

SIMULATION AND OPTIMIZATION OF
HEAT TRANSFER EQUIPMENT USED
IN REFRIGERATION SYSTEMS

BY

C. ROBERT SAMUEL

DEPARTMENT OF MECHANICAL ENGINEERING

thesis

submitted in fulfilment of the requirements of
the degree of

DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY, DELHI

1983

CERTIFICATE

This is to certify that this ^{dissertation} ~~thesis~~ entitled
'Simulation and Optimization of Heat Transfer Equipment
used in Refrigeration Systems' being submitted by
Mr. C. Robert Samuel to the Indian Institute of Technology,
Delhi, for the award of the Degree of Doctor of Philosophy
in Mechanical Engineering is a record of bonafide research
work carried out by him. He has worked under my supervision
and guidance, and has fulfilled the requirement for the
submission of this thesis, which in my opinion has reached
the requisite standard.

The results contained in this work has not been
submitted in part or in full, to any other university or
Institute for the award of any degree or diploma.

C.P. Arora

Dr. C.P. Arora
Professor,
Department of Mechanical Engineering,
Indian Institute of Technology, Delhi.

ACKNOWLEDGEMENTS

The author is very grateful to his research supervisor Professor C.P. Arora for suggesting the problem for research, for his able guidance, helpful suggestions and moral encouragement during the period of this investigation. The author also wishes to thank Professor J.S. Rao, Head, Department of Mechanical Engineering, who helped the author in his work during the period his research supervisor was abroad.

The investigation involved the development and execution of a large number of computer programs. The author wishes to record his thanks to the Head, Computer Centre, for making available the ICL-2960 Computer facility in the Institute for this work. The author is thankful to the several members of the computer centre who helped the author in this work. Especially the author thanks Mr. Joseph Kurian for his valuable help.

The author thanks Mr. M.M. Pande, Chairman, M/s. Utility Engineers India (P) Ltd., New Delhi, for gladly making available specifications, rating and field data on shell and tube condensers and DX-chillers manufactured by them.

The research was carried out under the Quality Improvement Programme of the Government of India. The author wishes to record his thanks to the Principal, Regional Engineering College, Calicut, for sponsoring him for research under this programme.

The author thanks Mr. V.P. Gulati for his elegant typing, Mr. N.M. Jayachandran for the neat tracings of the figures and Mr. Thomas of M/s. Maitri Photostat for the photocopies of the tracings.

Finally the author thanks his wife Ruby and their daughters Lydia, Deborah and Ruth for their patience, understanding and cooperation during the period of this investigation.



C. Robert Samuel

ABSTRACT

The main objective of this investigation is to develop suitable simulation and optimization routines for the heat exchangers used in refrigeration practice. The investigation is carried out with R-22 as refrigerant on (1) shell and tube condenser, (2) flooded chiller, and (3) DX-chiller.

The simulation algorithm for shell and tube condenser solves the mathematical model for the condenser processes using logarithmic mean temperature iterative scheme. This algorithm is used to study the effect of geometry and operating conditions on the performance of the condenser. Based on this study, an empirical model for the shell and tube condenser is developed, and this model is used in the optimization routine for the condenser by univariate search. The optimal tube diameter for shell and tube condenser is found to be 1/2 inch nominal size K class copper tube converted to integral fin tubes of fin height 0.8 mm and fin ratio 0.4 at 748 fins per meter. The optimal water pass length is 4 m to 6 m, and the variation of optimizing function in this range is small.

The logarithmic mean temperature iterative scheme is made use of in the simulation of flooded chiller also. The simulation algorithm is used to study the effect of geometry and operating conditions on the performance of the flooded

chiller. Based on this study, an empirical model for flooded chiller is developed. The optimization routine for flooded chiller makes use of this model for optimization using gradient search. The optimal tube diameter and optimal water pass length are found to be related and both are considerably affected by the operating conditions.

The variation of heat transfer coefficient in the DX-chiller is considerably large and is non linear, and hence the simulation of DX-chiller is more complex and the solution by Runge Kutta discretization tends to oscillate. Hence the simulation routine makes use of damping constants in obtaining a fast accurate solution while using Runge Kutta discretization. The optimization routine generates a set of alternate designs having slightly lower optimizing function, discards those alternatives with excessive refrigerant pressure drop or less than rated capacity. Of the remaining alternatives, the alternative with the lowest refrigerant pressure drop is selected as the next improved design. The results of optimization indicate that the 19 mm outer diameter copper tube used is optimal. Further, the ratio of the tubes in a certain pass to the total number of tubes in the test commercial 8 pass DX-chiller is also optimal. However, the optimal length of each pass is found to be about 1.2 m.

The three simulation algorithms are validated on test commercial heat exchangers. Optimization of these heat exchangers resulted in 23 per cent saving on the shell and tube condenser, 8.3 per cent on the flooded chiller and 22 per cent on the DX-chiller, indicating that there is ample scope for optimization of the commercial heat exchangers used in refrigeration practice.

CONTENTS

	PAGE
CERTIFICATE	.. i
ACKNOWLEDGEMENTS	.. ii
ABSTRACT	.. iii
CONTENTS	.. vi
LIST OF FIGURES	.. xi
LIST OF TABLES	.. xv
NOMENCLATURE	.. xvi
CHAPTER 1 INTRODUCTION	.. 1
CHAPTER 2 SIMULATION AND OPTIMIZATION OF SHELL AND TUBE CONDENSER	.. 8
2.1 Introduction	.. 8
2.2 Simulation of Shell and Tube Condenser	.. 12
2.2.1 Mathematical Model	.. 12
2.2.2 Method of Solution	.. 18
2.2.2.1 The Capacity Estimation Problem	.. 19
2.2.2.2 The Condensing Temperature Estimation Problem	.. 28
2.2.3 Validation	.. 29
2.3 Parametric Study and Derivation of Influence Coefficients	.. 29
2.3.1 Condensing Temperature (t_k)	.. 32

CONTENTS (Contd.)

	PAGE
2.3.2 Difference Between Condensing Temperature and Water Inlet Temperature (t_p) ..	34
2.3.3 Water Mass Velocity (G_c) ..	36
2.3.4 Tube Inside Diameter (d_i) ..	38
2.3.5 Tube Outside to Inside Area Ratio(R_A)..	41
2.3.6 Length of Water Pass (lp) ..	43
2.3.7 Fraction of Tubes Submerged (X) ..	45
2.3.8 Evaluation of K_Z , K_Y and K_W ..	47
2.3.9 Design of Shell and Tube Condenser Using Empirical Model ..	48
2.4 Optimization of Shell and Tube Condenser ..	50
2.4.1 Statement of the Problem ..	50
2.4.2 Solution Procedure ..	55
2.4.3 Results of Optimization ..	56
CHAPTER 3 SIMULATION AND OPTIMIZATION OF FLOODED CHILLER { ..	57
3.1 Introduction ..	57
3.2 Simulation of Flooded Chiller ..	60
3.2.1 Mathematical Model ..	60
3.2.2 Method of Solution ..	67
3.2.3 Validation ..	72

CONTENTS (Contd.)

	PAGE
3.3 Parametric Study and Derivation of Influence Coefficients ..	73
3.3.1 Influence Coefficients ..	73
3.3.2 Surface Roughness (R_p) ..	76
3.3.3 Evaporator Temperature (t_e) ..	79
3.3.4 Approach ($t_{c2} - t_e$) ..	79
3.3.5 Cooling Range ($t_{c1} - t_{c2}$) ..	83
3.3.6 Area Ratio (R_A) ..	86
3.3.7 Tube Inside Diameter (d_i) ..	89
3.3.8 Length of Water Pass (lp) ..	92
3.3.9 Evaluation of K_Z and K_Y ..	92
3.3.10 Design of Flooded Chiller Using Empirical Model ..	95
3.4 Optimization of Flooded Chiller ..	96
3.4.1 Statement of the Problem ..	96
3.4.2 Solution Procedure ..	100
3.4.3 Results of Optimization ..	100
CHAPTER 4 SIMULATION AND OPTIMIZATION OF DIRECT EXPANSION CHILLER ..	112
4.1 Introduction ..	112
4.2 Simulation of Direct Expansion Chiller ..	114
4.2.1 Mathematical Model ..	114

CONTENTS (Contd.)

	PAGE
4.2.2 Method of Solution Using Damping Constants ..	123
4.2.3 Validation ..	135
4.2.4 Estimation of DX-chiller Capacity ..	135
4.3 Optimization of Direct Expansion Chiller ..	140
4.3.1 Statement of the Problem and Method of Solution ..	140
4.3.2 Results of Optimization ..	152
CHAPTER 5 DYNAMIC STORAGE OF ELEMENTS TECHNIQUE ..	155
5.1 Introduction ..	155
5.2 Dynamic Storage of Elements Technique ..	156
5.3 Mechanism of Dynamic Storage ..	161
5.4 Some Test Results ..	166
CHAPTER 6 CONCLUSIONS ..	168
REFERENCES ..	178
APPENDIX A LOGARITHMIC MEAN TEMPERATURE ITERATIVE SCHEME ..	186
APPENDIX B THERMODYNAMIC AND THERMOPHYSICAL PROPERTIES OF REFRIGERANT 22 ..	192
APPENDIX C THERMOPHYSICAL PROPERTIES OF WATER ..	206

CONTENTS (Contd.)

	PAGE
APPENDIX D SPECIFICATIONS OF TEST SHELL AND TUBE CONDENSER ..	210
APPENDIX E SPECIFICATIONS OF TEST FLOODED CHILLER ..	211
APPENDIX F SPECIFICATIONS OF TEST DX-CHILLER ..	212
ABOUT THE AUTHOR ..	213
ANNEXURE COMPUTER PROGRAMS AND SAMPLE OUTPUTS	