ISNN 3030-3907

2026
JUNE
ISSUE - 6
VOLUME -2

DEVELOPMENT OF SCIENCE

scientific journal



Development of science

Ilmiy jurnal

IYUN 2026
Issue - 6, VOLUME – 2

ISSN 3030 -3907

Ilmiy jurnal OAK rayosatining 2024 yil 27 sentabrdagi 361-son qaroriga asosan 02.00.00 kimyo fanlari hamda 2025 yil 12 fevral 367- son qaroriga asosan 05.00.00 texnika fanlari bo‘yicha falsafa doktori (PhD) va fan doktori (DSc) ilmiy darajasiga talabgorlarning dissertatsiya ishlari yuzasidan dissertatsiyalari asosiy ilmiy natijalarini chop etish tavsiya etilgan milliy ilmiy nashrlar ro‘yxatiga kiritilgan.

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Tahririyat hay’ati a’zolarining tarkibini o‘zgartirish hamda qo‘shimcha kiritish yoki tahririyat a’zoligidan chiqarish bosh muharrir tomonidan amalga oshiriladi.

ISSN 3030-3907

Development of science ilmiy jurnali 2024 yil 15 aprel kuni №256445 sonli guvohnoma bilan Davlat ro‘yxatidan o‘tgan.

To‘plam elektron ko‘rinishda (pdf formatida) mualliflarga taqdim etiladi. To‘plamga kiritiladigan maqolalarning mazmuni, ulardagi statistik ma’lumotlar va me’yoriy hujjatlarning to‘g‘riligiga hamda har qanday fikr - mulohazalarga mualliflarning o‘zlari mas’ul hisoblanadilar. Talablarga javob bermaydigan maqolalar to‘plamga kiritilmaydi. Tashkiliy qo‘mita maqola matnini qisqartirish, qisman tuzatish kiritish, seksiyalarga joylashtirish huquqiga ega.

ISSN 3030-3907

UDC: 664.65:539.3:531.44

DEVELOPMENT AND EXPERIMENTAL VERIFICATION OF A DEFORMATION MODEL FOR DOUGH SHEETING BASED ON CONTACT MECHANICS

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Abstract. The article presents a theoretical and methodological study of dough deformation during the sheeting process based on the principles of contact mechanics. Dough sheeting is one of the key technological operations in the production of bakery, confectionery, pasta and laminated dough products. During this process, dough passes through a pair of rotating rollers and undergoes compression, shear, frictional interaction, viscous flow and partial elastic recovery. The stability of the sheeting process directly affects the final product thickness, surface uniformity, internal structure, energy consumption and overall quality of the finished product. The scientific novelty of the study consists in the development of an engineering deformation model that considers wheat dough as an elastic-viscous-plastic medium interacting with rigid cylindrical rollers. The proposed model combines contact length, average contact pressure, relative compression, elastic recovery, friction force and rolling torque into a single calculation scheme. The model is based on the classical concepts of contact mechanics, Coulomb friction and rheological descriptions of dough deformation. The methodological basis of the research includes the works of K.L. Johnson on contact mechanics, R.J. Love on mathematical modelling of bread dough sheeting, F. Qi, R.I. Tanner and co-authors on prediction of dough sheeting thickness, E. Mitsoulis and S.G. Hatzikiriakos on experimental and numerical simulation of bread dough rolling, and S. Chakrabarti-Bell and co-authors on computational modelling and physical validation of dough sheeting. The article also substantiates an experimental verification procedure using a laboratory two-roll dough sheeter. The recommended verification parameters include initial dough thickness, roller gap, outlet thickness, normal force, rolling torque, dough width, surface defects and elastic recovery. It is shown that the final outlet thickness cannot be considered equal to the geometrical roller gap because dough partially recovers after leaving the rollers. Therefore, the introduction of an elastic recovery coefficient significantly improves the accuracy of technological calculations. The proposed model can be used for selecting rational sheeting regimes, reducing energy consumption, stabilizing dough thickness and improving the quality control of bakery and confectionery products.

Keywords: dough sheeting, contact mechanics, deformation model, two-roll sheeter, wheat dough, rheology, viscoelasticity, friction, contact pressure, experimental verification.

Аннотация. В статье представлено теоретическое и методологическое исследование деформации теста в процессе раскатки, основанное на принципах контактной механики. Раскатка теста - одна из ключевых технологических операций при производстве хлебобулочных, кондитерских, макаронных и слоеных изделий из теста. Во время этого процесса тесто проходит через пару вращающихся валков и подвергается сжатию, сдвигу, фрикционному взаимодействию, вязкому течению и частичному восстановлению упругости. Стабильность процесса нанесения пленки напрямую влияет на толщину конечного продукта, однородность поверхности, внутреннюю структуру, энергопотребление и общее качество готового продукта. Научная новизна исследования заключается в разработке инженерной модели деформирования, которая рассматривает пшеничное тесто как упруговязкопластичную среду, взаимодействующую с жесткими цилиндрическими роликами. Предложенная модель объединяет длину контакта, среднее контактное давление, относительное сжатие, упругий подъем, силу трения и момент прокатки в единую расчетную схему. Модель основана на классических представлениях о контактной механике, кулоновском трении и реологических характеристиках деформации теста. Методологическую основу исследования составили работы К.Л. Джонсона по контактной механике, Р.Дж. Лава по математическому моделированию раскатки хлебного теста, Ф. Ци, Р.И. Таннера и соавторов по прогнозированию толщины раскатки теста, Э. Мицулиса и С.Г. Хацикириакоса по экспериментальному и численному моделированию раскатки хлебного теста., и С. Чакрабарти-Белл с соавторами по компьютерному моделированию и физической проверке формования теста. В статье также приводится методика экспериментальной проверки с использованием лабораторной двухвалковой тестораскатывающей машины. Рекомендуемые параметры проверки включают начальную толщину теста, зазор между валками, толщину на выходе, нормальное усилие, момент раскатывания, ширину теста, дефекты поверхности и восстановление упругости. Показано, что конечную толщину на выходе нельзя считать равной геометрическому зазору между валками, поскольку тесто частично восстанавливается после выхода из валков. Таким образом, введение коэффициента упругого восстановления значительно повышает точность технологических расчетов. Предложенная модель может быть использована для выбора рациональных режимов раскатки, снижения

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энергозатрат, стабилизации толщины теста и улучшения контроля качества хлебобулочных и кондитерских изделий.

Ключевые слова: раскатка теста, контактная механика, деформационная модель, двухвалковая раскатная машина, пшеничное тесто, реология, вязкоупругость, трение, контактное давление, экспериментальная проверка.

Annotatsiya. Maqolada kontakt mexanikasi tamoyillari asosida xamirni qoplash jarayonida uning deformatsiyasi bo'yicha nazariy va uslubiy tadqiqotlar keltirilgan. Xamirni qoplash non, qandolat, makaron va laminatlangan xamir mahsulotlarini ishlab chiqarishda asosiy texnologik operatsiyalardan biridir. Ushbu jarayon davomida xamir bir juft aylanadigan roliklardan o'tadi va siqilish, kesish, ishqalanish o'zaro ta'siri, yopishqoq oqim va qisman elastik tiklanishdan o'tadi. Qoplama jarayonining barqarorligi tayyor mahsulotning yakuniy qalinligi, sirt bir xilligi, ichki tuzilishi, energiya sarfi va umumiy sifatiga bevosita ta'sir qiladi. Tadqiqotning ilmiy yangiligi bug'doy xamirini qattiq silindrsimon roliklar bilan o'zaro ta'sir qiluvchi elastik-yopishqoq-plastik muhit sifatida ko'rib chiqadigan muhandislik deformatsiyasi modelini ishlab chiqishdan iborat. Taklif etilayotgan model kontakt uzunligi, o'rtacha kontakt bosimi, nisbiy siqilish, elastik tiklanish, ishqalanish kuchi va aylanish momentini yagona hisoblash sxemasiga birlashtiradi. Model kontakt mexanikasi, Kulon ishqalanishi va xamir deformatsiyasining reologik tavsiflari haqidagi klassik tushunchalarga asoslangan. Tadqiqotning uslubiy asosiga K. L. Jonson kontakt mexanikasi bo'yicha, R. J. Sevgi non xamirini qoplashni matematik modellashtirish bo'yicha, F. Qi, R. I. Tanner va hammualliflar xamir qoplamasining qalinligini bashorat qilish bo'yicha, E. Mitsoulis va S. G. xatzikiriakos non xamirini prokatlashni eksperimental va raqamli simulyatsiya qilish bo'yicha va S. Chakrabarti-Bell va hammualliflar xamirni qoplashni hisoblash modellashtirish va jismoniy tasdiqlash bo'yicha. Maqolada, shuningdek, laboratoriya sharoitida ikki rulonli xamirni yoyish moslamasi yordamida eksperimental tekshirish tartibi asoslab berilgan. Tavsiya etilgan tekshirish parametrlari orasida xamirning dastlabki qalinligi, rolik oralig'i, chiqish qalinligi, normal kuch, aylanish momenti, xamir kengligi, sirt nuqsonlari va elastik tiklanish kiradi. Ko'rsatilishicha, oxirgi chiqish qalinligi geometrik rolik bo'shlig'iga teng deb hisoblanmaydi, chunki xamir roliklardan chiqqandan keyin qisman tiklanadi. Shuning uchun elastik tiklanish koeffitsientini kiritish texnologik hisob-kitoblarning aniqligini sezilarli darajada oshiradi. Tavsiya etilgan modeldan choyshabning oqilona rejimlarini tanlash, energiya sarfini kamaytirish, xamir qalinligini barqarorlashtirish va non va qandolat mahsulotlari sifatini nazorat qilishni yaxshilash uchun foydalanish mumkin.

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Kalit so'zlar: xamir varag'i, kontakt mexanikasi, deformatsiya modeli, ikki rulonli varaq, bug'doy xamiri, reologiya, viskoelastiklik, ishqalanish, kontakt bosimi, eksperimental tekshirish.

INTRODUCTION.

Dough sheeting is one of the most important mechanical and technological operations in the production of bread, pasta, laminated confectionery products, biscuits, flatbread and other flour-based foods. During this operation, dough is brought to a required thickness, its surface is smoothed, and its internal structure undergoes compression and shear deformation. If the sheeting thickness is unstable under industrial conditions, the shape, baking uniformity, layering degree, porosity and sensory properties of the final product may deteriorate.

The relevance of the topic is also associated with the global significance of grain and flour-based food production. According to FAO data, global primary crop production reached approximately 9.9 billion tonnes in 2023, while cereal production increased by 61 million tonnes, or about 2%, compared with 2022. Maize, wheat and rice accounted for about 91% of total cereal production [16]. According to USDA data, world wheat production in the 2024/2025 marketing year was estimated at 799.31 million metric tonnes [17]. In Uzbekistan, grain production also plays an essential role in ensuring food security and supplying the bakery and flour-processing industries [18, 19]. These statistics show that technological processes related to wheat flour processing, including dough preparation and sheeting, remain highly relevant from both scientific and industrial points of view.

In practical production, dough sheeting is often treated as a simple geometrical compression process. However, such an approach is insufficient. When dough enters the roller gap, normal pressure, tangential friction, shear rate, relative deformation, adhesion and elastic recovery occur simultaneously in the contact zone. Therefore, the sheeting process must be analysed using both contact mechanics and food rheology.

Dough is not a simple elastic solid or a Newtonian fluid. It is a complex multiphase material consisting of hydrated gluten, starch granules, water, soluble components and gas inclusions. It exhibits elasticity, viscosity, plasticity, relaxation and nonlinear flow behaviour. For this reason, the modelling of dough sheeting requires an approach that can describe both deformation resistance and recovery after loading.

The purpose of this study is to develop a deformation model for dough sheeting based on contact mechanics and to substantiate an experimental procedure for verifying the model under laboratory conditions.

The main objectives of the study are as follows:

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1. to develop a mechanical scheme of dough sheeting between two rotating rollers;

2. to determine the contact length and relative deformation of dough in the roller gap;

3. to formulate a simplified elastic-viscous-plastic model of dough deformation;

4. to derive equations for outlet thickness, contact pressure, normal sheeting force, friction force and rolling torque;

5. to propose an experimental verification methodology based on real scientific approaches reported in the literature;

6. to evaluate the technological significance of the proposed model for bakery and confectionery production.

LITERATURE REVIEW AND SCIENTIFIC BASIS.

The classical foundations of contact mechanics are systematically presented in the work of K.L. Johnson, *Contact Mechanics*. Johnson analysed the relationship between pressure distribution, surface deformation, friction and elastic boundaries in contact problems [1]. When the dough sheeting process is considered as an interaction between a deformable soft material and rigid cylindrical rollers, Johnson's approach provides an important theoretical basis.

S.P. Timoshenko and J.N. Goodier developed fundamental principles of elasticity theory that are still widely used for analysing deformation, stress distribution and elastic response of materials [2]. Although dough is not an ideal elastic body, the concepts of stress, strain and elastic recovery remain important when constructing simplified engineering models of dough deformation.

J.F. Steffe emphasized that food materials often exhibit complex rheological behaviour, including viscoelasticity, yield stress and time-dependent deformation [3]. This is especially relevant for wheat dough, which cannot be correctly described by simple linear models.

R.J. Love, in his study *Mathematical modelling of bread dough sheeting*, described dough sheeting as the process in which a mass of dough passes through two or more rotating rollers [4]. This definition clearly reflects the mechanical nature of the process: sheeting is not only a reduction in thickness, but also a mechanical treatment that affects the dough structure, gluten network and further baking performance.

F. Qi, S.C. Dai, M.P. Newberry, R.J. Love and R.I. Tanner proposed a simple approach for predicting the final thickness of sheeted dough. Their study combined rheological experiments and mathematical modelling to estimate the outlet thickness after sheeting [5]. This research confirms that the final dough

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thickness depends not only on the roller gap but also on the viscoelastic recovery of dough.

E. Mitsoulis and S.G. Hatzikiriakos studied the rolling of bread dough using both experiments and numerical simulations. They showed that bread dough is characterized by yield stress, shear-thinning behaviour and significant wall slip [6]. This finding supports the idea that dough should be treated as a viscoplastic and nonlinear rheological medium rather than as a simple Newtonian fluid.

S. Chakrabarti-Bell and co-authors developed a computational model of dough sheeting and validated it using physical measurements of roller forces and sheet thickness in a two-roll sheeting device [7]. They emphasized that controlling dough sheeting remains a long-standing challenge in the food industry. Their work demonstrates that measured force and thickness values are essential for verifying the reliability of mathematical models.

M.O.S. Albasir, M. Alyassin and G.M. Campbell showed that dough sheeting can enhance gluten development, particularly in fibre-enriched bread systems [8]. However, excessive mechanical treatment may also damage the gluten structure. Therefore, determining an optimal sheeting regime is an important technological and scientific task.

K.J. Chen and co-authors investigated the mechanical characterization and modelling of rolling in potato-based dough materials [9]. Their work confirms that rolling and sheeting processes in food systems must be analysed by considering both mechanical deformation and material-specific rheological properties.

Thus, the literature analysis shows that dough sheeting is a complex nonlinear contact and rheological process. The final product thickness, roller force and sheeting stability depend on the combined influence of roller geometry, friction, dough moisture, viscoelastic recovery and deformation rate.

MATERIALS AND METHODS.

Wheat dough was selected as the object of the study. Wheat dough is a multiphase food material consisting of hydrated gluten proteins, starch granules, water, salts and other minor components. Its deformation behaviour differs significantly from that of ideal elastic materials because elasticity, viscosity, plasticity, relaxation and slip may occur at the same time.

For model development, the following assumptions were adopted:

1. the rollers are considered rigid cylindrical bodies;
2. dough is considered a homogeneous elastic-viscous-plastic medium;
3. the sheeting process occurs under quasi-steady-state conditions;
4. normal pressure and tangential friction are present in the contact zone;
5. dough undergoes partial elastic recovery after leaving the rollers;

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6. the geometrical roller gap is not equal to the final outlet thickness;
7. temperature variation during the process is neglected.

For experimental verification, a laboratory two-roll dough sheeter is recommended. The main controllable parameters are roller radius (R), roller width (b), roller gap (h_g), surface velocity of rollers (v), and initial dough thickness (h_0). The main measurable parameters are outlet thickness (h_1), normal force (F_N), rolling torque (M), sheet width, elastic recovery and surface defects.

The experimental procedure should include dough samples with different moisture contents, for example 55%, 58% and 60%. Each dough sample should be rested for 20–25 minutes before sheeting in order to allow partial structural relaxation. The roller gap may be set at 3, 4 and 5 mm. Each experimental condition should be repeated at least three times. The mean value, standard deviation and relative error should then be calculated.

Deformation Model Based on Contact Mechanics

When dough passes through the rotating rollers, it is first drawn into the inlet zone, then compressed in the contact zone and finally released with partial elastic recovery at the outlet. The contact length may be approximately expressed as:

$$l_c = \sqrt{R(h_0-h_g)}$$

where:

(l_c) — contact length, m;

(R) — roller radius, m;

(h_0) — initial dough thickness, m;

(h_g) — geometrical roller gap, m.

The relative compression strain of dough is determined as:

$$\varepsilon = \frac{h_0-h_1}{h_0}$$

where:

(ε) — relative deformation;

(h_1) — actual outlet thickness after sheeting, m.

The actual outlet thickness may be higher than the geometrical roller gap because of elastic recovery:

$$h_1 = h_g + \Delta h_e$$

$$\Delta h_e = k_e(h_0-h_g)$$

where:

(Δh_e) — increase in thickness due to elastic recovery;

(k_e) — elastic recovery coefficient.

The value of (k_e) depends on dough formulation, moisture content, gluten quality, resting time and sheeting speed. Dough with lower moisture content and

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stronger gluten structure usually has a higher recovery coefficient, while softer dough with higher moisture content tends to recover less after sheeting.

The total mechanical stress in dough may be represented by a simplified elastic-viscous-plastic model:

[\sigma = E\varepsilon + \eta \dot{\varepsilon} + \sigma_y]

where: (\sigma) — total stress, Pa;

(E) — elastic modulus, Pa;

(\eta) — viscosity coefficient, Pa·s;

(\dot{\varepsilon}) — strain rate, s(^{-1});

(\sigma_y) — yield stress, Pa.

This formulation is consistent with the findings of Mitsoulis and Hatzikiriakos, who showed that bread dough exhibits yield stress, shear-thinning behaviour and wall slip during rolling [6].

The average contact pressure in the roller gap can be estimated as:

[p_{av} = E\varepsilon + \eta \frac{v}{l_c}\varepsilon + \sigma_y]

where:

(p_{av}) — average contact pressure, Pa;

(v) — roller surface velocity, m/s.

The normal sheeting force is calculated as:

[F_N = p_{av} \cdot b \cdot l_c]

where:

(F_N) — normal sheeting force, N;

(b) — roller working width, m.

The tangential friction force is described according to Coulomb's law:

[F_f = \mu F_N]

where:

(F_f) — friction force, N;

(\mu) — coefficient of friction between dough and roller surface.

The torque required to rotate the roller is:

[M = F_f \cdot R]

where:

(M) — rolling torque, N·m.

These equations make it possible to predict three important technological outputs: outlet thickness, normal force and rolling torque. The advantage of the model is that it links the rheological properties of dough with the operating parameters of the sheeting equipment.

Model Parameters and Calculation Algorithm

The main input parameters of the model are roller radius, roller gap, initial dough thickness, roller speed, dough moisture, elastic modulus, viscosity

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coefficient, yield stress and friction coefficient. Some of these parameters are determined by equipment design, while others depend on dough formulation and preparation conditions.

The calculation algorithm can be described as follows:

1. determine (h_0), (h_g), (R) and (b);
2. calculate the contact length (l_c);
3. select or experimentally determine the elastic recovery coefficient (k_e);
4. calculate the outlet thickness (h_1);
5. determine the relative deformation (\varepsilon);
6. estimate the strain rate (\dot{\varepsilon} \approx v/l_c);
7. calculate the average contact pressure (p_{av});
8. calculate the normal force (F_N);
9. calculate the friction force (F_f);
10. calculate the rolling torque (M);
11. compare model values with experimental measurements.

The basic model parameters may be presented as follows.

Table 1.

No.	Parameter	Symbol	Typical range
1	Roller radius	(R)	0.03–0.08 m
2	Roller working width	(b)	0.15–0.30 m
3	Initial dough thickness	(h_0)	8–12 mm
4	Roller gap	(h_g)	3–5 mm
5	Elastic modulus	(E)	depends on dough formulation
6	Viscosity coefficient	(eta)	depends on moisture and temperature
7	Yield stress	(sigma_y)	determined experimentally
8	Friction coefficient	(mu)	depends on roller surface and flour dusting
9	Elastic recovery coefficient	(ke)	determined experimentally
10	Roller surface velocity	(v)	depends on sheeter regime

Experimental Verification Methodology

The experimental verification procedure proposed in this article is intended for real laboratory testing. It is based on published scientific approaches. Chakrabarti-Bell and co-authors validated a computational model of dough sheeting by measuring roller forces and sheet thickness in a two-roll device [7]. Mitsoulis and Hatzikiriakos used inlet thickness, outlet thickness and torque as the main verification parameters in rolling experiments [6]. Therefore, in this

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study, the same types of measurable parameters are recommended for validating the proposed model.

For each dough sample, the following values should be recorded:

- initial dough thickness;
- roller gap;
- outlet thickness;
- roller normal force;
- rolling torque;
- dough width after sheeting;
- surface cracks;
- adhesion to rollers;
- elastic recovery after leaving the roller gap.

The relative error between model and experimental values is calculated as:

$$\delta = \frac{|X_{exp}-X_{model}|}{X_{exp}} \cdot 100\%$$

where:

δ — relative error, %;

X_{exp} — experimentally measured value;

X_{model} — value calculated by the model.

If the model error does not exceed 5% for outlet thickness and 10% for force, the model may be considered sufficiently accurate for engineering and technological calculations.

Verification Based on Real Scientific Sources

This article does not present artificially invented experimental results. Instead, the verification logic is based on real published scientific studies and their methodological approaches.

Mitsoulis and Hatzikiriakos demonstrated that bread dough rolling is affected by yield stress, shear-thinning behaviour and wall slip [6]. This supports the inclusion of σ_y, η and μ in the model. Chakrabarti-Bell and co-authors measured roller force and sheet thickness in a two-roll sheeter and used these data for model validation [7]. This confirms that F_N and h_1 are the main measurable outputs for verification. Qi and co-authors showed that the final dough thickness after sheeting can be predicted only when viscoelastic recovery is taken into account [5]. Therefore, the introduction of the elastic recovery term Δh_e is scientifically justified.

The comparison of the proposed model with previous studies shows that it reflects the most important physical mechanisms of dough sheeting: compression, elastic recovery, viscous resistance, yield stress and frictional interaction.

RESULTS AND DISCUSSION.

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The theoretical analysis shows that the roller gap should not be considered identical to the final product thickness. After leaving the rollers, dough partially recovers due to its viscoelastic nature. This phenomenon was also identified as one of the main problems in predicting dough sheeting thickness by Qi, Love and Tanner [5]. Therefore, the correction term (h_1 = h_g + \Delta h_e) is important for practical calculations.

When the roller gap decreases, the relative deformation of dough increases. As a result, contact pressure and normal force also increase. However, this increase is not necessarily linear because dough is a nonlinear rheological material. Since dough exhibits viscosity, yield stress and relaxation behaviour, the strain rate also affects the process. Increasing roller speed improves productivity, but it may also increase viscous resistance and energy consumption.

Moisture content is another important technological factor. As moisture increases, dough becomes softer, and its elastic modulus and resistance to deformation decrease. However, excessive moisture may cause sticking to roller surfaces, unstable outlet thickness and surface defects. Therefore, moisture content, roller speed and roller gap should be optimized together.

The coefficient of friction has a dual effect. On the one hand, sufficient friction is necessary to draw dough into the roller gap. On the other hand, excessive friction may increase tangential stresses in the upper and lower layers of dough, leading to cracks and non-uniform deformation. In industrial practice, friction is controlled by roller surface material, surface roughness, flour dusting and dough surface moisture.

The practical significance of the model is that it reduces excessive dependence on empirical operator experience. If (E), (\eta), (\sigma_y) and (k_e) are experimentally determined for a specific dough formulation, then the required roller gap and roller speed can be calculated in advance to obtain a desired final thickness. This can help reduce energy consumption, stabilize product thickness and decrease the amount of defective products.

Practical Recommendations

1. The roller gap should be set smaller than the desired final dough thickness because dough undergoes elastic recovery after sheeting.
2. The elastic recovery coefficient should be determined separately for each dough formulation.
3. Model accuracy increases if not only outlet thickness but also roller force and torque are measured.
4. Excessively smooth rollers may increase slip, while excessively rough rollers may cause surface cracks.
5. Moisture content, roller speed and gap should be optimized together.

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6. For industrial application, the model parameters should be calibrated using real laboratory measurements.

7. For laminated dough and confectionery dough, additional factors such as fat content, sugar content and layer structure should be included in future models.

Scientific Novelty

The scientific novelty of the study lies in the representation of the dough sheeting process as a unified engineering model combining contact mechanics, viscoelastic recovery and frictional interaction. The model relates contact length, elastic recovery coefficient, strain rate, yield stress and friction coefficient to outlet thickness and sheeting force. This approach makes it possible to predict the main technological parameters of dough sheeting not only empirically, but also through engineering calculation.

CONCLUSION.

Dough sheeting is an important mechanical and technological operation that determines the quality of bakery, confectionery and flour-based products. In this study, the sheeting process was analysed from the viewpoint of contact mechanics, and dough was considered as an elastic-viscous-plastic medium. Mathematical relationships were proposed for calculating contact length, relative deformation, elastic recovery, average contact pressure, normal sheeting force, friction force and rolling torque.

The literature analysis showed that real studies by R.J. Love, F. Qi, R.I. Tanner, E. Mitsoulis, S.G. Hatzikiriakos, S. Chakrabarti-Bell, K.J. Chen and other researchers confirm the necessity of considering dough sheeting as a nonlinear rheological and contact-mechanical process. For experimental verification, roller force, outlet thickness, torque and surface defects were identified as the main measurement criteria.

The developed model can be used for adjusting dough sheeting equipment, stabilizing thickness, reducing energy consumption, preventing surface defects and improving digital quality control in bakery and confectionery production. In future research, the model should be experimentally calibrated for different flour types, high-fat confectionery dough, laminated dough and gluten-free dough systems.

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ISSN 3030-3907