



Flávio Henrique Marchesini de Oliveira

Viscoplastic Materials in Engineering Problems

Dissertação de Mestrado

Thesis presented to the Postgraduate Program in Mechanical Engineering of the Departamento de Engenharia Mecânica, PUC–Rio, as partial fulfillment of the requirements for the degree of Mestre em Engenharia Mecânica

Adviser : Prof. Paulo Roberto de Souza Mendes
Co–Adviser: Prof. Mônica Feijó Naccache

Rio de Janeiro
December de 2008



Flávio Henrique Marchesini de Oliveira

Viscoplastic Materials in Engineering Problems

Thesis presented to the Postgraduate Program in Mechanical Engineering of the Departamento de Engenharia Mecânica do Centro Técnico Científico da PUC–Rio, as partial fulfillment of the requirements for the degree of Mestre em Engenharia Mecânica. Approved by the following commission:

Prof. Paulo Roberto de Souza Mendes

Adviser

Departamento de Engenharia Mecânica — PUC–Rio

Prof. Mônica Feijó Naccache

Co–Adviser

Departamento de Engenharia Mecânica — PUC–Rio

Prof. Márcio da Silveira Carvalho

Departamento de Engenharia Mecânica — PUC–Rio

Prof. Roney Leon Thompson

Departamento de Engenharia Mecânica — UFF

Prof. José Eugênio Leal

Coordinator of the Centro Técnico Científico da PUC–Rio

Rio de Janeiro — December 17, 2008

Flávio Henrique Marchesini de Oliveira

Flávio Marchesini graduated in Chemical Engineering from Federal University of Rio de Janeiro (UFRJ). Then he started to work with Rheology and non-Newtonian Continuum Mechanics in the Rheology Group (GReo) at PUC-Rio.

Bibliographic data

Marchesini, Flávio Henrique

Viscoplastic Materials in Engineering Problems / Flávio Henrique Marchesini de Oliveira; adviser: Paulo Roberto de Souza Mendes; co-adviser: Mônica Feijó Naccache — 2008.

132 f.: il. (color); 29,7 cm

1. Dissertação (Mestrado em Engenharia Mecânica) - Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, 2008.

Inclui Bibliografia.

1. Engenharia Mecânica – Teses. 2. Materiais Viscoplasticos. 3. Escoamentos. 4. Reometria. 5. Expansões-contracções. 6. Deslocamento. 7. Tubos Capilares. 8. Poços de Petróleo. I. de Souza Mendes, Paulo Roberto. II. Naccache, Mônica Feijó. III. Pontifícia Universidade Católica do Rio de Janeiro. Departamento de Engenharia Mecânica. IV. Título.

CDD: 621

Acknowledgments

This thesis has been produced by research efforts in the last years, since I started to work at the Rheology Group (GReo) of PUC-Rio. During this period I learned and worked with a lot of people who helped me in my first steps in the science and in obtaining the necessary resources to the researches described in this thesis.

I would like to thank my family, my sister, all of my friends and specially my mother for all contributions, incentive, support and apprenticeship during my life.

I also would like to thank my co-adviser Mônica Naccache for all teaching, support and partnership, and Marcio Carvalho, Luís Fernando Azevedo and Roney Thompson for the contributions to my education.

I am indebted to André Leibsohn and Cristiane Miranda for the financial support and partnership. I am also indebted to Eduardo Dutra who helped me in my first steps in rheology and in learning how to operate the instruments. I thank Tatiana Kerber and Júlio Barros for the support during my stay in the laboratory, and Deivid Santos, Bruno Fonseca and Wálter Teixeira who worked with me, and contributed with a lot of ideas at the construction of the experiments.

I am grateful to Teresa Juliet Bastidas Peña for all contributions that she gave me. And also, André Braghini for the support, Jane Celnik for helping me in the execution of the small scale experiments of the Chapter V, and Renata Pereira, a great friend, who was my partner for two years in a lot of experiments including the pilot scale experiments of chapter V, and in the bureaucracy inherent to the research in Brazil. Moreover, I acknowledge Cátia Lima who was my student and prepared a lot of Carbopol dispersions for our measurements, and Alexandra Aliche for the special support at the end of this work.

I am particularly indebted to José Roberto Siffert, who is a great friend, and helped me through difficult moments and with whom I learned a lot of things in our partnership at the experiments of Chapter IV. I acknowledge with deep appreciation Priscilla Varges and Paula Mey, two of my best friends, who helped me in most of my first steps in the laboratory. Priscilla Varges and I realized the experiments of Chapter III, and Paula Mey helped me in the experiments of Chapter II.

Finally, I do not know how to thank my adviser Paulo Roberto de Souza Mendes, who I will never forget. I started to work with him in 2005 in a difficult moment and he was fundamental for my education and for my life, providing me all the supports necessary to realize this work and to surpass any problem.

Abstract

Marchesini, Flávio Henrique; de Souza Mendes, Paulo Roberto; Naccache, Mônica Feijó. **Viscoplastic Materials in Engineering Problems**. Rio de Janeiro, 2008. 132p. Dissertação de Mestrado — Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Viscoplastic or yield stress materials are found in a lot of natural processes, and in a wide variety of industries such as food, cosmetic, farmaceutical and petroleum. In these industries, knowing the accurate rheological properties of a viscoplastic material and its behavior in different flows are fundamental for the success of many operations. Nevertheless, the rheometry of this kind of material still presents some challenges, such as yield stress measurements, apparent wall slip, thixotropy and the breakdown of structure on loading the material into the rheometer geometry used. In addition to that, until now some phenomena in different flows involving viscoplastic materials are not well understood, and therefore more investigation is required. This thesis deals with viscoplastic materials, their rheological properties measurements, and their behavior in different kinds of flow. Moreover, a detailed analysis of flows such as viscometric, expansions-contractions, the displacements in capillary tubes, and the displacements inside oil wells was performed.

Keywords

Viscoplastic Materials. Flows. Rheometry. Expansions-contractions. Displacement. Capillary Tubes. Oil Wells.

Resumo

Marchesini, Flávio Henrique; de Souza Mendes, Paulo Roberto; Naccache, Mônica Feijó. **Materiais Viscoplasticos em Problemas de Engenharia**. Rio de Janeiro, 2008. 132p. Dissertação de Mestrado — Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Materiais viscoplasticos, os quais apresentam tensão limite de escoamento, podem ser encontrados em vários processos naturais e em diversas indústrias, tais como: alimentícia, de cosméticos, farmacêutica e do petróleo. Nessas indústrias o conhecimento preciso das propriedades reológicas dos materiais viscoplasticos e do comportamento desses materiais em diferentes escoamentos é fundamental para o sucesso de várias operações. Todavia, a reometria desse tipo de material ainda apresenta alguns desafios como as medidas de tensão limite de escoamento, deslizamento aparente, tixotropia e a quebra da microestrutura na colocação da amostra no reômetro. Além disso, existe o fato de que até hoje alguns fenômenos em diferentes escoamentos envolvendo materiais viscoplasticos ainda permanecem não tão bem compreendidos, o que requer uma investigação mais profunda. Nesse trabalho, uma abordagem dos materiais que apresentam comportamento viscoplastico, dos métodos utilizados para as medições de suas propriedades reológicas e do comportamento desses materiais em diferentes tipos de escoamento é realizada. Além disso, é executada uma análise detalhada de escoamentos, tais como: viscométricos, através de expansões-contracções, envolvendo deslocamentos em tubos capilares e de escoamentos envolvendo deslocamentos em poços de petróleo.

Palavras-chave

Materiais Viscoplasticos. Escoamentos. Reometria. Expansões-contracções. Deslocamento. Tubos Capilares. Poços de Petróleo.

Contents

I	Introduction	13
I.1	Basic concepts	13
I.2	Viscoplastic materials	17
I.3	Viscoplastic materials models	19
I.4	Overview	22
I.5	Note	23
II	Rheometry	24
II.1	Introduction	24
II.2	Analysis	26
	<i>Experimental measurements</i>	26
	<i>Viscosity function and rheological parameters</i>	27
	<i>Governing equations and boundary conditions</i>	28
II.3	Experiments	29
II.4	Numerical Solution	30
II.5	Results and Discussion	31
	<i>Experimental Results</i>	31
	<i>Numerical Results</i>	36
	<i>Comparison between experimental and numerical results</i>	40
II.6	Final Remarks	41
II.7	Note	42
III	Expansions-contractions Flows	43
III.1	Introduction	43
III.2	Analysis	45
	<i>Viscosity function and rheological parameters</i>	45
	<i>Governing equations and boundary conditions</i>	46
	<i>Governing parameters</i>	47
III.3	Numerical Solution	47
III.4	The Experiments	49
	<i>The visualization experiments</i>	49
	<i>Rheology of the Carbopol dispersions</i>	51
III.5	Results and Discussion	53
	<i>Flow visualization results</i>	53
	<i>Numerical results</i>	56
	<i>Comparison between experimental and numerical results</i>	62
III.6	Final Remarks	64
III.7	Note	64
IV	Displacements in Capillary Tubes	65

IV.1	Introduction	65
IV.2	Analysis	68
	<i>Viscosity function and rheological parameters</i>	68
	<i>Governing equations and boundary conditions</i>	69
	<i>Governing parameters</i>	70
IV.3	The Experiments	71
	<i>The displacement experiments</i>	71
	<i>Rheology of the Carbopol dispersions</i>	73
IV.4	Results and Discussion	75
	<i>Results for the fully-developed flow</i>	75
	<i>Fractional mass coverage results</i>	79
IV.5	Final Remarks	83
IV.6	Note	84
V	Displacements inside Oil Wells	85
V.1	Introduction	85
V.2	Analysis	87
	<i>Viscosity function and rheological parameters</i>	87
	<i>Governing parameters</i>	88
V.3	Experimental Investigation	90
	<i>Small scale experiments</i>	90
	<i>Pilot scale experiments</i>	91
	<i>Large scale experiments</i>	94
	<i>Rheological measurements</i>	96
V.4	Numerical Solution	97
V.5	Results and Discussion	97
	<i>Small scale</i>	97
	<i>Pilot scale</i>	99
	<i>Large scale</i>	108
V.6	Final Remarks	119
V.7	Note	120
VI	Conclusions	121
	Bibliography	123

List of Figures

I.1	The dimensionless shear stress function.	21
II.1	Scheme of bob-in-cup geometry.	26
II.2	The geometries.	29
II.3	Flow Curve of Carbopol dispersion 0,17% – investigation of the apparent slip region.	31
II.4	Viscosity of Carbopol dispersion 0,17% as a function of shear stress – investigation of the apparent slip region.	32
II.5	Flow Curve of different Carbopol dispersions without apparent slip.	32
II.6	Thixotropic Curves of Carbopol dispersion 0,15%.	33
II.7	Creep test realized in a UDS 200 Paar-Physica with a grooved Couette geometry of Carbopol dispersion 0,15%.	34
II.8	Inner and outer apparent wall slip velocities.	35
II.9	Velocity and strain rate for the smooth Couette geometry, and $\dot{\gamma}_{exp}/\dot{\gamma}_1 = 4.4 \times 10^{-3}$.	37
II.10	Velocity and strain rate for the smooth Couette geometry, and $\dot{\gamma}_{exp}/\dot{\gamma}_1 = 4.4$.	37
II.11	Velocity and strain rate for the vane geometry, and $\dot{\gamma}_{exp}/\dot{\gamma}_1 = 4.4 \times 10^{-3}$.	37
II.12	Velocity and strain rate for the vane geometry, and $\dot{\gamma}_{exp}/\dot{\gamma}_1 = 4.4$.	38
II.13	Velocity and strain rate for the grooved Couette geometry, and $\dot{\gamma}_{exp}/\dot{\gamma}_1 = 4.4 \times 10^{-3}$.	38
II.14	Velocity and strain rate for the grooved Couette geometry, and $\dot{\gamma}_{exp}/\dot{\gamma}_1 = 4.4$.	38
II.15	Velocity profile for the three geometries and dimensionless experimental outer wall shear rate equal to 4.4×10^{-3} and 4.4.	39
II.16	Strain rate profile for the three geometries and dimensionless experimental outer wall shear rate equal to 4.4×10^{-3} and 4.4.	39
II.17	Inner and outer shear stress for the three geometries.	40
II.18	Comparison of inner wall shear stress between experimental and numerical results.	41
III.1	The geometry.	46
III.2	Schematics of the apparatus.	50
III.3	The flow curves of the Carbopol dispersions.	51
III.4	The dimensionless viscosity of the Carbopol dispersions as a function of the dimensionless shear stress.	52
III.5	Effect of τ_R^* on the yield surface location, for $J = 2.8 \times 10^6$, $n = 4.8$ (Carbopol 0.09%), $L_o/R_o = 1.0$, and $R_o/R = 5$. From left to right, the pictures correspond respectively to $\tau_R^* = 3.0, 5.3, 8.4, 10.5$, and 0.0.	53
III.6	Effect of L_o/R_o on the yield surface location, for $J = 2.8 \times 10^6$, $n = 4.8$ (Carbopol 0.09%), $\tau_R^* = 5.3$, and $R_o/R = 5$. From left to right, the pictures correspond respectively to $L_o/R_o = 1.0, 1.5$, and 2.0.	54

III.7	Effect of R_o/R on the yield surface location, for $J = 2.8 \times 10^6$, $n = 4.8$ (Carbopol 0.09%), $\tau_R^* = 5.3$, and $L_o/R_o = 1.0$. From left to right, the pictures correspond respectively to $R_o/R = 3$ and 5.	54
III.8	Effect of rheology on the yield surface location, for $\tau_R^* = 4.0$, $R_o/R = 3$, and $L_o/R_o = 1.5$. From left to right, the pictures correspond respectively to $(J, n) = (1.8 \times 10^6, 0.42)$ and $(2.8 \times 10^6, 0.48)$.	55
III.9	Displacement efficiency as a function of τ_R^* . Carbopol 0.09%.	56
III.10	Displacement efficiency as a function of τ_R^* . Carbopol 0.11%.	56
III.11	Isobands of τ^* . $R_o/R = 6.3$, $L_o/R_o = 1$, $J = 18000$, $n = 0.4$, $\tau_R^* = 1.9$	57
III.12	Isobands of τ^* . $R_o/R = 6.3$, $L_o/R_o = 1$, $J = 18000$, $n = 0.4$, $\tau_R^* = 3.6$	58
III.13	Displacement efficiency as a function of R_o/R . $\tau_R^* = 3.6$, $J = 18000$, $n = 0.4$.	58
III.14	Head loss and displacement efficiency as a function of L_o/R_o . $\tau_R^* = 3.6$, $R_o/R = 6.3$, $n = 0.4$, $J = 18000$.	59
III.15	Displacement efficiency as a function of τ_R^* . $R_o/R = 6.3$, $J = 18000$, $n = 0.4$.	60
III.16	Head loss and displacement efficiency as a function of the jump number. $\tau_R^* = 3.6$, $R_o/R = 6.3$, $n = 0.4$, $J = 18000$.	60
III.17	Head loss and displacement efficiency as a function of the power-law index. $\tau_R^* = 3.6$, $R_o/R = 6.3$, $L_o/R_o = 1$, $J = 18000$.	61
III.18	Head loss as a function of R_o/R . $\tau_R^* = 3.6$, $J = 18000$, $n = 0.4$.	61
III.19	Head loss as a function of τ_R^* . $R_o/R = 6.3$, $J = 18000$, $n = 0.4$.	62
III.20	Comparison between the predicted and observed yield surface locations. $R_o/R = 5$, and $L_o/R_o = 1$. Left: Carbopol 0.09% and $\tau_R^* = 4.0$; right: Carbopol 0.11% and $\tau_R^* = 2.6$.	62
III.21	Predicted axial velocity and stress intensity radial distributions at the symmetry plane. $R_o/R = 5$, $L_o/R_o = 1$, and $\tau_R^* = 4.0$. $J = 4.0 \times 10^5$ and $n = 0.48$.	63
IV.1	Displacement of a viscoplastic material in a capillary.	66
IV.2	The boundary conditions as described from a reference frame attached to the bubble front.	70
IV.3	The experimental setup.	72
IV.4	The flow curves of the Carbopol dispersions.	73
IV.5	The dimensionless viscosity functions of the Carbopol dispersions.	74
IV.6	Dimensionless average velocity as a function of the dimensionless wall shear stress.	76
IV.7	Dimensionless viscosity profiles.	77
IV.8	Dimensionless velocity profiles.	78
IV.9	Interface shapes. (a) Carbopol 0.09%; (b) Carbopol 0.11%; (c) Carbopol 0.15%; (d) Carbopol 0.17%. The bubble speed increases from left to right; see Table IV.1 for the corresponding Ca_p , \bar{u}^* , τ_R^* , and m values.	80
IV.10	The fractional mass coverage as a function of the average velocity.	82

V.1	The geometry.	88
V.2	Small scale apparatus.	90
V.3	Pilot scale apparatus 1.	92
V.4	Pilot scale apparatus 2.	93
V.5	Large scale apparatus.	94
V.6	Interface evolution. Newtonian liquid 2 (glycerol) displacing a Newtonian liquid 1 (lower viscosity oil). Time increases from left to right.	98
V.7	Interface evolution. Viscoplastic material (Carbopol dispersion) displacing a Newtonian liquid (low viscosity oil). Time increases from left to right.	98
V.8	Interface evolution. Newtonian liquid (glycerol) displacing a Viscoplastic material (Carbopol dispersion). Time increases from left to right.	99
V.9	Interface evolution for the vertical case (0^0). Carbopol 0.10% (blue) displacing Carbopol 0.08% (white). Time increases from left to right, and from the top to the bottom.	100
V.10	Interface evolution for the inclined case (45^0). Carbopol 0.10% (blue) displacing Carbopol 0.08% (white). Time increases from left to right, and from the top to the bottom.	100
V.11	Interface evolution for the horizontal case (90^0). Carbopol 0.10% (blue) displacing Carbopol 0.08% (white). Time increases from left to right, and from the top to the bottom.	101
V.12	Comparison between experimental and numerical results of Carbopol 0.10% displacing Carbopol 0.08% in the vertical case (0^0). (a) and (b) correspond to the numerical results. (c) and (d) correspond to the experimental results.	102
V.13	Comparison between experimental and numerical results of Carbopol 0.10% displacing Carbopol 0.08% in the inclined case (45^0). (a) and (b) correspond to the numerical results. (c) and (d) correspond to the experimental results.	103
V.14	Comparison between experimental and numerical results of Carbopol 0.10% displacing Carbopol 0.08% in the horizontal case (90^0). (a) and (b) correspond to the numerical results. (c) and (d) correspond to the experimental results.	103
V.15	Volume fraction of the Carbopol 0.08% for the three cases, calculated by the numerical solution.	104
V.16	Experimental density and the density that would be obtained if the displacement were perfect versus volume of cement slurry used to displace the spacer.	105
V.17	Displacement of the spacer (light color) by the cement slurry (black color). (a) Downward displacement, and (b) upward displacement.	106
V.18	End of the displacement of the spacer (light color) by the cement slurry (black color). (a) Downward displacement, and (b) upward displacement.	106

V.19	Experimental density and the density that would be obtained if the displacement were perfect versus volume of water used to displace the cement slurry.	107
V.20	Displacement of the cement slurry by water (13 L). (a) Downward displacement, and (b) upward displacement.	108
V.21	Experimental and numerical densities versus volume of spacer used to displace the drilling mud, compared with the density that would be obtained if the displacement were perfect.	109
V.22	Interface evolution of the displacement of the drilling mud by the spacer material predicted by the numerical solution of the governing equations.	110
V.23	Experimental and numerical densities versus volume of cement slurry used to displace the spacer, compared with the density that would be obtained if the displacement were perfect.	111
V.24	Interface evolution of the displacement of the spacer material by the cement slurry predicted by the numerical solution of the governing equations.	112
V.25	Experimental and numerical densities versus volume of spacer used to displace the cement slurry, compared with the density that would be obtained if the displacement were perfect.	113
V.26	Interface evolution of the displacement of the cement slurry by the spacer material predicted by the numerical solution of the governing equations.	114
V.27	Pictures of slices of the tube after the cement slurry was displaced by the spacer.	115
V.28	Interface evolution of the cement plug 1 experiment predicted by the numerical solution of the governing equations.	115
V.29	Pictures of the cement plug 1. (a) The hole plug, and (b) slice located at the top of the plug.	116
V.30	Interface evolution of the cement plug 2 experiment predicted by the numerical solution of the governing equations.	117
V.31	Pictures of the cement plug 2. (a) The hole plug, and (b) and (c) views of the slice located between 2.75 m and 3.05 m from the bottom.	118
V.32	Pictures of the cement plug 2: views of the slice located between 3.05 m and 3.35 m from the bottom.	118
V.33	Pictures of the cement plug 2: views of the slice located between 2.15 m and 2.45 m from the bottom.	119

List of Tables

II.1	Geometries and meshes.	30
III.1	Mesh test for $\tau^* = 3.7$, $J = 18000$ and $n = 0.4$.	48
III.2	Meshes employed.	49
IV.1	Plastic capillary number, flow rate, and wall shear stress values of the flows shown in Fig. IV.9.	81
V.1	Properties of the materials used in apparatus 1.	91
V.2	Properties of the materials used in apparatus 2.	93
V.3	Large scale physical simulation - material replacement.	95
V.4	Large scale physical simulation - cement plug 1.	95
V.5	Large scale physical simulation - cement plug 2.	96