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Syllabus for
Pet904-2017 Capillary Pressure, Hysteresis and Wettability (10 sp)

The numbered points below the syllabus entries indicate the essential topics of that entry.

NOTE: This syllabus is almost identical to the previous one from 2006, except for the addition of two new items under "Special topics":

3. Scaling groups for spontaneous imbibition
4. Nonequilibrium effects in water-oil displacement

Books (and an article)

1. Thermodynamic basis

Castellan, G.W.: "Physical Chemistry", Addison-Wesley Publishing Company, Reading, Massachusetts (1983), Third Edition;

Chapter 18: "Surface Phenomena," pp 406-441. Basic physical understanding of surface phenomena. Introductory text.

1. Surface tension, forces between molecules, energy
2. Thermodynamic formulation of Young-Laplace eqn.
3. Gibbs free energy and spontaneous reactions
4. Spreading coefficient liquid-solid and liquid-liquid
5. Gibb's adsorption isotherm
6. Kelvin's eqn

Hiemenz, P.C. and Rajagopalan, R.: "Principles of Colloid and Surface Chemistry", Marcel Dekker (1997). Chapter 6: "Surface Tension and Contact Angle", pp 248-293; Chapter 10: "van der Waals Forces", pp 462-496.

1. Height of fluid interface in capillary tube, by the principle of virtual work
2. Contact angle and contact hysteresis
3. Water-air surface against a vertical wall
4. Surface tension measured by a hanging droplet
5. van der Waals forces
6. Graphs of energy versus distance between particles
7. Molecular interactions and "power laws"

8. Macroscopic consequences of van der Waals forces
9. Hamaker constant

Other books not part of syllabus

Rowlinson, J.S. and Widom, B.: *Molecular Theory of Capillarity*; Clarendon Press, Oxford (1982).

Israelachvili, J.: *"Intermolecular & Surface Forces"*, Academic Press (1992).

Kittel, C.: *"Introduction to Solid State Physics"*, John Wiley. Chapter 3: *"Crystal Binding"*. In Third Edition (1966) the van der Waals forces are explained by a classic argument. In the Seventh Edition (1996) the argumentation is by quantum mechanics and linear harmonic oscillators.

Adamson, A.W.: *"Physical Chemistry of Surfaces"*, John Wiley. Ch. I, II, III, IV.1-3, V.1-8, VI.

de Gennes, P.-G., Brochard-Wyart, F., and Quéré: *"Capillarity and Wetting Phenomena - Drops, Bubbles, Pearls, Waves"*, Springer (2004).

Berg, J.C.: *"An Introduction to Interfaces & Colloids - The Bridge to Nanoscience"*, World Scientific Publishing Co. (2010).

Butt, H.-J., Graf, K., and Kappl, M.: *"Physics and Chemistry of Interfaces"*, Wiley-VCH (2006).

2. Basics for petroleum engineering applications

Morrow, N.R. (ed.): *"Interfacial Phenomena in Petroleum Recovery,"* Surfactant Science Series Vol. 36, Marcel Dekker (1991);

Chapter 2 (George J. Hirasaki): *Thermodynamics of Thin Films and Three-Phase Contact Regions*; pp 23--76.

Chapter 3 (George J. Hirasaki): *Shape of Meniscus/Film Transition Region*; pp 77--99.

****Comment****: Chap 2 og 3 are shown in Hirasaki, G.J.: *"Wettability: Fundamentals and Surface Forces,"* SPEFE (June 1991) pp 217--226; *Trans., AIME*, 291. This is part of the syllabus also.

1. Disjoining pressure

2. Stability of thin films

Chapter 7 (Norman R. Morrow and James C. Melrose): *Application of Capillary Pressure Measurements to the Determination of Connate Water Saturation*; pp 258--287.

Chapter 8 (Robert W. Wunderlich): *Obtaining Samples with Preserved Wettability*; pp 289--318.

Chapter 9 (Louis E. Cuiec): Evaluation of Reservoir Wettability and Its Effect on Oil Recovery; Ch.7-9: pp 319--375.

1. Wettability and its quantification

Notes (one in Norwegian)

Derivation of the Young-Laplace equation by representing a smooth surface by radii of curvature in two normal planes and application of the principle of virtual work.

<http://www.ux.uis.no/~s-skj/PetFys04/Notater/Young-Laplace/>

1. Leiv Magne Sigveland: "Laplace si likning", Appendiks A i hovedoppgave til sivilingeniørstudiet ved Høgskolen i Stavanger, 1996.

2. Svein M. Skjaeveland: "Derivation of the Laplace equation"

1. Representation of a smooth interface by radii of curvature in a normal plane.

2. Derivation of Young-Laplace equation by the principle of virtual work.

3. A new file called "you-lap.pdf" with the paper "Derivations of the Young-Laplace equation" contains a combined English version of the linear algebra approach in 1. above, and the differential geometry approach in 2. above.

Journal papers

1. Long, J., Hyder, M.N., Huang, R.Y.M., Chen, P.: "Thermodynamic modeling

of contact angles on rough, heterogeneous surfaces," Advances in Colloid and Interface Science 118 (2005), Issue 1-3, 173-190.

1. Contact angle determined by Cassie's and Wentzel's equations.

2. Modelling the relationship between rough, heterogeneous surfaces and contact angle hysteresis by thermodynamics.

2. Morrow, N.R.: "Physics and Thermodynamics of Capillary Action in Porous

Media," Ind. & Eng. Chem. (June 1970) 62, No. 6, pp 32-56.

1. Thermodynamic description of reversible displacement.

2. Haynes jumps.

3. Thermodynamic description of the capillary pressure curve.

4. Hysteresis.

3. Hassanizadeh, S.M., Gray, W.G.: "Thermodynamic Basis of Capillary Pressure in Porous Media," Water Resources Research 29 (Oct. 1993), no. 10, p3389-3405.
 1. New theory with the capillary pressure as a function of both saturation and surface area to remove hysteresis.

4. Måløy, K.J., Furuberg, L., Feder, J., and Jøssang, T.: "Dynamics of Slow Drainage in Porous Media," Phys. Rev. Lett. (1992) 68, No. 14, pp 2161-2164. Only the two first pages.
 1. Drainage as a cooperative phenomenon.

5. Salathiel, R.A.: "Oil recovery by surface film drainage in mixed-wettability rocks," Journal of Petroleum Technology (Oct. 1973), 1216-1224.
 1. "Mixed wettability" as an explanation of low oil saturation after water flooding.

6. Radke, C.J., Kavscek, A.R., and Wong, H.: "A Pore-Level Scenario for the Development of Mixed Wettability in Oil Reservoirs", paper SPE 24880 presented at the 1992 Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Washington DC, Oct. 4--7.

The following published version of the paper is recommended:

- Kavscek, A.R, Wong, H., and Radke, C.J.: "A Pore-Level Scenario for the Development of Mixed Wettability in Oil Reservoirs", AIChEJournal, June 1993, Vol. 39, No. 6, pp 1072--1085.
1. "Pinning" and mixed wettability.
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7. Longeron, D., Hammervold, W.L., and Skjæveland, S.M.: "Water-Oil Capillary Pressure and Wettability Measurements Using Micropore Membrane Technique," paper presented at the 1994 International Symposium of the Society of Core Analysts, Stavanger, September 12-14, in Proceedings p 285-295.
 1. Measurement of capillary pressure by membranes.
 2. Wettability indices.
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8. Skjaeveland, S.M., Siqveland, L.M., Kjosavik, A., Hammervold, W.L., and Virnovsky, G.A.: "Capillary Pressure Correlation for Mixed-Wet Reservoirs," SPE Reservoir Evaluation & Engineering (Feb. 2000) pp. 60--67.
 1. Capillary pressure correlation for mixed wettability.

2. Hysteresis logic.
3. Modelling of contact movement.
9. Masalmeh, S.K., 2001. Experimental Measurements of Capillary Pressure and Relative Permeability Hysteresis. Paper SCA 2001-23 presented at the International Symposium of the Society of Core Analysts, Edinburgh, Sept. 17-19.
 1. Primary drainage, aging, wettability as function of reversal saturation.
10. Kaminsky, R. and Radke, C.J.: "Water Films, Asphaltene, and Wettability Alteration", paper SPE 39087 presented at the 1998 SPE/DOE Improved Oil Recovery Symposium, Tulsa, OK, April 19-22.
 1. Diffusion of oil molecules through water films during aging process.
11. Luis Cueto-Felgueroso and Ruben Juanes: "A discrete-domain description of multiphase flow in porousmedia: Rugged energy landscapes and the origin of hysteresis", Geophysical Research Letters, 2 Feb. 2016.
 1. The interpretation of hysteresis as a consequence of irreversible transitions and multistability.
12. Siyavash Motealleh, Mandana Ashouripashaki, David DiCarlo, and Steven Bryant: "Mechanisms of Meniscus Motion in Fractionally Wetted Porous Media", paper SPE 115732, 2008 ATCE in Denver, Co.
 1. Haines and Melrose events.

 Special topics in <http://www.ux.uis.no/~s-skj/KapHystFukt.06/Papers/>

NOTE: Starting Fall 2011, Special topic 1. is replaced by Special topics 3. and 4. while 2. is still included.

1. Three-phase capillary pressure
 - * Bradford, S.A., Leij, F.J.: "Fractional wettability effects on two- and three-fluid capillary pressure - saturation relations," Journal of Contaminant Hydrology 20 (1995), 89-109.
 - * Bradford, S.A., Leij, F.J.: "Predicting two- and three-fluid capillary pressure - saturation relationships of porous media with fractional wettability," Water Resources Research 32 (1996), 251-259.
 - * Bradford, S.A., Leij, F.J.: "Wettability effects on scaling two- and three fluid capillary pressure - saturation relations," Environ. Sci. Technol. 29 (1995), 1446-1455.
 1. Effect of wettability on three-phase capillary pressure:

- Saturation dependence
- Prediction from two-phase data
- Scaling

* Bradford, S.A., Leij, F.J.: "Estimating interfacial areas for multi-fluid soil systems," Journal of Contaminant Hydrology 27 (1997), 83-105.

1. Estimation of surface area for 2 and 3 phases from capillary pressure curve and thermodynamics
2. Wettability by chromatographic separation and areal fractions

Strand, S., Standnes, D.C., and Austad, T.: "New wettability test for chalk", paper presented at 8th International Symposium on Reservoir Wettability, 16-17 May 2004, Rice University, Houston, TX, USA.

Published as "New wettability test for chalk based on chromatographic separation of SCN and SO₄", J. Pet. Sci. Eng., 52 (2006).

3. Scaling groups for spontaneous imbibition

Papers in folder "Standnes.papers" are part of the syllabus. The the essential topics are:

1. scaling groups for spontaneous imbibition
2. capillary diffusion coefficient and assumption of constancy

Recommended Standnes papers:

- E&F Vol 24 2010 pp 1081-1087.pdf
- E&F Vol 24 2010 pp 2980-2984.pdf.
- E&F Vol 25 2011 pp 3053-3059.pdf

29Aug13: Papers of Schmid&Geiger added in folder "Schmid&Geiger.papers":

- Schmid Geiger 2012 - Universal scaling of spontaneous imbibition for
- water-wet systems.pdf Schmid Geiger 2013 - Universal scaling of
- spontaneous imbibition for arbitrary petrophysical properties.pdf

4. Nonequilibrium effects in water-oil displacement

Papers in folder "Barenblatt.papers" are part of the syllabus. The essential topics are:

1. Barenblatt's model for nonequilibrium local saturation
2. Comparison with the Hassanizadeh-Gray model

Recommended "Barenblatt" papers:

- TiPM1812b: On Barenblatt's Model of Spontaneous Countercurrent Imbibition
- 00087329.pdf: The Mathematical Model of Nonequilibrium Effects in Water-Oil Displacement.