CM4650 Polymer Rheology

CM4650
Polymer Rheology
Michigan Tech

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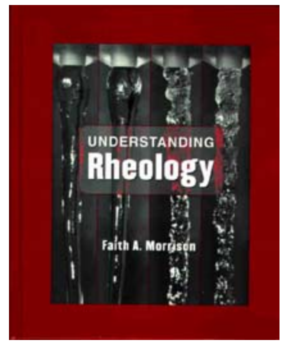
Department of Chemical Engineering
Michigan Technological University



Text:
Faith A. Morrison, Understanding Rheology
(Oxford University Press, 2001)

Errata: www.chem.mtu.edu/~fmorriso/cm4650/URerrata.html

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EMERGENCY EVACUATION PROCEDURES

Important: The Michigan Bureau of Fire Services has adopted new rules for colleges and universities effective 2015

1. Only residence halls are required to hold fire and tornado drills.
2. In lieu of fire drills in other university buildings all faculty and instructional staff are required to do the following on the first day of class:
   - Explain the university fire evacuation procedures to the class (see below).
   - Explain the locations of the primary and secondary exit routes for your class location.
   - Explain your designated safe location where the class will meet after evacuating the building.
3. The class instructor is responsible for directing the class during a building evacuation.

General evacuation procedure:

- Use the nearest safe exit route to exit the building. **The nearest safe exit from room 19-104A is the front (south) entrance that is close to the MUB circle. The secondary exit is in the middle of the building, either the west or east entrance (both are equally close).**
- Close all doors on the way out to prevent the spread of smoke and fire.
- After exiting, immediately proceed to a safe location at least 100 feet from the building. **Our designated safe location is at the mailbox near the entrance to parking lot 12 (near the MUB small parking lot).**
- Do not re-enter the building until the all-clear is given by Public Safety or the fire department.

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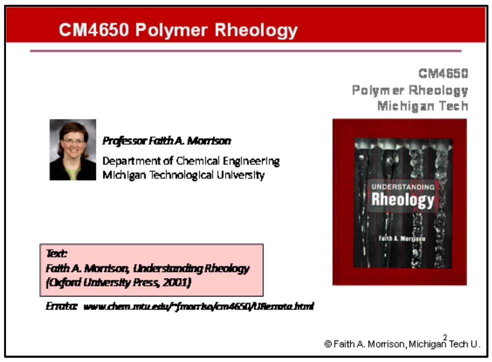

Let's begin with an Introductory Overview of the Topic

CM4650 Polymer Rheology: Introduction

Polymer Rheology

Rhe-

rei – *Greek* for flow

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14 weeks of lectures available on iTunesU (free!)

What is rheology anyway?

Rheology = the study of deformation and flow.

"What is Rheology Anyway?" Faith A. Morrison, *The Industrial Physicist*, 10(2) 29-31, April/May 2004.

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We are interested in fluids

How they deform;

How they { transmit, produce, react to imposed } stresses

Why?

Image from: www-math.mtu.edu

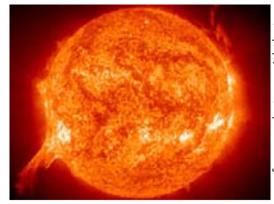

Image from: whatsupwiththat.com

Naruto Whirlpools, Japan

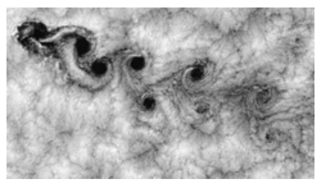

Image from: commons.wikipedia.org

Image from: www.123rf.com

Why?

- Advance technology
- Innovate
- Manage existing processes

Non-intuitive, unexpected outcomes—need a model to know what's going on!

(avoid surprises, undesirable fluid behavior; exploit phenomena)

- Lubrication
- Coating
- Product manufacturing (3D printing, foods, plastics)
- Raw material production (mining, paper, oil recovery)
- Geological interpretations
- Health flows (drug delivery, blood, lymph, mucus)
- Microfluidics (sensors, microdevices)

For many of these situations, the fluid/deformation behavior is **not Newtonian**

not Newtonian?

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For many important applications, the fluid/deformation behavior is not Newtonian

Newtonian

Continuum modeling with the Newtonian constitutive equation

$$\underline{\underline{\tau}} = \mu(\nabla\underline{v} + (\nabla\underline{v})^T)$$

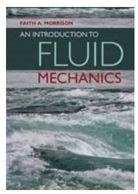
Non-Newtonian

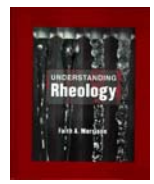
Continuum modeling with the some other constitutive equation

$$\underline{\underline{\tau}} = f(\underline{v})$$

?

Can predict $\underline{\underline{\tau}}, \underline{v}$ (continuum predictions)





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Fluid Mechanics is a Big Subject

Navier-Stokes: 1840's

- Mechanical Energy Balance
- Newtonian constitutive equation
- Navier-Stokes equations
- Laminar-Turbulent flow
- Potential flow
- Boundary layers—drag, lift
- Perturbation analysis
- Computational Fluid Dynamics (CFD)

A great deal of effort has gone into addressing the challenges in the Navier-Stokes equations

Rheology is also a Big Subject

Society of Rheology founded 1929

- Cauchy momentum equation
- Stress constitutive equation
- Stable/unstable flows

Stumbling block: What is the **stress-deformation relationship** if the fluid is non-Newtonian?

Much of the field of rheology is devoted to addressing challenges linked to modeling material-deformation/stress relationships.

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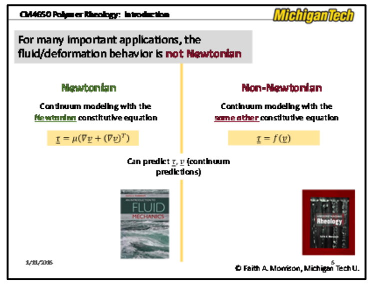
To get started, let's take a look at what Newtonian versus Non-Newtonian looks like in actual fluids.



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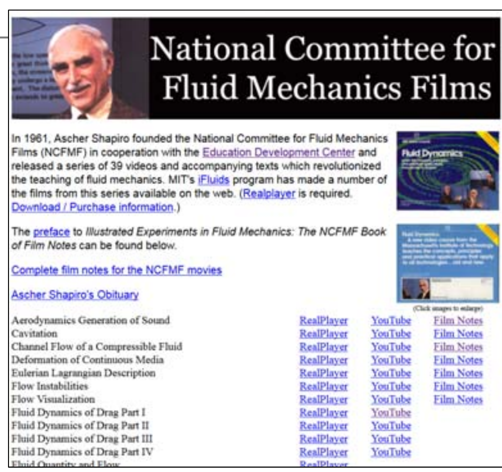

National Committee for Fluid Mechanics Films

In 1961, Ascher Shapiro founded the National Committee for Fluid Mechanics Films (NCFMF) in cooperation with the Education Development Center and released a series of 39 videos and accompanying texts which revolutionized the teaching of fluid mechanics. MIT's iFluids program has made a number of the films from this series available on the web. (Realplayer is required. Download / Purchase information.)

The preface to *Illustrated Experiments in Fluid Mechanics: The NCFMF Book of Film Notes* can be found below.

Complete film notes for the NCFMF movies

Ascher Shapiro's Obituary

Aerodynamics Generation of Sound	RealPlayer	YouTube	Film Notes
Cavitation	RealPlayer	YouTube	Film Notes
Channel Flow of a Compressible Fluid	RealPlayer	YouTube	Film Notes
Deformation of Continuous Media	RealPlayer	YouTube	Film Notes
Eulerian Lagrangian Description	RealPlayer	YouTube	Film Notes
Flow Instabilities	RealPlayer	YouTube	Film Notes
Flow Visualization	RealPlayer	YouTube	Film Notes
Fluid Dynamics of Drag Part I	RealPlayer	YouTube	
Fluid Dynamics of Drag Part II	RealPlayer	YouTube	
Fluid Dynamics of Drag Part III	RealPlayer	YouTube	
Fluid Dynamics of Drag Part IV	RealPlayer	YouTube	
Fluid Quantity and Flow	RealPlayer		

Hershel Markovitz,
Mellon Institute, 1964

NCFMF Film on *Rheological Behavior of Fluids*

- Search for "NCFMF"
- web.mit.edu/hml/ncfmf.html
- Also on YouTube

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Introduction to Non-Newtonian Behavior

Rheological Behavior of Fluids, National Committee on Fluid Mechanics Films, 1964

Velocity gradient tensor, $\underline{\underline{\dot{\gamma}}}$

Type of fluid	Momentum balance	Stress –Deformation relationship (constitutive equation)
Inviscid (zero viscosity, μ=0)	Euler equation (Navier-Stokes with zero viscosity)	Stress is isotropic
Newtonian (finite. constant viscosity, μ)	Navier-Stokes (Cauchy momentum equation with Newtonian constitutive equation)	Stress is a function of the **instantaneous** velocity gradient
Non-Newtonian (finite, variable viscosity η plus **memory** effects)	Cauchy momentum equation with memory constitutive equation	Stress is a *nonlinear* function of the **history** of the velocity gradient

$\underline{\underline{\tau}}(t) = \mu \underline{\underline{\dot{\gamma}}}(t)$

$\underline{\underline{\tau}}(t) = f\left(\underline{\underline{\dot{\gamma}}}\right)$

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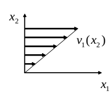
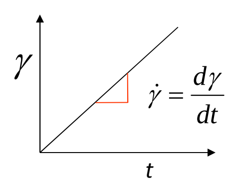
Rheological Behavior of Fluids – Newtonian

1. Strain response to imposed shear stress

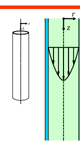
- shear rate is constant



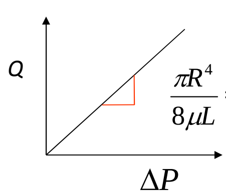


$$\dot{\gamma} = \frac{d\gamma}{dt} = \text{constant}$$

2. Pressure-driven flow in a tube (Poiseuille flow)



- viscosity is constant



$$Q = \frac{\pi \Delta P R^4}{8\mu L}$$

$$\frac{\pi R^4}{8\mu L} = \text{constant}$$

3. Stress tensor in shear flow

- only two components are nonzero

$$\underline{\underline{\tau}} = \begin{pmatrix} 0 & \tau_{12} & 0 \\ \tau_{21} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}_{123}$$

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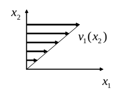
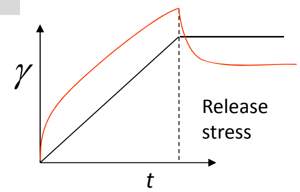
Rheological Behavior of Fluids – non-Newtonian

1. Strain response to imposed shear stress

- shear rate is variable





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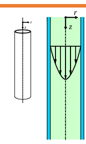
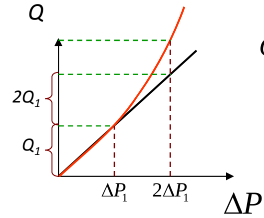


- viscosity is variable



$$Q = f(\Delta P)$$

3. Stress tensor in shear flow

- all 9 components are nonzero

Normal stresses

$$\underline{\underline{\tau}} = \begin{pmatrix} \tau_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \tau_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \tau_{33} \end{pmatrix}_{123}$$

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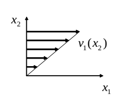
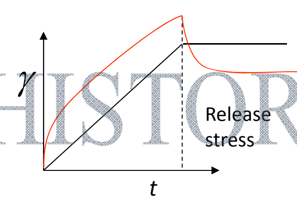
Rheological Behavior of Fluids – non-Newtonian

HISTORY

1. Strain response to imposed shear stress

- shear rate is variable





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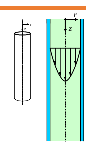
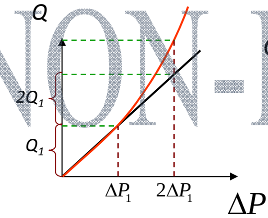


- viscosity is variable

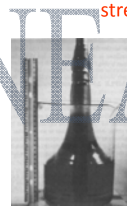
NON-LINEARITY



$$Q = f(\Delta P)$$

- all 9 components are nonzero

Normal stresses



$$\underline{\underline{\tau}} = \begin{pmatrix} \tau_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \tau_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \tau_{33} \end{pmatrix}_{123}$$

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Examples from the film of . . . .

Dependence on the history of the deformation gradient

- Polymer fluid pours, but springs back
- Elastic ball bounces, but flows if given enough time
- Steel ball dropped in polymer solution "bounces"
- Polymer solution in concentric cylinders – has fading memory
- Quantitative measurements in concentric cylinders show memory and need a finite time to come to steady state

Non-linearity of the function $\underline{\underline{\tau}} = f\left(\underline{\underline{\dot{\gamma}}}\right)$

- Polymer solution draining from a tube is first slower, then faster than a Newtonian fluid
- Double the static head on a draining tube, and the flow rate does not necessarily double (as it does for Newtonian fluids); sometimes more than doubles, sometimes less
- Normal stresses in shear flow
- Die swell

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NCFM Film on *Rheological Behavior of Fluids*

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Introduction to Non-Newtonian Behavior

Rheological Behavior of Fluids, National Committee on Fluid Mechanics Films, 1964

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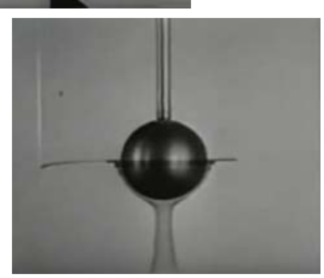
Introduction to Non-Newtonian Behavior

Rheological Behavior of Fluids, National Committee on Fluid Mechanics Films, 1964

Carefully designed experiments to distinguish material behavior



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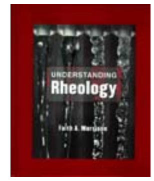
Course Outline

Part I:
- Vectors and tensors
- Newtonian fluids
- Exam 1

Part II:
- Standard Flows
- Material Functions
- Experimental Observations

Part III: Constitutive Equations
- Generalized Newtonian
- Exam 2
- Linear Viscoelastic
- Nonlinear Viscoelastic

Part IV:
- Rheometry
- Final Exam



"Carefully designed experiments to distinguish material behavior"

Stress-deformation models

Measurement techniques

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