

Rheology and Hydraulics of Oil-well Drilling Fluids

API RECOMMENDED PRACTICE 13D
SEVENTH EDITION, SEPTEMBER 2017

REAFFIRMED, MAY 2023



Special Notes

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any authorities having jurisdiction with which this publication may conflict.

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be utilized. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

Users of this recommended practice should not rely exclusively on the information contained in this document.

Sound business, scientific, engineering, and safety judgment should be used in employing the information contained herein.

All rights reserved. No part of this work may be reproduced, translated, stored in a retrieval system, or transmitted by any means, electronic, mechanical, photocopying, recording, or otherwise, without prior written permission from the publisher. Contact the Publisher, API Publishing Services, 200 Massachusetts Avenue, NW, Washington, DC 20001.

Copyright © 2017 American Petroleum Institute

Foreword

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

Shall: As used in a standard, “shall” denotes a minimum requirement in order to conform to the specification.

Should: As used in a standard, “should” denotes a recommendation or that which is advised but not required in order to conform to the specification.

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this publication or comments and questions concerning the procedures under which this publication was developed should be directed in writing to the Director of Standards, American Petroleum Institute, 200 Massachusetts Avenue, NW, Washington, DC 20001. Requests for permission to reproduce or translate all or any part of the material published herein should also be addressed to the director.

Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. A one-time extension of up to two years may be added to this review cycle. Status of the publication can be ascertained from the API Standards Department, telephone (202) 682-8000. A catalog of API publications and materials is published annually by API, 200 Massachusetts Avenue, NW, Washington, DC 20001.

Suggested revisions are invited and should be submitted to the Standards Department, API, 200 Massachusetts Avenue, NW, Washington, DC 20001, standards@api.org.

Contents

Page

1	Scope	1
2	Normative References	2
3	Acronyms, Abbreviations, Symbols, Definitions, and Units	2
4	Fluid Flow Fundamentals and Rheological Models	9
4.1	Flow Fundamentals and Rheological Models	9
4.2	Viscosity	10
4.3	Shear Stress	11
4.4	Shear Rate	13
4.5	Shear Stress/Shear Rate Relationship	14
4.6	Fluid Characterization	14
4.7	Newtonian Fluids	14
4.8	Non-Newtonian Fluids	15
4.9	Rheological Models	15
5	Rheological Parameters	17
5.1	Measurement of Rheological Parameters	17
5.2	Rheological Models	19
6	Prediction of Downhole Behavior of Drilling Fluids	22
6.1	Principle	22
6.2	Temperature Predictions of Circulating Drilling Fluids	22
6.3	Prediction of Downhole Rheological Properties	24
6.4	Prediction of Downhole Density	26
7	Pressure-loss Modeling	30
7.1	Principle	30
7.2	Basic Relationships	30
7.3	Surface-connection Pressure Loss	31
7.4	Drill-string and Annular Frictional Pressure Loss	32
7.5	Bit Pressure Loss	39
7.6	Downhole-tools Pressure Loss	39
7.7	Choke-line Pressure Loss	40
7.8	Casing Pressure	40
7.9	Equivalent Circulating Density	40
8	Swab/Surge Pressures	41
8.1	Principle	41
8.2	Controlling Parameters	42
8.3	Closed-string Procedure	44
8.4	Open-string Procedure	45
8.5	Transient Swab/Surge Analysis	45
9	Hole Cleaning	45
9.1	Description of the Challenge	45
9.2	Hole-cleaning Practices and Remedial Options	45
9.3	Cuttings Transport	47
9.4	Modeling Hole Cleaning in Vertical and Low-angle Wells	49
9.5	Modeling Hole Cleaning in Directional Wells	51
9.6	Weight-material Sag	54

Contents

	Page
10 Hydraulics Optimization	55
10.1 Optimization Objectives	55
10.2 Calculations	56
10.3 Reaming While Drilling with Pilot-bit Configuration	58
10.4 Bit-nozzle Selection	59
10.5 Pump-off Pressure/Force	59
11 Rigsite Monitoring	59
11.1 Introduction	59
11.2 Annular Pressure-loss Measurement	59
11.3 Validation of Hydraulics Models	63
11.4 Interpretation of Downhole Pressure Measurements	64
Annex A (informative) Worked Example Parameters	66
Annex B (informative) Downhole-properties Example	68
Annex C (informative) Pressure-loss Example	72
Annex D (informative) Swab/Surge-pressures Example	74
Annex E (informative) Hole-cleaning Example	76
Annex F (informative) Hydraulics-optimization Example	79
Bibliography	83
Figures	
1 Parallel Plates with Fluid-filled Gap Showing Effects of Upper Plate Sliding Past Lower Plate	11
2 Rheograms of Three Rheological Models on Rectangular Coordinates	16
3 Couette-type, Mechanical Rotational Viscometer with Dial Readout	18
4 Viscosity of Several Base Fluids as Function of Temperature	25
5 Isothermal Plot of a 15.3 lbm/gal Synthetic-based Drilling Fluid	27
6 Cuttings Transport Mechanisms in Vertical and Deviated Wells	48
7 Effect of Yield Point on Critical Flow Rate	52
8 Rheology Factor Chart for 8 1/2-in. Holes	53
9 Hole-cleaning Chart for 8 1/2-in. Holes	53
10 Optimizing Maximum Impact Force	58
11 Drilling Pressure Window	60
12 Time-based Log Format	62
13 Cuttings Mobilization	64
A.1 Wellbore Profile Schematic	67
E.1 Rheology Factor Chart for 8 1/2-in. Holes	77
E.2 Hole-cleaning Chart for 8 1/2-in. Holes	78
F.1 Wellsite Nozzle Test	80
F.2 On-site Nozzle Test for Maximum Hydraulic Impact Force	81
Tables	
1 Acronyms and Abbreviations	2
2 Symbols, Definitions, and Units	4
3 Types of Viscometers for Measuring Drilling Fluid Rheological Properties	19
4 Example HTHP Viscometer Test Matrix	25
5 Temperature and Pressure Coefficients for Determining Fluid Density Using Equation (42)	29
6 CSC Values for Surface-connection Cases	32

Contents

	Page
7 Example Hole Cleaning Operational Practices	46
8 Hydraulic Optimization Equations	57
9 Interpretation Guide	65
B.1 Hydraulic Data by Section	68
B.2 Downhole Density Calculations Under Static and Dynamic Conditions	69
B.3 Test Matrix for HTHP Viscometer Data	70
B.4 Results for Different Rheological Models	70
B.5 Herschel-Bulkley Parameters (Numerical Method)	70
B.6 Herschel-Bulkley Parameters (Measurement Method)	70
B.7 Bingham Plastic Parameters	71
C.1 Spreadsheet Data of Pressure Loss in Drill String	72
C.2 Spreadsheet Data of Pressure Loss in Annulus	73
C.3 Data for Pressure Losses vs Flow Rate	73
D.1 Closed-string Example	74
D.2 Open-string Example	75
D.3 Iterative Process for the Open-string Example	75
F.1 Rig Data for Flow Rate and Standpipe Pressure	79
F.2 Calculated System Parasitic Pressure Loss	80
F.3 Impact Force Methods Comparison	82

Rheology and Hydraulics of Oil-well Drilling Fluids

1 Scope

1.1 The objective of this recommended practice (RP) is to provide a basic understanding of and guidance about drilling fluid rheology and hydraulics to assist with drilling wells of various complexities, including high-temperature/high-pressure (HTHP), extended-reach drilling (ERD), and highly directional wells.

1.2 Office and wellsite engineers are the target audience for this document. The complexity of the equations provided is such that a competent engineer can use simple spreadsheet programs to conduct analyses. Given that the equations used herein are constrained by this spreadsheet limitation, more advanced numerical solutions containing multiple subroutines and macros are not offered. This limitation does not suggest that only the results given by the spreadsheet methods are valid engineering solutions.

1.3 Rheology is the study of the deformation and flow of matter. For this document, rheology is the study of the flow characteristics of drilling fluids and how these characteristics affect movement of the fluids. The discussion of rheology in this document is limited to single-phase liquid flow.

1.4 Rheological properties directly affect flow characteristics and hydraulic behavior. Properties must be controlled for drilling fluids to perform their various functions. Certain properties are measured at the wellsite for monitoring and treatment and in the laboratory for development of new additives and systems, formulation for specific applications, and diagnosis of special problems.

1.5 Measurement of rheological properties also makes possible mathematical descriptions of circulating fluid flow important for the following hydraulics-related determinations:

- a) calculating frictional pressure losses in pipes and annuli,
- b) determining equivalent circulating density (ECD) of the drilling fluid under downhole conditions,
- c) determining flow regimes,
- d) estimating hole-cleaning efficiency,
- e) estimating swab/surge pressures, and
- f) optimizing the drilling fluid circulating system to improve drilling efficiency.

1.6 The concepts of viscosity, shear stress, and shear rate are important in understanding the flow characteristics of fluids. Specific measurements are made on fluids to determine rheological parameters under a variety of conditions. From this information, the circulating system can be designed and evaluated to accomplish desired objectives.

1.7 Drilling fluid hydraulics involves hydrostatic pressures, frictional pressure losses, carrying capacity, swab/surge pressures, and equivalent static and circulating densities, among others. Mathematical models relating shear stress to shear rate and formulas for estimating drilling fluid hydraulics are included. Calculation methods used herein consider the effects of temperature and pressure on drilling fluid rheology and density.

1.8 The U.S. customary (USC) unit system is used in this RP. However, any consistent system of units may be used where so indicated, as in the development of equations in Section 4. The term "pressure" means "gauge pressure" unless otherwise noted.

NOTE The term "consistent units" refers to a set of units that does not require an extra conversion factor to complete a calculation. In consistent International System of units (SI unit), time is expressed in seconds (s), length in meters (m), mass in kilograms (kg), force in newtons (N), temperature in degrees Celsius (°C), and absolute temperature in kelvins (K).