Table of contents

Acknowledgments I

Abstract II

Table of contents IV

List of figures VII

List of tables XI

1 Introduction 1

1.1 Motivations and objectives 1

1.2 State of the art and scientific challenges 6

1.2.1 Failure modes of cement sheath integrity 6

1.2.2 Experimental study on cement sheath integrity 10

1.2.3 Theoretical study on cement sheath integrity 15

1.2.4 Challenges in cement sheath integrity evaluation 27

1.3 Thesis outline 29

2 Fundamentals of cement sheath integrity analysis 33

2.1 Stress-strain of thick-walled cylinder 33

2.1.1 Elastic stress-strain caused by pressure load 34

2.1.2 Elastic-plastic stress-strain caused by pressure load 38

2.2 Temperature-differential stress of cement sheath 42

2.2.1 Numerical simulation of wellbore temperature field 43

2.2.2 Cement sheath temperature-differential stress calculation model 47

3 Laboratory experiments on cement sheath integrity evaluation 53

3.1 Basic idea 53

3.2 Materials and experimental methods 54

3.2.1 Sample preparation 54

3.2.2 Cement sheath integrity testing device and method 56

3.3 Mechanical properties test of cement stone 61

3.3.1 Uniaxial and triaxial testing 62

3.3.2 Cyclic loading test 64

3.4 Cement sheath integrity evaluation experiment 65
3.4.1 Cement sheath integrity under different loading modes 65
3.4.2 Failure analysis of cement sheath after cyclic load testing 68
3.5 Summary 72
4 Theoretical analysis of cement sheath integrity under the effects of wellbore temperature and pressure 74
4.1 Basic idea 74
4.2 Cement sheath integrity based on elastic-plastic mechanics theory 75
4.2.1 Displacement calculation of casing-cement sheath-formation system 76
4.2.2 Calculation of micro-annulus at cement sheath interface 79
4.2.3 Failure analysis of cement sheath under casing internal pressure 83
4.3 Cement sheath integrity under temperature-differential stress 88
4.3.1 Wellbore temperature distribution during fluid injection 89
4.3.2 Temperature-differential stress in cement sheath due to cooling effect 94
4.4 Analysis of cement sheath integrity under combined stress 95
4.4.1 Combined stress distribution of cement sheath 96
4.4.2 Analysis of cement sheath micro-annulus during fracturing 98
4.4.3 Analysis of cement sheath micro-annulus after fracturing 99
4.5 Analysis of influencing factors on cement sheath integrity 102
4.5.1 Influence of construction pressure 102
4.5.2 Influence of construction time 103
4.5.3 Influence of the temperature difference between inner and outer walls of the cement sheath 104
4.5.4 Influence of Young's modulus and Poisson's ratio on temperature-differential stress 105
4.6 Summary 106
5 Integrity evaluation of modified cement sheath systems 109
5.1 Basic idea 109
5.2 Effects of elasticity and strength on cement sheath integrity 109

5.2.1 Raw materials 109
5.2.2 Mechanical parameters of cement stone 111
5.2.3 Cement sheath sealing integrity evaluation results 112
5.3 Effects of expansion agent and toughening agent on cement sheath integrity 116
5.3.1 Raw materials 116
5.3.2 Cement sheath sealing integrity evaluation results 117
5.4 Application Examples 121
5.5 Summary 123
6 Conclusions and outlook 124
Reference 128
Appendix: calculation method of interface micro-annulus 138
A. Interface micro-annulus affected by wellbore cooling 138
B. Interface micro-annulus affected by wellbore pressure reduction 142