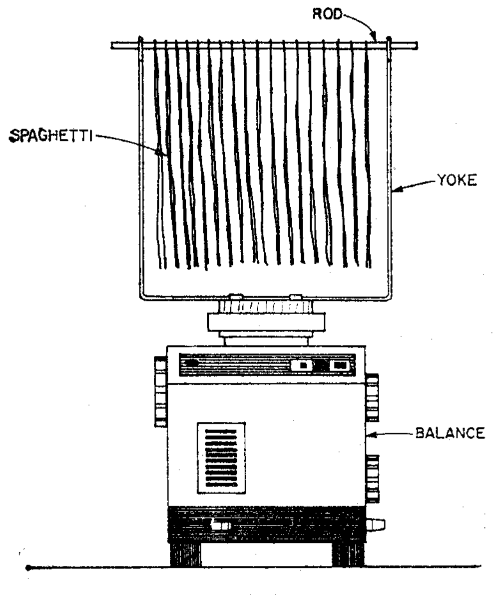

Fig. 3. Weighing assembly

Results and Discussion

The log $(-dX/d\theta)$ vs. log $(\bar{X}-X_e)$ curves plotted in Figures 4 through 8 contain two regions: a straight line region for moderate and low values of $(\bar{X}-\bar{X}_e)$, which occur in the latter part of drying; and a concave downward curved region for the initial period of drying. The extent of the straight line region is greatest for the 40% soak material, where it extends up to $(\bar{X}-X_e)$ equals 0.6 to 1.0, and lowest for unsoaked material, where it extends up to $(\bar{X}-X_e)$ equals 0.15 to 0.6. The curves are characterized in Table 2, which lists: $(-dX/d\theta)_1$ and $(-dX/d\theta)_{0.2}$, the values of $(-dX/d\theta)$ when $(\bar{X}-X_e)$ equals 1.0 and 0.2 respectively; and also the slope of the straight line region of the curve.

The slopes of the straight line regions range from 1.6 to 2.4. Though the trend is not wholly clear or consistent, on the average the slopes tend to increase slightly as the glycerine soak concentration increases. A slope of 1.0 would be expected if the final falling rate period

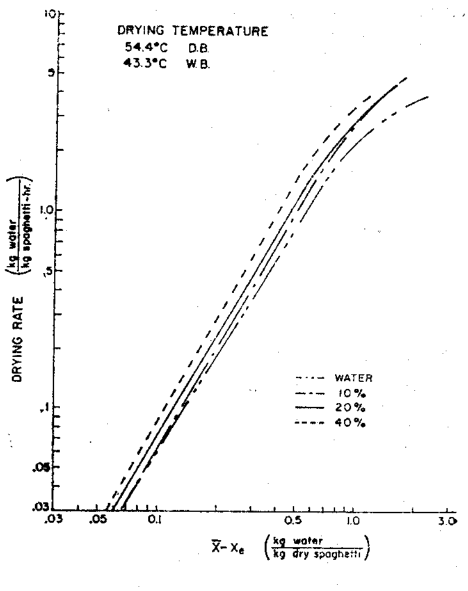

Fig. 4. Drying curve at 54.4°C (D.B.)

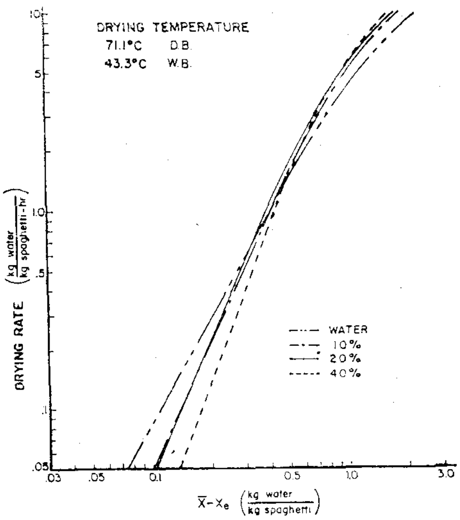

Fig. 5. Drying curve at 71.1°C(D.B.)

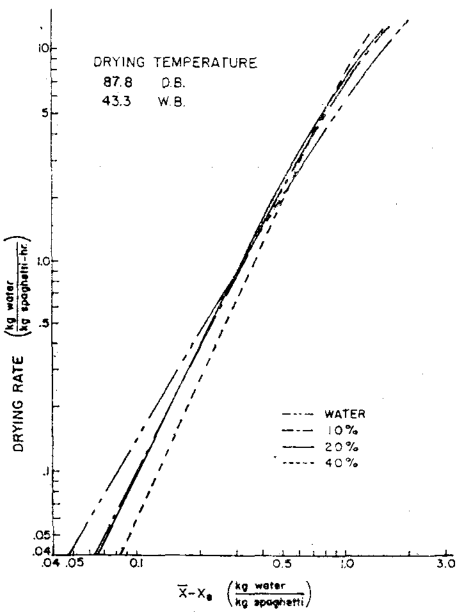

Fig. 6. Drying curve at 104.4°C(D.B.)

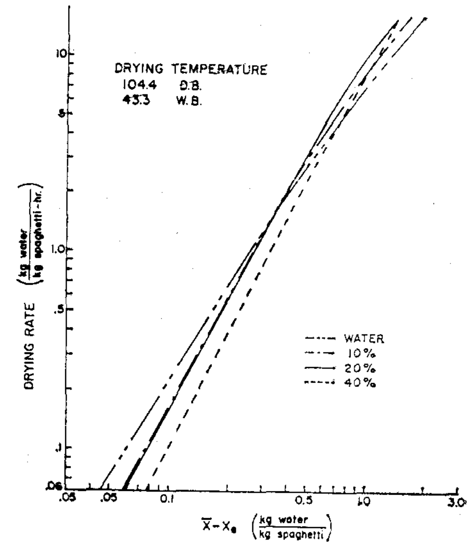

Fig. 7. Drying curve at 87.8°C(D.B.)

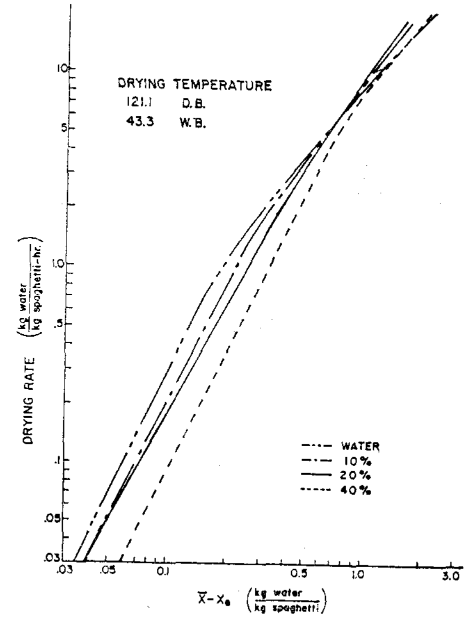

Fig. 8. Drying curve at 121.1°C(D.B.)

conformed to a typical model for constant drying conditions. When drying data for cellular solid foods is plotted in a similar manner, the log $(-dX/d\theta)$ vs. log $(\bar{X}-X_e)$ slope for the final falling rate period is usually very close to 1.0 (e.g. 1.0 for carrot dices, 1.2 for potato slices, and, based on the data of Chun and Kim[6] (1974), 0.8 for hot red peppers). Thus, the log $(-dX/d\theta)$ vs. log $(\bar{X}-X_e)$ slopes for drying spaghetti are quite different from those obtained with other solid foods. The $(-dX/d\theta)_1$ values characterize the drying rate during the initial period of drying. As might be expected these increase markedly as the drying temperature increases. The $(-dX/d\theta)_{0.2}$ values characterize the drying rates during the falling rate period. These values increase significantly as drying temperature increases for the 0%, 10% and 20% glycerine soake spaghetti, but the comparable increase for the 40%

Table 2. Drying curve characteristics.

Air temperature (dry bulb*)	Characteristics	Liquid soak glycerine concentration			
		0%	10%	20%	40%
54.4°C	slope	1.64	1.74	1.76	1.82
	$-(dX/d\theta)_1$	2.3	2.3	2.9	3.4
	$-(dX/d\theta)_{0.2}$	0.19	0.21	0.25	0.30
71.1°C	slope	1.72	2.17	2.28	2.39
	$-(dX/d\theta)_1$	4.2	5.0	5.5	5.5
	$-(dX/d\theta)_{0.2}$	0.29	0.23	0.23	0.14
87.8°C	slope	1.72	2.00	2.06	2.22
	$-(dX/d\theta)_1$	5.8	6.9	7.3	7.7
	$-(dX/d\theta)_{0.2}$	0.46	0.39	0.39	0.26
104.4°C	slope	1.65	1.85	1.91	1.98
	$-(dX/b\theta)_1$	6.0	7.0	9.8	7.0
	$-(bX/d\theta)_{0.2}$	0.67	0.59	0.59	0.38
121.1°C	slope	2.08	2.05	1.90	2.05
	$-(dX/d\theta)_1$	8.3	9.1	9.8	9.1
	$-(dX/d\theta)_{0.2}$	1.15	0.84	0.66	0.37

*Wet bulb temperature 43.3°C in all cases.

glycerine soaked spaghetti is much less marked. The curvature of the log $(-dX/d\theta)$ vs. log $(\bar{X}-X_e)$ plots in the high $(\bar{X}-X_e)$ region is greater at low temperatures than at high temperature.

At 121.1°C the highest air temperature tested the log $(-dX/d\theta)$ vs. log$(\bar{X}-X_e)$ plot for water soaked spaghetti consists of two straight line segments, one for low $(\bar{X}-X_e)$ values, which has a slope of 2.08 as cited in Table 2, and the other for high $(\bar{X}-X_e)$ values, which has a slope of 1.18. The average value of these two slopes is 1.63 which is close to 1.68, the average value of the slopes for the drying curves of water soaked spaghetti at lower drying temperatures.

Drying Times

The drying times required to reduce the spaghetti water activity to the a_w value which glycerine-free spaghetti would have when it contains 12% moisture (wet basis) were calculated from the drying weight loss data. At a 12% moisture content (0.1364 kg water/kg dry spaghetti) and room temperature the equilibrium relative humidity, and hence, the a_w for spaghetti is 0.65. At a relative humidity of 0.65, the equilibrium miosture content of an aqueous glycerine solution is 0.48 kg of water /kg of glycerine. Therefore, X_0, the value of X when a_w for the spaghetti at room temperature equals 0.65 is given by equation (1) :

$$X_0 = 0.1364 + \frac{G}{S}(0.48)\frac{\text{kg water}}{\text{kg dry spaghetti}} \quad (1)$$

The drying times were calculated by interpolating using the experimental $(\bar{X}-X_e)$ vs. time data to find that time at which (X_0-X_e) equalled $(X-X_e)$. X_e was calculated using equation (2) :

$$X_e = X_e^1 + \frac{G(X_e)}{S} \quad (2)$$

where X_e^1 and X_e are the respective equilibrium miosture contents for durum wheat and glycerine at the humidity conditions prevailing in the dryer.

The calculated drying times are listed in Table 1. It can be readily observed that as temperature increases the drying times decrease much more markedly than$(-dX/d\theta)_1$ and $(-dX/d\theta)_{0.2}$ increase. The primary reason for the very large reduction in drying time is a combination of the increase in drying rate at corresponding values of $(X\text{-}X_e)$ and the reduction in X_e with increased temperature. The reduction in X_e markedly increased the value of $(X\text{-}X_e)$ and hence the drying rate near the end of the drying process. However, since X_e tends to be very close to zero at temperatures higher than 95°C reduction in $(\bar{X}\text{-}X_e)$ became progressively less significant at high temperatures.

Browning

Marked browing occurred at the highest drying temperatures. The onset of browning was more rapid and the extent of browning was greater as the drying temperature and glycerine concentation increased. The effect of temperature would be readily expected. The effect of glycerine concentration is less well known. Glycerine does not take part in the Maillard reaction. Normally the Maillard reaction shows a peak in reaction rate at a_w s of about 0.67–0.75 (Loncin[7]), Karel and Labuza[8]), Labuza[9]). Eichner and Karel[10]) studying the Maillard reaction using a model system consisting of glycine and glucose found that maximum browning occurred at 0.4 when glycerine was added to the system.

The samples produced were markedly overdryed, thus the extent of browning was much greater than if the drying had been stopped at the desired value of X_0. The sample weighing times at which browning was first observed for particular samples were noted. Thus the true onset of browning had to occur between the preceding sample weighing time and weighing time at which browning was first observed. These time ranges are listed in Table 1 for the various drying and soaking conditions. In all instances where browning occurred, the browning time was very much longer than the drying time needed to produce the required X_0 values. Despite the absence of visible browning during the practical drying time range, the possibility of inducing delayed browning cannot be ruled out. Pigment formation does not occur during the early stages of the Maillard reaction sequence-but once these initial reactions occur they can induce delayed pigment formation.

Product Quality

The acceptability of resorting to higher drying temperatures to achieve shorter drying times depends on obtaining adequate product quality, particularly: free from fissures; a smooth product surface, and the absence of any significant color changes. These factors were evaluated for the spaghetti obtained at each drying temperature and glycerine soak concentration. In additjon the degree of plasticization was measured by: 1) measuring the maximum diameter of curvature at which spaghetti strand breakage occurred when the spaghetti was bent to conform to the surface of cylinders of progressively smaller diameter; and 2) measuring of the maximum per centage elongation which occurred before a strand failed in tension when pulled manually. Depending on whether or not the strand exhibited detectable elongation under manually applied tension it was rated elastic or not elastic. The unrehydrated dried spaghetti samples were also chewed to evaluate their texture. The results of these tests are listed in Table 3.

It should be borne in mind that the samples tested were overdried, with the degree of overdrying increasing as the drying temperature increased. Sample quality no doubt suffered from this overdrying. Thus processing conditions leading to a sample whose quality was marginal or slightly submarginal might well have yielded an acceptable product if the drying han been stopped at correct product moisture level. Taking this factor into consideration it

Table 3. Texture and appearance characteristics of dried spaghetti

Drying Temp. (°C)	Characteristics	Glycerine soak concentration			
		0 %	10 %	20 %	40 %
54.4	Fissures	some	none	none	none
	Surface finish	smooth, mottled	smooth, very shiny	smooth, very shiny	smooth, very shiny
	Breakable diam. (mm)	140	35	0	0
	Elastic	no	no	yes	yes
	Extension at failure	—	—	25～30%	25～30%
	Texture	hard	hard	hard chewy	chewy
	Other	translucent		translucent	translucent
71.1	Fissures	some	some internal	none	bands
	Surface finish	corrugated, mottled	smooth, slight mottling	shiny, smooth	smooth, shiny
	Breakable diam. (mm)	120	100	50	O, bads at 25
	Elastic	no	no	no	yes
	Extension at failure	—	—	—	25%
	Texture	hard	hard	tough	tough, chewy
	Other		slight microscopic limpling	translucent	translucent
87.8	Fissures	no	very few	none	none
	Surface finish	highly corrugated	finely corrugated	mottled, fine dimples	smooth, shiny
	Breakable diam. (mm)	>760	100	110	3, bands at 75
	Elastic	no	no	no	yes
	Extension at faiure	0%	—	—	5 to 10%
	Texture	crumbly, herd	Oard	tough	tough
	Other	translucent	opaque, light tan	translucent, tan	tan, translucent
104.4	fissures	no	very	none	none
	Surface Finish	highly corrugated	irregular, very finely corrugated	matte	matte to shiny
	Breakable diam. (mm)	>750	180	120	3, bands at 60
	Flastic	no	no	no	slghtly
	Extension al failure	—	—	—	2%
	Texture	crisp, hard	tough		tough to chewy
	Other			transl ut, tan	translucent, tan
121.1	Fissures	many	internal	none	none
	Surface finish	fine, corrugated	fluted	matte, some blisters	matte, dark brown
	Breakable diam. (mm)	>750	>750	130	125
	Elastic	no	No	no	no
	Extenson at failure	0%	—	—	—
	Texture	crispy, crumbly	crunchy	tough	tough
	Other	hollow center	brow	brown, opaque	burnt taste

appears that for a 43.3°C W.B. temperature: 1) glycerine-free spaghetti could not be dried successfully even at temperatures as low as 54.4°C; 2) spaghetti soaked in 10% glycerine could be dried successfully at 54.4°C and possibly at 71.1°C; 3) spaghetti soaked in 20% glycerine could be dried successfully at 71.1°C and possibly at 87.8°C; and 4) spaghetti soaked in 40% glycerine could be dried successfully at 87.8°C and possibly at 104.4°C.

The effects of plasticization are readily apparent in the marked reduction in breaking diameter as the glycerine soak concentration was increased. For samples dried at 71.1°C and lower, the 40% glycerine-treated spaghetti could be bent sharply double (zero bend diameter) without breaking. The 40% glycerine treated samples developed ring-like surface fissures or bands when flexed to the diameter listed beside the notation "bands" in Table 3. When such strands were pulled apart, failure occurred due to gradual necking down at the bands created by prior flexing or at bands which developed during pulling. Thus, such bands were not deep cracks and did not cause the propagation of deep cracks.

Based on the estimated tolerable drying temperatures and the calculated drying times listed in Table 1 : cooked spaghetti subjected to a 10 % glycerine soak could be dried in between 3.2 and 1.2 hours; for a 20% glycerine soak, spaghetti could be dried in between 0.8 and 0.4 hours; for 40% glycerine soaked spaghetti, drying could be accomplished in between, 0.24 and 0.17 hours. The greatest portion of the potential reduction in drying time can be achieved at low levels of glycerine addition and through the use of drying conditions which do not excessively reduce thermal efficiency. For example, the infusion of 0.15 kg of glycerine/kg-dry spaghetti and the use of 54.4°C D.B. 43.2°C W.B. drying temperatures could reduce drying time by 80% and the use of a 71.1°C D.B. could increase the percentage reduction to 93% (both compared to a normal 18 hour drying time).

A peculiar textural change was produced in the spaghetti subjected to the 10% glycerine soak and dried at 121.1°C. The surface became highly indented with flute like depressions. When chewed it was crisp to crunchy and had apleasant taste, It, therefore, might represent an attractive snack product. The glycerine-free spaghetti dried at 121.1°C was crisp to crumbly, had a hollowcore, and a bland taste. With the addition of suitable flavoring agents it also might be used as a snack product.

Rehydration

The measured weight increase per unit weight of as-is dried product during rehydration in 100°C boiling water is plotted in Figure 9 for glycerine-free spaghetti and various glycerine-soaked spaghetti is dried at 71.7°C. It can be seen that the rate of weight increase per unit weight of as-is dried product the is greatest for the glycerine-free spaghetti and decreases as the glycerine soak concentration increases, though the differences between the rates of weight increase for the various glyc-

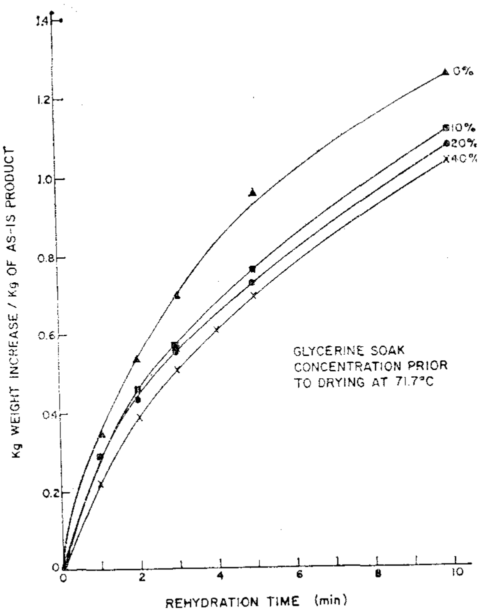

Fig. 9. Weight increase of spaghetti during rehydration in 100°C boiling water

erine contanining samples are not great. The faster weight increase of the glycerine-free product may be due to the fissures found in that product and to the fact that it has a greater surface to volume ratio than the glycerine contaning products. Similar behavior was observed for rehydration at 75°C and 25°C except that the rates of weight increase at 75°C and 25°C were respectively only roughly 0.28 and 0.40 times as large as the rates at 100°C.

Abstract

Cooked spaghetti soaked in 10%, 20%, and 40% aqueous glycerine solutions for ten minutes absorbed sufficient glycerine to plasticize that spaghetti during and after subsequent drying. The plasticizing action of the glycerine prevented fissuring(checking) and surface corrugation of the spaghetti at elevated drying temperature and large wet-bulb dry-bulb temperature difference. The drying temperature and the wet-bulb dry-bulb differences up to which such protection was provided as the glycerine soak concentration increased. Despite the reduction in drying rate, the drying time required to produce spaghetti with a water activity of 0.65 (the level normally required for stability) decreased as glycerine content increased. At high drying temperatures glycerine addition increased the extent of browning and shortened the period required to induce detectale browning, but in all instances browning started well after the product a_w reached the 0.65 value required for the completion of drying. Because glycerine addition reduced drying times at any given set of drying conditions and permitted the use of higher drying temperatures, relatively low levels of glycerine addition (e.g. 0.15 kg glycerine/kg dry spagetti) can shorten spagnetti drying times by roughly 80% and perhaps by as much as 93%.

Acknowledgement

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Nomenclature

a_w　Water activity

G　Weight of glycerine absorbed by spaghtti (kg)

S　Dry weight of spaghetti (kg)

X　Moisture content(kg-absorbed water/kg-dry spaghetti)

X_e　The mosture content of spaghetti in equilibrium with the dryer air(kg)

X_e^1　The moisture content of glycerine-free spaghetti in equilibrium with the dryer air(kg)

$\overline{X}_n$　The average moisture content of spaghetti during the n th drying interval(kg)

X_o　Moisture content at a_w of spaghetti 0.65

X_e　kg water/kg of glycerine for glycerine solution equilibrium with dryer air

θ　Drying time (hr)

$dX/d\theta$　Drying rate(kg water/kg dry spaghetti-hr)

$(dX/d\theta)_1$　Drying rate at $(\overline{X}-X_e)=1.0$ (kg water/kg dry spaghetti)

$(dX/d\theta)_{0.2}$　Drying rate when $(\overline{X}-X_e)=0.2$ (kg water/kg dry spaghetti)

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