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Non-newtonian fluids: Guide to classification and characteristics

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NON-NEWTONIAN FLUIDS : GUIDE TO CLASSIFICATION AND CHARACTERISTICS

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NON-NEWTONIAN FLUIDS : GUIDE TO CLASSIFICATION AND CHARACTERISTICS

1. NOTATION AND UNITS

See Appendix A for Glossary of Terms.

		<i>Units</i>	
		<i>SI</i>	<i>British</i>
a	parameter in Cross model (Table 5.1)	s^m	s^m
a	parameter in Prandtl-Eyring and Powell-Eyring models (Table 5.1)	N/m^2 (Pa)	lbf/ft^2
a	parameter in Williamson model (Table 5.1)	m^2/N (Pa^{-1})	ft^2/lbf
a	parameter in Reiner-Philippoff model (Table 5.1)	m^4/N^2 (Pa^{-2})	ft^4/lbf^2
a	parameter in Meter model (Table 5.1)	m^{2m}/N^m (Pa^{-m})	ft^{2m}/lbf^m
a	parameter in Ellis model (Table 5.1)	m^{2-2m}/N^{1-m} (Pa^{1-m})	ft^{2-2m}/lbf^{1-m}
A	area	m^2	ft^2
b	parameter in Prandtl-Eyring and Powell-Eyring models (Table 5.1)	s	s
b	parameter in Van Wazer model (Table 5.1)	s^m	s^m
c	concentration or volume fraction of dispersed phase	—	—
c	parameter in Powell-Eyring model (Table 5.1)	$N\ s/m^2$ ($Pa\ s$)	$lbf\ s/ft^2$
F	force	N	lbf
K	consistency coefficient	$N\ s^n/m^2$ ($Pa\ s^n$)	$lbf\ s^n/ft^2$
L	plate gap dimension (see Section 4.1)	m	ft
m	exponent in various rheological flow models (Table 5.1)	—	—
n	exponent in various rheological flow models (Table 5.1)	—	—
V	velocity	m/s	ft/s
$\dot{\gamma}$	shear rate	s^{-1}	s^{-1}

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τ	shear stress	N/m ² (Pa)	lbf/ft ²
μ	dynamic viscosity	N s/m ² (Pa s)	lbf s/ft ²
μ_0	asymptotic value of viscosity at very low shear rate	N s/m ² (Pa s)	lbf s/ft ²
μ_∞	asymptotic value of viscosity at very high shear rate	N s/m ² (Pa s)	lbf s/ft ²
$[\mu]$	intrinsic viscosity (Section 4.1)	–	–
μ_B	Bingham plastic viscosity	N s/m ² (Pa s)	lbf s/ft ²
μ_C	Casson viscosity	N s/m ² (Pa s)	lbf s/ft ²
μ_N	Newtonian viscosity	N s/m ² (Pa s)	lbf s/ft ²
μ_{red}	reduced viscosity (Section 4.1)	–	–
μ_{rel}	relative viscosity (Section 4.1)	–	–
μ_s	viscosity of solvent or continuous phase (Section 4.1)	N s/m ² (Pa s)	lbf s/ft ²
μ_{sp}	specific viscosity (Section 4.1)	–	–
ν	kinematic viscosity	m ² /s	ft ² /s
τ_y	yield stress	N/m ² (Pa)	lbf/ft ²
τ_{yB}	Bingham yield stress	N/m ² (Pa)	lbf/ft ²
τ_{yC}	Casson yield stress	N/m ² (Pa)	lbf/ft ²
τ_{yHB}	Herschel-Bulkley yield stress	N/m ² (Pa)	lbf/ft ²
τ_{yV}	Vocadlo yield stress (Table 5.1)	N/m ² (Pa)	lbf/ft ²

2. INTRODUCTION

2.1 Purpose and Scope of ESDU Data Items on Non-Newtonian Fluids

Knowledge of fluid rheology is important in the design of process equipment such as pipelines, pumps, extruders, mixers, coaters and heat exchangers. Rheological behaviour can be divided into Newtonian and non-Newtonian categories and most fluids show non-Newtonian characteristics over at least part of the shear rate range that can be achieved in practice. There are many different forms of non-Newtonian behaviour, and each of these forms has to be considered separately in the design process.

In general, fluids behave as Newtonian if they are composed of low molecular weight material (whether as a pure liquid or in the form of single-component molecular solutions), or when the temperature is well above the melting point. Newtonian behaviour is characterised by viscosity that is constant with respect to shear rate (see Section 3.1). Design data for process equipment carrying Newtonian fluids are well developed. For example, data for pipeline systems carrying Newtonian fluids are provided in Volumes 1-4 of the ESDU Fluid Mechanics, Internal Flow Sub-series.

This Data Item, the first in a group on the flow characteristics of non-Newtonian fluids, provides an introductory guide to their identification, classification and characterisation, including measurement methods.

ESDU 95012²² provides more detailed guidance on obtaining the viscometric or flow curve data necessary for estimating frictional pressure drop for pipeflow of non-Newtonian fluids. ESDU 95012 also provides guidance on the selection and use of the different viscometric geometries available, and advises on obtaining the viscometric data necessary for the generation of the flow curve.

ESDU 91025²³ provides methods and computer programs for the estimation, using the flow curve and by scale-up of small-scale pipeline flow data, of frictional pressure drop in fully-developed, isothermal flow in straight pipes of uniform circular cross section.

ESDU 04005³⁰ contains a worked example that illustrates the use of a tube viscometer to measure viscometric data and develop the flow curve.

2.2 Scope of This Item

Some examples of fluids that may exhibit non-Newtonian behaviour are listed in Table 2.1. They include polymer solutions and melts having high molecular weights, suspensions of solids in liquids (which may be undissolved polymer particles), and emulsions of droplets of a denser or lighter liquid in a second immiscible liquid medium. The identification and classification of the fluids is carried out from two points of view: firstly in terms of the phase condition (Section 3.2.1) and secondly in terms of the rheological type (Section 3.2.2).

Fluids are classified according to the phase condition as **either** homogeneous or pseudohomogeneous **or** heterogeneous. This Data Item is applicable to fluids that can be classified as homogeneous or pseudohomogeneous. The behaviour of such fluids can be complicated as they can show both Newtonian and non-Newtonian characteristics under different conditions of composition, temperature and shear rate (see Section 3.1).

It is difficult to predict whether a particular fluid will exhibit non-Newtonian behaviour under a given set of conditions, and **it must be recognised that a rheological test is the only sure method of ascertaining the rheological properties of a fluid.**

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TABLE 2.1 Examples of fluids exhibiting non-Newtonian flow behaviour

Adhesives	Peat slurries
Biological fluids	Plastic melts
Cement slurries	Polymer solutions
Chalk slurries	Printing inks
Chocolate	Quicksand
Coal slurries	Rock slurries
Detergent slurries	Rubber solutions
Food sauces	Sand slurries
Greases	Sewage sludges
Hand creams	Shampoo
Margarine	Soap slurries
Mayonnaise	Starch solutions
Metal oxide slurries	Tomato paste
Oil well drilling muds	Toothpaste
Paints	Wet beach sand
Paper pulp	

The layout of this Data Item is as follows.

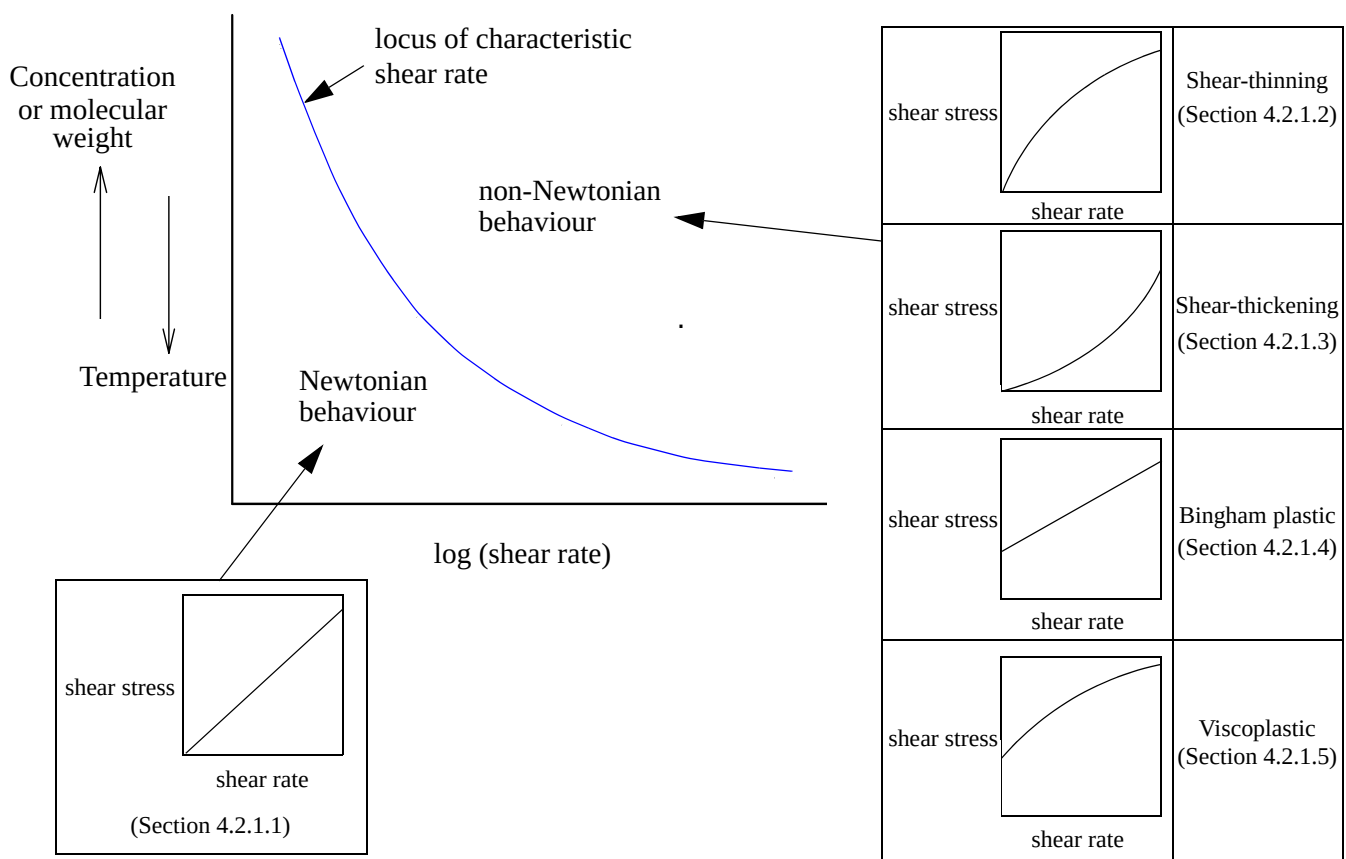
- Section 3 summarises the classification and behaviour of Newtonian and non-Newtonian fluids.
- Section 4 introduces the concepts of viscosity and the flow curve and discusses the flow behaviour exhibited by fluids under steady-state shear.
- Section 5 outlines various flow curve models used for characterising the flow behaviour exhibited by fluids under steady-state shear.
- Section 6 summarises five types of viscometric geometry used for flow curve determination of non-Newtonian fluids. These are described in more detail in ESDU 95012²².
- Appendix A gives a glossary of rheological terms.

3. NON-NEWTONIAN FLUIDS

3.1 Newtonian and Non-Newtonian Behaviour

Fluids, in general, may exhibit over a shear rate range both Newtonian and non-Newtonian behaviour. This phenomenon is illustrated for an example fluid by Sketch 3.1, which shows the existence of characteristic shear rates below which it exhibits Newtonian behaviour. This behaviour is observed where there is a linear relationship between shear stress and shear rate with a zero intercept and a slope of constant viscosity. Any deviation from Newtonian behaviour is said to be non-Newtonian. There are many different types of non-Newtonian behaviour (see Section 3.2.2). Flow curves (that is, plots of shear stress against shear rate) illustrating Newtonian and non-Newtonian behaviour are given in the Sketch 3.1.

In a homologous series of fluids (such as suspensions of increasing solids content, polymer solutions of increasing concentration or polymer melts of increasing molecular weight), the characteristic shear rate above which the behaviour of the fluid is no longer Newtonian decreases with increasing concentration or molecular weight or with decreasing temperature. Sketch 3.1 shows that for the high concentration or molecular weight material, the characteristic shear rate is so low that, under normal conditions, only non-Newtonian behaviour would be apparent.



Sketch 3.1 Illustration of Newtonian and non-Newtonian flow curve behaviour

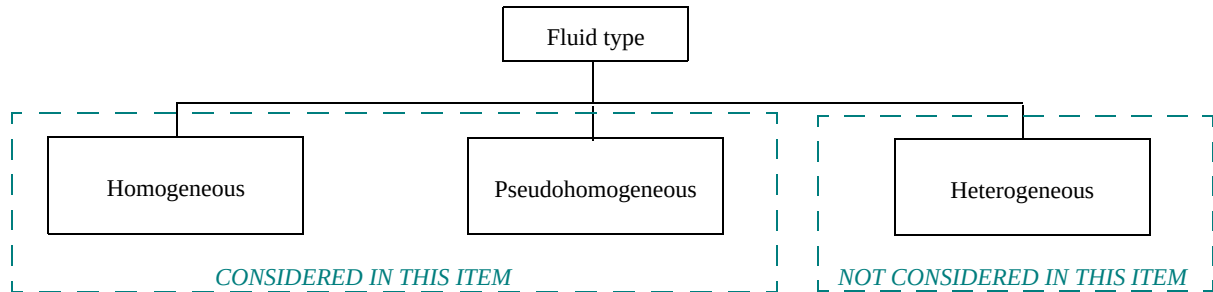
3.2 Classification of Fluids

Fluids are classified in two ways:

- by consideration of the effect of phase condition on the flow behaviour (see Section 3.2.1)
- by rheological type (see Section 3.2.2).

3.2.1 Classification by phase condition

Fluids may be classified by their phase condition as homogeneous, pseudohomogeneous (that is, able to be treated as homogeneous) or heterogeneous, as summarised in Sketch 3.2.



Sketch 3.2 Classification of fluids by effect of phase condition on flow behaviour

A number of factors affect the phase condition, one of which is sedimentation under gravity. Suspensions may be either *settling* or *non-settling*. For instance, coarse-particle, granular and flocculated suspensions tend to settle whereas stabilised fine-particle suspensions have a low settling tendency. However, the distinction between non-settling and settling suspensions is not clear as judgement has to be made with regard to the time frame over which settling is deemed to be important. This can be done only by considering the engineering application in question. For example, in the case of pipeline design, the suspension settling rate needs to be related to the residence time of the suspension in horizontal, vertical or inclined pipework. Guidelines on how this is done are given in Appendix A of ESDU 95012.

If solid particles (which may be polymer solids in a non-solvent) or droplets of a denser, second immiscible liquid in a suspending liquid medium settle sufficiently slowly under gravity or if the droplets of a lighter, immiscible liquid in a suspending liquid medium rise sufficiently slowly so as not to cause creaming, the suspension (or emulsion) can be characterised viscometrically. These 'non-settling' suspensions are considered to be *pseudohomogeneous* (that is, the particles or droplets are uniformly distributed throughout the suspending medium). Hence, the usual viscometric methods for measuring the flow curve of *homogeneous* fluids can be used for these suspensions, although it is necessary to be aware of the nature of the material when making the measurement. This is discussed in Section 7 of ESDU 95012. For instance, in the case of suspensions of high solids and/or fibre content, knowledge of the concentration at which flow inhomogeneities will develop is required.

If, however, the solid particles or droplets in a suspending liquid medium undergo rapid settling, the suspension can no longer be treated as pseudohomogeneous (that is, the suspension is *heterogeneous*). With these suspensions, flow curve measurements using rotational or tube viscometry are difficult and often meaningless. It may be possible instead to use the Metzner-Otto method to measure the flow curve. This method maintains the particles in suspension whilst carrying out the measurements, and is described in Appendix B of ESDU 95012.

The settling behaviour of suspensions (or creaming of emulsions) is governed primarily by the relative density of the phases and the particle (or droplet) size. There are other factors that can make a fluid heterogeneous during flow, such as the particles being fibrous, or the dispersed phase concentration being very high. In fibrous suspensions, such as wood pulps, micelial fermentation broths and raw sewage sludges, the elongated particles can become entangled when sheared and form into clumps. At high dispersed-phase concentrations, cracks can develop in the particle packing on shearing and the particles can clump together and move *en masse*^{17,21}. These suspensions readily become heterogeneous when sheared and exhibit complicated behaviour that cannot be interpreted simply in terms of the flow curve. There are therefore limitations in terms of particle shape and dispersed-phase concentration under which a suspension is homogeneous or can be treated as such.

This Item considers only homogeneous liquids and pseudohomogeneous suspensions, either non-settling or within the limitations of particle shape and concentration discussed above.

3.2.2 Classification by rheological type

Homogeneous and pseudohomogeneous fluids may be further classified into various rheological types on the basis of their behaviour when subjected to shear. For these fluids, there are three main types of rheological behaviour: *purely viscous*, *thixotropic* and *viscoelastic*.

Purely viscous behaviour is characterised by the viscosity responding instantaneously to a step change in shear rate or shear stress. This is characterised by a flow curve that is either a curve through the origin or a curve or straight line that shows an intercept on the shear stress axis. The viscosity is shear rate-dependent and time-independent.

Thixotropic behaviour is characterised by shear rate-dependent and time-dependent viscosity. For a well-rested sample (that is, one that has been allowed to rest for a time to recover from the effects of previous shear) when a step increase in shear rate or shear stress is applied the viscosity decreases with the time of shear. Thixotropic behaviour is generally associated with particulate systems (that is, solid/liquid suspensions, colloids, slurries, pastes and emulsions).

Viscoelastic behaviour is also characterised by shear rate-dependent and time-dependent viscosity and, for a well-rested sample, when a step increase in shear rate or shear stress is applied the viscosity increases with the time of shear. Viscoelastic behaviour is generally associated with polymeric systems.

Many fluids can show a combination of thixotropic and viscoelastic behaviour thus making time-dependent behaviour very difficult to characterise.

If thixotropic or viscoelastic materials are held under constant shear for a sufficiently long time (typically minutes/hours for thixotropic materials or seconds/minutes for viscoelastic materials) the viscosity will attain a steady-state value. Plotting this viscosity as a function of shear rate in the form of a shear stress versus shear rate plot will yield the *equilibrium flow curve* for thixotropic materials or the *steady-shear flow curve* for viscoelastic materials. This means that under steady-state operation in a process (such as pipeline pumping), it may be possible to relate the flow of thixotropic fluids to the equilibrium flow curve or viscoelastic fluids to steady-state flow curve as if they were time-independent.

The three types of flow curves (purely viscous, equilibrium and steady-state) are similar and can be treated in the same way (and are referred to as simply 'the flow curve'). They are summarised in Table 3.1.

TABLE 3.1 TYPES OF RHEOLOGICAL BEHAVIOUR

Type of rheological behaviour	Response to step increase in shear stress or shear rate	Flow curve measured under steady-state shear
Purely viscous	Viscosity achieves shear rate- or shear stress-dependent values instantaneously.	Purely viscous flow curve
Thixotropic	Viscosity decreases with time	Equilibrium flow curve
Viscoelastic	Viscosity increases with time	Steady-shear flow curve