Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

### HEAT RECOVERY REFRIGERATION

#### IN

### NEW ZEALAND DAIRY SHEDS

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Agricultural Science

in

Agricultural Engineering

at Massey University Palmerston North New Zealand

GRANT ERROL STINSON

1982

82.15563

#### ABSTRACT

Increased energy costs initiated an investigation into refrigeration heat recovery as one conservation alternative available for reducing water heating costs on farm dairies. A theoretical energy balance was conducted, from which the potential of recovering refrigeration condenser heat was estimated at up to 60% of the water heating energy requirements.

Preliminary tests with heat exchangers lead to the use of a tube-in-tube, counter flow, heat exchanger with fins on the refrigerant side, and cores on the water side, to improve the heat transfer characteristics. The exchanger, designed to provide 300 litres of  $60^{\circ}$ C water from a 2.25 kW refrigeration system cooling 2000 litres of milk per day, had an area of 0.84 m<sup>2</sup>, and an overall thermal conductance of 100 W.m<sup>-2</sup>.°C<sup>-1</sup>. This heat exchanger was inserted between the compressor and condenser of the refrigeration plant and tested with two condenser systems (air and water), four condenser pressures (6.5 bar, 7.5 bar, 10 bar and 12 bar), two milk inlet temperatures( $23^{\circ}$ C and  $1\delta^{\circ}$ C), and two milk final temperatures ( $4^{\circ}$ C and  $7^{\circ}$ C). In addition, tests on receiver pressure and suction superheat were performed to determine overall system performance.

Increasing condenser pressure increased cooling times from 2 hours 32 minutes to 3 hours 17 minutes, after the completion of the 1200 litre morning milking (thus failing to comply with the 3 hour cooling regulation at high condenser pressures.) Also, C.O.P. decreased from 3.05 to 2.35 for the water cooled condenser system (2.70 to 2.00 for the air cooled condenser system due to fan power consumption). Gross heat recovery rose from 4.2 kWh.day<sup>-1</sup>.m<sup>-3</sup> to 8.1 kWh.day<sup>-1</sup>.m<sup>-3</sup> for the water cooled system, giving water outlet temperatures of 45°C to 64°C as condenser pressure rose. The corresponding ranges for air cooled condensers were 3.8 kWh.day<sup>-1</sup>.m<sup>-3</sup> to 6.6 kWh.day<sup>-1</sup>.m<sup>-3</sup>, and 38°C to 55°C. Changing milk inlet and final temperatures gave a proportional change in cooling times and total heat recovery, but had no effect on C.O.P. or heat recovery rates. Suction superheating increased total heat recovery by 15%, and water outlet temperatures by 9%.

ii

Increases in gross heat recovery with increasing condenser pressure were partially offset by additional compressor power, and yielded nett heat recoveries of 4.0 kWh.day<sup>-1</sup>.m<sup>-3</sup> to 6.0 kWh.day<sup>-1</sup>.m<sup>-3</sup> for water cooled, and 3.6 kWh.day<sup>-1</sup>.m<sup>-3</sup> to 4.3 kWh.day<sup>-1</sup>.m<sup>-3</sup> for air cooled, condenser systems.

The maximum gross and nett heat recoveries (at 12 bar condenser pressure) were applied to the energy requirements of a monitored 220 cow town supply dairy. This analysis showed that the gross heat recovery was 51% of the water heating requirements, but the nett heat recovery dropped to 17% of the total heating and refrigeration demand. Based on current electricity and equipment prices, it is estimated that the payback period for this level of recovery would be 16-17 years. Changing the electricity pricing structure, to reflect up to a 1:3 differential in favour of water heating power costs, results in the 6.5 bar condenser pressure giving optimum results, but the nett returns are significantly lower than those reported.

The potential for improved savings is greater from larger capacity systems as the capital investment is not proportionally increased with an increase in scale. The production of this thesis was only made possible due to the cooperation and dedication of a number of people. Therefore, I wish to take this opportunity to acknowledge the following.

- Dr D.J. Warburton and Dr C.J. Studman, Agricultural Engineering Department, Massey University; for their patience, understanding and advice during the supervision of this project.
- Mr J.S. Tyler and Mr A. McLellan, Agricultural Engineering Department, Massey University; for their assistance in the preparation of the Figures.
- Mr S.E. Compton and Mr R.E. Belgrave, Agricultural Engineering Department, Massey University; for their advice and assistance in the construction of the experimental equipment.
- Mr J. Bowen, Fridge Heat Limited; for his advice and supply of the experimental equipment.
- Mr J. Jenkins, Mauri Engineering; for his many helpful suggestions and the construction of the primary heat exchangers.
- McAlpine-Prestcold Refrigeration; for the loan of the refrigeration system.
- Manawatu Co-Op Dairy Company; for the loan of the milk vat and accessories.
- Massey University Agricultural Research Foundation; for a grant of \$7000.
- Massey University Computer Centre Staff; for their help in data preparation.
- Massey University Photographic and Printery Units; for their helpful advice and assistance in the production of plates and figures.

- The staff of No. 1 Dairy Unit, Massey University; for their cooperation during the field trials.
- Mrs M. Warburton; for her patience and assistance in the preparation of this thesis.

1.2

Chap	ter	Page
1	INTRODUCTION	1
	1:1 New Zealand Dairy Industry	2
	1:2 Present Electricity Usage	2
	1:3 Sources of Energy	3
	1:4 Research Objectives	4
2	REVIEW OF LITERATURE	5
	2:1 Dairy Farm Milk Quality	6
	2:1.1 Milk Quality Standards	6
	2:1.2 Milk Quality Control	6
	2.1.2.1 Plant Cleaning Procedures	8
	2:1.2.2 Milk Cooling	9
	2:2 Dairy Shed Resource Requirements	13
	2:2.1 Total Electricity Usage	13
	2:2.2 Water Heating Requirements	13
	2:2.2.1 Water Temperature	13
	2:2.2.2 Water Volumes	14
	2:2.3 Refrigeration Power Requirements	15
	2:3 Principles of Refrigeration	15
	2:3.1 Summary of a Refrigeration Cycle	16
	2:3.1.1 The Compression Process	16
	2:3.1.2 Desuperheating	16
	2:3.1.3 Condensation	18
	2:3.1.4 Subcooling	18
	2:3.1.5 Expansion Process	18
	2:3.1.6 Evaporation and Suction Superheating	19
	2:3.2 The Effect of Changing Operating Conditions	19
	2:3.2.1 The Effect of Changing Condenser Pressure	20
	2:3.2.2 The Effect of Increasing Suction Superheating	20
	2:3.3 Conclusion	27

	2:4 Application of Refrigeration to the Dairy Industry	27
	2:4.1 Refrigeration Heat Loads	27
	2:4.1.1 Milk Loads	27
	2:4.1.2 Environmental Loads	28
	2:4.2 Milk Refrigeration Systems	28
	2:4.2.1 Ice Bank System	28
	2:4.2.2 Chilled Water Refrigeration System	30
	2:4.2.3 Direct Expansion Refrigeration System	30
	2:5 Heat Recovery Systems	33
072	2:5.1 Heat Exchanger Design and Performance	34
	2:5.1.1 Tube-in-Tube	34
	2:5.1.2 Coil-in-Tank	37
	2:5.1.3 Shell and Tube	37
	2:5.2 Desuperheater Heat Recovery System Performance	37
	2:5.2.1 In-line Heat Exchanger - 'Once Through'	37
	2:5.2.2 In-line Heat Exchanger - Circulating	39
	2:5.3 Complete Condensing Heat Recovery Systems	41
	2:5.3.1 Complete Condensing - 'Once Through'	41
	2:5.3.2 Complete Condensing - Circulating	41
	2:5.3.3 Complete Condensing - 'Coil-in-Tank'	42
	2:5.4 Condenser Pressure Control	43
	2:5.4.1 Minimum Condenser Pressure Control	43
	2:5.4.2 Maximum Condenser Pressure Control	44
	2:6 Effect of Heat Recovery on Water Heating	44
	2:7 Discussion and Conclusions	46
3	EXPERIMENTAL DESIGN	48
	3:1 Experimental Basis	49
	3:2 Experiment I	49
	3:3 Experiment II	50
	3:3.1 Condenser System	50
	3:3.2 Condenser Pressures	50
	3:3.3 Milk Temperatures	52
	3:3.4 Suction Superheating	52

	3:3.5 Primary Heat Exchanger	52
	3:3.6 Receiver Pressure	52
	3:4 Experiment III	53
4	EXPERIMENTAL EQUIPMENT, METHODS AND DATA ANALYSIS	55
	4:1 Laboratory Plant	56
	4:1.1 Mechanical Equipment	56
	4:1.1.1 Refrigeration System	56
	4:1.1.2 Heat Recovery Exchangers	62
	4:1.2 Instrumentation	63
	4:2 Field Plant	63
	4:2.1 Instrumentation	65
	4:3 Experimental Methods	65
	4:3.1 Experiment I	65
	4:3.2 Experiment II	66
	4:3.3 Experiment III	67
	4:4 Data Analysis	67
	4:4.1 Experiment 1	67
	4:4.2 Experiment II	68
	4:4.2.1 Equations of Refrigerant Properties	69
	4:4.2.2 Calculation of System Variables	71
	4:4.3 Experiment III	72
	4:4.3.1 Water Heating	72
	4:4.3.2 Refrigeration	72
	4:4.3.3 Total Power Consumption	73
5	EXPERIMENT I RESULTS AND DISCUSSION	74
	5:1 Test Primary Heat Exchanger Without Cores	75
	5:2 Test Primary Heat Exchanger With Cores	75
	5:3 Test Primary Heat Exchanger Under Simulated Parallel	
	Flow Arrangement	80
	5:4 Test Primary Heat Exchanger Headloss	03
	5:5 Primary Heat Exchanger Design	84

Page

	5:5.1	Basic Arrangement	84
	5:5.2	Heat Exchanger Dimensions	84
	5:5.3	Final Design	85
6	EXPERIME	NT II RESULTS AND DISCUSSION	90
	6:1 Int	roduction	91
	6:2 Coo	ling Times	91
	6:2.1	The Effect of Condenser Pressure and Condenser	<b>.</b>
		System	92
÷	6:2.2	The Effect of Milk Inlet and Final Temperature	97
	6:2.3	The Effect of Increasing Receiver Pressure	97
	6:2.4	Conclusions on Cooling Times	102
	6.3 Vat	Temperature	102
	6.3 1	The Effect of Condenser Pressure and Condenser	102
	0.9.1	System	103
	6:3.2	The Effect of Changing Milk Inlet and Final	109
	0.9.1	Temperature	105
	6:3.3	Conclusions on Vat Temperature	107
		signant Flor	108
	6:4 Ker	The Effect of Condenser Pressure and Condenser	100
	0:4.1	Sustem	108
	6.1. 2	The Effect of Changing Milk Inlat and Final	100
	0:4.2	Tampa ratura	110
	6.1. 2	The Effect of Increasing Receiver Pressure	110
	6.1.1.	The Effect of the Addition of the Primary Heat	110
	0.4.4	Exchanger	113
	6.4 5	The Effect of the Vapour By-Pass	113
	6.4.6	Conclusion on Refrigerant Flow	113
	0.4.0		
	6:5 Ref	rigeration Effect (R.E.)	116
	6:5.1	The Effect of Condenser Pressure and Condenser	
	Se	System	116
	6:5.2	The Effect of Changing Milk Inlet and Final	
		Temperatures	118
	6:5.3	The Effect of Changing Receiver Pressure	118
	6:5.4	Conclusion on R.E.	119

Page

.

 $\mathbb{R}^{2}$ 

6:6 Compressor Head Pressure	119
6:6.1 The Effect of Condenser Pressure	119
6:7 Instantaneous Compressor Power Consumption (I.C.P.C.)	121
6:7.1 The Effect of Changing Condenser Pressure	121
6:7.2 The Effect of Changing Condenser System	121
6:7.3 The Effect of the Primary Heat Exchanger	124
6:7.4 The Effect of Changing Milk Inlet and Final	
Temperature	126
6:7.5 Total Refrigeration Power Consumption	126
6:7.6 Conclusions on Power Consumption	128
6:8 Coefficient of Performance (C.O.P.)	128
6:8.1 The Effect of Condenser Pressure	128
6:8.2 The Effect of Condenser System	130
6:8.3 The Effect of the Primary Heat Exchanger	130
6:8.4 The Effect of Changing Milk Inlet and Final	
Temperatures	133
6:8.5 The Effect of Suction Superheating	133
6:8.6 Conclusions on C.O.P.	133
6:9 Primary Heat Exchanger Model	134
6:10 Heat Recovery	135
6:10.1 The Effect of Condenser Pressure	135
6:10.2 The Effect of Condenser System	135
6:10.3 The Effect of Changing Milk Inlet and Final	
Temperature	137
6:10.4 The Effect of Suction Superheating	137
6:10.5 Conclusions on Heat Recovery	142
6:11 Primary Heat Exchanger Water Outlet Temperature	142
6:11.1 The Effect of Condenser Pressure and Condenser	
System	142
6:11.2 The Effect of Suction Superheating	144
6:11.3 Conclusions on Primary Water Outlet Temperature	144
6:12 Overall Thermal Conductance of the Primary Heat	
Exchanger	145

# Page

	6:13 Analysis of a Combined Heat Recovery-Refrigeration	
	System	145
	6:13.1 Performance of the Heat Recovery System in	
	Relation to Refrigeration	146
	6:13.2 Combined Water Heating and Refrigeration Heat	
	Recovery System	153
	6:13.3 Selection of Final Operating Conditions	156
	6:14 Conclusions	156
7	EXPERIMENT III RESULTS AND DISCUSSION	160
	7:1 Water Heating	161
	7:1.1 Vat Cylinder	161
	7:1.2 Machine Cylinder	165
	7:2 Refrigeration Systems	170
	7:3 Total Power Consumption	175
	7:4 Conclusions	175
8	ECCNOMIC ASSESSMENT OF HEAT RECOVERY AND IMPACT ON THE	
	NEW ZEALAND INDUSTRY	177
	8:1 Economic Assessment of Refrigeration Heat Recovery	178
	8:1.1 Economic assessment of Experimental and Field	
	Plants	178
	8:1.2 Potential for Increasing Heat Recovery Savings	186
	8:2 The Impact of Heat Recovery on Water Heating Energy	
	Requirements	189
	8:3 The Impact of Heat Recovery on the New Zealand Dairy	
	Industry	189
9	CONCLUSIONS	192
	9:1 The Refrigeration System	193
	9:2 Heat Recovery	193
	9:3 Economic Assessment	194

Page

9:4	Application to a Town Supply Farm	195
9:5	General Conclusions	195

.

•

LIST OF FIGURES

		Page
2:1	Growth rates of milk bacteria for various temperature	
	conditions	11
2:2	Growth response of milk bacteria	11
2:3	Typical refrigeration cycle	17
2:4	The effect of increasing condenser pressure	21
2:5	The effect of compression ratio on volumetric efficiency	22
2:6	The effect of increasing suction superheat	23
2:7	Schematic diagram of a liquid/vapour heat exchanger	35
2:8	The effect of a liquid vapour heat exchanger	26
2:9	Schematic diagram of an ice bank chiller system	29
2:10	Schematic diagram of a water chiller system	29
2:11	Schematic diagram of a direct expansion refrigeration system	31
2:12	Schematic diagram of 3 heat exchanger types	35
2:13	Schematic diagram of five coil arrangements for a	
	coil-in-tank heat exchanger	38
2:14	Desuperheating heat recovery systems retaining air	
	cooled condenser	40
2:15	Schematic diagram of a refrigerant system with a refrigerant	
	vapour by-pass line and receiver pressure control valve	45
4:1	Schematic diagram of experimental plant	57
4:2	Plate showing experimental plant and instrumentation	58
4:3	Plate showing condensers and control valves	59
4:4	Plate showing compressor and control valves	60
4:5	Plate showing evaporator, expansion valve heat exchangers	
	and evaporator refrigerant flow meter	61
4:6	Field plant measurements	64
5:1	The effect of refrigerant and water flow rates on overall	
	thermal conductance of the test primary heat exchanger	77
5:2	The effect of cores on the overall thermal conductance of	
	the test primary heat exchanger at high refrigerant flow	
	rates	79
5:3	The effect of low refrigerant and water flow rates on the	
	overall thermal conductance of the test primary heat	
	exchanger	82

<b>c</b> . <i>h</i>	Polationship baturan boodland and a fit	Page
5.4	Construction drawing of print heat	83
5:5	Construction drawing of primary neat exchanger	87
5:0	Plate showing primary heat exchanger tubes	88
5:/	Plate showing primary heat exchanger end connections	88
5:0	Plate showing primary heat exchanger in outer casing prior	
	to filling with insulation	89
5:9	Plate showing primary heat exchanger installed on	
	experimental plant	89
<i>.</i> .		
6:1	The effect of condenser pressure on cooling times	95
6:2	The effect of milk inlet and final temperature on cooling	
	imes - water system	98
6:3	The effect of milk inlet temperature, primary heat exchanger	с.
	and receiver pressure on cooling times - air system	99
6:4	The effect of milk cooling differential on cooling time	101
6:5	The effect of condenser pressure on vat temperature -	
	water system	104
6:6	The effect of condenser pressure on vat temperature -	
	air system	104
6:7	The effect of milk inlet and final temperature on vat	
	temperature - 7.5 bar condenser pressure	106
6:8	The effect of milk inlet and final temperature on vat	
	temperature - 10 bar condenser pressure	106
6:9	The effect of condenser pressure on refrigerant flow	
	rates - water system	109
6:10	The effect of condenser pressure on refrigerant flow	
	rates - air system	109
6:11	The effect of milk inlet and final temperature on	
	refrigerant flow rates - 7.5 bar condenser pressure	111
6:12	The effect of milk inlet temperature on refrigerant	
	flow rates - 10 bar condenser pressure	111
6:13	The effect of increasing receiver pressure from 6.0 bar	
	to 7.0 bar on refrigerant flow rates	112
6:14	The effect of the inclusion of the primary heat	
	exchanger on refrigerant flow rates	114
6:15	The effect of condenser pressure on the difference in	
	refrigerant flow rate between receiver and evaporator	
	flow meters - air system	115

		200
		Page
6:16	The effect of condenser pressure on refrigeration	
	effect (RE) - water system	117
6:17	The effect of condenser pressure on refrigeration effect	
	(RE) - air system	117
6:18	The effect of refrigerant flow on head pressure	120
6:19	The effect of condenser pressure on instantaneous	
	compressor power consumption (ICPC) - water system	122
6:20	The effect of condenser pressure on instantaneous	
	compressor power consumption (ICPC) - air system	122
6:21	The effect of the primary heat exchanger on power	
	consumption	123
6:22	A comparison of total refrigeration power consumption	127
6:23	The effect of condenser pressure on COP - water system	129
6:24	The effect of condenser pressure on COP - air system	129
6:25	The relationship between COP and condenser pressure	131
6:26	The effect of the inclusion of the primary heat	
	exchanger on COP	132
6:27	The effect of condenser pressure on heat recovery -	
	water system	136
6:28	The effect of condenser pressure on heat recovery -	
	air system	136
6:29	The effect of condenser pressure on total heat recovery	138
6:30	The effect of milk inlet and final temperatures on heat	
	recovery - water system	139
6:31	The effect of milk inlet temperature and receiver pressure	
	on heat recovery - air system	140
6:32	The effect of condenser pressure on water outlet	
	temperature	143
6:33	The effect of condenser pressure on the ratio of extra	
0. T. T. T. C.	compressor power consumption and heat recovery	148
6:34	The relationship between heat recovery, additional	
	compressor energy and condenser pressure - 1:1 pricing	
	ratio	149
6:35	The relationship between heat recovery, additional	
, , ,	compressor energy and condenser pressure - 1:3 pricing	
	ratio	150
		1.000

)

		Page
6:36	Total refrigeration and water heating energy as a	
	percentage of the energy required by the standard system -	
	1:1 pricing ratio	154
6:37	Total refrigeration and water heating energy as a	
	percentage of the energy required by the standard system -	
	1:3 pricing ratio	154
7:1	Relationship between vat cylinder volume and power	
	consumption	162
7:2	A comparison between theoretical and experimental total	
	and heating power consumption - vat cylinder	164
7:3	The relationship between machine cylinder volume and	
	power consumption	166
7:4	The relationship between standing power (after final	
	temperature is reached) and the volume of water heated	167
7:5	A comparison between theoretical and experimental total	
	and heating power consumption - machine cylinder	169
7:6	The relationship between milk volume cooled to $4^{\circ}$ C and	
	power consumption - 2.25 kW system	173
7:7	The relationship between milk volume cooled to $4^{\circ}$ C and	
	power consumption - 3.75 kW system	173
7:8	A comparison between total, water heating and refrigeration	
	power	176
8:1a	The effect of milk volume on heat recovery savings	181a
8:1b	Heat recovery correction curves and pricing lines	181a
8:1c	Heat recovery annual savings and payback curves	181a
8:2	Filling sequence for machine and vat water heating	
	cylinders and the heat recovery buffer storage cylinder	185
8:3	The effect of primary heat exchanger area on heat	
	recovery for the water cooled system operating at a	
	condenser pressure of 12 bar, with and without a suction	
	superheater	188

.

)

LIST OF TABLES

.

>

		Page
2:1	Quality standards, test frequency and penalty levels for	
	raw milk	7
2:2	Categories of approved cleaning systems and temperature	
	ranges	10
2:3	Summary of U values and water temperatures for a tube-in-tube	
	heat exchanger - water 'once through'	36
2:4	Summary of U values and water temperatures for a tube-in-tube	
	heat exchanger - recirculating 180 litres	36
3:1	Sequence of settings for Experiment I	51
3:2	Summary of test runs for Experiment II	54
5:1	Overall thermal conductance values for the test primary	
	heat exchanger without cores	76
5:2	Overall thermal conductance values for the test primary	
	heat exchanger with cores at a refrigerant flow rate of	
	2.0 l.min <sup>-1</sup>	78
5:3	Overall thermal conductance values and Reynolds numbers	
	for the test primary heat exchanger with cores	81
5:4	Determination of the length of heat exchanger per leg	86
6:1	Cooling loads and rates for the refrigeration system -	
	800 litres	93
6:2	Cooling loads and rates for the refrigeration system -	
	1200 litres	94
6:3	Significance tables for 800 and 1200 litre loading	96
6:4	Experimental and theoretical cooling time as a percentage	
	of the cooling time required for a 23°C - 4°C differentail	100
6:5	Data summary for test runs with and without (NP) primary	
	heat exchanger	125
6:6	Experimental and theoretical heat recovery totals as	
	percentages of the heat recovery for a $23^{\circ}$ C to $4^{\circ}$ C milk	
	cooling differential	141

		Page
7:1	Data summary for 2.25 kW refrigeration system	171
7:2	Data summary for 3.75 kW refrigeration system	172
8:1	Summary of payback period calculation for a \$2000	
	investment and annual savings of \$100	184
8:2	The contribution of heat recovery to water heating energy	
	requirements from heat recovery systems cooling 2000 litres	
	of milk from 23°C to 4°C	190

э. ,

)

## APPENDICES

)

		Page
A2	DERIVATION OF HEAT RECOVERY VIABILITY EQUATION	197
Α3	THEORETICAL ANALYSIS OF A COMPLETE CONDENSING HEAT RECOVERY SYSTEM	200
Α4	EXPERIMENTAL EQUIPMENT, METHODS AND DATA ANALYSIS	205
A6	EXPERIMENT II DATA TABLES AND HEAT EXCHANGER MODEL	268
A7	EXPERIMENT III DATA TABLES	305

NOTE: Appendix numbers refer to chapters from which they were first referenced.