

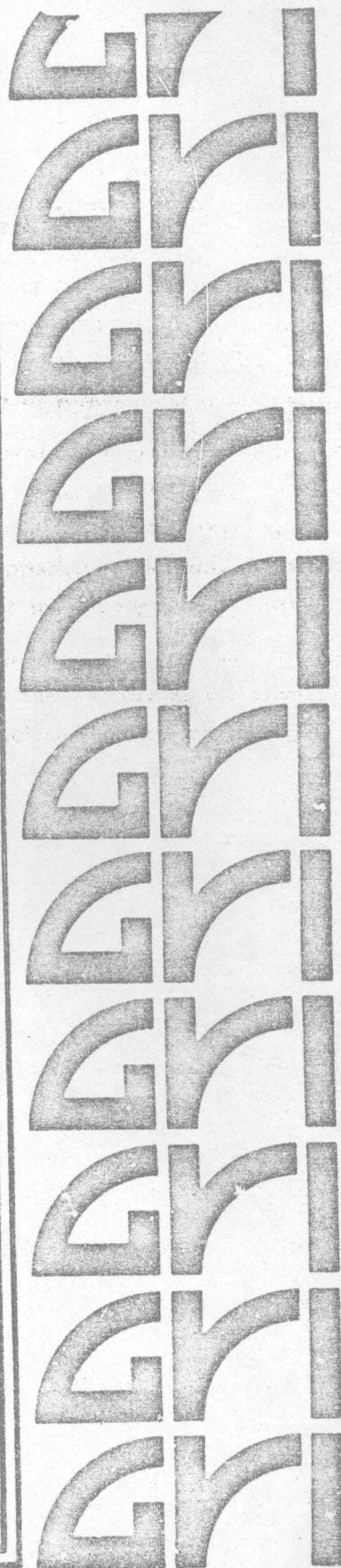
**ADVANCED HEAT-PIPE
HEAT EXCHANGER AND
MICROPROCESSOR-BASED
MODULATING BURNER
CONTROLS DEVELOPMENT**

FINAL REPORT

January 1985 - December 1987

**Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631**

**REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
SPRINGFIELD, VA 22161**



GRI DISCLAIMER

LEGAL NOTICE - This report was prepared by Tecogen Inc., a subsidiary of Thermo Electron Corporation as an account of work sponsored by the Gas Research Institute (GRI). Neither GRI, members of GRI, nor any person acting on behalf of either:

- a. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- b. Assumes any liability with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

50272-101

REPORT DOCUMENTATION PAGE		1. REPORT NO. GRI-88/0109	2.	3. Recipient's Accession No. PB88 217070/AS	
4. Title and Subtitle Advanced Heat-Pipe Heat Exchanger and Microprocessor-Based Modulating Burner Controls Development				5. Report Date February 1988	
7. Author(s) A. Lowenstein, B. Cohen, S. Feldman, J. Marsala, M. Spatz, E. Smith, and J. Tandler				8. Performing Organization Rept. No. TE4367-36-88	
9. Performing Organization Name and Address Tecogen, Inc. 45 First Avenue P.O. Box 9046 Waltham, Mass. 02254-9046				10. Project/Task/Work Unit No.	
12. Sponsoring Organization Name and Address Gas Research Institute 8600 West Bryn Mawr Avenue Chicago, Ill. 60631				11. Contract(C) or Grant(G) No. (C) 5084-241-1069 (G)	
				13. Type of Report & Period Covered Final Jan. 1985 - Dec. 1987	
15. Supplementary Notes				14.	
16. Abstract (Limit: 200 words) <p>The work presented in this report includes: 1) the development of a heat-pipe condensing heat exchanger, 2) the development of a nominal 100,000-Btu/hr modulating air/gas valve, 3) the experimental performance studies of water/copper thermosyphons, 4) the field operation of a six-zone warm-air heating system, 5) the adaptation of a conventional venturi-type burner to modulation, and 6) the results of a one-day workshop for manufacturers of HVAC equipment on heat-pipe heat exchangers. Several of the accomplishments of the project included:</p> <ul style="list-style-type: none"> • A unique air/gas valve was adapted to furnaces with heat-pipe and drum-type heat exchangers, providing these furnaces with over a 5-to-1 turndown capability. • A six-zone warm-air heating system was tested for two winters with the modulating furnaces previously described. The systems performed well, maintaining zones at their setpoints and providing almost continuous furnace operation at outdoor temperatures below 35°F. • A data base for the application of copper/water thermosyphons was started. Very high heat transport capacities were demonstrated for a thermosyphon with a unique internal artery. • A ten-tube heat-pipe heat exchanger was incorporated into a conventional clam-shell furnace as its second-stage condensing heat exchanger with only a small increase in the furnace's dimensions. With the heat-pipe heat exchanger, the furnace reached a 92-percent steady-state efficiency. 					
17. Document Analysis					
a. Descriptors					
b. Identifiers/Open-Ended Terms					
c. COSATI Field/Group					
18. Availability Statement				19. Security Class (This Report) Unclassified	
				21. No. of Pages 206	
				20. Security Class (This Page) Unclassified	
				22. Price	

(See ANSI-Z39.18)

See Instructions on Reverse

 OPTIONAL FORM 272 (4-77)
 (Formerly NTIS-35)
 Department of Commerce

Report No. TE4367-36-88

**ADVANCED HEAT-PIPE HEAT EXCHANGER
AND MICROPROCESSOR-BASED
MODULATING BURNER CONTROLS DEVELOPMENT**

FINAL REPORT
January 1985 - December 1987

Prepared by:

**A. Lowenstein, B. Cohen, S. Feldman, J. Marsala,
M. Spatz, E. Smith, and J. Tandier
Tecogen Inc.**

**A Subsidiary of Thermo Electron Corporation
45 First Avenue
P.O. Box 9046**

Waltham, Massachusetts 02254-9046

Prepared for:

**Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631
Contract Number: 5084-241-1069**

RESEARCH SUMMARY

TITLE	Advanced Heat-Pipe Heat Exchanger and Micro-processor-Based Modulating Burner Controls Development
CONTRACTOR	Tecogen Inc. GRI Contract Number: 5084-241-1069
PRINCIPAL INVESTIGATORS	A. Lowenstein, B. Cohen, S. Feldman, J. Marsala, E. Smith, M. Spatz and J. Tandler
TIME SPAN	January 1985 through December 1987
OBJECTIVES	Improve the competitiveness of gas-fired, residential, HVAC equipment by developing advanced designs that exploit heat-pipe heat exchangers and modulating burners. Perform basic studies both to improve the function of heat-pipe heat exchangers and modulating burners, and to characterize their performance so that they can more readily be incorporated into HVAC equipment. Finally, develop and test prototypes of equipment that use these novel components.
TECHNICAL PERSPECTIVE	<p>Both heat pipes and modulating burners can greatly enhance the function of thermal equipment. Heat pipes, which provide an extremely high thermal conductivity path for heat to be transferred between two fluid streams, can produce very compact and lightweight heat exchangers in comparison to conventional clamshell designs. They also have the unique ability to act as a thermal diode, reducing standby losses in some applications by preventing heat from leaving the system via the path it entered.</p> <p>Modulating burners can improve the operation of many thermal systems that have a variable heating load. For example, a residential, warm-air furnace that is designed to meet a house's design load is greatly oversized for much of the heating season. If a modulating burner is incorporated into the furnace, its efficiency can be improved by operating it continuously at lower firing rates and blower speeds rather than cycling it at maximum firing</p>

Page iii and iv blank.

v

rate and blower speed. Operating nearly continuously, the warm-air furnace also becomes less intrusive to the homeowner.

RESULTS

Task 1 - Condensing Heat-Pipe Heat Exchanger:

A ten-tube manifolded heat-pipe heat exchanger that would convert a conventional clamshell furnace into a high-efficiency condensing unit was developed. The heat exchanger was incorporated into the cabinet of the clamshell furnace with only a small increase in its dimensions. With the condensing heat exchanger, the furnace exceeded a 92-percent steady-state efficiency. However, almost all furnace manufacturers have now developed their own condensing furnaces. Because the original incentive for this task no longer exists, it has been discontinued.

Task 2 - Modulating Burner and Controls

Development: A thorough investigation of the parameters that affect the performance of a variable orifice modulating air/gas valve was completed. Based on this work, a valve was designed that maintained a nearly constant air-to-fuel ratio over a 7-to-1 turndown range. A means of varying the air-to-fuel ratio on a predetermined schedule that ensures that the burner operates stably in a particular application is described.

Task 3 - Heat-Pipe Technology: The performance of a single-tube copper/water thermosyphon was characterized as a function of fluid inventory and inclination angle. As part of this work, the maximum heat-transport capacity of the thermosyphon was measured. The effect of antifreeze, oil and noncondensable gas on the performance of the thermosyphon was also determined. An internal artery was developed for the thermosyphon that increased its heat transport capacity 300 percent.

Task 4 - Desiccant Technology - Residential

Applications and Development: The potential of several thermally regenerable desiccants to be applied in total air treatment systems was explored. Under subcontract to Tecogen, Arthur D. Little, Inc., prepared a report on consumer attitudes towards indoor comfort and air quality.

Task 7 - Field Evaluation of a Zoned Heating System: A six-zone warm-air residential heating system using the modulating valve developed in Task 2 was tested during the 1985-86 heating season. The system was operated by a controller developed by Johnson Controls. The system ran for over 2000 hours with almost no problems, while it effectively maintained zone temperatures at their setpoints.

Task 9 - Field Evaluation of a Modulating Furnace: A Yukon condensing furnace retrofit with the air/gas valve developed in Task 2 was operated as part of a zoned heating system. The zoned heating system, which was first operated in Task 7, was modified to: (1) achieve longer periods of continuous operation, and (2) allow the homeowner to adjust temperature setpoints remotely from the zones. The system operated satisfactorily throughout the three-month test. Essentially, continuous furnace operation was achieved below 35°F outdoor temperature, with damper cycling rates three to ten times lower at these temperatures than they had been in the earlier test.

Task 11 - The Development of a Modulated Venturi-Type Burner: A venturi burner made by Wayne Home Equipment was modified to increase the range of firing rates over which it could be modulated. By installing a baffle to maintain a more constant primary-to-secondary air ration and an extension to the gas orifice so that gas could be introduced at the lowest pressure location in the venturi, the modulating range was increased from 1.8 to 6.6. Further work on modulating burners will focus on induced-draft residential furnaces in a parallel GRI project.

Task 13 - Heat-Pipe Technology Development: The effect of manifolding on the heat transport capacity of a heat-pipe heat exchanger was studied. Manifolded heat-pipe heat exchangers of 7, 10, and 18 tubes were operated in a gas-fired test rig, as was a single-tube device. While all manifolded heat exchangers could transport much higher heat fluxes per-tube than the single-tube device before failure

occurred, per-tube capacities decreased as the number of manifolded tubes increased. Furthermore, manifolded systems had higher heat transport capacities in a vertical position than when tilted 45 degrees. Explanations for the preceding observations are given in this report.

Task 14 - Heat-Pipe Workshop: A heat-pipe technology workshop, sponsored by GRI and hosted by Tecogen, was held on May 22, 1987 for manufacturers of gas-fired appliances and heating equipment. The objectives of the workshop were to: (1) gauge industry's interest in heat-pipe heat exchangers, (2) identify the barriers to their wider implementation, and (3) determine whether GRI can help overcome these barriers. A summary of the workshop is included in the report.

TECHNICAL APPROACH

The research in this project on both modulating burners and heat-pipe heat exchangers has proceeded as follows: (1) determine the most promising applications for the new technologies through activities such as the workshops, studies of users' needs and discussions with manufacturers, (2) develop a better understanding of each device's performance characteristics through controlled operation in the laboratory, and (3) test novel designs of thermal equipment using either device under conditions that simulate field operation.

PROJECT IMPLICATIONS

The Advanced Heat Pipe Heat Exchanger and Microprocessor-Based Modulating Burner Controls Development Project has served the GRI Residential Space Conditioning Program in a number of ways, including:

1. Developed a modulating burner capable of precisely controlling the air-to-fuel ratio and capable of stable operation over a wide range of output, for use in future modulating furnaces or any other appliance needing a gas-powered modulatable heat input
2. Provided extensive basic information about the operation of heat pipes and the improvement of the heat transfer rate of such pipes
3. Provided GRI with two patent filings on heat pipe technology

This background technology will be essential in the future applications of heat pipes and may be critical in future GRI developments in modulating furnaces and zoned systems. All information from this project, as well as the modulating furnace concept itself, is being transferred to Building Systems, Area 4.1.8.

Bill Ryan
Project Manager
Residential Space Cooling

TABLE OF CONTENTS

<u>Chapter</u>		<u>Page</u>
	RESEARCH SUMMARY	v
1	INTRODUCTION	1
2	OBJECTIVES	3
	2.1 TASK 1 - CONDENSING HEAT-PIPE HEAT EXCHANGER	3
	2.2 TASK 2 - MODULATING BURNER AND CONTROLS DEVELOPMENT	4
	2.3 TASK 3 - HEAT-PIPE TECHNOLOGY DEVELOPMENT	4
	2.4 TASK 4 - DESICCANT TECHNOLOGY - RESIDENTIAL APPLICATIONS AND DEVELOPMENT	5
	2.5 TASK 7 - FIELD EVALUATION OF A ZONE-CONTROLLED HEATING SYSTEM	5
	2.6 TASK 9 - FIELD EVALUATION OF A MODULATING FURNACE	5
	2.7 TASK 11 - THE DEVELOPMENT OF A MODULATED VENTURI-TYPE BURNER	6
	2.8 TASK 13 - HEAT-PIPE TECHNOLOGY DEVELOPMENT	6
	2.9 TASK 14 - HEAT PIPE WORKSHOP.....	6
3	TECHNICAL PROGRESS	9
	3.1 TASK 1 - CONDENSING HEAT-PIPE HEAT EXCHANGER	9
	3.1.1 Summary	9
	3.1.2 Background	9
	3.1.3 Cost and Market Analyses	12
	3.1.4 Laboratory Testing of the Condensing Heat Exchanger	16
	3.1.5 The Design and Performance Tests of an Integrated Heat-Pipe/Clamshell Condensing Furnace	21
	3.1.6 Conclusion	24

TABLE OF CONTENTS (Cont'd)

<u>Chapter</u>	<u>Page</u>
3.2 TASK 2 - MODULATING BURNER AND CONTROLLER DEVELOPMENT.....	24
3.2.1 Background	24
3.2.2 Application Analysis	27
3.2.3 Modulating Burner Development.....	31
3.2.4 The Design of a Constant-Stoichiometry Modulating Valve	40
3.2.5 The Design of Modulating Valves with Variable Stoichiometry	53
3.2.6 The Development of a Controller for the Modulating Valve	53
3.2.7 Modulation of a Wayne Home Equipment Burner.....	56
3.3 TASK 3 - HEAT-PIPE TECHNOLOGY DEVELOPMENT	67
3.3.1 Background	67
3.3.2 Objective of the Heat-Pipe Technology Task	73
3.3.3 Description of the Laboratory Test Apparatus.....	73
3.3.4 Experimental Results	79
3.3.5 Performance of a Single-Tube Thermosyphon with an Internal Downcomer	101
3.3.6 Conclusion	104
3.4 TASK 4 - DESICCANT TECHNOLOGY - RESIDENTIAL APPLICATIONS AND DEVELOPMENT	105
3.5 TASK 7 - FIELD EVALUATION OF A ZONE-CONTROLLED HEATING SYSTEM	106
3.6 TASK 9 - FIELD EVALUATION OF A MODULATING FURNACE.....	106
3.6.1 Background	106
3.6.2 Improvements in System Hardware	107
3.6.3 Objectives for Improving the Control Algorithm	109
3.6.4 Description of New Algorithm.....	110
3.6.5 Test Results	119
3.6.6 Conclusions	127
3.7 TASK 11 - THE DEVELOPMENT OF A MODULATED VENTURI-TYPE BURNER	130
3.7.1 Overview.....	130
3.7.2 Background	131
3.7.3 Wayne Home Equipment - Venturi Burner Modulation Tests	133

TABLE OF CONTENTS (Cont'd)

<u>Chapter</u>	<u>Page</u>
3.8 TASK 13 - PERFORMANCE OF MANIFOLDED THERMOSYPHON HEAT EXCHANGERS.....	141
3.8.1 Test Rig	141
3.8.2 Instrumentation.....	144
3.8.3 Test Procedure.....	144
3.8.4 Results and Discussion	145
3.8.5 Comparison to Single-Tube Dry-Out Tests from Task 3.....	152
3.8.6 Future Work.....	154
3.9 TASK 14 - HEAT-PIPE WORKSHOP.....	154
3.9.1 Introduction.....	154
3.9.2 Technical Presentations.....	154
3.9.3 Summary of the Open Discussion.....	167
APPENDIX A - THERMOSYPHON PERFORMANCE DATA	171
APPENDIX E - HEAT-PIPE WORKSHOP ATTENDEES....	187

LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
3.1 Schematic Representation of the Add-On Generic Condensing Heat-Pipe Heat Exchanger Concept.....	11
3.2 Conventional Warm-Air Furnace Typical Startup Transient	17
3.3 Condensing Heat Exchanger Working Fluid Inventory Evaluation.....	19
3.4 Condensing Heat Exchanger Working Fluid Inventory Evaluation.....	20
3.5 Segmented Manifold Testing.....	22
3.6 Segmented Manifold Testing.....	23
3.7 Clamshell Furnace with Heat-Pipe Heat Exchanger.....	25
3.8 Exploded View of the Modulating Valve	32
3.9 Burner Performance	34
3.10 Characteristics of Rotating Orifice Valve.....	36
3.11 Entrance Effects.....	38
3.12 Burner Performance	39
3.13 Burner Performance	41
3.14 Exploded View of the New Design of the Modulating Valve	42
3.15 Comparison of Gas Orifice t/d for New and Old Designs.	45
3.16 Gas Orifice Discharge Coefficient for New and Old Designs	46
3.17 Flow Through Gas Orifice for New and Old Designs.....	47
3.18 Orifice Coefficients for Perforated Plates.....	48
3.19 Comparison of Air Orifice t/d for New Design (Versions A and B) and Old Design	50
3.20 Air Orifice Discharge Coefficient for New Design (Versions A and B) and Old Design	51
3.21 Flow Through Air Orifices for New Design (Versions A and B) and Old Design	52
3.22 Additional Airflow Through Fixed-Area Orifice	54

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.23 Effect of Secondary Air on Percent CO ₂	55
3.24 Wayne Powered Burner Retrofit with a Modulating Air/Gas Valve	57
3.25 Stability Limits of First Burner Design	59
3.26 Effect of Ceramic Tile Characteristics on Low-Frequency Stability	61
3.27 Comparison of Fan Curves Used to Stabilize Furnace Pressure	63
3.28 Effect of Regulator and Fan Modifications on Burner Stability	65
3.29 Undesirable Flame Characteristics in Stabilized Burner System	66
3.30 Improvement in Flame Characteristics with Baffle Upstream of Tile	68
3.31 Thermosyphon Operation	69
3.32 Support Systems for the Thermosyphon Test Rig	75
3.33 Auxiliary Systems for Test Rig	76
3.34 Cross-Sectional Drawing of Single-Tube Thermosyphon Test Device	77
3.35 Cross-Sectional Drawing of Two-Tube Manifolded Thermosyphon	78
3.36 Typical Performance Contours Illustrating Data Points Used to Calculate Contours of Effective Thermal Conductivity Using a Least-Squares Analysis	81
3.37 The Effect of Thermosyphon Tilt Angle on Effective Thermal Conductivity (Evaporator Filled to 25%)	84
3.38 The Effect of Thermosyphon Tilt Angle on Effective Thermal Conductivity (Evaporator Filled to 50%)	85
3.39 The Effect of Thermosyphon Tilt Angle on Effective Thermal Conductivity (Evaporator Filled to 100%)	86
3.40 The Effect of Thermosyphon Working Fluid Inventory on Effective Thermal Conductivity (at a Tilt Angle of 15°)	87

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.41 The Effect of Thermosyphon Working Fluid Inventory on Effective Thermal Conductivity (at a Tilt Angle of 45°)	88
3.42 The Effect of Thermosyphon Working Fluid Inventory on Effective Thermal Conductivity (at a Tilt Angle of 90°)	89
3.43 The Effect of Intentional Air Addition to Working Fluid Vapor on Effective Thermal Conductivity.....	92
3.44 The Effect of Antifreeze in Working Fluid on Effective Thermal Conductivity.....	93
3.45 The Effect of Oil Contamination of Working Fluid on Effective Thermal Conductivity	95
3.46 Thermosyphon Pressure, Heat Removal Rate and Temperature Traces During a Typical Dry-Out Test on Single-Tube Thermosyphon	97
3.47 Dry-Out Limits for Single-Tube and Double-Tube Thermosyphons.....	98
3.48 Comparison of Dry-Out Limits Observed in Single-Tube Thermosyphon with Pool Boiling Theory.....	99
3.49 Flow Separator 45 Degrees (Effective Thermal Conductivity).....	102
3.50 Flow Separator 90 Degrees (Effective Thermal Conductivity)	103
3.51 Zoned Control Hardware Schematic.....	108
3.52 Block Diagram of Major Components of Control System ..	111
3.53 Block Diagram of Feedback Algorithm	113
3.54 Scheduled Furnace Supply Temperature and Pressure Versus Furnace Firing Rate	116
3.55 Furnace Temperature and Pressure Control	117
3.56 Maximum and Minimum Zone Temperature Errors Versus Outside Air Temperature	120
3.57 Average Zone Cycling Frequency Versus Outdoor Air Temperature.....	121

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>	<u>Page</u>
3.58 Time Response of Supply Temperature During the Startup Transient	123
3.59 Time Response of Supply Temperature for Three Hours of Furnace Operation	124
3.60 Supply Air Temperature Versus Outdoor Air Temperature	125
3.61 Furnace On-Time Versus Outdoor Air Temperature.....	126
3.62 Furnace Cycling Frequency Versus Outdoor Air Temperature.....	128
3.63 Average Furnace Firing Rate Versus Outdoor Air Temperature.....	129
3.64 Atmospheric Burner Characteristics.....	132
3.65 Modified Tecogen Valve.....	135
3.66 Combustion Air Blower Conceptual Arrangement.....	137
3.67 Induced Draft Conceptual Arrangement	139
3.68 Burner Test Schematic	140
3.69 Diagram of Heat-Pipe Heat Exchanger Test Rig	142
3.70 18 Tube Manifolded Heat-Pipe Heat Exchanger	143
3.71 1, 7, and 10 Tube Manifolded Heat-Pipe Heat Exchanger.....	146
3.72 Dry-Out Test Summary - 95% WF Inventory	147
3.73 Dry-Out Test Summary - 190% WF Inventory	148
3.74 Dry-Out Test Summary - 45° Tilt Angle	149
3.75 Dry-Out Test Summary - 90° Tilt Angle	150
3.76 Dry-Out Test Summary - Single-Tube	153
3.77 Operation of a Wicked Heat Pipe	155
3.78 Operation of a Thermosyphon.....	156
3.79 A Comparison of the Temperature Gradients in a Heat Pipe and Clamshell Heat Exchanger.....	158
3.80 The Implementation of a Heat Pipe as a Thermal Diode in a Water Heater	159

LIST OF ILLUSTRATIONS (Cont'd)

<u>Figure</u>		<u>Page</u>
3.81	The Use of a Noncondensable Gas to Block Heat Transfer from the End of a Heat Pipe	160
3.82	Cutaway of Manufacturing Prototype Noncondensing Heat Pipe Furnace.....	162
3.83	Average Furnace Firing Rate Versus Outdoor Air Temperature.....	163
3.84	Conceptual Design of a 200,000 Btu/hr Heat-Pipe Unit Heater	164
A.1	Single-Tube Thermosyphon Baseline Data	173
A.2	Single-Tube Thermosyphon Baseline Data	174
A.3	Single-Tube Thermosyphon Baseline Data	175
A.4	Single-Tube Thermosyphon Baseline Data	176
A.5	Single-Tube Thermosyphon Baseline Data	177
A.6	Single-Tube Thermosyphon Baseline Data	178
A.7	Single-Tube Thermosyphon Baseline Data	179
A.8	Single-Tube Thermosyphon Baseline Data	180
A.9	Single-Tube Thermosyphon Baseline Data	181
A.10	Single-Tube Thermosyphon with Intentional Air Addition	182
A.11	Single-Tube Thermosyphon with Antifreeze Added to Working Fluid	183
A.12	Single-Tube Thermosyphon with Oil Contaminated Working Fluid	184
A.13	Single-Tube Thermosyphon with Oil Contaminated Working Fluid	185
A.14	Single-Tube Thermosyphon with Oil Contaminated Working Fluid	186