

FOULING OF SURFACES

by

JON STEINAR GUDMUNDSSON

A Thesis
Submitted to the Faculty of Science
and Engineering in Fulfilment of
the Requirements for the Degree of
Doctor of Philosophy

Department of Chemical Engineering
University of Birmingham
England

August 1977

SYNOPSIS

Three fouling and deposition systems have been studied; paraffin wax in kerosene solutions and silica in geothermal waters at cooled surfaces and particulate magnetite in demineralised water at unheated surfaces. The paraffin wax fouling increased rapidly and asymptotically to an average fouling resistance that fluctuated at random with time due to build-up and break-down processes. The deposition (initial and asymptotic) decreased with flowrate and bulk temperature but increased with concentration and the difference in temperature between the cooled wall and the solution cloud point. The asymptotic fouling resistance was inversely proportional to the flowrate squared.

The magnetite deposition increased asymptotically with time and showed similar characteristics to the paraffin wax system. The deposition was sensitive to suspension bulk temperature (increasing with temperature) and the initial rate of deposition was inversely proportional to the flowrate.

A deposition-release model was developed to describe the behaviour of the paraffin wax and particulate magnetite systems where the initial rate of fouling and the asymptotic fouling resistance are inversely proportional to the friction velocity^{and friction velocity} squared, respectively. The deposit build-up and break-down in the two systems is considered to be adhesion/cohesion controlled. A feature of the model is the inclusion of a strength of deposit term.

The silica fouling increased linearly with time and is apparently controlled by the dehydration of silicic acids. At certain conditions the silica deposits assume a transversely rippled structure and the fouling resistance curve becomes spoon-like in shape. The pressure drop across rippled surfaces is excessive; some magnetite deposits are rippled. It is suggested that rippled deposits are formed due to the phenomena of flow separation and reattachment when the foulant is close to saturation and the depositing material highly adherent.

Til pabba og mömmu

ACKNOWLEDGMENTS

I would like to thank my supervisor Dr T R Bott for his friendship, helpful discussions and constant encouragement throughout the course of this work. I would also like to thank Dr I H Newson for his interest and support in all aspects of the studies.

Special thanks are due to Mr C A O'Keefe and Mr N J Hallas for their extensive help with the experimental work at Harwell. I would also like to thank Mr T A Packer for his help in developing the x-ray measurement technique.

My sincere thanks are extended to all members of the workshops at Birmingham and Harwell who constructed the experimental equipment without which the research could not have been made.

I would like to thank the Department of Chemical Engineering at Birmingham, the National Energy Authority in Iceland, and the Engineering Sciences Division at Harwell for providing experimental and other facilities to carry out the work.

I extend my gratitude to the Atomic Energy Research Establishment at Harwell for the provision of a studentship and the Science Research Council for providing funds to build some of the apparatus.

Finally, I would like to thank Miss S J Batten for her excellent typing of the manuscript.

FOREWORD

This thesis is divided into six main parts for the convenience of the reader. Each part can stand on its own and includes all the appropriate tables, figures, nomenclature and references.

There is an introduction to the subject and then four parts dealing with the experimental studies. The work is brought together in the last part.

At the end of each of the four parts concerned with the experiments there are several published papers and reports based on the work.

CONTENTS

PART I - HEAT TRANSFER FOULING	1
1. Introduction	1
2. Classification	3
2.1 Introduction	3
2.2 Types of Fouling	3
2.3 Variables	4
2.4 Industries of Interest	5
3. Previous Studies	6
3.1 Introduction	6
3.2 Deposition-release	6
3.3 General Studies	13
Nomenclature	16
References	18
PART II - PARAFFIN WAX DEPOSITION AND FOULING	26
1. Introduction	26
2. Previous Work	26
2.1 Introduction	26
2.2 Paraffin Wax Solutions	27
2.3 Deposition Variables	27
2.3.1 Flowrate and Time	27
2.3.2 Temperature	28
2.3.3 Surface Properties	28
2.4 Summary	29
3. Fouling Studies	29
3.1 Introduction	29
3.2 Experimental	30
3.3 Temperature Profile	31
3.4 Comments	33
4. Deposition Studies	35
4.1 Introduction	35
4.2 Apparatus	35
4.3 Experimental	36
4.4 Comments	38
5. Discussion	38
5.1 Mechanism	38
5.2 Model	39
6. Conclusions	44
7. Recommendations	44

Nomenclature	45
References	47
Paper A : Paraffin Wax Deposition in Cooled Heat Exchanger Tubes	
Paper B : Deposition of Paraffin Wax from Flowing Systems	
Paper C : Solubility of Paraffin Wax in Kerosene	
PART III - SILICA FOULING BY GEOTHERMAL WATERS	49
1. Introduction	49
2. Silica in Water	50
3. Experimental Work	50a
4. Discussion	52
5. Conclusions	55
6. Recommendations	55
Nomenclature	56
References	57
Paper D : Utilisation of Geothermal Energy in Iceland	
Paper E : Deposition of Silica from Geothermal Waters on Heat Transfer Surfaces	
Paper F : Deposition - The Geothermal Constraint	
PART IV - RIPPLED DEPOSITS	59
1. Introduction	59
2. Deposit Roughness	59
2.1 Effects of Deposit	59
2.2 Deposits in Fouling	60
2.3 Rippled Surfaces	61
3. Pressure Drop Measurements	61
4. Mechanism of Formation	63
5. Discussion	63
6. Conclusions	65
7. Recommendations	65
Nomenclature	71
References	72
Paper G : Rippled Deposits - Formation and Pressure Drop Effects	

Paper H : Rippled Silica Deposits in Heat Exchanger Tubes

Paper I : A Review of Rippled Magnetite Deposits in Supercritical Once-Through Boilers

PART V - DEPOSITION OF PARTICULATE MAGNETITE	75
1. Introduction	75
2. Review of Previous Work	76
2.1 Introduction	76
2.2 Deposition Conditions	76
2.2.1 Transfer Regimes	76
2.2.2 Corrosion Products	77
2.3 Deposits	78
2.4 Effects of Deposits	80
2.4.1 Pressure Drop	80
2.4.2 Heat Transfer	81
2.4.3 Radioactivity	83
2.4.4 Corrosion	85
2.5 Deposition Variables	85
2.5.1 Heat Flux	85
2.5.2 Concentration	88
2.5.3 Time	89
2.5.4 Fluid Velocity	91
2.5.5 Temperature	92
2.5.6 Electrophoresis	93
2.5.7 Other	94
2.6 Deposition Expressions	94
2.6.1 Empirical	94
2.6.2 Deposition and release	95
2.6.3 Evaporation	98
2.6.4 Other expressions	99
2.7 Conclusions	
3. Deposition of Particles	103
3.1 Introduction	103
3.2 Deposition Regimes	103
3.3 Stopping Distance Model	105
3.4 Analysis of Data	107
3.5 Concluding Remarks	111
4. Preliminary Work	112
4.1 Introduction	112
4.2 Deposition of Magnetite	112
4.2.1 Introduction	112
4.2.2 Ambient Conditions	113
4.2.3 Heated Conditions	114
4.3 Magnetite Particles in Water	115
4.3.1 Introduction	115
4.3.2 The Powder	115

4.3.3 Colloidal Theory	116
4.3.4 Particle Size Measurement	119
4.3.5 Particle Stability	120
4.4 Discussion	122
5. Apparatus and Procedures	123
5.1 Introduction	123
5.2 Circulation System	123
5.3 Test Section Assembly	124
5.4 X-Ray System	125
5.4.1 Introduction	125
5.4.2 Radiation	126
5.4.3 Description	127
5.4.4 Stability	128
5.4.5 Calibration	132
5.4.6 Conclusions	133
5.5 Experimental Procedures	133
5.5.1 Circulation	133
5.5.2 Test Section	135
5.5.3 X-ray Method	135
5.5.4 Sampling	136
6. Results and Calculations	137
6.1 Introduction	137
6.2 Calculation Method	138
6.3 Deposition Results	139
6.4 Deposit Examination	142
7. Discussion	144
7.1 General	144
7.2 Deposition Results	145
7.3 Particulate Deposition Model	148
7.4 Measurement Technique	151
8. Conclusions	154
9. Recommendations	156
Nomenclature	176
References	179
Paper J : Particle Diffusivity in Turbulent Pipe Flow	
 PART VI - FOULING STUDIES IN PERSPECTIVE	 186
1. Introduction	186
2. Mechanisms	186
3. Deposition - Release Model	188
4. Developments	191
5. Concluding Remarks	193
Nomenclature	194
References	195