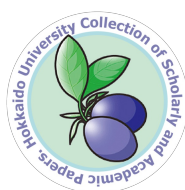




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An idea of a facile rheometry for evaluating shear-thinning viscosity

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A facile rheometry for estimating the shear-thinning viscosity of fluid foods based on their spreading behavior is proposed for on-site evaluation. The method called the gap flow test (GFT) aims to inversely estimate the rheological parameters K and n in the power-law model quantitatively by analyzing the temporal evolution of the radial spreading in the gap between parallel disks. Inspired by the line spread test used in clinical sites, GFT retains its simplicity on the operation and affordability while enhancing reproducibility by preventing unstable spreading due to individual differences or material factors. The rheological parameters were estimated via a preconstructed database linking spreading characteristics to the rheological properties measured by rheometers. Numerical simulations based on a physical model describing spreading in GFT clarified how K and n influence the spreading dynamics. Validation tests of the method with homogeneous and heterogeneous fluids demonstrated that despite the current sparse database and the use of a simple fitting regression plane, the values of the properties obtained provide good estimations. The corresponding errors were attributable to extrapolation or insufficient shear, both of which could be mitigated by refining experimental conditions and expanding the database.

I. INTRODUCTION

A. Background

With the global increase in the aging population, the prevalence of dysphagia and aspiration pneumonia has become a significant public health concern^{1,2}. This issue is particularly pronounced in Japan, where population aging is especially severe, and the proportion of aspiration pneumonia among all cases of pneumonia is notably high^{3,4}. Aspiration pneumonia is one of the leading causes of death in older adults and is often associated with impaired swallowing function, frailty, and a diminished cough reflex. The risk of aspiration is particularly high in patients with dysphagia, as food boluses or beverages may inadvertently enter the airway, potentially leading to respiratory infections. As a result, the prevention of aspiration has become a major focus in clinical and long-term caregiving contexts⁵.

In such environments, meals and beverages modified by adding thickening agents are often provided to reduce the risk of aspiration. Thickening agents have become widely used as an approach to control the physical properties to ensure safe swallowing. However, while adequate thickening can improve swallowing safety, excessive thickening may compromise palatability, potentially leading to an increase in the risk of dehydration and malnutrition⁶. Importantly, perceived viscosity in the oral cavity cannot be represented by a single shear rate; the dominant sensory stimuli vary depending on the characteristics of the food or fluid being taken in, the individual's swallowing ability, and other factors^{6,7}. Moreover, the physical

importance of evaluating viscosity based on a representative shear rate remains unclear in the context of the highly complex swallowing flow process⁸.

To achieve caregiving food that ensures both safety and palatability, it is essential to enable the on-site evaluation of rheological and tribological properties. The properties, such as cohesiveness, extensional viscosity, yield stress, and shear-thinning viscosity, are considered critical for safe swallowing^{9–15}. Rheometers, which are widely recognized as the standard tools in food engineering and related disciplines, can accurately assess these properties. Such conventional rheometers are however often unsuitable for heterogeneous and complex fluids like food boluses, which contain dispersed particles ranging from micrometers to millimeters in size. Furthermore, they have issues of high cost and operational complexity for the on-site evaluation. The necessity of expert knowledge to interpret measurement results further limits their practicability in hospitals, care facilities, or home-care contexts.

To address the need for a globally consistent approach to the assessment of the texture of meals and beverages, the International Dysphagia Diet Standardisation Initiative (IDDSI) established a framework that standardizes terminology, descriptions, and testing methods across age groups and care environments^{16,17}. This framework aims to provide practical and unified guidelines for classifying thickened liquids and food textures in clinical and home-care contexts. It serves as a useful tool for categorizing thickened fluids into defined levels and promotes discussions of the relationship between flow behavior observed in the IDDSI flow test with a syringe and shear rheological properties¹⁸.

Despite its simplicity and wide applicability across various contexts, the IDDSI framework does not accommodate all types of foods and beverages. For instance, the IDDSI flow test with syringes cannot accurately assess

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the flow behavior of heterogeneous fluids containing dispersed particulates larger than the syringe nozzle. As alternatives to the method that involves flow through narrow passages, methods such as the line spread test (LST)^{19–21}, which estimates the viscosity of semi-solid and fluid foods by measuring their radial spreading on a flat plate released from an annulus, and Bostwick consistometer^{22,23}, which assesses viscosity based on unidirectional spreading within a horizontal channel, have been developed. While LST offers a rapid and low-cost way of classifying viscosity, it suffers from significant variability due to human factors during the test. The IDDSI flow test, LST, and Bostwick consistometer are all simple and inexpensive methods that allow intuitive classification of viscosity and texture without requiring specialized knowledge, making them highly applicable in clinical and caregiving contexts. However, discrepancies among the evaluations of these methods have been reported²⁴, indicating that a reliable and valid assessment of material properties requires a clear understanding of the characteristics and limitations of each method²⁵. Investigation into the underlying flow behavior and dynamics is therefore necessary. In addition, these facile methods do not directly provide detailed information on the rheological properties that are critical to safe swallowing, such as shear-thinning behavior and yield stress.

Protorheology, which has attracted attention in recent years, refers to an intuitive approach to understand rheological properties through simple flow observations such as spreading, or through actions like pressing or stretching materials, relying on visual and tactile perception^{26–28}. Representative examples include the slump test^{29,30}, used in construction sites to evaluate the yield stress of concrete, and the poke test commonly employed in home breadmaking to assess the degree of dough fermentation³¹. The IDDSI framework, LST, and Bostwick consistometer can also be regarded as forms of proto-rheological methods. These methods are considered useful not only for enhancing the reliability and interpretability of laboratory-based measurements, but also as accessible entry points into rheology for a wide range of practitioners^{26–28}. Notably, many proto-rheological tests can be realized with simple and low-cost tools, sometimes costing as little as fifty cents³⁰. Simple flow tests based on intuitive observations from perspectives of protorheology, such as the slump test and the IDDSI flow test, have been shown to enable not only qualitative classification but also quantitative estimation of rheological properties through theoretical analysis and numerical simulations^{30,32,33}.

B. Idea of gap flow test

In the context mentioned above, we focused on the dynamics of spreading flows in LST or Bostwick consistometer, where a wide range of shear rates is realized – initially rapid spreading followed by a gradual slowdown.

This series of behaviors reflects not only the representative viscosity but also the various rheological properties of the fluid. We therefore considered analyzing the spreading dynamics, rather than relying solely on a single endpoint measurement, which could yield more detailed rheological information. The concept of gap flow test (GFT) that we propose in this paper is extending LST to evaluate shear-thinning characteristics from the time evolution of the spreading distance of test liquids. Recently, a similar update has been proposed on the syringe test³⁴. Time variation of withdrawing liquid volume from a syringe due to gravity also reflects shear-thinning viscosity. Also, similar spreading behavior of viscoplastic fluids was adopted to imitate dam-breaks^{35–37}.

There are two key requirements to be satisfied for the establishment of GFT. The first is reproducibility of the measurement. In LST, the fluid often spreads non-uniformly on the sheet and it reduces the reproducibility. This is due to unstable elevation of the annulus by human-induced and material property-induced reasons. The second is keeping the advantages of LST, such as simplicity and low cost. LST is easy to use, and anyone can evaluate the degree of thickness without special knowledge in a short time, a few minutes. Moreover, a kit for LST consisting of the annulus and the sheet is provided commercially with a cost of about 3,000 JPY (approximately 20 USD) unlike sophisticated rheometers costing approximately 100,000 USD, which are used for measurement of rheological properties in fundamental research and industry.

C. Objective

This study aimed to develop a facile method for evaluating shear-thinning viscosity of fluid foods in practical contexts, inspired by LST. Along the protorheological approach, the proposed method focuses on shear-thinning viscosity, one of the key rheological functionalities associated with safe swallowing, and seeks to inversely estimate it through the observation of fluid spreading dynamics. The method is proposed with the expectation that it can be used in a complementary manner alongside existing simple methods such as the IDDSI framework, providing an intuitive yet informative assessment of rheological properties based on everyday observable phenomena.

In the following, design, theoretical background, and numerical test of GFT are described in Sec. II. Demonstrations of GFT on polymer solutions and fluid foods to evaluate its applicability are summarized in Sec. III. Finally, Sec. IV provides conclusions and future perspectives of the research.

II. GAP FLOW TEST

A. Design

A device for GFT is designed to satisfy the requirements mentioned above (Fig. 1). The device consists of three acrylic parts: a cylinder with an annular protrusion on one side, a cover disk hollowed circularly at the center with a guide for leading to pull the cylinder straight up, and a bottom disk (Fig. 1(a) and Fig. 8 in Appendix A). Pulling up the cylinder is guided by the cover disk toward the top position at which the bottom of the cylinder accords with the bottom surface of the cover disk. Since the thickness of the protrusion is equal to that of the cover disk, the gap width between the disks remains constant after the inner cylinder is lifted to the top position (see Fig. 1(b)). The gap width can be adjusted by spacers inserted between the disks depending on the degree of viscosity and size of ingredients in test fluids (Fig. 1(a)). Thanks to the geometry adopted in the device, test fluids spread axisymmetrically in the gap without uncertain horizontal fluctuations of the cylinder due to human operations. This radial spread of the test fluids reflects their rheological properties. The main dimensions of the device are 29 mm and 70 mm of the inner diameter ($2r_0$) and the height of the cylinder, 100 mm in a radius of the disks (see Fig. 1(b)). Further details of the device are summarized in Fig. 8 (Appendix A).

The gap width Δh was set to 5 mm, which was chosen in consideration of measurements involving millimeter-sized dispersions. The assembled device was placed horizontally on a small stage, making a space between the device and a desk with a height of 25 cm to set a camera. The test fluid was poured into the inner cylinder with the volume of 20 mL, where the corresponding height of the fluid layer, H_0 , is 30.3 mm. The sample volume and geometry were selected with reference to the typical conditions employed in the LST. A smartphone (iPhone 11, Apple Inc.) for video recording of the spreading fluid was located on the desk beneath the device. The recording was conducted in 1080p HD at 60 fps. In the measurement, the cylinder was lifted up to the top position onto the guide (see Fig. 1(b)) and was kept in the position during the recording. Radial positions of the spreading front of the test fluid were captured by a simple image analysis from the movie recorded, and time variations of the spreading distance in the radial direction were obtained.

B. Theory

Among various rheological properties, GFT evaluates shear-thinning viscosity which is a typical feature of general fluid foods and food bolus. To describe shear-thinning viscosity, some rheological models have been proposed, such as Carreau-Yasuda and Casson models. Because of the simplicity and the limited range of the shear rate in GFT, here we employ the power-law model,

$\eta = K\dot{\gamma}^{n-1}$, where η and $\dot{\gamma}$ represent the viscosity of test fluids and the shear rate, respectively. Rheological characteristics are captured by two parameters, K and n , along the model; the parameter K , referred as consistency index, corresponds to the viscosity at a unit shear rate, while the power-law index n quantifies the degree of shear-thinning. The model relates the instantaneous shear rate acting on the fluids and viscosity as a response from the fluids in the spreading behavior. Capturing the spreading behavior in the GFT device therefore enables the estimation of the rheological parameters K and n .

For the estimation, a physical model describing the spreading behavior is proposed to provide a preliminary understanding of how variations in K and n affect the spreading behavior. The model assumes a radially spreading laminar flow that occupies the entire height of the gap between the disks driven by static pressure due to the fluid filled in the inner cylinder (see Fig. 1(b)). Interfacial properties such as wettability and surface tension are not taken into account to the simple model. At the initial state, a fluid layer is kept stationary with a height H_0 within an open-top cylindrical container (inner cylinder) with a radius r_0 . The bottom area of the hollow part of the cylindrical container is given as $A_0 = \pi r_0^2$. The corresponding total volume of the test fluid is thus $V_{\text{total}} = A_0 H_0 = \pi r_0^2 H_0$. At the subsequent moment, the fluid begins to flow radially and axisymmetrically in the gap from the bottom of the container with a constant thickness Δh , as the top surface of the test fluid layer within the container descends at velocity v (see Fig. 1(b)). The descending velocity v depends on the radial position in the inner cylinder, but for the sake of model simplification, it represents a representative value of the descending velocity here. Although the spreading fluid flow has a non-uniform velocity distribution across the gap height, a representative spreading velocity $u(r, t)$ at each radial position r and time t is adopted for simplicity. The following relation is derived from the continuity equation, $2\pi r u \Delta h = 2\pi r_f u_f \Delta h = A_0 v$. Here, the subscript “f” represents values at the spreading front, specifically at the interface position between the test fluid and ambient air.

Assuming that the initial potential energy E_p is converted into kinetic energy E_k and viscous dissipation Φ along the spreading, the equation for energy conservation between the initial state, $t = 0$, and any subsequent moment, $t > 0$, is expressed as

$$E_p(0) - E_p(t) = E_k(t) + \Phi(t). \quad (1)$$

Each term in the equation above is described by the spreading velocity at the front, $u_f(t)$, and an integral-differential equation is formulated. First, the radial position of interface r_f is expressed as

$$r_f(t) = r_0 + \int_0^t u_f(\tau) d\tau. \quad (2)$$

The volume of the fluid that has flowed into the gap, $V_{\text{gap}}(t)$, is given by $V_{\text{gap}}(t) = [\pi r_f(t)^2 - A_0] \Delta h$. The

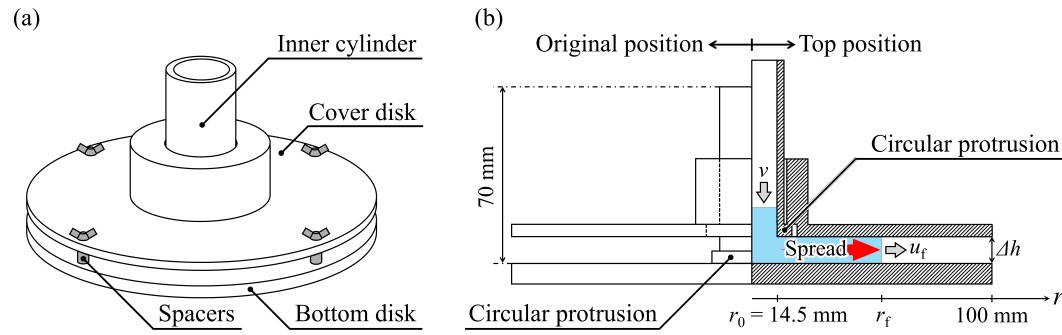


FIG. 1. Schematics of the gap flow test (GFT) device: (a) overview and (b) side and vertical cross-sectional view with a test fluid spreading and main dimensions. A more detailed geometry of the device is summarized in Appendix A.

volume remaining inside the cylindrical container is thus $V_{\text{cyl}}(t) = V_{\text{total}} - V_{\text{gap}}(t)$, with being the head height $H(t) = H_0 - V_{\text{gap}}(t)/A_0$. The potential energy E_p and kinetic energy E_k of the system at a given time can be expressed with the gravitational acceleration g and the fluid density ρ as

$$E_p(t) = \int_0^{H(t)} \rho g A_0 y dy \quad (3)$$

and

$$E_k(t) = \frac{1}{2} \rho V_{\text{cyl}} v^2 + \int_{r_0}^{r_f} \frac{1}{2} \rho \cdot 2\pi r \Delta h u(r)^2 dr. \quad (4)$$

For the viscous dissipation term, the representative shear rates in the cylindrical container and in the gap are given respectively by

$$\dot{\gamma}_{\text{cyl}}(t) = \frac{v}{r_0}, \quad (5)$$

$$\dot{\gamma}_{\text{gap}}(r, t) = \frac{u(r, t)}{\Delta h/2}. \quad (6)$$

The total viscous dissipation after the initial time, $\Phi(t)$, can be expressed as

$$\Phi(t) = \int_0^t V_{\text{cyl}} \eta_{\text{cyl}} \dot{\gamma}_{\text{cyl}}^2 d\tau + \int_0^t \int_{r_0}^{r_f(\tau)} 2\pi \Delta h r \eta_{\text{gap}} \dot{\gamma}_{\text{gap}}(r, \tau)^2 dr d\tau, \quad (7)$$

where the viscosities in the cylindrical container and in the gap, η_{cyl} and η_{gap} , are expressed based on the assumption of the power-law fluid as $\eta_{\text{cyl}}(t; K, n) = K \dot{\gamma}_{\text{cyl}}(t)^{n-1}$ and $\eta_{\text{gap}}(r, t; K, n) = K \dot{\gamma}_{\text{gap}}(r, t)^{n-1}$. In the physical model, distributions of the descending and spreading velocity in radial and gap height directions, respectively, are neglected and the corresponding shear rates are represented by Eqs. 5 and 6, respectively. The viscosity dealt with in the model is regarded as the locally averaged viscosity in the directions.

Each term in Eq. 1 is now expressed by $u_f(t)$, $u(r, t)$ and $v(t)$. Using the continuity equation, all $u(r, t)$ and $v(t)$ can be replaced with expressions involving $u_f(t)$, thereby allowing Eq. 1 to be regarded as an equation solely in terms of $u_f(t)$. Solving the equation analytically is, however, challenging because the interval of integration includes time-dependent functions. To address this, we differentiated both sides of Eq. 1 with respect to time t , reducing the problem to solve the following equation for $u_f(t)$, under the initial condition $u_f(0) = 0$:

$$\frac{dE_p}{dt} + \frac{dE_k}{dt} + \frac{d\Phi}{dt} = 0. \quad (8)$$

C. Numerical experiment

Based on this physical model, numerical experiments were conducted with various conditions sets to investigate the influences of K and n on the spreading behavior. The numerical experiments also elucidate the motion of spreading front in ideal conditions to be compared with actual ones.

To analyze the spreading behavior, $u_f(t)$ is discretized in the time direction with the time step Δt , as $u_{f,i} = u_f(t_i = i\Delta t)$, $i = 0, 1, 2, \dots$. The corresponding spreading distance is thus $r_{f,i} = r_f(t_i)$. Starting from the initial condition $u_{f,0} = 0$, if a recurrence relation for $u_{f,i}$ can be derived from the differential equation, Eq. 8, $u_f(t)$ can be determined numerically.

The discretized differential equation was solved for $u_{f,i+1}$ using the bisection method. The solution of this equation is uniquely determined within an appropriate search range close to the previous solution $u_{f,i}$. The rheological parameters K and n in the power-law model were varied to examine their influences on spreading distance $r_f(t)$. The range of K was set to $2.5 \times 10^4 \text{ mPa} \cdot \text{s}^n \leq K \leq 4.0 \times 10^6 \text{ mPa} \cdot \text{s}^n$ with 7 steps logarithmically, and the range of n was set to $0.3 \leq n \leq 1.0$ with 15 steps linearly, resulting in a total of 105 conditions. The values of other physical parameters used in the numerical experiments are specified in Table I. The maximum index of i

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TABLE I. Setting parameters in numerical experiments

Parameter	Value	
Δh	5	[mm]
V_{total}	20	[mL]
r_0	15	[mm]
ρ	0.997	[mg/mm ³]
g	9.8	[m/s ²]
Δt	0.001	[s]
N_t	60000	[-]

is defined as N_t , and thus the time range for calculating the spreading behaviors is $0 \leq t \leq N_t \Delta t$.

The normalized spreading distance in the case of $K = 10^5 \text{ mPa} \cdot \text{s}^n$ and $n = 0.50$ is shown in Fig. 2 as an exemplary case. Here we assume that the test fluid initially filled in the inner cylinder has completely spread in the gap at the terminal condition. The spreading distance at the terminal condition, r_∞ , is used for normalization, and is calculated as $r_\infty = \sqrt{V_{\text{total}}/\pi\Delta h} \simeq 35.7 \text{ mm}$. Some fitting curves including simple power-law fitting were examined to approximate a series of discretized values of $r_f(t)$, and finally, $r_f(t)$ is well fitted by the following function, which is characterized by two parameters, τ and m :

$$\frac{r_f(t) - r_0}{r_\infty - r_0} = 1 - \exp \left[- \left(\frac{t}{\tau} \right)^m \right]. \quad (9)$$

The parameter τ represents the characteristic time scale of spreading. A larger τ indicates slower spreading, whereas a smaller τ corresponds to a more rapid spreading. The parameter m describes the initial rate of spreading. The spreading behavior under consideration is rapid initially and tends to slow down gradually over time. Given that the second derivative of $r(t)$ is negative for all time t , the parameter m is constrained to be in the range of $0 < m < 1$. The fitting was performed using the least squares method for the first 20 seconds of the profile, during which the flow speed changes prominently. In this case, the spreading behavior is characterized by $\tau \approx 22.6 \text{ s}$, $m \approx 0.411$.

The spreading behaviors were examined for 104 other sets of K (7 cases) and n (15 cases), and the obtained profiles were fitted with Eq. 9 for delving into the relationship between the rheological parameters and the characteristic parameters of spreading, τ and m . The fitting provided excellent agreement for all cases (not shown in a figure). The fitting results are summarized in Fig. 3, where the series of plots was obtained for the same value of K with modifying the value of n . The rheological parameters influence the spreading behavior, namely, τ tends to increase with higher values of K , and m increases with higher values of n under almost all conditions. Furthermore, these figures indicate that, according to the calculations based on the model, in regions with large K , the contribution of τ to n tends to be more significant than that of m , whereas in regions with small K , the contribution of m becomes greater than that of τ . These monotonic variations suggest that it is practicable

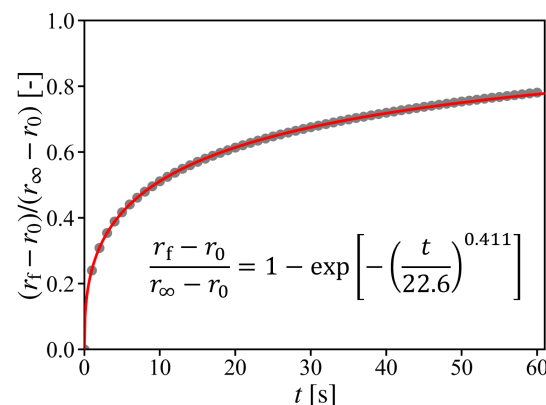


FIG. 2. The normalized spreading distance at time t in the case of the consistency index $K = 10^5 \text{ mPa} \cdot \text{s}^n$ and the power-law index $n = 0.50$. The gray plots represent the results of numerical experiments at integer-second intervals as representative data. The red curve indicates the regression curve obtained by fitting the plots with the function expressed in Eq. 9. The coefficient of determination R^2 exceeds 0.99.

to estimate the rheological parameters K and n based on the spreading behavior characterized by τ and m . The relations mentioned above, however, were obtained from numerical experiments with ideal conditions excluding influences of surface tension, yield stress, and etc. We therefore discuss the applicable range of the GFT under the actual conditions in the following section.

D. Limitations

The proposed method in this paper, GFT, has several limitations in terms of physical properties and composition of test fluids. These limitations are denoted in advance to the experimental demonstration section. The first concern is regarding a measurable viscosity range. In GFT, the flow with a sufficiently small Reynolds number is assumed, and the test fluid should have reasonable viscosity. Low-viscosity fluid spreads quickly without fulfilling the gap height and potentially induces turbulence. In such cases, the interfacial shape is no longer concentric, so it can be identified from the captured images. On the one hand, high-viscosity fluid that spreads too slowly to exhibit shear-thinning behavior due to low shear rates is also unsuitable. It is necessary to increase the initial head of the solution filled in the inner cylinder or to widen the gap.

The second concern arises when a test fluid possesses a yield stress. In GFT, also in LST, the initial head must provide sufficient force to drive and spread a fluid. Fluid with a large yield stress will prevent the transduction of potential energy to kinetic energy dissipated in the spreading process. Since a test fluid of $V_{\text{total}} = 20 \text{ mL} = 2.0 \times 10^{-5} \text{ m}^3$ is used for the measurements, and assuming its density ρ [kg/m³], gravitational ac-

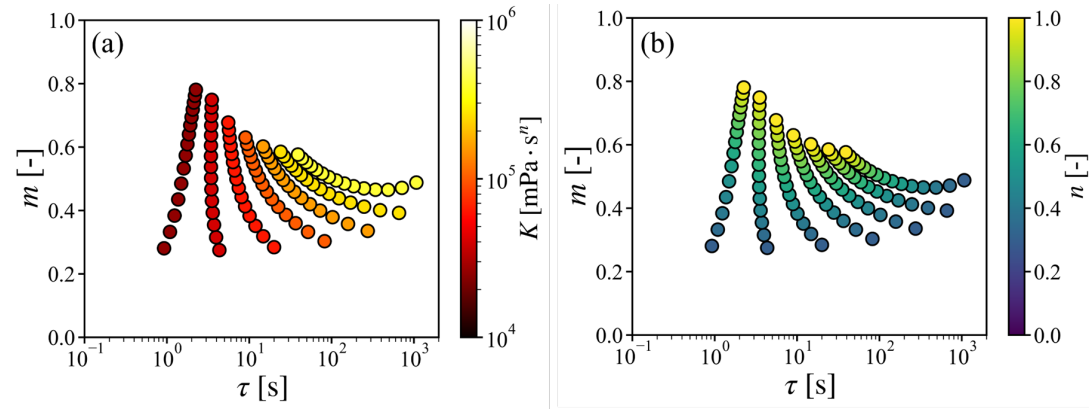


FIG. 3. Scatter plots of τ and m , with the color of each plot corresponding to (a) K and (b) n based on the numerical experiment.

celeration $g = 9.8 \text{ m/s}^2$ and the inner diameter of the inner cylinder of the GFT device $2r_0 = 29 \times 10^{-3} \text{ m}$, the yield stress σ_Y limitation is estimated as $\sigma_Y \ll \rho g H_0 = \rho g V_{\text{total}} / (\pi r_0^2) \approx 0.30 \rho \text{ [Pa]}$.

The third concern pertains to the wettability. Fluids with high wettability, such as those with significantly different spreading distances between the interfaces of the upper and lower disks and the test fluid, or with low wettability, such as those that are prone to slide between the disks due to slight inclinations, are out of the scope of this method. These fluids also affect the descending motion of the test fluid in the inner cylinder by modifying the distribution of the descending velocity v and making the remaining film on the inner surface of the cylinder. Fluids examined using this method should exhibit nearly identical spreading distances at both interfaces and ideally spread in a circular pattern. This discrepancy in the interface positions can potentially be reduced by decreasing the gap width, which promotes more uniform spreading in the vertical direction between the disks.

The fourth concern is regarding the size of particles or bubbles included in the test fluid. If the size is comparable to the gap width between the disks, Δh , they may obstruct the flow from the inner cylinder to the gap space, preventing accurate measurement of the actual spreading distance. To ensure reliable measurements, the dispersion size should empirically be smaller than $\Delta h/10$, consistent with practices observed in other experimental studies on suspensions^{38,42}. This limitation could potentially be mitigated by increasing the gap width, which promotes more uniform spreading in the radial direction between the disks.

The limitations mentioned above can be summarized by dimensionless parameters. According to Buckingham II-theorem, dimensionless spreading distance of homogeneous shear-thinning fluids in GFT can be described by five dimensionless parameters in addition to dimensionless time, t^* , as $r_f/r_0 = \phi(t^*; Re, Fr, \Lambda, \Gamma, n)$. Reynolds and Froude number, Re and Fr , indicate suitable vis-

cosity range in comparison with inertia and gravity acceleration. Geometrical parameters, $\Lambda = H_0/\Delta h$ and $\Gamma = r_0/\Delta h$, represent contribution of the geometrical confinement on the spreading behavior. Details of the dimensionless parameters are summarized in Appendix B. In addition to these, the physical model describing the spreading behavior neglects elastic properties of the test materials, interface tension, and velocity distributions across the gap height. Deborah number, De , Weissenberg number, Wi , and Weber number, We , are therefore explicitly regarded to be smaller than unity in GFT. An example case at which inertia effect or influence of the velocity distribution cannot be neglected will be explained in Sec. III A.

III. DEMONSTRATIONS OF GAP FLOW TEST

A. Establishment of database based on actual phenomena

The gap flow test (GFT) was demonstrated using various test fluids. The relationship between the rheological properties, K and n , and the characteristic parameters of the spreading behavior, τ and m , was investigated based on observations of real phenomena through rheological measurements and GFT. Homogeneous fluid media were used as test fluids to satisfy the conditions described in the previous section and to ensure rheological measurements using a standard torque-type rheometer (MCR 702e, Anton Paar GmbH, Austria). The test fluids selected include aqueous solutions of xanthan gum-based thickening agents (XGS) (Softia S, NUTRI Co., Ltd., Japan), starch-based thickening agents (Toromerin Granules, NUTRI Co., Ltd., Japan) and polyacrylamide (PAM) aqueous solutions (Accofloc N-100S, MT AQUAPOLYMER Inc., Japan; 13 millions of molecular weight of polymers), as well as pure glycerin (DG, NOF CORPORATION, Japan) and pure starch

syrup (Mizuame, Sudo Jam Co., Ltd., Japan). Additionally, mixtures of glycerin with a small amount of 2.9 wt% XGS and mixture of starch syrup with a small amount of 3.8 wt% XGS were also utilized. These are representative Newtonian fluids (pure glycerin and starch syrup) and shear-thinning fluids (aqueous solutions). Various concentrations of these solutions lead to different degrees of shear-thinning behavior. The viscosity curves for all test fluids, obtained through rheological measurements, are well described by the power-law model (see Fig. 9 in Appendix C). It was also confirmed that the range of the shear rate and shear stress realized in GFT covers the range exhibiting the shear-thinning viscosity represented by the power-law model, where the maximum and the minimum shear stress are 300 Pa and 2.8 Pa, respectively, and the maximum shear rate is 88.2 s^{-1} in the setting condition of Δh and H_0 . Details of the estimations are summarized in Appendix C.

The demonstrations were conducted with the device and the setup described in Sec. II A. The initial spreading behavior of the test fluid appears axisymmetric without the influence of any initial disturbances despite human-hand operation (Fig. 4(a)). The spreading motions of all test fluids were nearly axisymmetric, as illustrated by sequential snapshots in Figs. 4(b-d), where a black background was used for easier detection of the interface position. The radial position of the spreading front, $r_f(t)$, was determined through a straightforward image processing for interface detection applied to sequential images. Azimuthal deviation of the detected $r_f(t)$ is within 2.55 mm. The time variations of the interface position, $r_f(t)$, observed during GFT exhibit an exponential-like behavior, consistent with the results of the numerical experiment (see Fig. 2). As shown in Fig. 5, $r_f(t)$ was also well fitted by the function in Eq. 9, although unideal effects, e.g., a velocity distribution across the gap height, which are neglected in the numerical experiment, are expected.

While most test fluids followed the expected spreading behavior, some exhibited spreading distances exceeding r_∞ . Two possible factors may account for this deviation. One is that the strong influence of inertial effects during downward flow inside the inner cylinder caused a concavity near the spreading center. Another is that the test fluid spreads into the gap in the form of a truncated cone with bulging sides, leading to a significant difference between the interface positions on the upper and lower disks. The test materials exhibiting the above mentioned behavior were excluded from the analysis to create the database.

While not all test fluids exhibited ideal spreading, the observed deviations from the expected spreading pattern were within an acceptable range, and the experimentally derived database was established to account for these differences. Despite these deviations, the fitting based on Eq. 9 yielded the coefficient of determination R^2 values exceeding 0.91 for all test fluids, with nearly all cases achieving values above 0.95. These suggest that the assumptions on the physical model discussed in Sec. IIB

and the limitations of GFT summarized in Sec.II D are reasonably satisfied in the actual GFTs of the present test materials. The fitting time range was defined as the earlier of either 20 seconds after the onset of spreading or the time at which the normalized spreading radius r_f/r_∞ exceeds 0.95.

Distributions of τ and m obtained from the spreading behaviors of the test materials in GFT by function fitting as shown in Fig. 5 are shown in Fig. 6 to confirm relationship of them with K and n , where these rheological properties were determined by the torque-type rheometer in advance as summarized in Table II. In these figures, pink plots with non-circular symbols represent test fluids discussed in more detail in the following Sec. IIIB. In Fig. 6(a), while the order of consistency index K differs from that examined in the numerical experiments shown in Fig. 3(a), the trend exhibited is the same, e.g. τ takes larger values for larger values of K . Figure 6(b) also indicates the relation with similar trend between characteristics parameters of spreading and n expected through the numerical experiment (see Fig. 3(b)), e.g. m increases with higher value of n . These results suggest that the physical model proposed in Sec. IIB, which simulates the spreading behavior of fluid, essentially captures the underlying physics of the phenomenon, also the relationship quantified by the experiment works as a database to determine the rheological properties of unknown materials through the spreading motion. In the following sections, we validate the estimation of the rheological properties K and n using GFT from the database.

B. Validation of rheological evaluation using GFT

Using the database obtained through the observed spreading behaviors, the estimation of rheological properties, here K and n under the assumption of the power-law model, was demonstrated. The test fluids are three types of commercially available Worcester-like sauces with different viscosities and flavors for typical Japanese dishes, Chuno (medium-condensed) sauce (BULL-DOG CO., LTD., Japan), Tonkatsu (for pork cutlet) sauce (BULL-DOG CO., LTD., Japan), and Okonomi (for Okonomi-yaki) sauce (Otafuku Sauce Co., Ltd., Japan), and three types of porridge (Ajinomoto Co., Inc., Japan), plain rice porridge, egg porridge, and red bean porridge, which were also examined in our previous study³⁹ as fluid foods containing mm-sized ingredients. Additionally, five types of aqueous solutions of thickening agents were used. These agents were identical to those employed in the construction of the experimentally derived database, but at different concentrations. Both the sauces and the porridge contains dispersed particles, such as fruit pulp or rice grains. The sauces were selected as representative dispersions with relatively small particles in comparison with the gap size, whereas the porridge contain mm-sized ingredients that are comparable to the gap size. The thickening agent solutions were selected with the expect-

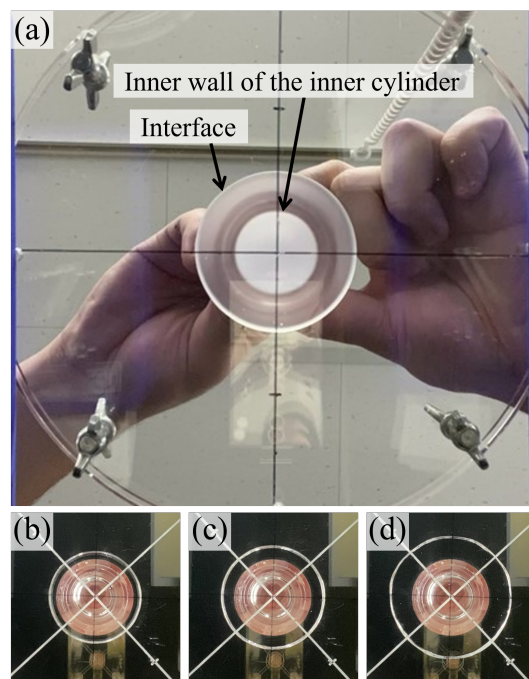


FIG. 4. (a) A snapshot representing the initial spreading behavior of the 5.3 wt% aqueous solution of the starch-based thickening agent. Sequential snapshots during GFT of Glycerin+XGS (0.15 wt%) at (b) $t = 0.5$ s, (c) $t = 1$ s, and (d) $t = 10$ s, where the black plate is set on the cover disk as a black background for easier detection of the interface.

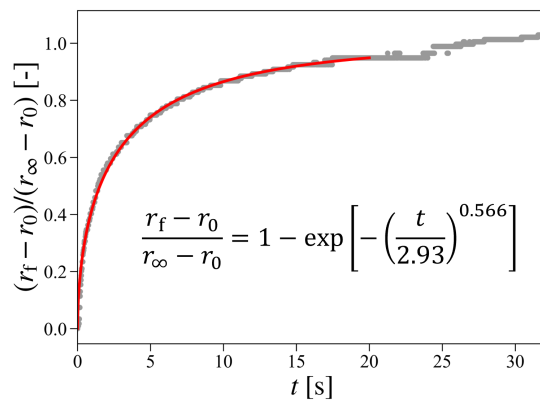


FIG. 5. Normalized spreading distance at time t of the 4.9 wt% aqueous solution of the starch-based thickening agent, which has the consistency index $K = 6.45 \times 10^3 \text{ mPa} \cdot \text{s}^n$ and the power-law index $n = 0.430$. The gray plots represent the normalized position of the interface observed during GFT. The red curve indicates the regression curve obtained by fitting the plots to the function expressed in Eq. 9. The coefficient of determination R^2 exceeds 0.99.

tation that their spreading characteristic parameters, τ and m , would be interpolated within the database shown in Fig. 6.

GFT was conducted on all eleven test fluids. The obtained spreading characteristic parameters, τ and m , were mapped onto the experimentally derived database (Fig. 6). The specific values are listed in Table II. The estimation of the rheological properties K and n was performed through interpolation from three closely surrounding points on the database. To ensure that the contributions of each parameter to the estimation were equivalent, all parameters were normalized using the conversion formulae: $\log \tau^* = \log \tau / (\log \tau_{\max} - \log \tau_{\min})$, $m^* = m / (m_{\max} - m_{\min})$, $\log K^* = \log K / (\log K_{\max} - \log K_{\min})$ and $n^* = n / (n_{\max} - n_{\min})$. Here, subscripts “max” and “min” mean the maximum and the minimum values in the database, respectively. The interpolation was conducted on planes defined in the $\log \tau^* - m^* - \log K^*$ coordinate space and $\log \tau^* - m^* - n^*$ coordinate space respectively formed by the three points. Index numbers of the three points to be identified in Fig. 6, along with the estimated values K_{GFT} and n_{GFT} , are also summarized in Table II. Although several interpolation methods, including those using higher-order polynomials, can also be considered, the interpolation method based on the plane equation was adopted as the simplest and most intuitive approach here. As the database is enriched in the future, such high-order fitting will become feasible.

Comparisons between the estimated values K_{GFT} and n_{GFT} and the true values K_{Rheo} and n_{Rheo} obtained from rheometer-based viscosity measurements fitted to the power-law model are shown in Fig. 7. For the sauce samples, viscosity was measured in a steady shear test using a 50-mm parallel plate jig for the torque-type rheometer, considering the potential clogging of fruit pulp in a case of using a cone and plate geometry. For the porridge samples, the rheological properties were referenced from the results of Ohie *et al.* measured by velocity-profiling-assisted rheometer^{39–41}, which is capable to evaluate flow curve of heterogeneous fluid media with mm-sized ingredients, out of the measurable range of the torque-type rheometer. Figure 7 indicates that the accuracy of the estimation results is different depending on the test fluids: in some cases, both K and n show reasonable agreement (e.g. thickening agent solutions), while in others, only K is well estimated (e.g. porridge). The thickening agent solutions could be evaluated well with maximum relative error of 140% for K and 37.1% for n despite limited number of the data points, because the selected points for estimation were in close proximity to the spreading characteristic points of test fluids. Although some large deviations exist because of the reasons discussed below, the overall results are mostly consistent with the expectations. This suggests that the database would work for the facile rheometry even with the currently insufficient amount of the data.

Two primary factors are considered to account for the inaccuracies in the estimation. The first one is that the

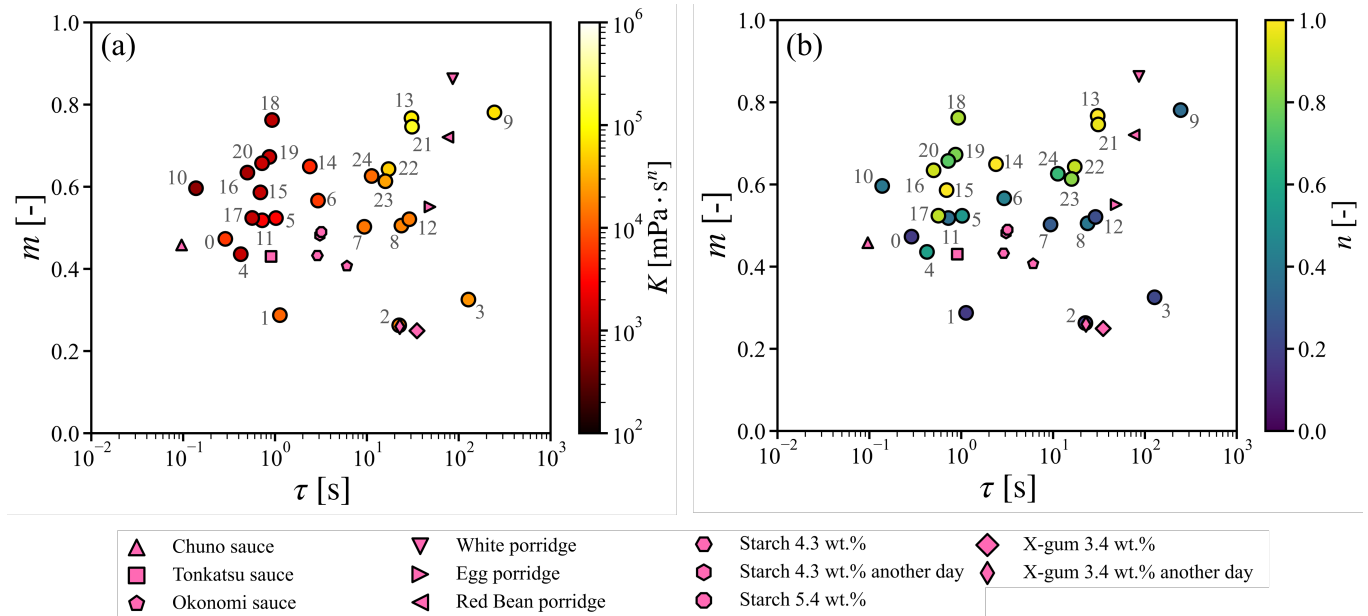


FIG. 6. Scatter plots of τ and m , with the color of each circular plot corresponding to (a) K and (b) n , based on actual spreading behaviors. The number written close to each circular plot corresponds to the index described in Table III in Appendix. Pink plots with other symbols indicate the test fluids used to validate the rheological property evaluation using GFT described in Sec. III B.

estimation was performed through extrapolation rather than interpolation, because of the absence of appropriate three neighboring points for the interpolation. This issue primarily affected Chuno sauce and some types of porridge. A potential improvement would be an increase of the number of data points to cover a wider area on the map of the database, thereby creating a denser mapping for more reliable interpolation. Alternatively, although the model proposed in Sec. II B incorporates several assumptions for simplification, one possible approach is to make a more detailed model and construct a database by simulating the gap flow behaviors with it. The second factor is that smooth spreading motion was suppressed due to the high viscosity of the test fluid or the large size of the dispersed particles (see Fig. 7(c)); the shear-thinning behavior of the test fluids may not exhibit because of limited range of shear rate realized in the spreading. This issue was observed in all types of porridge. This led to an overestimation of n , resulting in an apparent characterization closer to a Newtonian fluid ($n = 1$), i.e., without exhibiting shear-thinning behavior. To address this, increasing the gap width Δh to relax the confinement by the disks or increasing the initial volume of the test fluid to enhance the driving force could improve the shear rate, thereby enhancing the accuracy of the estimation. Among the porridge samples, which were presumed not to exhibit shear-thinning viscosity, the consistency index K was relatively well estimated for egg porridge and red bean porridge, where interpolation was possible.

Overall, even in cases where the estimation accuracy was limited, the underlying causes were clearly identi-

fied, and the estimation results for all test fluids, both homogeneous and heterogeneous, were generally in agreement with expectations. Toward the facile rheometry, which can be used in clinical sites without special skills on the measurement, simple and easy instructions for suitable setting of Δh are required in addition to enrichment of the database. The instruction should be described quasi-quantitatively, for example, "low", "middle", and "high" viscosity as used in the line spread test. The present results reinforced the physical background of the rheometry by means of proto-rheology to support the development.

IV. CONCLUSION

This study aimed to develop a facile method for evaluating shear-thinning viscosity of fluid foods in practical contexts, inspired by the line spread test (LST). The proposed approach, the gap flow test (GFT), estimates shear-thinning viscosity by analyzing the spreading behavior of fluids through a pre-established database of corresponding relationship between rheological properties and spreading characteristics. One of the strengths of the GFT concept is that it quantifies shear-thinning properties by observing a series of spreading behaviors, which richly contain information related to shear-rate-dependent viscosities. GFT further retains the affordability and simplicity of LST while preventing the unstable spreading caused by human factors and material properties. It should be emphasized that the entire GFT

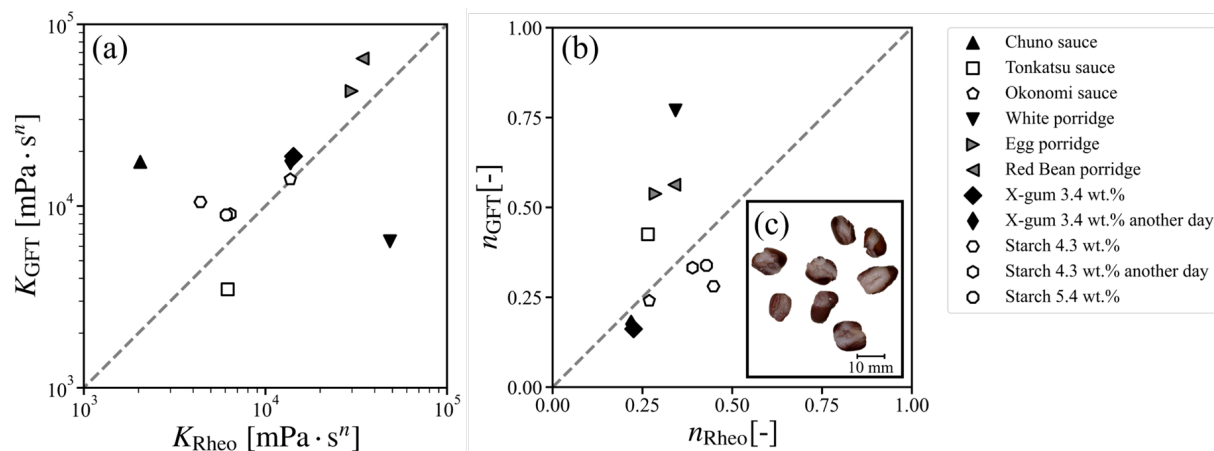


FIG. 7. Comparisons between the estimated values based on GFT and the true values obtained from the rheological measurements, (a) consistency K and (b) power-law index n . Open plots represent cases where interpolation was successfully performed, while closed plots indicate cases requiring extrapolation. Gray plots correspond to porridge samples, for which insufficient shear rate during spreading is presumed. In Fig. 7(b), the plot for Chuno sauce was not shown in the frame because the estimated value is extremely off due to the extrapolation. The corresponding values are summarized in Table II. (c) An example of the presence of large particles, showing the particle size of red beans contained in the red bean porridge sample. The particle size is approximately twice or more than the gap width set in GFT ($\Delta h = 5$ mm), which was one of the factors hindering the ideal spreading process.

TABLE II. Specifications of spreading characteristic parameters obtained by GFT, the value of K and n estimated from them, K_{GFT} and n_{GFT} , and the value of K and n based on the rheological measurements, K_{Rheo} and n_{Rheo} . The rheological properties K_{Rheo} and n_{Rheo} for porridge are quoted from the results of Ohie *et al.*³⁹

Test fluid	τ [s]	m [-]	index of selected points	K_{GFT} [mPa · s ⁿ]	n_{GFT} [-]	K_{Rheo} [mPa · s ⁿ]	n_{Rheo} [-]
Chuno sauce	9.59×10^{-2}	0.459	0,10,17	1.75×10^4	-0.622	2.04×10^3	0.357
Tonkatsu sauce	9.03×10^{-1}	0.430	1,4,6	3.48×10^3	0.425	6.20×10^3	0.265
Okonomi sauce	6.05×10^0	0.407	1,2,7	1.40×10^4	0.240	1.37×10^4	0.269
Plain porridge	8.58×10^1	0.863	9,13,21	6.40×10^3	0.770	4.85×10^4	0.342
Egg porridge	4.84×10^1	0.551	3,12,21	4.29×10^4	0.538	2.98×10^4	0.286
Red bean porridge	7.61×10^1	0.721	9,12,21	6.48×10^4	0.563	3.43×10^4	0.339
3.4 wt% XGS	3.50×10^1	0.249	2,3,8	1.88×10^4	0.162	1.43×10^4	0.225
3.4 wt% XGS*	2.27×10^1	0.260	2,3,8	1.77×10^4	0.176	1.37×10^4	0.219
4.3 wt% starch-based aq.	2.89×10^0	0.433	1,6,7	1.05×10^4	0.281	4.38×10^3	0.447
4.3 wt% starch-based aq.*	3.06×10^0	0.482	1,6,7	9.03×10^3	0.333	6.41×10^3	0.389
5.4 wt% starch-based aq.	3.19×10^0	0.490	1,6,7	8.94×10^3	0.339	6.08×10^3	0.428

* taken another day

setup can be constructed at a cost of approximately 50 pounds, making it sufficiently low-cost for practical use in hospitals, care facilities, or home-care contexts.

Through numerical simulations based on a physical model, the relationship between rheological properties and spreading characteristics was investigated. Experimental validation confirmed that the trends observed in numerical simulations were consistent with actual spreading behaviors, demonstrating that GFT successfully captures rheological properties reflected in the spreading behavior. By constructing a database describing the relation between τ and m as spreading characteristic parameters and K and n as rheological properties, a framework for viscosity estimation was established. The ef-

fectiveness of GFT was confirmed across a range of test fluids, including both homogeneous fluids and heterogeneous dispersions such as commercial sauces and porridge. Despite employing the current sparse database and an approximate plane-based interpolation, the estimated values were within the expected range for most test fluids. For the thickening agent solutions, the maximum relative error of 140% for K and 37.1% for n . This suggests that GFT offers a level of accuracy that may be sufficient for practical applications to classify fluid foods into several categories based on consistency index and power-law index.

While GFT generally provided reasonable estimations, certain test fluids exhibited deviations in the estimated

values. One major factor was the insufficient shear rate in highly viscous fluids with large particles, such as porridge, where the lack of sufficient shear prevented shear-thinning behavior. This issue can potentially be addressed by increasing the gap width or the initial volume to enhance the applied shear rate. Another factor was extrapolation due to limited data in the map of the database, particularly affecting Chuno sauce and some porridge samples. Expanding the experimental dataset would improve estimation accuracy, and as more data is collected, the precision of the method is expected to increase.

Beyond the power-law model, GFT can be extended to other rheological models considering a yield stress such as the Herschel-Bulkley model. In such cases, the residual head height after a sufficiently long time, equivalent to the spreading distance at the terminal condition, may provide insight into yield stress estimation. Unsteady spreading motion in the gap utilized in GFT reflects rich rheological information of the test fluid foods, and it has potential to be general rheological tools with more detailed analysis beyond facile rheometry.

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DATA AVAILABILITY

The data that support the findings of this study including the data base are available from the corresponding author upon reasonable request.

Appendix A: Parts drawing of the device for GFT

Drawings of each part of the gap flow test (GFT) device are shown in Fig. 8.

Appendix B: Dimensionless parameters describing spreading behaviors in GFT

On the physical model describing the spreading behavior, there are seven independent parameters. According to the Buckingham II-theorem, time variations of the spreading distance can be expressed as a function with five dimensionless parameters in addition to dimensionless time, $t^* = \sqrt{g/H_0}t$. The dimensionless parameters are:

1. Reynolds number, $\rho g H_0 / K (H_0 / g)^{n/2}$, expresses the ratio of inertial to viscous forces, reflecting the flow regime governed by shear-thinning viscosity.

2. Froude number, $Fr = u_f / \sqrt{g H_0}$, indicates the relative importance of inertial and gravitational forces.
3. Vertical strain ratio, $\Lambda = H_0 / \Delta h$, represents the geometrical confinement in the vertical direction. It reflects the vertical compaction of the flow and is one of the key factors determining the time required for the gravitational potential energy to be fully dissipated. Larger Λ implies more pronounced vertical-to-radial transition dynamics.
4. Cross-flow scale ratio, $\Gamma = r_0 / \Delta h$, characterizes geometrical relationship between the two orthogonal flow regions. The numerator r_0 represents the horizontal extent of the vertical downflow within the cylindrical domain, while the denominator Δh corresponds to the vertical thickness of the radially spreading thin film. This ratio captures the scaling of shear rate structures and curvature across the transition between vertical and radial flow, playing a key role in determining the overall flow and deformation.
5. Power law index, n : the flow behavior index from the power-law model directly controls how apparent viscosity responds to local shear rate. In this spreading context, where shear rates vary between the descending and spreading regions, n modulates the spatial viscosity distribution and affects the velocity field.

While the model presented in Sec. II B is simplified, the actual spreading behavior can be more generally expressed by including additional dimensionless numbers that account for viscoelastic properties and interfacial tension. Accordingly, the generalized dimensionless form becomes:

$$r_f / r_0 = \phi(t^*; Re, Fr, \Lambda, \Gamma, n, Wi, De, We). \quad (B1)$$

This formulation incorporates not only the dominant geometrical, inertial, and shear rheological effects, but also potential contributions from viscoelasticity and interfacial tension, expressed through the Deborah number De , Weissenberg number Wi , and Weber number We .

In the present study, the test fluids are not strictly ideal power-law fluids, but rather complex materials that may exhibit non-negligible viscoelastic and interfacial effects. While these are not explicitly modeled, we consider that their influence is effectively embedded within the empirically determined rheological parameters—specifically, the effective consistency index K and the power law index n —through the use of an experimental data-driven estimation framework. Therefore, even if the flow conditions partially deviate from the ideal assumptions of $De \ll 1$, $Wi \ll 1$, or $We \ll 1$, the model still provides physically meaningful predictions by treating K and n as effective parameters that implicitly capture these complexities. This interpretation justified the simplification of the generalized form to:

$$r_f / r_0 = \phi(t^*; Re, Fr, \Lambda, \Gamma, n).$$

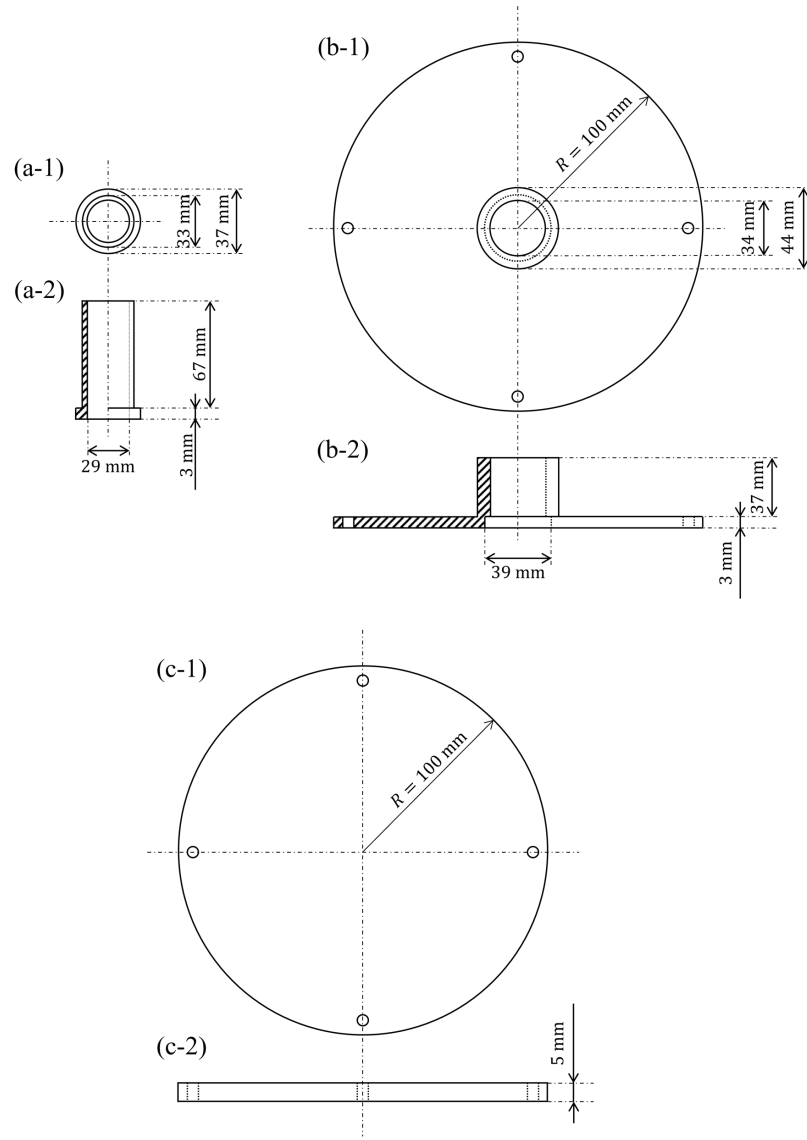


FIG. 8. Parts drawings of the device for GFT: (a-1) top view and (a-2) side and vertical cross-sectional view of the inner cylinder with hook part on the bottom side, (b-1) top view and (b-2) side and vertical cross-sectional view of the perforated disk with outer cylinder for pulling the inner cylinder up straight, (c-1) top view and (c-2) side view of the bottom disk.

Specifically, the dimensionless form of the differentiated equation for energy conservation described in

Sec. II B is given as follows:

$$\begin{aligned}
 & \frac{dE_p}{dt} + \frac{dE_k}{dt} + \frac{d\Phi}{dt} = 0 \\
 & \Leftrightarrow (1 + \Lambda - r^{*2}) \\
 & + \frac{2\Lambda}{\Gamma^2} \left[-r^{*2} F r^2 + (1 + \Lambda - r^{*2}) \left(F r^2 + \frac{\Gamma}{\Lambda} r^* \frac{dF r}{dt^*} \right) \right] \\
 & + \Lambda \left[\left(F r^2 + \frac{\Gamma}{\Lambda} r^* \frac{dF r}{dt^*} \right) \log r^* + \frac{1}{2} F r^2 \right] \\
 & + \frac{\Gamma}{Re} (2r^* F r)^n \left[\frac{2}{1-n} \Lambda^{n+1} (r^{*(1-n)} - 1) \right. \\
 & \left. + \left(\frac{\Lambda}{\Gamma^2} \right)^{n+1} (1 + \Lambda - r^{*2}) \right] = 0
 \end{aligned} \tag{B2}$$

where $r^* = r_f/r_0$.

Appendix C: Viscosity curves of the test fluids

Viscosity curves of the test fluids were obtained by a steady shear test of the rheometer with a 50 mm cone-plate jig to quantify the shear-thinning properties of the fluids. In consideration of the shear rate range observed in GFT, the shear rate range for viscosity curve measurements was set at 0.01 s^{-1} to 20 s^{-1} . All the results of viscosity curve measurements are shown in Fig. 9. Dashed lines in each panel indicate the viscosity corresponding to the maximum shear stress acting on the test fluids estimated by the potential of the initial head $\rho g H_0$ as the maximum driving force of the system. In addition to this, the minimum shear stress can be estimated from the minimum static pressure $\rho g \Delta H$ at a discrete step prior to the terminal condition, $r_{f,i} = r_\infty - \Delta r$, where Δr denotes the spatial resolution of the image processing. The value is estimated as $\rho g \Delta H = \rho g (2r_\infty - \Delta r) \Delta r \Delta h / r_0^2 \simeq 0.564 \rho \Delta h = 2.82 \text{ Pa}$. Colored area in the figure indicates the available widest shear rate range in GFT estimated from $r_f(t)$ obtained by the image processing on 0.50 wt% PAM aq. solution and Eq. 6. The value of the parameters K and n obtained by fitting each viscosity curve to the power-law model $\eta = K \dot{\gamma}^{n-1}$ are shown in Table III.

REFERENCES

- ¹United Nations, Department of Economic and Social Affairs Population Division <https://population.un.org/wpp/graphs>
- ²Cabinet office of Japan, "Status of Aging Population" (in Japanese). https://www8.cao.go.jp/kourei/whitepaper/w-2024/html/zenbun/s1_1_2.html
- ³Statistics Bureau, Ministry of Internal Affairs and Communication, "Senior Citizens in Japan from a Statistical Perspective: In Commemoration of Respect-for-Senior-Citizens Day" (in Japanese). <https://www.stat.go.jp/data/topics/pdf/topics138.pdf>
- ⁴Ueda, A., and K. Nohara, "Criteria for diagnosing aspiration pneumonia in Japan—a scoping review," *Respir. Investig.* **62**, 128–136 (2024).
- ⁵Oguchi, K., and E. Saitoh, "A Historical Review of Medical Treatment for Dysphagia," *IRYO* **61**, 83–85 (2007) (in Japanese).
- ⁶Ruark, J. L., G. H. McCullough, R. L. Peters, and C. A., and Moore, "Bolus consistency and swallowing in children and adults," *Dysphagia* **17**, 24–33 (2002).
- ⁷Shama, F., and P. Sherman, "Identification of stimuli controlling the sensory evaluation of viscosity II. Oral methods," *J. Texture Stud.* **4**, 111–118 (1973).
- ⁸Mizunuma, H., "Fluid Mechanics of Swallowing," *Nagare: Journal of Japan Society of Fluid Mechanics* **39**, 14–19 (2020)(in Japanese).
- ⁹Nishinari, K., M. Takemasa, L. Su, Y. Michiwaki, H. Mizunuma, and H. Ogoshi, "Effect of shear thinning on aspiration—Toward making solutions for judging the risk of aspiration," *Food Hydrocoll.* **25**, 1737–1743 (2011).
- ¹⁰Nishinari, K., *et al.*, "Rheology for safe swallowing 1," *Nihon Reorogi Gakkaishi* **51**, 219–248 (2023).
- ¹¹Nishinari, K., *et al.*, "Rheology for safe swallowing 2," *Nihon Reorogi Gakkaishi* **51**, 295–316 (2023).
- ¹²Nishinari, K., *et al.*, "Rheology for safe swallowing 3," *Nihon Reorogi Gakkaishi* **52**, 37–64 (2024).
- ¹³Nishinari, K., M. Turcanu, M. Nakauma, and Y. Fang, "Role of fluid cohesiveness in safe swallowing," *npj Science of Food* **3**, 5 (2019).
- ¹⁴Vickers, Z., H. Damodhar, C. Grummer, H. Mendenhall, K. Banaszynski, R. Hartel, J. Hind, A. Joyce, A. Kaufman, and J. Robbins, "Relationships among rheological, sensory texture, and swallowing pressure measurements of hydrocolloid-thickened fluids," *Dysphagia* **30**, 702–713 (2015).
- ¹⁵Takahashi, K., R. Yoshida, K. Ohie, S. Kumagai, and Y. Tasaka, "Adhesion testing of dysphagia diets for the quantitative evaluation of swallowing," *Food Hydrocolloids* **171**, 111816 (2026).
- ¹⁶Cichero, J. A. Y., *et al.*, "Development of international terminology and definitions for texture-modified foods and thickened fluids used in dysphagia management: the IDDSI framework," *Dysphagia* **32**, 293–314 (2017).
- ¹⁷IDDSI framework documents, testing methods, <https://www.iddsi.org/images/Publications-Resources/DetailedDefnTestMethods/Czech/TestingMethodsCzech26Nov2024-ForReview.pdf>.
- ¹⁸Hanson, B., R. Jamshidi, A. Redfearn, R. Begley, and C. M. Steele, "Experimental and computational investigation of the IDDSI flow test of liquids used in dysphagia management," *Ann. Biomed. Eng.* **47** 2296–2307 (2019).
- ¹⁹Mann, L. L., and K. Wong, "Development of an objective method for assessing viscosity of formulated foods and beverages for the dysphagic diet," *J. Am. Diet. Assoc.* **96**, 585–588 (1996).
- ²⁰Paik, N.-J., T. R. Han, J.-W. Park, E.-K. Lee, M.-S. Park, and I.-K. Hwang, "Categorization of dysphagia diets with the line spread test," *Arch. Phys. Med. Rehabil.* **85**, 857–861 (2004).
- ²¹Nicosia, M. A., and J. Robbins, "The usefulness of the line spread test as a measure of liquid consistency," *Dysphagia* **22** 306–311 (2007).
- ²²Milczarek, R. R., and K. L. McCarthy, "Relationship between the Bostwick measurement and fluid properties," *J. Texture Stud.* **37**, 640–654 (2006).
- ²³Balmforth, N. J., R. V. Craster, P. Perona, A. C. Rust, and R. Sassi, "Viscoplastic dam breaks and the Bostwick consistometer," *J. non-Newtonian Fluid Mech.* **142**, 63–78 (2007).
- ²⁴Ross, Jane, M. Schwarz, M. Seabrook, and A. Coccetti, "Low technology audit methods of pre-packaged thickened fluids using the Bostwick Consistometer, the Line Spread Test and the Flow Test: A comparison of compliance," *JCPSLP* **22** 116–121 (2020).
- ²⁵Côté, Claudia, I. Germain, T. Dufresne, and C. Gagnon, "Comparison of two methods to categorize thickened liquids for dysphagia management in a clinical care setting context: The Bostwick consistometer and the IDDSI Flow Test. Are we talking about the same concept?," *J. Texture Stud.* **50** 95–103 (2019).
- ²⁶Hossain, M. T., and R. H. Ewoldt, "Protoreology," *J. Rheol.* **68** 113–144 (2024).
- ²⁷Hossain, M. T., and R. H. Ewoldt, "Do-it-yourself rheometry," *Phys. Fluids* **34** 053105 (2022).
- ²⁸Hossain, M. T., R. Tiwari, and R. H. Ewoldt, "Protoreology in practice: Avoiding misinterpretation," *Curr. Opin. Colloid Interface Sci.* **74**, 101866 (2024).
- ²⁹Clayton, S., T. G. Grice, and D. V. Boger, "Analysis of the slump test for on-site yield stress measurement of mineral suspensions," *Int. J. Miner. process.* **70** 3–21 (2003).
- ³⁰Pashias, N., D. V. Boger, J. Summers, and D. J. Glenister, "A fifty cent rheometer for yield stress measurement," *J. Rheol.* **40** 1179–1189 (1996).
- ³¹Hsu, E. Jane, "Design of a measurement device for bread dough proofing," *Diss. Massachusetts Institute of Technology*, (2020).
- ³²Mizunuma, H., "Intermediate viscosity in a gravity-driven flow and its application to simple viscometry," *J. Rheol.* **69**, 131–138 (2025).
- ³³Lecanu, R., G. Della Valle, C. Leverrier, and M. Ramaioli, "Predicting the gravity-driven flow of power law fluids in a syringe: a rheological map for the IDDSI classification," *Rheol. Acta* **63**,

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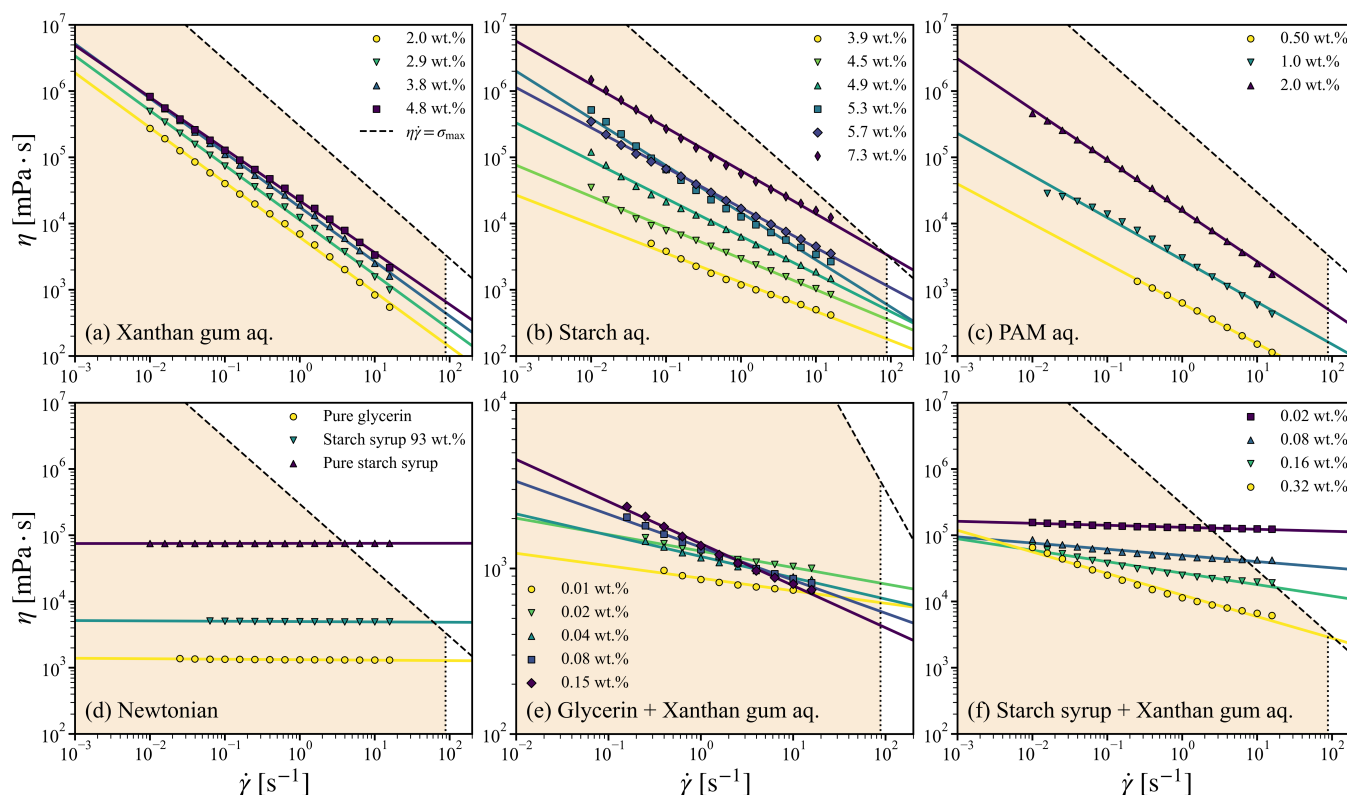


FIG. 9. Viscosity curves of (a) xanthan gum-based aqueous solutions, (b) starch-based aqueous solutions and (c) PAM aqueous solutions at different concentrations, as well as (d) Newtonian fluids, (e) glycerin mixed with a 2.9 wt% xanthan gum-based aqueous solution and (f) starch syrup mixed with a 3.8 wt% xanthan gum-based solution at different concentrations. In the legends of (e) and (f), the concentrations are calculated as the amount of solving xanthan gum-based thickening agents divided by the total amount of solvent, including glycerin or starch syrup and the water present in the thickening solution. Dashed lines in each panel indicate the viscosity corresponding to the maximum shear stress acting the test fluids estimated by static pressure $\rho g H_0$, and colored area is the available widest shear rate range in GFT estimated from $r_f(t)$ obtained by the image processing on 0.50 wt% PAM aq. solution and Eq. 6.

- 459–469 (2024).
- ³⁴Divoux, T., D. Tamarii, C. Barentin, S. Teitel, and S. Manneville, “Yielding dynamics of a Herschel–Bulkley fluid: a critical-like fluidization behaviour,” *Soft Matter* **8**, 4151–4164 (2012).
- ³⁵Valette, R., A. Pereira, S. Riber, L. Sardo, A. Larcher, E. Hachem, “Viscoplastic dam-breaks,” *J. Non-Newtonian Fluid Mech.* **287**, 104447 (2021).
- ³⁶Isukwem, K., and A. Pereira, “Dam break of viscoplastic elliptical objects,” *J. Non-Newtonian Fluid Mech.* **336**, 105376 (2025).
- ³⁷Isukwem, K., C.-A. Charles, T. Phou, L. Ramos, C. Ligoure, E. Hachem1, and A. Pereira, “Inverse Leidenfrost impacting drops,” *J. Fluid Mech.* **1002**, A32 (2025).
- ³⁸Barnes, H. A., “Measuring the viscosity of large-particle (and flocculated) suspensions—a note on the necessary gap size of rotational viscometers,” *J. non-Newtonian Fluid Mech.* **94**, 213–217 (2000).
- ³⁹Ohie, K., S. Kumagai, Y. Tasaka, and Y. Murai, “Rheology of fluid foods containing millimeter-sized ingredients examined by velocity-profiling-assisted rheometry and prediction of spreading and descending behaviors,” *J. Rheol.* **69**, 111–120 (2025).
- ⁴⁰Ohie, K., T. Yoshida, and Y. Tasaka, “Coupling a torque rheometer with an ultrasonic velocity profiler for evaluating multiphase fluids in oscillatory shear flows,” *J. Rheol.* **68**, 665–678 (2024).
- ⁴¹Ohie, K., Y. Yoshida, Y. Tasaka, and Y. Murai, “Flow prediction of complex fluids in a circular pipe by utilizing a velocity-profiling-assisted rheometer,” *Ind. Eng. Chem. Res.* **61**, 18157–18164 (2022).
- ⁴²Ohie, K., D. Nishizuka, T. Yoshida, and Y. Tasaka, “Cost-effective production of density-controllable monodisperse spheres for experiments in fluids,” *Phys. Fluids* **36**, 091704 (2024).

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TABLE III. The value of parameters obtained by fitting each viscosity curve to the power-law model $\eta = K\dot{\gamma}^{n-1}$ and obtained by fitting each time variation of normalized spreading distance to Eq. 9.

Fig.	Solution	Index	Concentration	K [mPa · s ⁿ]	n [-]	τ [s]	m [-]
9(a)	Xanthan gum-based aq.	0	2.0 wt%	6.22×10^3	0.173	2.39×10^{-1}	0.440
		1	2.9 wt%	1.13×10^4	0.174	1.04×10^0	0.277
		2	3.8 wt%	1.77×10^4	0.178	2.25×10^1	0.261
		3	4.8 wt%	2.21×10^4	0.218	1.23×10^2	0.328
9(b)	Starch-based aq.	4	3.9 wt%	1.30×10^3	0.561	4.33×10^{-1}	0.820
		5	4.5 wt%	2.96×10^3	0.530	1.05×10^0	0.577
		6	4.9 wt%	6.45×10^3	0.430	2.93×10^0	0.567
		7	5.3 wt%	1.46×10^4	0.288	9.34×10^0	0.499
		8	5.7 wt%	1.74×10^4	0.396	2.37×10^1	0.505
9(c)	PAM aq.	9	7.3 wt%	6.29×10^4	0.348	2.47×10^2	0.777
		10	0.50 wt%	6.17×10^2	0.398	2.04×10^{-1}	0.569
		11	1.0 wt%	2.83×10^3	0.364	7.07×10^{-1}	0.523
9(d)	Pure starch syrup	12	2.0 wt%	1.56×10^4	0.235	2.89×10^1	0.519
	Starch syrup aq.	13	–	7.54×10^4	0.997	3.31×10^1	0.610
	Pure glycerin	14	93 wt%	4.98×10^3	1.00	2.39×10^0	0.664
9(e)	Glycerin + XGS	15	–	1.32×10^3	0.992	7.06×10^{-1}	0.618
		16	0.01 wt%	8.72×10^2	0.925	5.02×10^{-1}	0.640
		17	0.02 wt%	1.27×10^3	0.901	5.47×10^{-1}	0.524
		18	0.04 wt%	1.18×10^3	0.871	9.32×10^{-1}	0.795
		19	0.08 wt%	1.34×10^3	0.801	8.75×10^{-1}	0.768
9(f)	Starch syrup + XGS	20	0.15 wt%	1.41×10^3	0.746	7.32×10^{-1}	0.734
		21	0.02 wt%	1.32×10^5	0.970	3.10×10^1	0.745
		22	0.08 wt%	4.97×10^4	0.907	1.72×10^1	0.642
		23	0.16 wt%	2.68×10^4	0.827	1.59×10^1	0.613
		24	0.32 wt%	1.25×10^4	0.675	1.13×10^1	0.626