

**DATA RECONCILIATION WITH GROSS ERROR DETECTION BY NLP  
FOR HEAT EXCHANGER SYSTEMS**

Pathompong Kongchuay

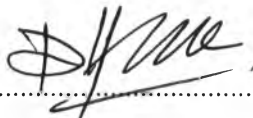
A Thesis Submitted in Partial Fulfilment of the Requirements  
for the Degree of Master of Science  
The Petroleum and Petrochemical College, Chulalongkorn University  
in Academic Partnership with  
The University of Michigan, The University of Oklahoma,  
Case Western Reserve University, and Institut Français du Pétrole  
2014

I28370612

**Thesis Title:** Data Reconciliation with Gross Error Detection by NLP for Heat Exchanger Systems  
**By:** Mr. Pathompong Kongchuay  
**Program:** Petroleum Technology  
**Thesis Advisors:** Asst. Prof. Kitipat Siemanond

---


Accepted by The Petroleum and Petrochemical College, Chulalongkorn University, in partial fulfilment of the requirements for the Degree of Master of Science.

  
..... College Dean  
(Asst. Prof. Pomthong Malakul)

**Thesis Committee:**

  
.....  
(Asst. Prof. Kitipat Siemanond)

  
.....  
(Assoc. Prof. Thirasak Rirksomboon)

  
.....  
(Asst. Prof. Chanin Panjapornpon)

## ABSTRACT

5573024063: Petroleum Technology Program  
Pathompong Kongchuay: Data Reconciliation with Gross Error  
Detection by NLP for Heat Exchanger Systems.  
Thesis Advisor: Asst. Prof. Kitipat Siemanond 119 pp.  
Keywords: Data reconciliation/ Gross error detection/ Least-square/ Heat  
exchanger/ Multiple gross errors

The measured data from instruments in process control activities usually consist of random and gross errors which reduce reliability of measurement. Data reconciliation (DR) technique is applied to improve the accuracy of measured data and satisfy the law of conservation. Moreover if data contains bias or gross errors in the system, DR is not as accurate as expected. This work performed DR with gross error detection (GED) technique to improve the data measurement of a simulated hot-oil heat exchanger and utility heat exchanger network. There are two kinds of GED: the conventional GED method and the traditional measurement test modified by NLP. The gross errors or bias in some measured data, including volumetric flow rates, supply and target temperatures of hot and cold process streams and overall heat transfer coefficient were generated. The DR with GED using NLP was done by commercial optimization software, GAMS, with a least-square objective function. The conventional GED and conventional gross error elimination applied statistical methods: basic global test and basic measurement test, respectively. The DR with GED technique produced more accurate estimates of process variables showing reductions in standard deviation. The other method, the modified measurement test, was studied for performance comparison. The performance of the modified measurement test using NLP was significantly better than one of the conventional method, in terms of the performance measures evaluation using the overall power (OP).

## บทคัดย่อ

ปฐมพงษ์ คงช่วย : การประยุกต์ใช้การตรวจสอบข้อผิดพลาดกับการปรับความสอดคล้องของข้อมูลแบบไม่เชิงเส้นสำหรับเครื่องแลกเปลี่ยนความร้อน (Data Reconciliation with Gross Error Detection by NLP for Heat Exchanger System) อ. ที่ปรึกษา : ผศ.ดร.กิติพัฒน์ สีมานนท์ 119 หน้า

โดยปกติข้อมูลการวัดจากเครื่องวัดในการควบคุมกระบวนการ ประกอบไปด้วยความผิดพลาดแบบสุ่ม และความผิดพลาดแบบกรอสซึ่งทำให้ความเสถียรภาพของการวัดลดลง เทคนิคการปรับความสอดคล้องของข้อมูลถูกใช้เพื่อปรับปรุงความแม่นยำของข้อมูลการวัดเพื่อให้สอดคล้องกับกฎความสัมพันธ์ทางมวล และพลังงานของกระบวนการนั้นๆ ยิ่งไปกว่านั้นหากข้อมูลการวัดในระบบถูกรบกวนไปด้วยความผิดพลาดแบบกรอส ประสิทธิภาพของเทคนิคการปรับความสอดคล้องของข้อมูลจะลดลง งานวิจัยนี้ประยุกต์ใช้การตรวจสอบข้อผิดพลาดกับการปรับความสอดคล้องของข้อมูลแบบไม่เชิงเส้นสำหรับอุปกรณ์แลกเปลี่ยนความร้อนทั้งแบบเดี่ยว และแบบหล่อกันเป็นโครงข่ายอย่างง่าย การตรวจสอบข้อผิดพลาดในงานวิจัยนี้แบ่งเป็นสองวิธีคือแบบดั้งเดิม และแบบประยุกต์ ความผิดพลาดแบบกรอสในบางข้อมูลการวัด รวมถึงอัตราการไหลเชิงปริมาตร อุณหภูมิขาเข้า และอุณหภูมิขาออกของสายน้ำร้อน และสายเย็นอื่นๆ รวมถึงสัมประสิทธิ์การแลกเปลี่ยนความร้อนถูกสร้างขึ้น การประยุกต์ใช้การตรวจสอบข้อผิดพลาดกับการปรับความสอดคล้องของข้อมูลแบบไม่เชิงเส้นถูกดำเนินการโดยใช้โปรแกรมระบบการจำลองทางพีซีชนิดทั่วไป ร่วมกับฟังก์ชันจุดประสงค์แบบค่าน้อยที่สุดกำลังสอง การตรวจสอบข้อผิดพลาด และการกำจัดความผิดพลาดแบบกรอสประยุกต์ใช้วิธีการทางสถิติอย่างง่าย โดยใช้เทคนิคที่เรียกว่าโอบอลเมทส และเมทริกซ์คอสมอสตามลำดับ การประยุกต์ใช้การตรวจสอบข้อผิดพลาดกับการปรับความสอดคล้องของข้อมูลสร้างข้อมูลที่มีความแม่นยำ โดยแสดงในรูปการลดลงของค่าเบี่ยงเบนมาตรฐาน อีกทั้งวิธีการในการตรวจสอบข้อผิดพลาดยังถูกเปรียบเทียบเชิงประสิทธิภาพด้วยตนเอง โดยประสิทธิภาพของการตรวจสอบข้อผิดพลาดแบบประยุกต์ มีประสิทธิภาพในการตรวจสอบที่ดีกว่าแบบดั้งเดิมอย่างมีนัยสำคัญ แสดงออกมาในรูปของการทดสอบที่เรียกว่าโอบอลออลพาวเวอร์

## ACKNOWLEDGEMENTS

This work would not have been possible without the assistance of the following individuals:

First and foremost, I sincerely appreciate Asst. Prof. Kitipat Siemanond, my advisor, for providing invaluable knowledge, creative comments and kind support throughout this research work.

I would like to thank Assoc. Prof. Thirasak Rirksomboon and Asst. Prof. Chanin Panjapornpon for being my thesis committee. Their suggestions and comments are very beneficial for me and this work.

This thesis work is funded by The Petroleum and Petrochemical College; and The National Center of Excellence for Petroleum, Petrochemicals, and Advanced Materials, Thailand, furthermore I would like to express my gratitude to The Petroleum and Petrochemical college, Chulalongkorn University.

I deeply would like to thank to my family, especially my mother for their love, understanding, encouragement, and support me at all time.

I also would like to thank Mr. Natchanon Angsutorn, Ph.D. student of The Petroleum and Petrochemical College, for some useful suggestions and also Ms. Papatsara Singhmaneeskulchai, process engineers at Technip Engineering Co., Ltd., for great preliminary suggestion.

And finally, I extremely appreciate all PPC staff and my friends who gave me encouragement and support.

## TABLE OF CONTENTS

	<b>PAGE</b>
Title Page	i
Abstract (in English)	iii
Abstract (in Thai)	iv
Acknowledgements	v
Table of Contents	vi
List of Tables	ix
List of Figures	xii
<b>CHAPTER</b>	
<b>I INTRODUCTION</b>	<b>1</b>
<b>II THEORETICAL BACKGROUND &amp; LITERATURE REVIEW</b>	<b>2</b>
2.1 Error in Measurement	2
2.1.1 Random Errors	2
2.1.2 Gross Errors	3
2.2 Data Improvement Techniques	3
2.2.1 Process Variable Classification	5
2.2.2 Data Reconciliation and Gross Error Detection Technique	9
<b>III EXPERIMENTAL &amp; METHODOLOGY</b>	<b>26</b>
3.1 Materials	26
3.2 Experimental Procedures	26
3.2.1 Simulating Data of Heat Exchanger Systems	26
3.2.2 Data Reconciliation and Gross Error Detection Technique	26

<b>CHAPTER</b>	<b>PAGE</b>
<b>IV RESULTS AND DISCUSSION</b>	<b>27</b>
4.1 Simulating Data of a Hot-oil Heat Exchanger as a Case Study	27
4.1.1 Generating Simulated Values	27
4.1.2 Generating Random Errors	28
4.1.3 Generating Gross Errors	29
4.2 Data Recociliation Technique (for Model A)	33
4.3 Gross Error Detection (for Model A)	38
4.3.1 The Conventional Gross Error Detection	38
4.3.2 The Modified Measurement Test Using NLP Method	48
4.3.3 The Performance Evaluation for Gross Error Detection Techniques	54
4.4 Simulating Data of Utility Heat Exchanger Network	56
4.4.1 Generating Simulated Values	56
4.4.2 Generating Measured Values with Random and Gross errors	58
4.5 Data Reconciliation Technique (for Model B)	60
4.6 Gross Error Detection (for Model B)	66
<b>V CONCLUSIONS AND RECOMMENDATIONS</b>	<b>74</b>
<b>REFERENCES</b>	<b>76</b>
<b>APPENDICES</b>	<b>78</b>
<b>Appendix A</b> Physical Data for a Hot-oil Heat Exchanger (Model A)	78
<b>Appendix B</b> Data Reconciliation Source Code of GAMS for Model A (Random Error Only)	79
<b>Appendix C</b> Data Reconciliation Source Code of GAMS for Model A (Random Error with 1 Position of Gross Error)	82

<b>CHAPTER</b>	<b>PAGE</b>
<b>Appendix D</b> Data Reconciliation Source Code of GAMS for Model A (Random Error with 2 Positions of Gross Error)	85
<b>Appendix E</b> Data Reconciliation Source Code of GAMS for Model A (After Discarding 1 Position of Gross Error for 1-position Case)	88
<b>Appendix F</b> Data Reconciliation Source Code of GAMS for Model A (After Discarding 1 Position of Gross Error for 2-position Case)	91
<b>Appendix G</b> Physical Data for Utility Heat Exchanger Network (Model B)	94
<b>Appendix H</b> Data Reconciliation Source Code of GAMS for Model B (Random Error Only)	95
<b>Appendix I</b> Data Reconciliation Source Code of GAMS for Model B (Random Error with 2 Positions of Gross Error)	100
<b>Appendix J</b> Data Reconciliation Source Code of GAMS for Model B (After Discarding 1 Position of Gross Error)	105
<b>Appendix K</b> Data Reconciliation Source Code of GAMS for Model B (After Discarding 2 Positions of Gross Error)	110
<b>Appendix L</b> Chi-squared Distribution Table	115
<b>Appendix M</b> Normal Distribution Table	116
<b>CURRICULUM VITAE</b>	119



## LIST OF TABLES

TABLE		PAGE
4.1	Physical data of a hot-oil heat exchanger (Model A)	28
4.2	True values of a hot-oil heat exchanger (Model A)	28
4.3	Measured values of a hot-oil heat exchanger (Model A)	29
4.4	Measured values of a hot-oil heat exchanger (Model A): including gross error only at $F_{oil}$	30
4.5	Measured values of a hot-oil heat exchanger (Model A): including gross error at $F_{oil}$ and $T_{et,m}$	31
4.6	First reconciliation of process variables in a hot-oil heat exchanger (Model A) with only random errors occurring in the measurement	36
4.7	First reconciliation of process variables in a hot-oil heat exchanger (Model A) with both random errors and one gross error only at $F_o$	37
4.8	First reconciliation of process variables in a hot-oil heat exchanger (Model A) with both random errors and two gross errors at $F_o$ and $T_{et,m}$	37
4.9	Objective function of data reconciliation compared to Chi- squared distribution value of Model A	40
4.10	Measurement adjustment and confidence interval of a hot-oil heat exchanger (Model A) with both random errors and one gross error only at $F_o$	42
4.11	Measurement adjustment and confidence interval of a hot-oil heat exchanger (Model A) with both random errors and two gross errors at $F_o$ and $T_{et,m}$	42

TABLE	PAGE
4.12 Second reconciliation of process variables in a hot-oil heat exchanger (Model A) after discarding the gross error in the first time (with both random errors and one gross error only at $F_o$ )	43
4.13 Second reconciliation of process variables in a hot-oil heat exchanger (Model A) after discarding the gross error in the first time (with both random errors and two gross errors at $F_o$ and $T_{c1,m}$ )	44
4.14 Measurement error SD, reconciled error SD and standard deviation reduction of a hot-oil heat exchanger (Model A) with both random errors and one gross error only at $F_o$	46
4.15 The following test statistic of a hot-oil heat exchanger (Model A) with only random errors occurring in the measurement for first DR	50
4.16 The following test statistic of a hot-oil heat exchanger (Model A) with both random errors and one gross error only at $F_o$ for first DR	50
4.17 The following test statistic of a hot-oil heat exchanger (Model A) with both random errors and one gross error only at $F_o$ for second DR (after discarding $F_o$ variable)	51
4.18 The following test statistic of a hot-oil heat exchanger (Model A) with both random errors and two gross errors at $F_o$ and $T_{c1,m}$ for first DR	51
4.19 The following test statistic of a hot-oil heat exchanger (Model A) with both random errors and two gross errors at $F_o$ and $T_{c1,m}$ for second DR (after discarding $F_o$ variable)	52
4.20 The statistical test criterion for Model A (for 7, 6 and 5 variables, respectively)	53

<b>TABLE</b>	<b>PAGE</b>
4.21 The GED performance evaluation	54
4.22 Physical data of utility heat exchanger network (Model B)	57
4.23 True values of utility heat exchanger network (Model B)	58
4.24 Average measured values of utility heat exchanger network (Model B)	58
4.25 Measured values of utility heat exchanger network (Model B): including gross error at $F_o$ and $T_{ctl,m}$	59
4.26 First reconciliation of process variables in utility heat exchanger network (Model B) with only random errors occurring measurement	64
4.27 First reconciliation of process variables in utility heat exchanger network (Model B) with both random errors and two gross errors at $F_o$ and $T_{ctl,m}$	65
4.28 The following test statistic of utility heat exchanger network (Model B) with both random errors and two gross errors at $F_o$ and $T_{ctl,m}$ for first DR	66
4.29 Second reconciliation of process variables in utility heat exchanger network (Model B) after discarding $F_o$ variable	67
4.30 The following test statistic of utility heat exchanger network (Model B) with both random errors and two gross errors at $F_o$ and $T_{ctl,m}$ for second DR (after discarding $F_o$ variable)	68
4.31 Final reconciliation of process variables in utility heat exchanger network (Model B) after discarding variable $T_{ctl,m}$	69
4.32 The following test statistic of utility heat exchanger network (Model B) with both random errors and two gross errors at $F_o$ and $T_{ctl,m}$ for final DR	70
4.33 Measurement error SD, reconciled error SD and standard deviation reduction of utility heat exchanger network (Model B)	72

## LIST OF FIGURES

FIGURE	PAGE
2.1	Example of random errors. 2
2.2	Example of gross errors. 3
2.3	Steps for data improvement. 4
2.4	Classification of process variables. 5
2.5	Sensor redundancy. 6
2.6	Topological redundancy. 6
2.7	Online data collection and conditioning system. 11
2.8	Sub-problems in data reconciliation. 14
2.9	Chi-squared distributions. 18
2.10	Flowsheet of MIMT using NLP algorithm. 24
4.1	Measured variables of a hot-oil heat exchanger (Model A). 27
4.2	True value, measured value and some bias of hot-oil volumetric flow rate variable, $F_o$ (Model A). 32
4.3	True value, measured value and some bias of ethane product inlet temperature variable, $T_{et,m}$ (Model A). 32
4.4	The conventional gross error detection algorithm. 39
4.5	True value and reconciled values: heat duty of system (with both random errors and one gross error only at $F_o$ ). 45
4.6	Standard deviation reduction percentage of a hot-oil heat exchanger (Model A) with both random errors and one gross error only at $F_o$ . 47
4.7	The traditional measurement test algorithm. 48
4.8	The utility heat exchanger network flowcharts (Model B). 56
4.9	True value and reconciled values: heat duty of 1 <sup>st</sup> heat exchanger system. 71

<b>FIGURE</b>	<b>PAGE</b>
4.10 True value and reconciled values: heat duty of 2 <sup>st</sup> heat exchanger system.	72
4.11 Standard deviation reduction percentage of utility heat exchanger network (Model B).	73