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Simulation of dosage process of viscous products

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1. Introduction

A number of filling and folding technologies are available for wrapping pasty products, such as butter, melted cheese, etc. A basic principle, which is generally common for almost all these technologies is that the product is filled into a preformed wrapper bag, subsequently folded and calibrated. Overall simplicity of the principle itself usually covers a number of complicated subtasks to be fulfilled when developing packing machinery. Accuracy, reliability and safety of filling, a nice, sharp-edged shape of final pack of the product whose consistency may vary a lot (from solid to a very soft) are among them. Various methods are used when trying to achieve an acceptable result, but experimental (empirical) methods combined with practical experience and the digital simulation of viscous fluid flow are among those used most commonly. Serious disadvantages of experimental methods are the long process time and the related high cost, therefore simulation is becoming more and more common nowadays.

The study of viscous fluid flow phenomenon has a long and distinguished history, dating back to Taylor [1]. After Taylor viscous fluids were introduced to computer graphics by Miller & Pearce [2], who extended particle systems with inter-particle forces to approximate melting and flowing of viscous substances. The first work in computer graphics to simulate viscous fluids using the 3D Navier-Stokes equations was Foster & Metaxas [3]. Stam [4] introduced an implicit viscosity solve which enabled much larger time steps, greatly improving simulation efficiency. Carlson et al. [5] adapted the classic decoupled solve model to handle free surface liquids and variable viscosity. Rasmussen et al. [6] studied the case of free surface variable viscosity, but rather than dropping terms they eliminated the coupling between velocity components by proposing a combined implicit-explicit integration scheme. Several papers have examined non-Newtonian fluids, i.e. fluids whose stress is non-linearly related to the strain rate, and whose behaviour lies on the continuum between fluid and solid. Zhu & Bridson [7] added a simplified frictional plasticity model to a fluid simulator to animate the motion of sand. To simulate large viscoplastic flow Bargteil et al. [8] added remeshing and basis updates to the invertible finite element method of Irving et al. [9]. Wojtan & Turk subsequently extended this scheme with an embedded deformation method and an explicit surface tracker to retain thin features and speed up meshing [10]. Goktekin et al. introduced an explicit method for simulating viscoelastic liquids [11], by adding an elasticity step to a fluid simulator based on an estimate of accumulated strain. Batty & Bridson [12] presents new method which is fully implicit and unconditionally stable, and properly handles rotation and correctly capturing the true free surface boundary condition, and can capture the buckling of purely viscous Newtonian fluids. There are also examples of SPH methods [13], vorticity-based methods [14], and Lattice Boltzmann methods [15] that support viscous fluids, though none in graphics have displayed viscous buckling. In computational physics, a few papers have successfully tackled this phenomenon including the SPH method of Rafiee et al. [16] and the unstructured mesh finite element method of Bonito et al. [17]. Also a lot of effort was made trying to model a 3D Flow of fluids analytically. For example, Hyoseob et al. [18] adopt one-dimensional flow model by Jang et al. for computation of advecting property of fluid momentum in two or three-dimensional directions. This method produce zero numerical error during one time increment so that it is distinguished from any other numerical scheme which produces small or large numerical error within one time increment.

Despite achievements within viscous fluid flow modelling, a number of issues still remain problematic. Most of the studies focus on development of various visualization tools used mainly for demonstration of the machine and/or product behaviour, while quantitative analysis of product flow, which is important for development of real machinery, was paid little attention so far as well as the product flow and a character of its levelling in the areas containing free surfaces.

This study focuses on quantitative analysis of transient flow of viscous incompressible material from inside of the nozzle to outside into a forming box whose bottom and sides are fixed dimension surfaces while its top is free and makes no restrictions to the free flow of the material. A special numerical computational fluid dynamics (CFD) model was developed, which takes into account not only a real shape of elements neighbouring the transient zone, but also the upward-downward movement of the box during the filling cycle. As a result a 3-D character of the material spread in the box, including levelling is being analyzed as a function of movement law of the forming box and the changing operational speed of filling machine.

2. Method and computational model

Numerical computational model was developed based on finite element analysis (FEA) code ANSYS AUTODYN (Swanson Analysis Systems, Inc., Houston, TX, USA). The model is applicable to a complex shape of the nozzle, enables investigation of the process at various rates of product viscosity, discharge speed and takes into account vertically and both directions moving forming box at variable speed.

In what follows, the constitutive model together with the selection of necessary material parameters for the model, and the geometry and boundary conditions adopted are described.

An elasto - viscoplastic model, provided within the material response library of the finite element code AUTODYN, was selected for the description of the flow behavior of the viscous material, like butter. The essential components of the model are described below.

The total strain, ε, is decomposed into elastic, ε^{el}, and plastic, ε^{pl}, components so that the total strain rate, $\dot{\varepsilon}$, can be expressed as:

$$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{pl}, \tag{1}$$

where $\dot{\varepsilon}^{el}$ and $\dot{\varepsilon}^{pl}$ represent the elastic and inelastic strain rates, respectively.

The elastic part is treated as being linear and was expressed in Cartesian index notation as:

$$\dot{\varepsilon}_{ij}^{el} = \frac{1+\nu}{E}\dot{S}_{ij} + \frac{1-2\nu}{3E}\dot{\sigma}_{kk}\delta_{ij}, \tag{2}$$

where E is the Young's modulus, ν the Poisson's ratio, $\dot{\sigma}$ the rate of change of stress and $\dot{S}$ is the rate of change of the deviatoric stress. The plastic term is defined as:

$$\dot{\varepsilon}^{pl} = \frac{3}{2}\dot{\bar{\varepsilon}}^{pl}\frac{S}{\bar{\sigma}}, \tag{3}$$

where S and $\bar{\sigma}$ represent the deviatoric and equivalent stresses, respectively, and $\dot{\bar{\varepsilon}}^{pl}$ is the equivalent inelastic strain rate which is defined as:

$$\dot{\varepsilon}^{pl} = 0 \text{ for } \bar{\sigma} < \sigma_0, \tag{4}$$

$$\dot{\varepsilon}^{pl} = \left(D\frac{\bar{\sigma}}{\sigma_0} - 1\right)^p \text{ for } \bar{\sigma} \geq \sigma_0, \tag{5}$$

where σ_0 is the static equivalent yield stress, and D and p are material parameters that contain the flow consistency and flow index, respectively. The material parameters D and p were calculated by the following procedure.

The shear stress form of the Herschel-Bulkley relationship is transformed to its uniaxial form. For a material that obeys the von Mises criterion, the uniaxial form of the Herschel-Bulkley relationship, may be obtained from the graph of shear stress against shear strain rate by plotting $\tau = \sigma/\sqrt{3}$ as a function of $\dot{\gamma}^{pl} = \sqrt{3}\dot{\varepsilon}^{pl}$ from its shear-form equation.

Herschel-Bulkley relationship may be written as:

$$\sigma = \sigma_0 + k\left(\dot{\varepsilon}^{pl}\right)^n, \tag{6}$$

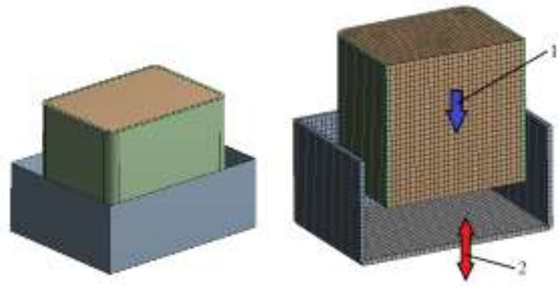
where k is the plastic flow consistency.

Because $\sigma_0 = \sqrt{3\tau_0}$ and $k = k_{sc}\left(\sqrt{3}\right)^{1+n}$ we can obtain, that:

$$\sigma = \sigma_0 + \left(\frac{\sigma_0}{D^{1/p}}\right)\left(\dot{\bar{\varepsilon}}^{pl}\right)^{\frac{1}{p}}. \tag{7}$$

As may be seen from the above material model description, the material is assumed to exhibit no work hardening. In other words, a constant static yield stress value exists as the strain rate approaches zero. Hence, the flow behaviour of the paste is described by an elasto-viscoplastic material constitutive model, without work hardening [18].

Several modifications of CFD model applicable to the variable shape of discharge nozzle have been developed enabling for 3-D flow simulation of the product with different visco-elastic properties and different flow rates (speed). Besides, the models take into account a cyclic upward-downward movement of the forming box, which has been used as a mean to guarantee a perfect filling of the box corners with the product as well as provide as even as possible the top profile (levelling) of the product portion. Fig. 1 presents a physical (a) and a FEA (b) model of the installation used for viscous product dosing into the 200 gr. packs.



a b

Fig. 1 Computational model: a - geometrical b - finite element (fragment): *1* - direction of movement of viscous material, *2* - direction of movement of forming box

The developed models were used to calculate flow of the material with different properties and at various capacities.

Mechanical characteristics of viscous material are shown in Table.

Table

Mechanical properties of viscous material

Property	Value	Unit
Density	918	kg m^{-3}
Dynamic viscosity	80	Pa s
Shear modulus	200000	Pa
Gruneisen coefficient	1.18	
Parameter C1	2908	m s^{-1}
Parameter S1	1.56	
Parameter quadratic S2	0	m s^{-1}

3. Results of numerical simulation

A filling process of the product with properties comparable to butter at 15ºC was investigated. Pack size was set to be 200 gr. and filling capacity rate 2.5 packs per second. It was supposed that forming box can be moved vertically against the nozzle during the product discharge cycle at a variable speed. The aim was to get an optimal law of the box movement in order to guarantee a proper filling of the box corners and leveling of top surface, which was expected to be as even as possible in order to guarantee a nice shape of final pack.

As an example, distribution of total displacements for material with viscosity comparable to butter of the product at different time of forming are presented on Fig. 2. Discharge time of the dose was set to be 0.1166 s, while the box speed law corresponds to Fig. 3.

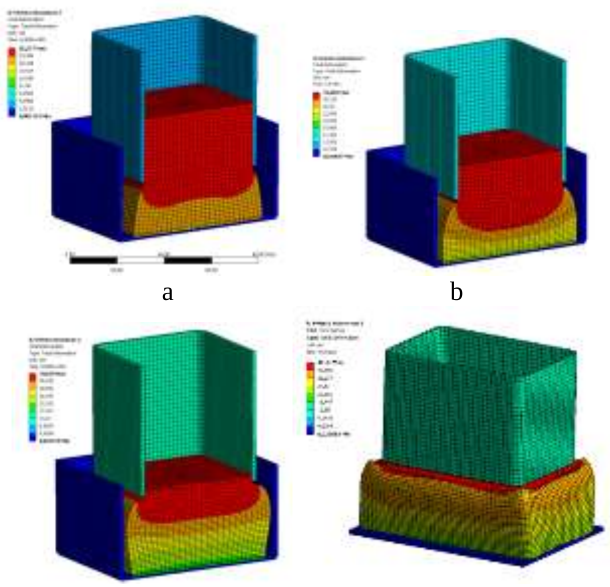


Fig. 2 Simulation results of the butter-like product discharge into a rectangular forming box with partially free top surface: a - distribution of total displacement after 0.0055 s after the discharge start; b - distribution of total displacement after 0.007 s after the discharge start; c - distribution of total displacement after 0.0085 s after the discharge start; d - distribution of total displacement after 0.009 s after the discharge start

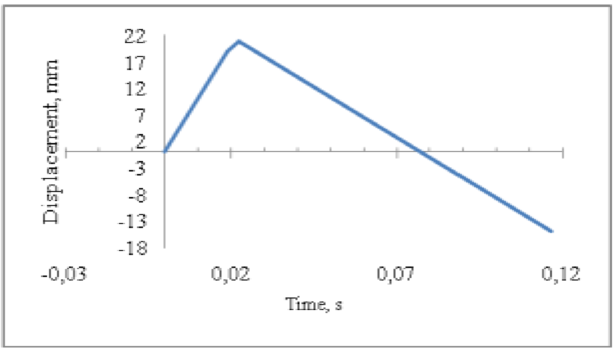


Fig. 3 Forming box speed law (Ansys-Autodyn boundary conditions (displacement versus time) for forming box movement

Fig. 4 illustrates the different forming laws of the forming box movement have been analyzed in these studies. Discharge time was set to 0.1166 s (this value correspond the capacity rate 2.5 packs per second on rotor type packing machines). In all cases mechanical properties of viscous material was set as mentioned above.

The worst results were obtained with laws series 2 and 3 of forming box movement (Fig. 4), although to realize these laws practically is easiest way (especially law of box movement series 2). The best results were obtained when forming box moves according law series 1 and 7.

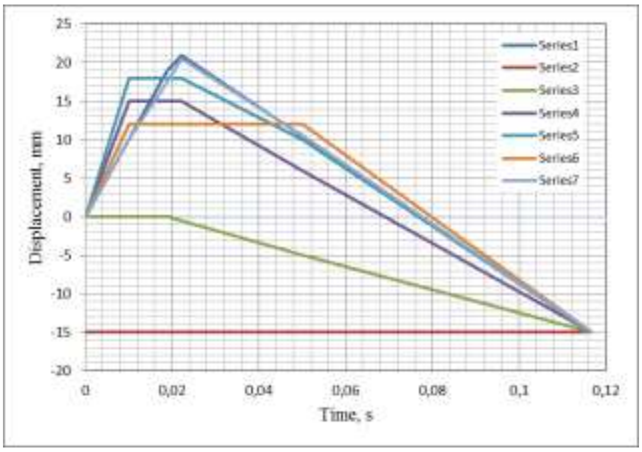


Fig. 4 The different forming laws of the forming box movement

A filling process of the product with properties different to butter properties also was made. Numerical analysis performed at different levels of viscosity of the product (30 – 100 Pa s) indicate tight relationship between the viscosity and the shape of the product portion discharged into the box. The lower viscosity gives the better filling quality of the box, including levelling of top surface. On another hand the best results were also obtained when forming box moves according law series 1.

The finite element model results are in good correlation with experimental results obtained in butter filling and wrapping machine type ARM (FASA).

4. Conclusions

1. A numerical computational fluid dynamics (CFD) model applicable for numerical simulation of filling process of movable open-top forming box with butter-like pasty product has been developed. The model enables calculation of 3-D parameters of the product flow at various product discharge speed and viscosity level rates.

2. Research performed at different levels of viscosity of the product indicate tight relationship between the viscosity and the shape of the product portion discharged into the box. The lower viscosity gives the better filling quality of the box, including levelling of top surface.

3. The filling quality of the box is dependent on the speed the box is being moved during the filling. Too high speed rate causes poor filling of the box in it‘s corner areas, while too low speed causes overfilling.

4. High viscosity makes the filling of corner areas problematic. Further increase of viscosity causes incomplete filling even of bottom corners of the box irrespectively of the box movement speed and law.

5. Box movement towards the nozzle in the initial stage of the product discharge and backwards in its later stage is favourable for quality filling and helps to fully fill all corners of the box.

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KLAMPIŲ PRODUKTŲ DOZAVIMO PROCESO SKAITINĖ ANALIZĖ

R e z i u m ė

Straipsnyje pateiktas klampaus produkto, pavyzdžiui, sviesto, dozavimo proceso modeliavimas laike naudojant skaitinius metodus. Modelis įgalina modeliuoti produkto dozavimo procesą, kai produktas išstumiamas iš antgalio į judančią pagal užduotą dėsnį atvirą pakuotę, įvertinant klampios masės laisvo paviršiaus elgseną. Atlikus skaičiavimus surastas racionalus formos į kurią dozuojamas produktas judėjimo dėsnis siekiant gauti maksimaliai gražią fasuojamo produkto formą, t.y. taisyklingą, stačiakampę pakuotės formą ir lygius jospaviršius.

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SIMULATION OF DOSAGE PROCESS OF VISCOUS PRODUCTS

S u m m a r y

The paper presents an investigation of transient flow of viscous incompressible material from inside of the nozzle to outside in to a forming box by using specially developed 3-D numerical model. Model is fitted for quantitative analysis of product flow parameters in the area, which is characterised as having free surfaces and makes no restrictions to free flow of the product. An optimal law of the forming box movement was obtained in order to improve the box filling quality and guarantee a nice product levelling of it’s free top surface.

Keywords: viscous products, dosage, numerical simulation.

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