



**UNIVERSITI PUTRA MALAYSIA**

**EFFECT OF FILM THICKNESS ON NARROWBAND  
THERMOCHROMIC LIQUID CRYSTAL CALIBRATION**

**NADIA BINTI ABDULLAH**

**FK 2009 29**



**EFFECT OF FILM THICKNESS ON NARROWBAND THERMOCHROMIC  
LIQUID CRYSTAL CALIBRATION**

**By**

**NADIA BINTI ABDULLAH**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,  
in Fulfilment of the Requirement of the Degree of Master of Science**

**January 2009**



## DEDICATION

*To my family, with love:*

*It takes many inches to become a mile...be patient and persevere,  
and the mile will come in time...*



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Master of Science

**EFFECT OF FILM THICKNESS ON NARROWBAND THERMOCHROMIC LIQUID CRYSTAL CALIBRATION**

By

**NADIA BINTI ABDULLAH**

**January 2009**

**Chairman : Abd. Rahim Abu Talib, PhD**

**Faculty : Engineering**

Thermochromic liquid crystals (TLCs or TLC) are complex organic substances which selectively reflect visible light as function of temperature. Narrowband TLCs are attractive for temperature measurements due to their higher precision in temperature measurements associated with their narrow bandwidths, and calibrations of narrowband TLCs are less affected by variations in illumination-viewing angles and background illumination. In order to properly utilize narrowband TLCs and intensity-matching methods for quantitative temperature measurements, it is important to investigate film thickness effects on intensity-based calibrations of narrowband TLCs, which have been previously ignored in previous research. Film thicknesses of 10, 20, 30, 40 and 50  $\mu\text{m}$  were investigated on green intensity-based calibrations of R35C1W narrowband TLC during heating and cooling. The results showed an increase in magnitude of peak green intensity with increasing film thickness, with a percentage increase of approximately 18% when film thickness increased from 10  $\mu\text{m}$  to 50  $\mu\text{m}$ . The results also showed an inconsistent shift in peak green temperature, with a maximum temperature shift of 0.40°C, suggesting that film thickness effects may be insignificant for narrowband TLCs compared with wideband TLCs.



A theoretical method for estimating the volume of coating formulation required to achieve a desired film thickness was presented in this research, based on the film coverage and dry solids content of the TLCs. Results were presented for seven samples of sprayable narrowband TLCs with desired film thicknesses of 10, 20, 30, 40 and 50  $\mu\text{m}$  based on a square shaped model surface area. The percentage uncertainties in volume of coating formulation was obtained to be significant, within 57 – 67%, however, the results were attributed mainly to the lack in accuracy of the electronic balance, which was  $\pm 1$  g. Simulation results showed that if the accuracy was increased to  $\pm 0.001$  g, the percentage uncertainties decreased to less than 5% for all samples. The method is easily implemented, and is likely to be beneficial to users intending to employ sprayable TLCs for temperature measurements.

In this research, a graphical user interface (GUI) was developed to process images and data in transient calibration of TLCs. The GUI functions to generate full intensity-based calibration curves based on single colour intensity in the Red-Green-Blue (RGB) colour space. The GUI greatly simplifies, streamlines and automates image and data processing, which at present, is carried out by low-level programming and keyboard-entered commands. The GUI is likely to be a useful tool for users intending to utilize TLCs for temperature measurements.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan Ijazah Sarjana Sains

**KESAN KETEBALAN LAPISAN TERHADAP PENENTUKURAN CECAIR  
HABLUR TERMOKROMIK JALUR SEMPIT**

Oleh

**NADIA BINTI ABDULLAH**

**Januari 2009**

**Pengerusi : Abd. Rahim Abu Talib, PhD**

**Fakulti : Kejuruteraan**

Cecair hablur termokromik (TLC) adalah sebatian organik kompleks yang memantulkan cahaya nampak secara memilih dengan perubahan suhu. Penggunaan TLC jalur sempit adalah menarik kerana kepersisan pengukuran suhu yang tinggi, dan penentukuran TLC jalur sempit kurang terjejas dengan perubahan sudut pencahayaan- pemandang dan pencahayaan latar. Dalam mengaplikasikan TLC jalur sempit dan kaedah padanan keamatan cahaya untuk pengukuran suhu, kajian ketebalan lapisan terhadap penentukuran TLC jalur sempit adalah penting kerana aspek ini tidak diberi perhatian khusus pada penyelidikan sebelumnya. Kesan ketebalan lapisan 10, 20, 30, 40 dan 50  $\mu\text{m}$  terhadap penentukuran berasaskan keamatan cahaya hijau telah dikaji untuk TLC jalur sempit R35C1W semasa pemanasan dan penyejukan. Hasil kajian menunjukkan bahawa magnitud puncak keamatan cahaya hijau bertambah apabila ketebalan lapisan bertambah, dengan peratusan sebanyak 18% apabila ketebalan lapisan bertambah dari 10  $\mu\text{m}$  hingga 50  $\mu\text{m}$ . Hasil kajian juga menunjukkan peralihan suhu puncak keamatan cahaya hijau yang tidak konsisten apabila ketebalan lapisan bertambah, dengan nilai maksimum sebanyak 0.40°C. Hasil kajian mencadangkan bahawa kesan ketebalan lapisan mungkin tidak ketara untuk TLC jalur sempit berbanding dengan TLC jalur lebar.

Suatu kaedah teoretikal telah dikemukakan dalam penyelidikan ini, bertujuan menganggarkan isipadu perumusan TLC yang diperlukan untuk mencapai ketebalan lapisan yang diinginkan berdasarkan luas liputan dan kandungan pepejal kering TLC. Hasil kajian telah dikemukakan untuk tujuh sampel TLC jalur sempit jenis semburan dengan ketebalan lapisan 10, 20, 30, 40 dan 50  $\mu\text{m}$  berdasarkan luas permukaan model berbentuk segiempat sama. Hasil kajian menunjukkan bahawa peratusan ketakpastian isipadu perumusan TLC adalah tinggi, dalam lingkungan 57 – 67%. Peratusan ketakpastian yang tinggi mungkin disebabkan oleh kejituan neraca elektronik yang rendah, iaitu sebanyak  $\pm 1$  g. Hasil simulasi menunjukkan bahawa apabila kejituan neraca elektronik adalah  $\pm 0.001$  g, peratusan ketakpastian kesemua sampel adalah kurang daripada 5%. Kaedah anggaran ketebalan lapisan yang telah dikemukakan adalah mudah dan mungkin memanfaatkan para pengguna TLC.

Sebuah antara muka pengguna grafik (GUI) telah dicipta dalam penyelidikan ini, bertujuan memproses imej dan data daripada penentuan TLC. GUI tersebut berfungsi untuk menghasilkan keluk penentuan TLC berasaskan keamatan cahaya dalam model warna Merah-Hijau-Biru (RGB). GUI yang dihasilkan bertujuan memudahkan, menyelaraskan dan mengautomatikan pemrosesan imej dan data, dan mungkin menjadi alat pemrosesan imej yang berguna kepada pengguna yang ingin mengaplikasikan TLC untuk pengukuran suhu.

## ACKNOWLEDGEMENTS

All Praise Be to Allah the Almighty, the Most Compassionate, the Most Merciful, for granting me the knowledge, strength, courage, patience and perseverance in order for me to complete my Masters degree successfully.

Warmest thanks go to my supervisors, Dr. Abd. Rahim Abu Talib, Dr. Abdul Aziz Jaafar and Dr. Mohamad Amran Mohd Salleh, for their continuing guidance, encouragement and support, both through the thick and thin.

Gracious thanks go to the chairman of my viva voce, Dr. Renuganth Varatharajoo and my panel of examiners, Dr. Faizal Mustapha, Dr. Nor Mariah Adam and Dr. Shahrir Abdullah, for their constructive comments and criticisms in order for me to improve the quality of my Masters thesis. Gracious thanks are also due to my anonymous journal and conference paper reviewers for many helpful comments and criticisms in order for me to improve the quality of my research work and publications.

My greatest appreciation goes to Dr. Mike Parsley of Hallcrest Technologies Limited UK for many helpful discussions regarding the method for estimating film thickness and the use of liquid crystals in my research. Heartfelt thanks go to Sal Lazarra of Hallcrest Technologies Limited USA for helpful discussion on the colour-temperature profiles of liquid crystals used in my research.





Gracious thanks go to Prof. Peter Thomas Ireland of Rolls-Royce UK for contributing to my understanding of intensity-based calibrations. Cordial thanks are also due to Dr. Srinath Ekkad of Virginia Tech University and Prof. Mike Owen of University of Bath for helpful hints on adiabatic wall temperature. Heartfelt thanks go to Mr. Graham Henstridge of Capgo Pty Ltd Australia for helpful discussion on possible sources of error in temperature measurements. I am grateful for the knowledge which they imparted to me although it is not cited in my Master thesis.

Special thanks go to Dr. Siti Mazlina Mustapha Kamal and the technical staff of Agricultural Laboratory and Food Transportation Laboratory, Department of Food and Process Engineering, Universiti Putra Malaysia, for their cooperation and technical assistance in my research.

Special thanks go to my mentor, Dr. Zairil Azhar Zaludin, for being there for me during the adversities of my life in the university ever since my Bachelor degree years. He is indeed a fine mentor. Words will never be enough for me to express my appreciation for all the help, encouragement and support which he has given me.

Cordial thanks are also due to Dr. Thamer Ahmed Mohamed from the Department of Civil Engineering UPM, Dr. Azmin Shakrine Mohd Rafie, Dr. Rizal Zahari and again, Dr. Faizal Mustapha and Dr. Abdul Aziz Jaafar, for giving me the opportunity to gain invaluable teaching and learning experience from my tutorial sessions and laboratory demonstrations during my Master programme. I am grateful for all the knowledge which they have generously imparted to me.



My warmest appreciation goes to Kuok Foundation Berhad for the financial support which they have granted me to pursue my studies, especially Madam Lynette Ng, for her kindness and for having faith in me. I greatly acknowledge the financial support provided by the Malaysian Ministry of Higher Education under the Fundamental Research Grant No.: 01-01-07-032FR for funding my research.

I am grateful to my colleague, Dhaney, for all the help which he has given me throughout my research, and for all his corny jokes which made me double up with laughter. I really appreciate the help, encouragement and support from all my juniors and friends, especially Cookie, Zamela and Farah. May Allah S.W.T. bless you all in this world and the Hereafter. I am greatly indebted to Auntie Ani Karsan and Leonard Kwong Ho Mun, the two special individuals who helped kicked off my studies.

Last but definitely not least, I am very thankful to my family, especially my mother, who endlessly prayed for my success, for having faith in me, for believing in my capabilities, for her love, encouragement and moral support, and for being there for me both during the ups and downs in my life. Thank you all.

*“We can only do to the best of our capability; perfection is only for*

*Allah the Almighty.”*



## APPROVAL SHEET NO. 1

I certify that a Thesis Examination Committee has met on 8 January 2009 to conduct the final examination of Nadia binti Abdullah on her thesis entitled “Effect of Film Thickness on Narrowband Thermochromic Liquid Crystal Calibration” in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

**Renuganth Varatharajoo, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Faizal Mustapha, PhD**

Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Ir. Nor Mariah Adam, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Shahrir Abdullah, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Kebangsaan Malaysia  
(External Examiner)

---

**BUJANG KIM HUAT, PhD**

Professor and Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date: 19 March 2009



## APPROVAL SHEET NO. 2

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

**Abd. Rahim Abu Talib, PhD**

Senior Lecturer  
Department of Aerospace Engineering  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Abdul Aziz Jaafar, PhD**

Senior Lecturer  
Department of Aerospace Engineering  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Mohamad Amran Mohd Salleh, PhD**

Senior Lecturer  
Department of Chemical and Environmental Engineering  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

---

**HASANAH MOHD GHAZALI, PhD**

Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date: 9 April 2009



## **DECLARATION**

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any degree at Universiti Putra Malaysia or other institutions.

**NADIA ABDULLAH**

Date: 4 May 2009



## TABLE OF CONTENTS

<b>Item</b>	<b>Page</b>
<b>DEDICATION</b>	ii
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	v
<b>ACKNOWLEDGEMENTS</b>	vii
<b>APPROVAL SHEET NO.1</b>	x
<b>APPROVAL SHEET NO.2</b>	xi
<b>DECLARATION</b>	xii
<b>LIST OF TABLES</b>	xvi
<b>LIST OF FIGURES</b>	xxii
<b>LIST OF NOTATIONS</b>	xxv
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	<b>1</b>
1.1 Temperature Measurement Methods	1
1.1.1 Thermocouples	1
1.1.2 Infrared Thermography	3
1.1.3 Liquid Crystal Thermography	5
1.2 Research Motivation	6
1.3 Research Objectives	9
1.4 Thesis Layout	9
<b>2 LITERATURE REVIEW</b>	<b>11</b>
2.1 Thermochromic Liquid Crystals	11
2.2 Calibration of Thermochromic Liquid Crystals	13
2.2.1 The Need for Calibration	13
2.2.2 Selection of Calibration Method	14
2.3 Liquid Crystal Thermography	19
2.3.1 General	19
2.3.2 Steady-State Liquid Crystal Thermography	20
2.3.3 Transient Liquid Crystal Thermography	23
2.4 Film Thickness Effects on Thermochromic Liquid Crystal Calibrations	25
2.5 Image Processing Tools for Thermochromic Liquid Crystal Calibrations	28
<b>3 ESTIMATION OF FILM THICKNESS OF THERMOCHROMIC LIQUID CRYSTALS</b>	<b>31</b>
3.1 Overview	31
3.2 Methodology	32
3.2.1 Sample Preparation	32
3.2.2 Estimation of Film Thickness	36
3.2.3 Achievable Film Thickness, Absolute Difference and Percentage Difference between Achievable and Ideal Dry Film Thickness	43



3.2.4	Uncertainty Analysis	44
3.3	Results and Discussion	61
3.3.1	Dry Solids Content	61
3.3.2	Volume of Coating Formulation	61
3.3.3	Achievable Film Thickness, Absolute Difference and Percentage Difference between Achievable and Ideal Dry Film Thickness	62
3.3.4	Partial Derivatives of Volume of Coating Formulation Relative to Measured Variables	65
3.3.5	Systematic and Random Uncertainties of Measured Variables at Standard Deviation Level	68
3.3.6	Overall, Relative and Percentage Uncertainties of Measured Variables	71
3.3.7	Systematic, Random, Overall, Relative, Percentage and Simulated Uncertainties of Volume of Coating Formulation	72
3.3.8	Systematic, Random, Overall, Relative and Percentage Uncertainties in Coating Formulation, Dry Solids and Dry Solids Content	77
3.3.9	Advantages and Restrictions in the Method of Estimating Film Thickness	81
3.4	Summary	84
<b>4</b>	<b>GRAPHICAL USER INTERFACE FOR THERMOCHROMIC LIQUID CRYSTAL IMAGE PROCESSING</b>	<b>86</b>
4.1	Overview	86
4.2	Methodology	87
4.2.1	Phases in GUI Development	87
4.2.2	Application Software: MATLAB GUIDE	88
4.2.3	GUI Development Process	89
4.3	Results and Discussion	93
4.3.1	Description of the Developed GUI	93
4.3.2	Image and Data Processing Sequence	98
4.3.3	Capabilities of the GUI	101
4.3.4	Restrictions of the GUI and Areas for Further Improvement	101
4.4	Summary	108
<b>5</b>	<b>THE EFFECTS OF FILM THICKNESS ON THERMOCHROMIC LIQUID CRYSTAL CALIBRATIONS</b>	<b>109</b>
5.1	Overview	109
5.2	Methodology	110
5.2.1	Sample Preparation	110
5.2.2	Experimental Rig	113
5.2.3	Experimental Procedure	119
5.3	Results and Discussion	124
5.3.1	Baseline Calibrations	124
5.3.2	Film Thickness Test	139
5.3.3	Additional Considerations	158
5.4	Summary	160

<b>6 CONCLUSION</b>	162
6.1 General Conclusions and Recommendations for Future Work	162
<b>REFERENCES</b>	165
<b>APPENDICES A</b>	173
<b>BIODATA OF THE STUDENT</b>	177





## LIST OF TABLES

<b>Table</b>	<b>Title</b>	<b>Page</b>
3.1	Specifications of aqueous slurries manufactured by Hallcrest Technologies Limited	33
3.2	Coating formulation and its classification for samples A through G	33
3.3	Total volume of coating formulation and proportions of TLC, binder and water for samples A through G	35
3.4	Mean weight of coating formulation, mean weight of dry solids and dry solids content	41
3.5	Dry solids content for samples A through G	61
3.6	Estimated volume of coating formulation to achieve dry film thicknesses of 10, 20, 30, 40 and 50 $\mu\text{m}$ for samples A through G	62
3.7	Achievable dry film thickness obtained for samples A through G	63
3.8	Absolute difference between achievable and ideal dry film thickness for samples A through G	64
3.9	Percentage difference relative to ideal dry film thickness for samples A through G	64
3.10	Estimated partial derivatives for volume of coating formulation relative to measured variables for samples A through G for an ideal dry film thickness of 10 $\mu\text{m}$	65

<b>Table</b>	<b>Title</b>	<b>Page</b>
3.11	Estimated partial derivatives for volume of coating formulation relative to measured variables for samples A through G for an ideal dry film thickness of 20 $\mu\text{m}$	66
3.12	Estimated partial derivatives for volume of coating formulation relative to measured variables for samples A through G for an ideal dry film thickness of 30 $\mu\text{m}$	66
3.13	Estimated partial derivatives for volume of coating formulation relative to measured variables for samples A through G for an ideal dry film thickness of 40 $\mu\text{m}$	66
3.14	Estimated partial derivatives for volume of coating formulation relative to measured variables for samples A through G for an ideal dry film thickness of 50 $\mu\text{m}$	67
3.15	Estimated number of degrees of freedom, coverage factor, and overall, relative and percentage uncertainties in length of copper plate	69
3.16	Estimated number of degrees of freedom, coverage factor, and overall, relative and percentage uncertainties in width of copper plate	69
3.17	Estimated number of degrees of freedom, coverage factor, and overall, relative and percentage uncertainties for weight of container of samples A through G	70
3.18	Estimated number of degrees of freedom, coverage factor, and overall, relative and percentage uncertainties for weight of container and coating formulation of samples A through G	70
3.19	Estimated number of degrees of freedom, coverage factor, and overall, relative and percentage uncertainties for weight of container and dry solids of samples A through G	70

<b>Table</b>	<b>Title</b>	<b>Page</b>
3.20	Bias errors in electronic balance	71
3.21	Estimated total number of degrees of freedom, coverage factor, and systematic, random, overall, relative and percentage uncertainties for volume of coating formulation of samples A through G for an ideal dry film thickness of 10 $\mu\text{m}$	73
3.22	Estimated total number of degrees of freedom, coverage factor, and systematic, random, overall, relative and percentage uncertainties for volume of coating formulation of samples A through G for an ideal dry film thickness of 20 $\mu\text{m}$	73
3.23	Estimated total number of degrees of freedom, coverage factor, and systematic, random, overall, relative and percentage uncertainties for volume of coating formulation of samples A through G for an ideal dry film thickness of 30 $\mu\text{m}$	73
3.24	Estimated total number of degrees of freedom, coverage factor, and systematic, random, overall, relative and percentage uncertainties for volume of coating formulation of samples A through G for an ideal dry film thickness of 40 $\mu\text{m}$	74
3.25	Estimated total number of degrees of freedom, coverage factor, and systematic, random, overall, relative and percentage uncertainties for volume of coating formulation of samples A through G for an ideal dry film thickness of 50 $\mu\text{m}$	74
3.26	Estimated total number of degrees of freedom, coverage factor, and systematic, random, overall, relative and percentage uncertainties for volume of coating formulation of samples A through G for an ideal dry film thickness of 10 $\mu\text{m}$	76
3.27	Estimated systematic and random uncertainties, and mean weight of coating formulation for samples A through G	77

<b>Table</b>	<b>Title</b>	<b>Page</b>
3.28	Estimated overall, relative and percentage uncertainties for weight of coating formulation of samples A through G	78
3.29	Estimated systematic and random uncertainties, and mean weight of dry solids for samples A through G	78
3.30	Estimated overall, relative and percentage uncertainties for weight of dry solids of samples A through G	79
3.31	Estimated systematic and random uncertainties, and dry solids content of samples A through G	80
3.32	Estimated overall, relative and percentage uncertainties for dry solids content of samples A through G	80
5.1	Samples for baseline calibrations and film thickness test	112
5.2	Red start, blue stop, predefined heating and predefined cooling temperatures for samples A10 through C10	121
5.3	Percentage difference in peak red intensity and temperature between heating and cooling at ROI 1 for samples A10, B10 and C10	130
5.4	Percentage difference in peak green intensity and temperature between heating and cooling at ROI 1 for samples A10, B10 and C10	131
5.5	Percentage difference in peak blue intensity and temperature between heating and cooling at ROI 1 for samples A10, B10 and C10	131
5.6	Percentage difference in peak green intensity and temperature for ROI 2 relative to ROI 1 during heating and cooling for samples A10, B10 and C10	136

<b>Table</b>	<b>Title</b>	<b>Page</b>
5.7	Percentage difference in peak green intensity and temperature for ROI 3 relative to ROI 1 during heating and cooling for samples A10, B10 and C10	137
5.8	Percentage difference in peak green intensity and temperature for ROI 3 relative to ROI 2 during heating and cooling for samples A10, B10 and C10	138
5.9	Percentage difference in peak green intensity and temperature during heating for samples B20, B30, B40 and B50 relative to B10	143
5.10	Percentage difference in peak green intensity and temperature during cooling for samples B20, B30, B40 and B50 relative to B10	143
5.11	Indicated surface temperatures for increasing film thickness at a constant hue for R45C10W TLC	144
5.12	Percentage difference in peak red intensity and temperature between heating and cooling at ROI 1 for samples B10 through B50	145
5.13	Percentage difference in peak green intensity and temperature between heating and cooling at ROI 1 for samples B10 through B50	146
5.14	Percentage difference in peak blue intensity and temperature between heating and cooling at ROI 1 for samples B10 through B50	146
5.15	Sources of uncertainty in temperature measurement system, and systematic, random and overall uncertainties in surface temperature without thermocouple calibration	154

<b>Table</b>	<b>Title</b>	<b>Page</b>
5.16	Sources of uncertainty in temperature measurement system, and systematic, random and overall uncertainties in surface temperature with thermocouple calibration	157
A.1	Weight measurement of stainless steel container for samples A through G	173
A.2	Weight measurements of stainless steel container and TLC coating formulation for samples A through G	173
A.3	Weight measurements of stainless steel container and TLC dry solids for samples A through G	173
A.4	Measurements of length and width for copper and aluminium plates	174
A.5	Baseline measurements of loads $m_1$ and $m_2$	174
A.6	Cornerload measurements of loads $m_1$ and $m_2$	175
A.7	Linearity measurements of loads $m_1$ and $m_2$	176

## LIST OF FIGURES

<b>Figure</b>	<b>Title</b>	<b>Page</b>
2.1	Nomenclature of Thermochromic Liquid Crystals	12
3.1	Definition of dry film thickness	36
3.2	General methodology for small sample uncertainty analysis of an experimental result without correlated systematic uncertainties	60
3.3	Estimation of volume of coating formulation required to achieve a desired dry film thickness	82
3.4	Idealized hypothetical situation of the dry film thickness	83
3.5	Real situation of the dry film thickness	83
4.1	MATLAB GUIDE Layout Editor	88
4.2	Overall graphical user interface development process	92
4.3	Image Preview window	93
4.4	Image Info window	94
4.5	Image Inputs and Processing window	95
4.6	Data Processing and Plot Generation window	96
4.7	Graphical results of full intensity-based calibration	96
4.8	Normalized Intensity window	97

<b>Figure</b>	<b>Title</b>	<b>Page</b>
4.9	Normalized averaged intensity calibration curve for R30C1W TLC	98
4.10	Image processing sequence	100
4.11	Go To function in M-file Editor	104
5.1	Schematic of experimental rig (viewed from top)	114
5.2	Region of interest (ROI 1) for averaging image frames	124
5.3	Heating and cooling calibration for sample A10 based on red, green and blue intensities	125
5.4	Heating and cooling calibration for sample B10 based on red, green and blue intensities	125
5.5	Heating and cooling calibration for sample C10 based on red, green and blue intensities	126
5.6	Estimation of temperature interval for red intensity for sample B10	127
5.7	Estimation of temperature interval for green intensity for sample B10	128
5.8	Estimation of temperature interval for blue intensity for sample B10	128
5.9	Selected regions of interest for averaging image frames	132



<b>Figure</b>	<b>Title</b>	<b>Page</b>
5.10	Heating and cooling green intensity calibration for sample A10 for three regions of interest	133
5.11	Heating and cooling green intensity calibration for sample B10 for three regions of interest	134
5.12	Heating and cooling green intensity calibration for sample C10 for three regions of interest	134
5.13	Film thickness effects on green intensity-based calibrations of R35C1W TLC during heating	140
5.14	Film thickness effects on green intensity-based calibrations of R35C1W TLC during cooling	141
5.15	Position of thermocouple tip in copper plate	159
5.16	Multiple measuring junctions due to exposed thermocouple wires embedded within thermally conductive adhesive	159