Journal of Macromolecular Science, Part A
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597274

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To cite this Article (1969) 'Bagley Entrance Pressure Drop Method', Journal of Macromolecular Science, Part A, 3: 5, 1033 — 1036

To link to this Article: DOI: 10.1080/10601326908051932

URL: http://dx.doi.org/10.1080/10601326908051932

J. MACROMOL. SCI.–CHEM., A3(5), pp. 1033-1036, August, 1969

LETTER TO THE EDITOR

Bagley Entrance Pressure Drop Method

The method of eliminating the entrance pressure drop to obtain true flow curves from capillary rheometers with small length-to-diameter ratios is due to Bagley [1]. The method, which is applicable to all time-independent fluids, consists of seven steps.

1) Plot ln ΔP_{TOT} versus in γ_{app} for a number of L/D values, where ΔP_{TOT} is the total pressure drop across the capillary and associated reservoir and the apparent shear rate, γ_{app}, is given by

$$\gamma_{app} = \frac{32Q}{\pi D^3} \tag{1}$$

where Q is the volumetric flow rate.

2) Choose a number of γ_{app} and determine the corresponding ΔP_{TOT} for the L/D values used.

3) Plot these ΔP_{TOT} versus L/D with the γ_{app} as the parameters.

4) Fit straight lines through the ΔP_{TOT} – L/D curves.

5) Extrapolate the straight lines to L/D = O, thus obtaining ΔP_{ent} at the chosen γ_{app}.

6) The true wall shear stress (τ_{TW}) is thus calculated from the equation

$$\tau_{TW} = \frac{D}{4L}\left(\Delta P_{TOT} - \Delta P_{ent}\right) \tag{2}$$

and the true wall shear rate (γ_{TW}) from the equation

$$\gamma_{TW} = \frac{\gamma_{app}}{4}\left[3 + \frac{d \ln \gamma_{app}}{d \ln \tau_{TW}}\right] \tag{3}$$

7) The true flow curve is obtained by plotting ln τ_{TW} versus ln γ_{TW}.

This method has been used extensively in rheological characterization studies [1–13].

In applying Bagley's method most experimenters have varied L/D by changing both L and D while holding the diameter of the reservoir (D_R) constant. While at first glance this may seem perfectly valid, it can lead to errors and unexplainable annomolies [3, 4]. The recent work of Sylvester and Rosen [14], Astarita and Greco [15], and LaNieve and Bogue [6] has shown that the excess entrance pressure loss in the entrance region of a cylindrical tube depends not only on the rheological properties of the fluid and the true wall shear stress (or Reynolds number), but also on the ratio of tube to reservoir diameter–contraction ratio ($\beta = D/D_R$). For Re < 1.0, which is common in capillary rheometer studies, the dimensionless excess entrance pressure drop for Newtonian fluids can be written [14, 15]

$$\frac{g_c \Delta p_{ent}}{\frac{1}{2}\rho V^2} = \frac{K'}{Re} \tag{4}$$

where K′ depends on the contraction ratio, β, as shown in Table 1. Rearrangement of Eq. (4) yields [16]

$$\Delta P_{ent} = \frac{K'}{16} \tau_{TW} \tag{5}$$

Table 1

Investigation	β	K′
LaNieve and Bogue [6]	0.007	36.8
Sylvester and Rosen [14]	0.0156	295.0
Astarita and Greco [15]	0.1616	795.0

It is evident from Table 2 that the contraction ratio, β, has a significant effect on the entrance pressure loss.

Both non-Newtonian and viscoelastic fluids have also been considered [14] but these effects seem to be adequately eliminated by Bagley's method provided it is properly used and a sufficiently large range of the independent variables is studied. Thus, for Bagley's method to be used accurately, it is necessary to vary L/D by varying L while holding the tube and

Table 2

τ_{TW} ($lb_f/in.^2$)	$\beta = 0.007$ ΔP_{ent} ($lb_f/in.^2$)	$\beta = 0.0156$ ΔP_{ent} ($lb_f/in.^2$)	$\beta = 0.1616$ ΔP_{ent} ($lb_f/in.^2$)
1.0	2.3	18.4	49.7
0.1	0.23	1.84	4.97
0.01	0.023	0.184	0.497
0.001	0.0023	0.018	0.05
0.0001	0.0002	0.002	0.005

reservoir diameters constant or by varying L along with D_R and D such that their ratio ($\beta = D/D_R$) remains constant.

As an example of the above, it is believed that the anamolous results of Jastrzebski [4] were due in part to the effects of varying β. In Jastrzebski's experiments β varied from 0.053 to 0.15; thus, referring to Table 2 it can be seen that at a given wall shear stress the excess entrance pressure drop could be in error by as much as 200%. Therefore, while Bagley's method is a valuable experimental technique, its effective use requires more experimental care than has been shown in the past.

NOMENCLATURE

D = tube diameter, in.

D_R = reservoir diameter, in.

g_c = gravitational constant, in. $lb_m/lb_f sec^2$

L = capillary length, in.

ΔP_{TOT} = total observed pressure drop, $lb_f/in.^2$

ΔP_{ent} = excess entrance pressure drop, $lb_f/in.^2$

Q = volumetric flow rate, $in.^3/sec$

Re = Reynolds number, dimensionless

V = volumetric average velocity, in./sec

β = contraction ratio, dimensionless

γ_{app} = apparent shear rate defined by Eq. (1), sec^{-1}

γ_{TW} = true wall shear rate, sec^{-1}
ρ = fluid density, $lb_m/in.^3$
τ_{TW} = true wall shear stress, $lb_f/in.^2$

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Accepted by editor January 15, 1969
Received for publication April 8, 1969