



Table of contents

LIST OF FIGURES	XVII
LIST OF TABLES	XXIII
NOMENCLATURE	XXV
1 INTRODUCTION	1
1.1 State of the art	5
1.2 Goal of the research and the structure of this report	6
2 THEORETICAL BACKGROUND & RESEARCH STATUS	7
2.1 Fundamental fluid dynamics and thermodynamics equations	7
2.1.1 First law of thermodynamics	7
2.1.2 Fundamental fluid dynamics equations	10
2.1.3 Special cases of the fluid dynamics equations	14
2.2 Heat transfer: a boundary condition for the energy equation	17
2.2.1 Heat transfer	17
2.2.2 Heat transfer in boundary layers	19
2.3 Phase change	23
2.3.1 Saturation curve	23
2.3.2 Evaporation and boiling	24
2.3.3 Condensation	25
2.3.4 Interfacial resistance	27
2.4 Sloshing	29
2.4.1 Mechanics of sloshing	29
2.4.2 Thermodynamics of sloshing	36
3 EXPERIMENTAL SETUP AND RESULTS	41
3.1 Experimental setup	41
3.2 Experimental Results	44
3.2.1 Self-pressurisation experiment results	44
3.2.2 Active Pressurisation Experiment Results	50
3.3 An explanation of the condensation occurring during sloshing	56
3.4 Determination of heat flow into the fluid	58
3.4.1 Heat flow into the liquid volume	58
3.4.2 Heat flow into the ullage volume	59



3.4.3	Heat flow during other self-pressurization experiments	60
4	NUMERICAL MODELING OF THERMAL STRATIFICATION	61
4.1	Analysis of heat flow into the liquid	61
4.2	Mesh sensitivity analyses	64
4.2.1	Mesh sensitivity analysis for liquid heat flow in normal direction to the dewar wall	65
4.2.2	Mesh sensitivity analysis for liquid heat flow tangential through the dewar wall	76
4.2.3	Sensitivity study on the accommodation coefficient	80
4.2.4	Conclusions from sensitivity analyses	83
4.3	Full dewar model	83
4.3.1	Setting up the full conduction model	84
4.3.2	Results of the full conduction model	87
4.3.3	Conclusions from the FLOW3D full conduction model	95
4.4	A 1D engineering model for the simulation of thermal stratification in the liquid	96
4.4.1	Thermal conduction model	96
4.4.2	Results of the 1D model applied to the experiments	101
5	NUMERICAL MODELING OF SLOSHING INCLUDING HEAT AND MASS TRANSFER	107
5.1	Numerical modeling in FLOW 3D	107
5.1.1	Limitations of the numerical method used in FLOW 3D	109
5.1.2	Simplified FLOW 3D slosh model	114
5.1.3	Possible solutions for the error	119
5.2	A 1D model for the simulation of heat and mass transfer during sloshing	120
5.2.1	Energy balance	120
5.2.2	The energy balance for sloshing liquids	121
5.2.3	The Nusselt number in sloshing liquids	123
5.2.4	Implementation of the Nusselt number in the 1D model	126
5.2.5	Heat input during sloshing	127
5.3	Results of the 1D slosh model	129
5.4	Comparison of the 1D model with other experiments	132
5.5	Application of the 1D slosh model to the future ESC-B upper stage	136
5.6	Nusselt number dependency	139
5.6.1	Dimensional analysis	139
5.6.2	Application to the experiments	142
6	SUMMARY	145



7	CONCLUSIONS & RECOMMENDATIONS	149
7.1	Conclusions	149
7.2	Recommendations	149
8	REFERENCES	151
I.	CAD DRAWING OF THE DEWAR	155
II.	BESSEL FUNCTION	157
III.	EXPERIMENTAL DATA	159
IV.	NOTE ON C_p AND C_v IN LIQUIDS	165
V.	FITTING OF THE PRESSURE CURVE	169
VI.	ULLAGE TEMPERATURE DEVELOPMENTS	171
VII.	NITROGEN PROPERTY TABLES FROM NIST	177
VIII.	BOROSILICATE MATERIAL PROPERTIES FROM [40]	181