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MOTION OF A NONLINEARLY VISCOPLASTIC FLUID JET ALONG A PLATE MOVING AT AN ANGLE TO THE HORIZON

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UDC 532.135

Stationary stabilized flow of a plane fluid jet along a moving inclined plane is considered.

Used extensively in the wood processing industry is the process of infusion application of paint and varnish coatings as follows. The articles pass under an apparatus forming a plane jet (curtain) of downward incident varnish (Fig. 1) [1].

The fundamental parameter of the process is the coating thickness which governs its protective-decorative property and cost.

At present, coatings are applied on horizontally moving articles, hence, their thickness is determined from the relationship $h = Q/u_p$.

A number of papers has recently appeared that indicate the expediency of moving the article at an angle to the horizon. The passage to the new infusion scheme requires the determination of the thickness of the jet of varnish material on the moving inclined plane.

To solve such a problem, the equation of the rheological state of the fluid must be given, to describe the rheological behavior of varnish materials. A number of empirical models has been proposed. Without analyzing their confidence, a solution of the problem has been obtained in this paper for all the models proposed. To this end, the Shul'man [2, 3] four-parameter rheological equation of state has been taken, which generalizes all models of varnish materials. This would permit not only relating the coating thickness to the technological and rheological parameters of the process, but also to clarify how the selection of the rheological equation of state influences the relations describing the process as well as how intensively must the rheological properties of the varnish materials be studied to describe their application by infusion.

1. FORMULATION OF THE PROBLEM

Let there be a jet of nonlinearly viscoplastic fluid moving along a plate. We assume the flow stationary and stabilized. The fluid flow rate per unit jet width is Q. In its turn the plate moves at a velocity u_p at an angle α to the horizon. We direct the coordinate axes as shown in Fig. 1. We consider the angle α positive during upward motion of the plate and negative during downward motion.

In the case under consideration, the Shul'man rheological model will have the form

$$\tau = \operatorname{sign}\left(\frac{du}{dy}\right) |\tau|,$$

Ukraine Scientific Production Wood Processing Combine, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 4, pp. 597-605, April, 1987. Original article submitted November 26, 1985.

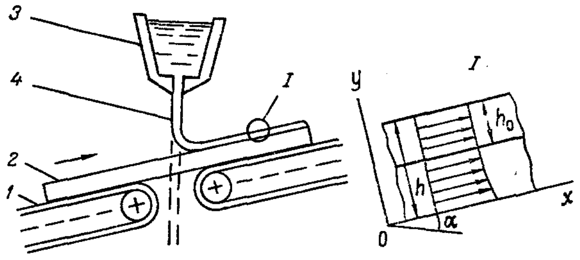

Fig. 1. Diagram of infusion application of a varnish coating: 1) belt conveyer; 2) article; 3) infusion apparatus; 4) jet of varnish material.

$$|\tau|^{\frac{1}{n}} = |\tau_0|^{\frac{1}{n}} + \left(\mu\left|\frac{du}{dy}\right|\right)^{\frac{1}{m}} \text{ for } |\tau| > |\tau_0|, \qquad (1)$$
$$\frac{du}{dy} = 0 \text{ for } |\tau| \leqslant |\tau_0|.$$

The following relationship holds for varnish materials [2]

$$1 \leqslant n \leqslant m. \qquad (2)$$

In the one-dimensional case the equation of motion in stresses will have the form

$$\frac{d\tau}{dy} = \rho g \sin\alpha. \qquad (3)$$

The tangential stresses on the free surface evidently vanish, consequently, the zone of quasisolid flow for $|\tau| \leq |\tau_0|$ will adjoin the free surface. Therefore, the boundary condition for Eq. (3) is

$$\tau(h - h_0) = \tau_0, \qquad (4)$$

$$h_0 = -\frac{\tau_0}{\rho g \sin\alpha}, \text{ but } h_0 \leqslant h. \qquad (5)$$

Let us integrate the motion equation (3) with the boundary condition (4)

$$\tau = \rho g \sin\alpha\,(y - h). \qquad (6)$$

Substituting (6) into (1), we obtain the equation of the jet velocity for the viscoplastic flow zone $0 \leq y \leq h - h_0$

$$u = -\operatorname{sign}(\alpha)\frac{1}{\mu}\int\{[\rho g \sin|\alpha|(h - y)]^{1/n} - |\tau_0|^{1/n}\}^m dy + C_1 \qquad (7)$$

with the boundary condition

$$u|_{y=0} = u_p. \qquad (8)$$

The integral I in (7) will be a rational function in just three cases: a) m is an integer; b) n is an integer; c) n + m is an integer. In the remaining cases I is not expressed in terms of elementary functions.

Let us consider each of the three cases in sequence.

2. CASE OF THE INTEGER VALUE OF THE PARAMETER m

From (2) $m \geq 1$. Therefore, the Newton binomial in the integrand of I is expanded in a series with a finite number of terms

$$u = -\operatorname{sign}(\alpha)\frac{1}{\mu}\int\sum_{k=0}^{m}(-1)^k C_m^k [\rho g \sin|\alpha|(h - y)]^{\frac{m-k}{n}}|\tau_0|^{\frac{k}{n}} dy + C_1,$$

where $C_m^k = m!/k!(m - k)!$.

After integrating with the boundary condition (8), we obtain the expression for the jet velocity for the viscoplastic flow zone:

$$u = \operatorname{sign}(\alpha)\frac{1}{\mu}\sum_{k=0}^{m}(-1)^k C_m^k \frac{n}{m - k + n}|\tau_0|^{\frac{k}{n}}(\rho g \sin|\alpha|)^{\frac{m-k}{n}}[(h - y)^{\frac{m-k}{n}+1} - h^{\frac{m-k}{n}+1}] + u_p. \qquad (9)$$

The fluid flow rate through unit jet width equals

TABLE 1. Fluid Mass Flow Rate Equations

Rheological model of the fluid	i	Q
Newton ($\tau_0=0;\ n=m=1$)	1	$-\dfrac{\rho g\sin\alpha}{3\mu}h^3+u_p h$
Shvedov–Bingham ($\tau_0\neq 0;\ n=m=1$)	2	$\operatorname{sign}(\alpha)\dfrac{1}{\mu}\Big[-\dfrac{1}{3}\rho g\sin\lvert\alpha\rvert h^3+\dfrac{1}{2}\lvert\tau_0\rvert h^2-\dfrac{1}{6}(\rho g\sin\lvert\alpha\rvert)^{-2}\lvert\tau_0\rvert^3\Big]+u_p h$
Casson ($\tau_0\neq 0;\ n=m=2$)	3	$\operatorname{sign}(\alpha)\dfrac{1}{\mu}\Big[-\dfrac{1}{3}\rho g\sin\lvert\alpha\rvert h^3+\dfrac{4}{5}(\rho g\sin\lvert\alpha\rvert)^{\frac{1}{2}}\times\lvert\tau_0\rvert^{\frac{1}{2}}h^{\frac{5}{2}}-\dfrac{1}{2}\lvert\tau_0\rvert h^2+\dfrac{1}{30}(\rho g\sin\lvert\alpha\rvert)^{-2}\lvert\tau_0\rvert^3\Big]+u_p h$
Shul'man ($\tau_0\neq 0;\ n=m=3$)	4	$\operatorname{sign}(\alpha)\dfrac{1}{\mu}\Big[-\dfrac{1}{3}\rho g\sin\lvert\alpha\rvert h^3+\dfrac{9}{8}(\rho g\sin\lvert\alpha\rvert)^{\frac{2}{3}}\times\lvert\tau_0\rvert^{\frac{1}{3}}h^{\frac{8}{3}}-\dfrac{9}{7}(\rho g\sin\lvert\alpha\rvert)^{\frac{1}{3}}\lvert\tau_0\rvert^{\frac{2}{3}}h^{\frac{7}{3}}+\dfrac{1}{2}\lvert\tau_0\rvert h^2-\dfrac{1}{168}(\rho g\sin\lvert\alpha\rvert)^{-2}\lvert\tau_0\rvert^3\Big]+u_p h$
Ostwald ($\tau_0=0;\ n=1$)	5	$-\dfrac{\rho g\sin\alpha}{3\mu}h^3\Big[\dfrac{3}{m+2}(\rho g\sin\lvert\alpha\rvert)^{m-1}h^{m-1}\Big]+u_p h$

$$Q=\int_0^{h-h_0}u\,dy+u_0h_0. \tag{10}$$

We find the velocity of the quasisolid zone motion from (9) for $y = h - h_0$:

$$u_0=\operatorname{sign}(\alpha)\frac{1}{\mu}\sum_{k=0}^{m}(-1)^kC_m^k\frac{n}{m-k+n}\lvert\tau_0\rvert^{\frac{k}{n}}(\rho g\sin\lvert\alpha\rvert)^{\frac{m-k}{n}}\left(h_0^{\frac{m-k}{n}+1}-h^{\frac{m-k}{n}+1}\right)+u_p. \tag{11}$$

Substituting (5), (9), (11) into (10), we obtain the expression for Q:

$$Q=\sigma_0(h-h_0)\Big[-\operatorname{sign}(\alpha)\frac{1}{\mu}\sum_{k=0}^{m}(-1)^kC_m^k\frac{n}{m-k+2n}\lvert\tau_0\rvert^{\frac{k}{n}}\times(\rho g\sin\lvert\alpha\rvert)^{\frac{m-k}{n}}h^{\frac{m-k}{n}+2}+\operatorname{sign}(\alpha)\frac{1}{\mu}\lvert\tau_0\rvert^{\frac{m}{n}+2}(\rho g\sin\lvert\alpha\rvert)^{-2}\sum_{k=0}^{m}(-1)^kC_m^k\frac{n}{m-k+2n}\Big]+u_p h, \tag{12}$$

where $\sigma_0\ (h-h_0)$ is the Heaviside unit function

$$\sigma_0(h-h_0)=\begin{cases}1 \text{ for } h-h_0>0,\\ 0 \text{ for } h-h_0\leqslant 0.\end{cases}$$

To conserve the generality of writing (12) for $\tau_0 = 0$ the indeterminacy 0^0 and 0! will be understood as $0^0 = 0! = 1$.

3. CASE OF THE INTEGER VALUE OF THE PARAMETER n

Let m be a noninteger. We represent m as follows: $m = a/b$.

Let us go from (7) to the variable t in the integral I:

$$[\rho g\sin\lvert\alpha\rvert(h-y)]^{1/n}-\lvert\tau_0\rvert^{1/n}=t^b;$$

$$I=-\int t^{mb}\frac{nb}{\rho g\sin\lvert\alpha\rvert}\left(t^b+\lvert\tau_0\rvert^{1/n}\right)^{n-1}t^{b-1}dt.$$

From (2) $n \geq 1$. Therefore, the Newton binomial in the integrand of I is expanded in a series with a finite number of terms:

TABLE 2. Expressions for the Functionals F_i

i	F_i
1	1
2	$1-\frac{3}{2}\frac{h_0}{h}+\frac{1}{2}\left(\frac{h_0}{h}\right)^3$
3	$1-\frac{12}{5}\left(\frac{h_0}{h}\right)^{\frac{1}{2}}+\frac{3}{2}\frac{h_0}{h}-\frac{1}{10}\left(\frac{h_0}{h}\right)^3$
4	$1-\frac{27}{8}\left(\frac{h_0}{h}\right)^{\frac{1}{3}}+\frac{27}{7}\left(\frac{h_0}{h}\right)^{\frac{2}{3}}-\frac{3}{2}\frac{h_0}{h}+$ $+\frac{1}{56}\left(\frac{h_0}{h}\right)^3$
5	$\frac{3}{m+2}\frac{\eta_{ef}}{\eta_{min}}$

$$I=-\frac{nb}{\rho g\sin|\alpha|}\int t^{mb+b-1}\sum_{k=0}^{n-1}C_{n-1}^{k}|\tau_0|^{\frac{k}{n}}t^{b(n-1-k)}dt,$$

where $C_{n-1}^{k}=(n-1)!/k!(n-1-k)!$.

After integrating and going over to the initial variable we obtain

$$\int\{[\rho g\sin|\alpha|(h-y)]^{\frac{1}{n}}-|\tau_0|^{\frac{1}{n}}\}^m dy=-\frac{1}{\rho g\sin|\alpha|}\sum_{k=0}^{n-1}C_{n-1}^{k}\frac{n}{m+n-k}|\tau_0|^{\frac{k}{n}}\{[\rho g\sin|\alpha|(h-y)]^{\frac{1}{n}}-|\tau_0|^{\frac{1}{n}}\}^{m+n-k}. \tag{13}$$

Substituting (13) into (7) with the boundary condition (8), we obtain an expression for the jet velocity for the viscoplastic flow zone $0\leq y\leq h-h_0$:

$$u=\operatorname{sign}(\alpha)\frac{1}{\mu}\frac{1}{\rho g\sin|\alpha|}\sum_{k=0}^{n-1}C_{n-1}^{k}\frac{n}{m+n-k}|\tau_0|^{k/n}\{[(\rho g\sin|\alpha|)^{1/n}\times(h-y)^{1/n}-|\tau_0|^{1/n}]^{m+n-k}-[(\rho g\sin|\alpha|h)^{1/n}-|\tau_0|^{1/n}]^{m+n-k}\}+u_p. \tag{14}$$

We find the velocity of the quasisolid zone motion from (14) for $y=h-h_0$

$$u_0=\operatorname{sign}(\alpha)\frac{1}{\mu}\frac{1}{\rho g\sin|\alpha|}\sum_{k=0}^{n-1}C_{n-1}^{k}\frac{n}{m+n-k}|\tau_0|^{k/n}\{[(\rho g\sin|\alpha|h_0)^{1/n}-|\tau_0|^{1/n}]^{m+n-k}-[(\rho g\sin|\alpha|h)^{1/n}-|\tau_0|^{1/n}]^{m+n-k}\}+u_p. \tag{15}$$

Substituting (5), (14), (15) into (10) and integrating by using (13), we obtain the expression for the flow rate Q:

$$Q=\sigma_0(h-h_0)\Big\{\operatorname{sign}(\alpha)\frac{1}{\mu}\frac{1}{(\rho g\sin|\alpha|)^2}\times\sum_{k=0}^{n-1}\sum_{l=0}^{n-1}C_{n-1}^{k}C_{n-1}^{l}\frac{n^2}{(m+n-k)(m+2n-l-k)}|\tau_0|^{\frac{k+l}{n}}[(\rho g\sin|\alpha|h)^{\frac{1}{n}}-|\tau_0|^{\frac{1}{n}}]^{m+2n-k-l}-\operatorname{sign}(\alpha)\frac{1}{\mu}\frac{1}{\rho g\sin|\alpha|}h\sum_{k=0}^{n-1}C_{n-1}^{k}\frac{n}{m+n-k}|\tau_0|^{\frac{k}{n}}[(\rho g\sin|\alpha|h)^{\frac{1}{n}}-|\tau_0|^{\frac{1}{n}}]^{m+n-k}\Big\}+u_ph. \tag{16}$$

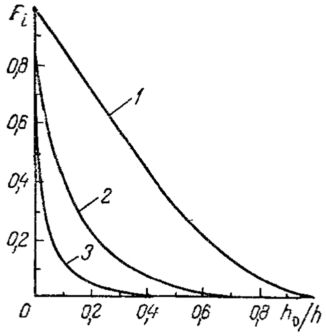

Fig. 2

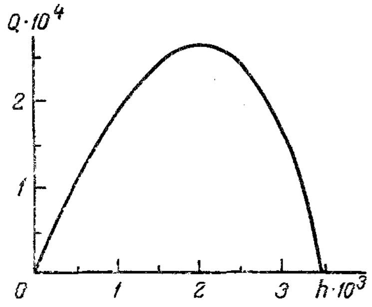

Fig. 3

Fig. 2. Dependence of the functional F_i on the ratio h_0/h: 1) F_2; 2) F_3; 3) F_4.

Fig. 3. Dependence of the fluid mass flow rate Q, m^2/sec, on the jet thickness h, m ($u_p = 0.2$ m/sec; $\alpha = 30°$; $\mu/\rho = 10^{-4}$ m^2/sec; $F_i = 1$).

4. CASE OF THE INTEGER VALUE OF THE SUM OF THE PARAMETERS n + m

Let n and m be nonintegers but such that the sum n + m is an integer. Let us represent m as follows: m = a/b.

Let us go over from (7) to the variable t in the integral I:

$$\frac{[\rho g \sin|\alpha|(h-y)]^{\frac{1}{n}} - |\tau_0|^{\frac{1}{n}}}{(h-y)^{\frac{1}{n}}} = t^b;$$

$$I = -bn\,|\tau_0|^{\frac{m}{n}+1} \int \frac{t^{bm+b+1}}{[(\rho g \sin|\alpha|)^{\frac{1}{n}} - t^b\,]^{m+n+1}}\,dt.$$

The integral is rationalized and therefore is expressed in terms of a finite number of elementary functions. This calculation is not presented in general form here because of its extreme awkwardness.

5. COMPARATIVE ANALYSIS OF NEWTON, SHVEDOV – BINGHAM, CASSON, SHUL'MAN (FOR n = m = 3), AND OSTVALD FLOWS ALONG A PLATE MOVING AT AN ANGLE TO THE HORIZON

The listed rheological models were proposed by different authors to approximate the flow curves of varnish materials. Consequently, it is of definite interest to perform a comparative analysis of the flow of these fluids that will permit the clarification to what degree the selection of the rheological model will influence the final result of describing the process of applying a coating on wood by infusion. As a final result we shall be interested in determining the jet thickness $h = f(Q, u_p, \alpha, \mu, \rho, n, m)$.

The mass flow rate equations for the fluids of interest to us and obtained from (12) and (16) are presented in Table 1. Since it is impossible to obtain the function h explicitly exactly for all the models, we use (5) to convert the mass flow rate equation for the first four models to the following form

$$F_i\left(-\frac{\rho g \sin\alpha}{3\mu}\right)h^3 + u_p h - Q = 0. \tag{17}$$

The expressions for the functionals F_i are presented in Table 2 and their magnitude is within the limits $0 \le F_i \le 1$ (Fig. 2). As is seen from (1), the parameter μ has the physical meaning of viscosity for high strain rates $|du/dy| \to \infty$.

In order to conserve the generality of writing (17) even for the Ostwald model, we convert the mass flow rate equation for this model by using the concept of the apparent viscosity η:

$$\eta = \mu^{\frac{1}{m}} \left|\frac{du}{dy}\right|^{\frac{1-m}{m}}.$$

For varnish materials $m \geq 1$. Therefore, as the strain rate grows the viscosity diminishes. The highest strain rate for jet flow along a plate will be for $y = 0$. The apparent viscosity will here be minimal

$$\eta_{\min} = \mu^{\frac{1}{m}} \left| \frac{du}{dy} \right|_{y=0}^{\frac{1-m}{m}} = \mu (\rho g \sin |\alpha| \, h)^{1-m}.$$

Substituting $\eta_{\min}$ into the mass flow rate equation, we obtain

$$Q = \frac{3}{m+2} \frac{\eta_{ef}}{\eta_{\min}} \left(-\frac{\rho g \sin \alpha}{3\eta_{ef}} \right) h^3 + u_p h.$$

Here η_{ef} is the Yakovlev [4] effective viscosity, i.e., the viscosity of varnish materials at high strain rates $|du/dy| > 10^4$-10^5 sec^{-1}. For lower strain rates the apparent viscosity can exceed η_{ef} by several orders.

Therefore, the generality of writing (17) is conserved even for the Ostwald model if the parameter μ is understood to be the viscosity for high strain rates exactly as for the other models, and F_i is understood to be the quantity $F_5 = 3\eta_{ef}/(m + 2)\eta_{\min}$. Here

$$F_5 \leqslant 1 \quad \text{for} \quad \left| \frac{du}{dy} \right|_{y=0} = \frac{(\rho g \sin |\alpha| \, h)^m}{\mu} > 10^4 - 10^5 \ \text{sec}^{-1};$$

$$F_5 \ll 1 \quad \text{for} \quad \left| \frac{du}{dy} \right|_{y=0} < 10^4 \ \text{sec}^{-1}$$

For $\alpha > 0$ Eq. (17) has three real roots, from which the root

$$h = -2 \sqrt{\frac{u_p \mu}{F_i \rho g \sin \alpha}} \cos \left(\frac{\beta}{3} + \frac{\pi}{3} \right) \tag{18}$$

is suitable according to the physical meaning, where

$$\beta = \arccos \left(-\frac{3}{2} \frac{Q}{u_p} \sqrt{\frac{F_i \rho g \sin \alpha}{u_p \mu}} \right);$$

and for $\alpha < 0$ one real root

$$h = \sqrt[3]{-\frac{3Q\mu}{2F_i \rho g \sin \alpha} + \sqrt{D}} + \sqrt[3]{-\frac{3Q\mu}{2F_i \rho g \sin \alpha} - \sqrt{D}}, \tag{19}$$

where

$$D = \left(-\frac{u_p \mu}{F_i \rho g \sin \alpha} \right)^3 + \left(\frac{3Q\mu}{2F_i \rho g \sin \alpha} \right)^2.$$

Let us note that the root of (17) for typical values of h, Q, u_p, α, μ, ρ for the application of varnish coatings on wood by infusion differs slightly from the quantity $h \approx Q/u_p$. The maximal relative error of such an approximation under the following constraints on the quantities $h \leq 0.5 \cdot 10^{-3}$ m; $u_p \geq 0.2$ m/sec; $\mu/\rho \geq 10^{-4}$ m^2/sec; $|\alpha| \leq 30°$, which are acceptable from the viewpoint of the technology of finishing wood by infusion, is $\Delta_{\max} = 2.1\%$.

6. MAXIMAL THICKNESS OF A JET ENTRAINED BY A PLATE MOVING AT AN ANGLE TO THE HORIZON

In forming a coating on an article moving upward at an angle to the horizon there exists a definite fluid flow rate above which the plate cannot entrain. This is related to the fact that as the jet thickness increases, the upper layers of the fluid stand all the more off from the plate. Consequently, the dependence of the fluid flow rate Q entrained by the moving plate on the jet thickness is extremal in nature (Fig. 3).

Let us investigate the function Q(h) for a maximum. To do this we find the derivative of the function

$$\frac{dQ}{dh} = -F_i \frac{\rho g \sin \alpha}{\mu} h^2 + u_p.$$

Equating dQ/dh to zero, we obtain

$$Q_{max} = \frac{2}{3}\sqrt{\frac{\mu}{F_i \rho g \sin\alpha}}\, u_p^{3/2} \text{ for } h_{max} = \sqrt{\frac{u_p \mu}{F_i \rho g \sin\alpha}}. \quad (20)$$

It is impossible to realize a flow with a large jet thickness. Therefore. if the flow rate of the varnish material by an infusion apparatus will be greater than Q_{max} there will be an excess quantity of fluid at the point of contact of the curtain with the plate from which a jet of thickness h_{max} is drawn from (20).

For a mass flow rate less than Q_{max} the jet thickness on the plate will be determined by relationships (18) and (19).

The following values of the quantities $u_{p\ min} = 0.2$ m/sec; $(\mu/\rho)_{min} = 10^{-4}$ m²/sec; $\alpha_{max} = 30°$; $F_{i\ max} = 1$ are characteristic for the application of varnish coatings on wood by infusion. For this combination of technological and rheological parameter magnitudes, the most possible jet thickness on a plate will evidently be least and equal to $h = 2 \cdot 10^{-3}$ m, which is much greater than the coating thickness usually being formed on wood.

Therefore, upon variating the technological and rheological parameters in the whole range of values of practical expediency from the viewpoint of the technology of wood finishing by infusion, all the fluid proceeding from the infusion apparatus will be entrained by the moving article. The jet thickness on the article will here be determined from the relationship $h \approx Q/u_p$ with an error not greater than 2.1% independently of the rheological model of the fluid. The error here will be smaller the greater the rheological behavior of the varnish materials differs from the Newtonian.

NOTATION

x, longitudinal coordinate; y, transverse coordinate; h, jet thickness; h_0, quasisolid zone thickness; u, longitudinal velocity component; u_0, velocity of quasisolid zone motion; u_p, velocity of plate motion; Q, bulk fluid mass flow rate through unit jet width per unit time; τ, shear stress; τ_0 ultimate shear stress; u, n, m, fluid constants, parameters of the Shul'man rheological model; ρ, fluid density; g, free-fall acceleration; α, angle between the plate and the horizon; δ_0, Heaviside unit function; F_i, functionals of the ratio between the quasisolid zone thickness and the jet thickness; a, b, positive integers; Δ, relative error; η, apparent viscosity; and η_{ef}, effective viscosity.

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