DESIGN AND DEVELOPMENT OF A MILK MINI - PASTEURISER

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A project report submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this project report is [illegible] own, unaided work. It is being submitted for the Degree of Master of Science in *Engineering in* the University of the Witswatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

10th day of August 1989

ABSTRACT

This Project Report identifies, in the Dairy Industry, a market need which can be satisfied by the development of an annular laminar flow convection assisted milk pasteuriser.

It is shown, through experimental work on a full sized model, that the original design concepts envisaged were unsound, but that a revised design could prove to be commercially viable.

Mathematical relationships are derived relating to the specific flow and heat exchange conditions. Comparison of these results with existing publications enhances the findings of some other workers, while casting doubt on the validity of certain accepted material.

In keeping with modern farming trends, the report examines the feasibility of PC usage in this application and offers it as an alternative to a proprietary control system.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS

Quantity	Symbol
Heat Transfer Flux	Q
Overall Heat Transfer Co-efficient	u
Area	A
Temperature	T
Reynolds No	Re
Grashof No	Gr
Prandtl No	Pr
Peclet No	Pe
Nusselt No	Nu
Surface Heat Transfer Co-efficient	h
Resistivity	R
Diameter	D
Thermal Conductivity	k
Length	l
Width	w
Mass	m
Velocity	v
Density	ʃ
Dynamic Viscosity	Γ
Specific Heat	c_p
Mass Velocity	G
Co-efficient of Thermal Expansion Cubic	β
Pressure	P
Time	t
Equivalent Diameter	D_e
Equivalent Diameter - Stephan HEDH(2)	d_h
Equivalent Diameter - Martinelli HEDH(2)	d
Equivalent *Diameter - Pohlhausen HEDH*(2)	S
Inside Diameter	d_i
Outside Diameter	d_o
Dimensionless Factors	A, F, C, c, f

25X1D

CHAPTER 1

INTRODUCTION

1.1 Purpose of Study

The purpose of this report was to validate the *conceptual design* of the pasteuriser, as shown in Figure 1.1.

1.2 Problem Definition

Discussions with small scale milk producers over a three year period indicated a need in the market for a packaged milk pasteurising plant capable of processing 50 to 200 litres of *milk per hour to* acceptable standards of hygiene.

Conventional commercial milk pasteurisers are available in capacities from 250 l/h upwards, however, this equipment is *ex import and thus* prohibitively expensive.

The smallest locally assembled unit is 750 l/h. A unit of 450 l/h had been previously assembled locally but production *of this unit was discontinued* due to technical problems associated with holding times as defined in section 1.2.1 following.

Conventional small pasteurisers are scaled down versions *of large industrial plants,* and most operate with either steam or hot water heated plate heat exchangers, using an element of regeneration.

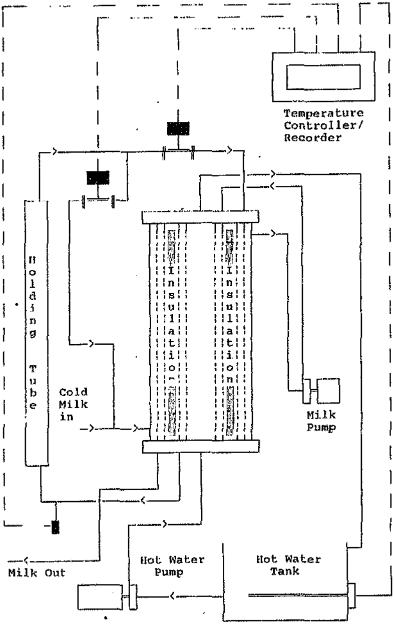


Figure 1.1 Conceptual Design of Milk Pasteuriser

The cost of the control and recording system, required under the Milk By-laws(1), does not decrease with a reduction in unit capacity, and thus becomes a disproportionately high percentage of the unit cost.

It *was* proposed that this cost could be substantially reduced by the use of a computer, in that, with suitable software, the control and recording functions could be undertaken by a PC already in use by a farmer for either accounting, feed control or other purposes.

The following criteria *limited the design,* in that practical considerations must take precedence over *design efficiency*.

1.2.1 Legislation

The unit must pasteurise to meet the requirements of the Standard Milk By Laws(1), extracts of which are as follows:-

"The pasteurisation of milk shall be performed by heating every particle of milk to, and holding it at, a temperature of at least 72°C for at least 15 seconds, the said process being hereinafter referred to as 'the high-temperature short-time method'. (HTST)

Apparatus used for pasteurising milk shall be so designed *and operated and* shall be provided with controls adequate so as to ensure that every particle of the milk is subject to the prescribed range of temperature for the prescribed period.

The record required to be kept in terms of sub-section (5) and all temperature charts shall be completed at the end of each day, shall be accurate and complete and shall at all times for a period of not less than six months be kept available for inspection by the medical officer of health".

1.2.2 Hygiene

The unit must be easily cleaned and be constructed in accordance with good food engineering principles.

1.2.3 Economic Considerations

The unit must be cheap to manufacture and maximise on local content.

1.2.4 Control System

The unit must have a control and recording system which is realistically priced and yet satisfies the requirements of 1.2.1.

1.2.5 Efficiency

The unit must optimise on regenerative heat exchange between incoming cold milk at 4°C and outgoing pasteurised milk at 72°C.

1.3 Structure of Report

The investigation was conducted in six phases, namely: a survey of related literature, a review of conceptual design, the manufacture of a scale model, the testing of this model under various flow conditions and the mathematical evaluation of these test results leading to the improved design of a prototype.

1.3.1 Literature Survey

A comprehensive survey of literature pertaining to milk pasteurisers and heat transfer was conducted at the Animal and Dairy Science Research Institute, Irene, the library of the University of the Witwatersrand and other commercial libraries.

1.3.2 Concept Design

The concept design was reviewed in the light of a preliminary literature survey with a view to the construction of scale test model.

1.3.3 Manufacture of Model

A full size model of the heating section of the proposed pasteuriser was manufactured from galvanised steel sheet. The heat exchanger comprised a single annulus surrounding a central electrically heated core containing water. The annulus was fitted with top and bottom connections for the working fluid and transparent panels through which to observe flow.

A constant head pump system maintained fluid flow in the annulus and a dye dosing mechanism was incorporated to observe flow conditions.

Thermometers were fitted at various points through the system to record the temperature distribution.

1.3.4 Experimental Work

The model was tested with water being pumped through the annulus in four modes.

In the first mode no heat was applied to the central core. The inlet water was connected to the bottom of the annulus and dye was introduced for a controlled period. The pattern of the dye in the annulus was observed, as was the rate of clearing.

In the second mode, the inlet water was connected to the top of the annulus and the test was in other respects as the first mode.

In the third mode, the first mode was repeated but in addition heat was applied to the central core and the temperatures through the system were recorded. This mode was convection assisted flow.

In the fourth mode, the third mode was repeated but the water inlet was connected to the top of the annulus. This mode was convection opposed flow.

The results of the tests are recorded in the Appendices and represented graphically in the text.

1.3.5 Mathematical Evaluation

The state of flow, the rate of decay of dye corruption and temperature gradients were established from the test results. It was shown that the heat transfer was greater in convection assisted flow than convection opposed.

A correction factor 'C' was calculated to be applied to the LMTD when using the standard Fourier Equation.

A Nusselt Number was calculated for the model in convection assisted mode and this Nusselt Number was then compared with those derived using correlations proposed by others researchers for similar flow and heat transfer conditions.

The required heat transfer areas were then calculated for all sections of the proposed pasteuriser.

1.3.6 Improved Design

The original conceptual design was revised such that all flows became convection assisted. The heating section of the pasteuriser was reversed from counter to parallel flow. A system to control the pasteuriser through a PC was proposed and draft software is included in the Appendices.

Design requirements for shells, piping, pumps, end plates and valves were examined and a prototype design suggested.

CHAPTER 2

LITERATURE SURVEY

2.1 General

The Literature Survey was conducted to research existing material in pasteurisation and related fields in order to appraise the following:-

2.1.1 The *Market*

The nature and extent of small pasteurising equipment available on the South African market at the time of writing was evaluated by reference to:-

Standard sales literature on available plant.
Journals of the Society of Dairy Technology.
The Milk Producer
The Shell Farmer
The Farmer's Weekly
Food Review
SA Wine and Beverages

2.1.2 Originality

It was ascertained whether the concept design, as *outlined in Chapter 1 of* this report, was innovative when compared with international and local development over the past five years. It was also determined, by reference to older standard works, whether such a design had been used in earlier development of HTST milk pasteurising plant.

2.1.3 Design Parameters

Current information on the design of existing pasteurisers and the pasteurisation process was collected to ensure that the project design was executed in accordance with good practice.

2.1.4 Published Works

Reference works and related papers containing data relevant to the annular heat exchanger embodied in the concept design were examined.

All international papers and patents related to milk pasteurising plant since 1981 were researched at the library of the Animal and Dairy Science Research Institute at Irene to ascertain whether a similar design of small pasteurisers had either been proposed, evaluated or patented.

Investigation in a similar vein was also conducted through several early volumes on milk processing and dairy engineering.

Material was also obtained from the AECI Technical Library, the Engineering Library of the University of the Witwatersrand and from the author's own library.

2.2 Heat Transfer

The following works were surveyed with reference to heat transfer in similar flow conditions.

2.2.1 Heat Exchanger Design Handbook

The HEDH(2) is a comprehensive study of heat exchanger theory, design and construction published in 5 volumes as follows:-

Vol 1	Heat Exchanger Theory
Vol 2	Fluid Mechanics and Heat Transfer
Vol 3	Thermal and Hydraulic Design of Heat Exchangers
Vol 4	Mechanical Design of Heat Exchangers
Vol 5	Physical Properties

A study of the HEDH(2) indicates that it does not cover the annular concentric heat exchanger proposed for the mini-pasteuriser as such, since no direct equation can be drawn from the text for a straightforward solution to the problem in question.

The text addresses the problem of a small annular exchanger with axial flow direction either in contra or parallel configurations, but has no example of concentric cylinders with the semi helical flow condition proposed.

If, however, a concentric cylinder is considered to be opened out in the form of a plate, there are parts of the plate heat exchanger section of HEDH(2) that might be applied. The principles in the general section on shell and tube exchangers could be applied to the concentric cylinders themselves.

It is suggested that, in validating the concept design, the following sections of HEDH(2) be applied, but reference is made to other sections in the course of the final calculations.

Volume 1 Heat Exchanger Theory

Sections 1.2.1.to 1.2.3. *provide the general* background theory related to the use of further *equations in the volume.*

Chapter 1 of this report suggests the determination of a factor 'C' for application to the standard LMTD in the Fourier heat transfer equation.

With this in mind the 'F' correction factor method outlined in 1.2.4. may be used and *in fact* 'C' approximates 'F' inasmuch as 'F' is applicable to *problems with constant* 'u', while 'C' is to be determined for a variable 'u' value.

$$F = \frac{\Delta T_m}{\Delta T_{lm}}$$

and

$$A = \frac{Q}{uF \, \Delta T_{lm}}$$

It is, however, the purpose of the report to experimentally determine values of ΔT and calculate a value for 'C' for the particular exchanger. The general principles of section 1.2.4. are applied.

Section 1.5.1. *covers the 'F' correction factor* method and outlines its background and conditions *for* validity, however, the charts included in this section only cover shell and tube exchangers, and cross flow arrangements.

The nearest application to the concept design is the ideal counterflow chart. This is clearly not applicable, since 'F' in this case would be equal to 1,0.

The closest shell and tube arrangement would appear to be the TEMA E shell, 2 in series, but this has *parallel flow conditions not present in the* concept design.

Volume 2 Fluid Mechanics and Heat Transfer

The concept of a double pipe heat exchanger and concentric annular ducts is covered in section 2.5.1. both for laminar and turbulent flow. In *these examples, however,* the flow is assumed to be axial, while in the concept design it is semi spiral.

Section 2.5.7. covers correlations obtained by Churchill(2) for buoyancy induced laminar flow for air in vertical channels.

It is possible that this data could be applied to the concept design, though it is specifically applicable to channels with open ends and may not be compatible with the closed circuit envisaged in the pasteuriser. However, one might consider the laminar pumped flow to be equivalent to open ended channels with free convection.

The topic is expanded further in sections 2.5.8 and 2.5.10, which cover laminar 'assisted' convection in vertical channels.

Volume 3 Thermal and Hydraulic Design of Heat Exchangers

Sections 3.1.1. to 3.1.3. provide a general background to heat exchanger design and 3.2.2. deals with double pipe heat exchangers, but these are again limited to axial flow and generally with finned inner tubes.

Section 3.3.9. on shell and tube heat exchangers covers the performance evaluation of a geometrically specified exchanger and the methods proposed in this section could be used to estimate the performance of the geometrically specified pasteuriser in order to determine the heat transfer area required.

Sections 3.5.7 and 3.5.8 refer to the estimation of heat transfer coefficients and transfer area respectively, but in general terms for consideration only in the calculation phase of the project.

As previously mentioned, the concentric cylinder can be considered in an opened out form as a plate exchanger.

The analogy though, while reflecting quite well the mainstream flow, does not give a true representation of the interaction between the two streams at X and Y in the stagnation zones.

Parallels, however, can perhaps be drawn with the data on plate heat exchangers contained in section 3.7. though the aspect ratio of the project exchanger is 1:3, while that recommended as a minimum for plate heat exchangers is 1:8.

This difference highlights the probability of extreme temperature gradients across the exchanger and the risk of enhanced.stagnation zone formation.

Volume 4 Mechanical Design of Heat Exchangers

This volume covers the construction detail of various industrial process heat exchangers and is not relevant to this project.

Volume 5 Physical Properties

Volume 5 contains physical properties recorded for calculation purposes in the preceding volumes, and as such are referred to as required.

2.2.2 Process Heat Transfer

Process Heat Transfer(4) is generally a basic work on heat transfer calculations, with Chapter 20 and its reference to flow in jacketed vessels being of possible relevance to the concept design.

2.2.3 Heat Transfer Equipment

Heat Transfer Equipment(8) is Volume 2 from the Process Equipment Series and in Chapter 10 covers design considerations for spiral plate heat exchangers proposing certain equations.

These empirical equations are of some relevance in calculating the performance of the concept design, in that the water to milk heat exchanger is a combination of axial and helical flow and the milk to milk in a lesser degree approximates the helical to helical flow. Certainly the section on spiral plate exchangers is of interest to the project.

2.2.4 Heat Transfer

In Chapter 6 of Heat Transfer(14) work done by

25x10

Howarth(14) in 1938 in determining the boundary layer thickness for laminar flow over inclined flat plates is covered.

The section on design considerations in Chapter 12 covers average exchanger temperature differences and might be used in conjunction with the paper by Bowman, Mueller and Nagle(13) to evaluate a convection factor for the test model.

Gebhart(14) includes a situation of variable 'u' value covered by the equations:-

$$q = \left[\frac{1}{A_T} \int_0^{A_T} U_o dA \right] A_T(\Delta t_o)_L$$

$$= (U_o)_{av} A_T(\Delta T_o)_L$$

The term in the first of the above equations is the average value of 'u' over the exchanger area.

2.2.5 Handbook of Heat Transfer Fundamentals

The Handbook of Heat Transfer Fundamentals(15) examines the low flow condition envisaged in the test model and raises the possibility that the concept of the conduction layer model and the possible development of a central temperature region might be relevant in verifying the stability of the conduction regime. The development of rolls or waves with the associated breakdown of the stagnation areas are also considered.

Chapter 5 entitled 'Forced Convection - External Flows', offers a simplified method for the calculation of conduction thickness for low speed flows with constant fluid properties.

2.2.6 Heat Transfer Engineering

Heat Transfer Engineering(12) is a valuable book on *basic heat transfer problems* with a chapter specifically related to the testing of experimental apparatus and the validation of experiment results.

Reference will be made to this work during the collection of data from the model tests.

2.2.7 Mean Temperature Differences in Design.

This paper by Bowman, Mueller and Nagel(13) covers in greater detail the relevant section of the Heat Exchanger Design Handbook(2) for heat exchanger *conditions which are* neither parallel nor counterflow.

The assumptions of the paper are consistent with those of the project, with the exception that the project has assumed a small change in 'u' value, brought about by a change in flow rate across the exchanger and associated possible change in boundary layer conditions.

It would appear from the paper that while the principles of infinitesimal stream sections, having a range of temperature differences, embodied in the text on crossflow exchangers can be to a certain extent valid for the project it is more likely that the 'C' factor ultimately determined will approximate that of the single shell and three tube pass arrangement indicated in Figure 6 of that text.

The results of the project experiment, to some extent, serve as extensions to the work carried out by Messrs Bowman, Mueller and Nagle(13).

2.3. Fluid Flow

Aspects of fluid flow comparable to the laminar flow through the annulus in the concept design were surveyed and the following literature was found to be relevant:-

2.3.1 Natural Convection between Concentric Vertical Cylinders.

This paper by de Vahl Davis and Thomas(26) covers natural convection and heat transfer between vertical concentric cylinders having radius ratios between 1 and 4 and aspect ratios between 1 and 20.

The concept design falls within this category. However, the paper is related primarily to convective heat transfer between the walls of closed annuli, rather than with the counterflow situation proposed in the project. It was decided nevertheless to include the paper in view of the very low project flow rates and possible relevance of natural convection assisting or retarding the propagation of stagnation zones.

2.3.2 Convection in Boxes. An experimental investigation in vertical cylinders and annuli.

This paper by Stork and Mullen(8) studies the formation of convective rolls in annuli when veiwed from an axial aspect. The nature of the experiment was such that the model dimensions were very small amd as such not similar to the test model.

However, the development of convective streams in relation to gap width is interesting and proved relevant in the experimental stage of the project. The paper includes photographic examples of convection roll development and similar development was found in the flow pattern of the test model.

It was expected that with a counterflow condition and possible stagnation zones, the flow pattern in the model, while remaining laminar, would have been nevertheless substantially different.

2.4 Milk Pasteurisation

The following works were researched to ascertain current trends in milk pasteurisation.

2.4.1 Milk and Dairy Products

Milk and Dairy Products(40) is an invaluable reference work on milk process technology and presented in a form easily understood by non-scientists. It provides a background on the microbiological aspects of pasteurised milk which is required to appreciate the effects of product retention in the possible stagnation zones of the regenerative heat exchanger.

2.4.2 ASHRAE Guide 1978 Applications

The ASHRAE(3) guide contains material of a general nature in Section 31 which is devoted to dairy and milk process technology. An interesting observation *in this section is that the minimum feasible* capacity for a continuous pasteurising plant is considered to be 900 l/h as against the 200 l/h envisaged in the concept design.

2.4.3 Dairy Science Abstracts

These publications summarise important scientific and technological literature on milk production and milk processing since 1939.

Dairy Science Abstracts(30) are published monthly by C A B International UK and contain approximately 8 000 abstracts per year taken from recent journals, reports, books, patents, standards and conference papers published throughout the world. Each issue has subject and author indexes, and there are cumulative annual indexes for each volume.

An initial investigation revealed some twenty five papers published internationally between 1981 and 1987 and having possible relevance to the project in that they focussed both on new methods of pasteurisation and on refinements to old methods.

The alternative process considered for the project was the use of microwave technology, but while this might still be a possibility for a future investigation, the complexity involved in producing a commercially viable prototype was considered unrealistic for this particular project.

It is interesting to note that, while microwave technology has been successfully applied to packaged milk, little has been researched on its application to flowing milk in a continuous plant.

It is apparent from experiments by Shibing(31), as published in the Egyptian Journal of Dairy Science 1983, that microwaves were successfully used on flowing buffalo milk without any resulting deterioration of creamline or flavour. It may well be that with the Advent of small domestic microwave cooker units a small pilot plant could be constructed.

The obvious advantage of a microwave unit over a conventional water heated plant is that no diversion valve would be required since, as a virtually instantaneous process, there would be no warm up time, and the system would either be 'off' or 'on' with the microwave unit interlocked electrically with the milk pump.

Regardless of whether the milk were pasteurised by microwaves or by a hot water heat exchanger, the plant would still have to have a regenerative heat exchanger to cool the outgoing milk.

The paper indicated that solar heaters have been used with some success on large plants in Australia, but generally to operate on the basis of thermal storage in the hot water supply, rather than direct heating of the milk itself.

This is commendable from an energy saving point of view but would not be practical for the small farmer.

After focussing the project proposal on a cylindrical annular heat exchanger, the Dairy Science Abstracts(30) were again reviewed and relevant papers copied where possible. These papers are discussed later in this Chapter.

The following papers were also considered relevant but at this stage were either not obtainable or not available in English. The Abstracts, however, are included for interest as follows:-

2008 Tulasidas, T.N.(21)

In Dairy Science Abstract 2008 Tulasidas, T.N.(21) information pertinent to heat transfer and basic design of plate heat exchangers is reviewed. An effort is made to develop a better concept on design and application of plate heat exchangers in the dairy industry, based on the available information.

4358 Wernimont, D.(22)

In Dairy Science Abstract 4358 Wernimont, D.(22) four heat exchange techniques used in aseptic processing of foods are described, and the applications in which they function best are given. Techniques are (i) plate heat exchanger, (ii) tubular exchanger, (iii) scraped-surface heat exchanger, and (iv) steam injection.

Optimal applications are considered to be (ii) for high-pulp juices and heat-sensitive products, eg whole and 2% fat milk, flavoured milk amd dairy creamer, (iii) for ice cream mixes, yoghurt, fats and oils: and *(iv) for products to be heated* rapidly, eg milk and ice cream mixes.

7589 Marinoza, R.A. (Canada)(23)

In Dairy Science Abstract 7589 Marinoza, R.A. (Canada)(23) an apparatus for pasteurising (with infrared radiation) or sterilizing (with ultraviolet radiation) liquid foods including milk, cream, fruit juices, beer, syrups, molasses etc is described. It *consists of a linear source of radiation surrounded* by a thin annular jacket, the inner wall of which is permeable to the radiation for it to reach the thin layer of product flowing through the jacket.

1310 Aule, O.; Noren, T. (Sweden)[24]

In Dairy Science Abstract 1310 Aule, O.[24] a plate heat-exchanger is described for use on the farm for pasteurising fresh uncooled milk to about 72°C, with efficient heat regeneration and an energy consumption of about 5 W/l milk. The milk is preheated regeneratively, further heated from electrically-heated hot water, held in a holding coil and cooled in stages to 2°-6°C ready for bulk storage on the farm.

4660 Wiggens, A. L.[25]

In Dairy Science Abstract 4660 Wiggens, A.[25] views the projected banning of sales of non-heat treated milk in Scotland in 1983, and in England and Wales in 1985, the choice of systems for on-farm pasteuristion is discussed and a list of systems tested at the West of Scotland Agricultural College is appended.

2.4.4 International Dairy Federation. Bulletin 200 Monograph on Pasteurised Milk

The Monograph on Pasteurised Milk[7] is a comprehensive study of all aspects of milk pasteurisation. It was compiled under the chairmanship of Dr O Cerf of France and approved for publication in 1986. As a recent work it summarises in 15 chapters current thinking with regard to biochemical, nutritional, hygienic, constructural and other aspects of pasteurising plant.

It deals also with historical data, distribution and legislation and as such is a vital reference work for a project of this nature.

The following notes summarise those areas of particular relevance to the concept design.

Chapter 6 Pasteurisation of Milk - Design and Operation

M G van de Berg[7]

This paper covers the principles of heating, pasteurising and cooling milk with particular reference to the process technology of flavours and bacterial growth as influenced by the design of the apparatus. It also addresses in simple terms the basic problems associated with leakage, cross contamination of raw to pasteurised milk, and the effects of corrosion and detergents.

Of particular interest in this paper is the section which covers the initial testing of a pasteurising plant, either of new design or one that has been significantly modified, to determine the acceptability of the unit as an effective means of pasteurisation.

The paper covers the question of efficient regeneration, holding times and holding efficency, as well as cooling and protection against under or over pasteurisation.

An interesting point is raised in section 6.6.3. of the paper relative to the growth of bacteria in stagnation zones of regenerative heat exchangers. It is suggested that this is acceptable with a reduced cycle time. The cycle times of the test model was checked against these criteria. Stagnation was not as critical an area as was at first thought.

Chapter 10 Mechanical design of pasteurisation equipment with special reference to hygiene.

H Wainess (USA)(7)

This paper addresses ,the particular aspect of mechanical design of pasteurisers where hygiene is a priminary consideration. The consideration of valve design and general interconnecting pipework design are covered both for batch and continuous pasteurising plant.

The general requirements for construction of heat *exchangers, as outlined in* Chapter 6 of the Monograph are expanded in some detail, both for plate and tubular configurations.

The paper also deals with the criteria applicable to the selection of milk pumps, design of holding tubes and milk to milk regenerative systems. Certain comments from this section on pressure distribution in these systems are incorporated in the prototype design.

Chapter 11 Instrumentation for Heat Transfer Systems.

H Wainess and K A Anderson (USA)(7)

In a critical process such as pasteurisation instrumentation and controls are of primary importance.

In their analysis of the system required Waines and Anderson(7) examine the accuracy requirements, construction and optimal locations for the various components comprising the instrumentation, control and recording systems for both batch and continuous processes.

This data was used as a basis for assessing the suitability of ancillaries specified for the prototype design.

The paper covers further the importance of pressure relationships within a regenerative heat exchanger, and suggests some form of pressure monitoring and control. This level of sophistication is not, however, envisaged for the prototype design.

Chapter 15 Consideration in relation to some technological and engineering aspects.

H G Kessler(7)

H Kessler(7) has examined critically in section 4.0 of this Appendix, the nature of residence time distribution in holding tubes and while this may possibly not be relevant to the concept design due to its potentially short cycle time the holding tube will nevertheless be calculated on the basis suggested in the paper within the limiting criteria of standard piping sizes and ease of cleaning.

It proved practically necessary for the project holding tube to fall short of the suggested criteria, being length to diameter ratio greater than 200, with no laminar flow and Re greater than 12 000.

2.5 Pasteurisation Plant

This section covers the works related to various types of pasteurisers and their constructional details.

2.5.1 The Market - Milk Industry

The Market - Milk Industry[17] describes on Page 322 a steam heated tubular milk pasteuriser, and also of particular interest, the Stassaniger double tube heat exchanger invented in France by Henri Stassano[17]. The significance of this heater is the narrow intertube gap of 0,6 - 0,8 mm. The book suggests that conventional tubular milk/water heat exchangers of that period had intertube gaps of around 12,0 mm.

2.5.2 Milk Production and Control

Milk Production and Control[18], as a standard work on milk production, provides background material in conjunction with other more recent papers. The chapters on pasteurisation plant contain additional data on constructional details not found in other works.

2.5.3 Dairy Engineering

Dairy Engineering[19], as an authoritative text of the time, is a useful reference work for constructional details of older machines. No reference was found to a unit similar to the concept design.

2.5.4 Liquid Milk. Developments in Heat Treatment Plant

Much of the paper by Cattell[27] is unrelated to the concept design, but certain sections concerning the fouling of milk heat exchangers plants with increasing temperature are of interest, as is the section on the evolution of plate heat exchanger design for pasteurisers.

Development in pasteurising plant over the last few years appears to have been concentrated on UHT (Ultra High Temperature) plant and aseptic processing, rather than new generation HTST (High Temperature Short Time) units progressing from the conventional plate heat exchanger.

2.6. Market Assessment

The following literature was perused and manufacturers approached to assertain the current availability of equipment and ancillaries.

2.6.1 7072 Attwell, P.

In *Dairy Science Abstract 7072 Attwell, P.*[28] *the* increasing demand in South Africa for small pasteurisers as smaller dairy operations enter the market is discussed, with various reasons for the trend being proposed. Several models of small or 'mini' pasteurisers supplied by various companies are then described, considering details such as capacity, construction and operating conditions.

The paper was used as a reference guide to the current 'state of the art' in the South African market.

2.6.2 6082 Thomas, E.B.: Peters, M.C.(USA) (CREPACO INC)

In Dairy Science Abstract 6082 Thomas, E.B.[29]

the heat-exchanger discussed comprises a vertical jacketed cylinder enclosing a dasher, which in conjunction with the interior cylinder walls forms a *passage through which the product flows. The* configuration and size of the various components may be varied depending on the type and density of the product treated and whether it is cooled or heated.

The heating/cooling agent may be a gas or liquid, and the plant may be provided with electrical heating. In the version described the plant is for use with milk products but other foods may be processed, and the plant may be operated aseptically.

The synopsis from the Dairy Science Abstracts 1985(30) indicated a possibility that the pasteuriser patented in the USA might have been of a similar design to the concept design.

However, the local agents for CREPACO INC were approached and details of their machine were obtained. It transpired that this is a vertical jacketed vessel of small diameter, with a central axial agitator. The product passes axially through the agitated tube and it is especially suitable for viscous liquids. The design concept is not similar to that proposed in the project.

2.6.3 APV (Pty) Ltd

Primarily in the large dairy market, APV (Pty) Ltd have attempted on various occasions to produce a competitive small pasteuriser. Their last venture, a unit with 1 000 l/h capacity, was a scaled down version of a large plant designed in the conventional manner. It had a plate heat exchanger, regenerative but no cooling section, and electric hot water heating. This unit has now been shelved.

2.6.3 *Alsa Engineering* (Pty) Ltd formerly Alfa Laval (Pty) Ltd

The company made great inroads into the local market with their Microtherm, a typical plate heat *exchanger* unit of 900 l/h capacity, but being innovative in that there was much plastic included in the design.

The plant was originally cheap and popular but with the fall in the value of the rand, as an imported item it became uneconomic.

In keeping with current Swedish thinking on South Africa, Alfa Laval have disinvested and changed their local name with the future of their equipment becoming uncertain in the short term.

2.6.4 Filmatic (Pty) Ltd

A Cape Town based company which has developed a range of small milk pasteurisers starting at 750 l/h. These are conventional units similar in design to the APV unit *described in 2.6.3 above.* The company is making good ground on the local market but relies on imported heat exchanger plates.

2.6.5 F Read & Sons Ltd - UK

The company produces the only truly mini pasteuriser with a capacity of 250 l/h. The excellent unit of compact plate heat exchanger design is unfortunately too expensive to import with the current *Rand/Sterling exchange* rate.

2.6.6 National Dairy Equipment (Pty) Ltd

NDE are agents for the Passilac pasteuriser, a Danish unit similar to the APV plant. This small pasteuriser with conventional design has not had a great deal of success primarily because of price and lack of aesthetic appeal in the design.

2.6.7 Computer Interface

It was determined that analogue/digital PC interface boards having from 3 channels upwards are available at a reasonable cost either from VKN Distributors (Pty) Ltd or Eagle Electronics (Pty) Ltd.

2.6.8 Diversion Valves

A significant cost centre in small pasteurisers has always been the stainless steel diversion valve. SAE Afikim in Israel offer a food quality polysulfone 2-way valve obtainable either with pneumatic or spring operated mechanism. This valve is a low cost item and should be suitable for conversion to 24 volt DC solenoid operation. Sample valves have been obtained from Isreal.

2.6.9 Controls

Literature has been obtained on standard Sekonic controller/recorder units from Temperature Controls (Pty) Ltd. These may be proposed in the project as a controller only, for use in conjunction with the PC recording functions.

2.6.10 Mephsa (SA) Argentina

An approach was made to the South American Trade

Consuls for details of small pasteurising plants. The intention was to determine the level of development of commercially produced plants in countries having *a similar third/first world* socio-economic mix to South Africa. Literature was obtained from MEPHSA (SA) but no mini-pasteuriser was available other than a rather interesting batch pasteurising unit.

CHAPTER 3

THEORETICAL REQUIREMENTS

3.1 Conceptual Design

An initial survey in the Food Industry, and the preliminary calculations included in Appendix A, indicated that the concentric cylindrical design proposed was both innovative and satisfied the requirements of 1.2.2, 1.2.3 and 1.2.4. However, certain areas nevertheless required investigation.

3.1.1 Flow Pattern

The flow distribution around the cylinder was thought to cause stagnation zones in the annulus, as indicated in Figure 3.1.

It was thought that the occurrence of these stagnation zones might induce a retention time of sufficient length to promote growth, in the outgoing milk, of the undesirable organisms remaining after pasteurisation.

The pasteurisation process eliminates 95% of undesirable organisms and the temperature in the stagnation zones appeared likely to be around 40°C, at which temperature the remaining 5% would readily propagate.

3.1.2 Anticipated Heat Transfer

It was suggested that the cylindrical heat exchanger with diagonally opposite connections would have stagnation zones, as depicted in Figure 3.1, with these stagnation zones having a lower temperature difference between each other than the temperature difference at the centre of the heat exchanger, zone 3.0.

The anticipated temperature gradient from inlet to outlet followed a helical path around the annulus and was comparable to a conventional counterflow heat exchanger. A further temperature gradient was anticipated crossing the direction of flow from stagnation zone 1.0 to stagnation zone 2.0. This temperature gradient is represented diagrammaticaly in Figure 3.2.

It followed from the above that the standard Fourier heat transfer equation, Q = uA LMTD, was no longer valid for this application where:-

u = Overall Heat Transfer Co-efficient
A = Area
LMTD = Log Mean Temperature Difference
Q = Heat Transfer Flux

since the LMTD is not a true reflection of the relationship of Q to heat transfer area A.

Initial calculations, included in Appendix A, indicated that the flow rate through the exchanger would be laminar and practical considerations precluded the reduction of cross sectional area to increase velocity. Similarly, cost and hygiene considerations restrictd the use of helical baffles or dimple plate.

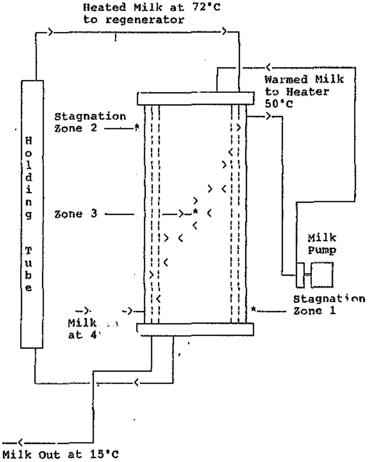


Figure 3.1 Anticipated Flow, Regenerative Exchanger

This laminar flow would inhibit heat transfer and promote stagnation zones.

It was necessary to determine a dimensionless factor 'C', being a function of cylinder diameter, height, internal spacing and flow rate, which might be applied to the overall heat transfer equation as Q = CuA LMTD. The application of this factor would correct the LMTD for this specific application and hence verify the area A necessary for the effective heat exchange required or, conversely to determine the maximum flow rate achievable from a practicably sized unit.

The determination of the correlation between the various elements comprising the factor 'C' for cylinders of different proportions and flow rates was outside the scope of this report.

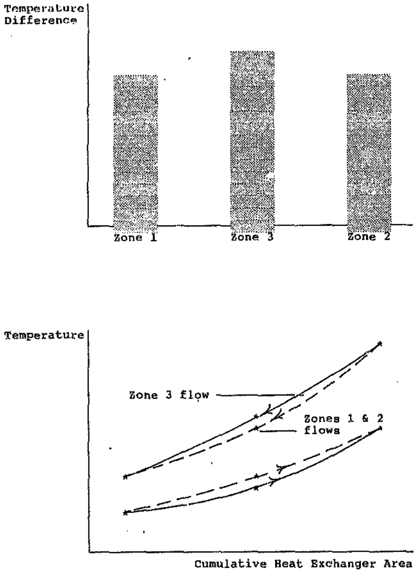


Figure 3.2 Regenerator: Anticipated Temperature Gradient

CHAPTER 4

MODEL DESIGN

4.1 General

This chapter describes the model constructed and the limitations of the model and the test rig used.

4.2 Model Construction

The model was constructed to verify the principles involved in the conceptual design. To undertake this verification it was only necessary to simulate flow through the first annulus of the proposed design. The model as such, was a single annulus around the centrally heated core. The use of a single annulus facilitated the fitting of transparent observation panels and simplified sealing of the annulus ends.

Various materials for construction were considered and in the event 0,8mm rolled galvanised mild steel sheets were used, with 3,0mm high impact plastic panels and soldered joints and fittings.

Heating of the water in the central core was provided by two 3,0kW immersion heaters with thermostats adjustable from 40°C to 75°C. Holes were drilled through the centres of the panels and at other strategic points in the annulus through which the bulbs of mercury and glass thermometers could be fitted. A hydraulic leak test was undertaken in the works before the holes in the annulus were drilled.

The central core was fitted with a valved drain point.

The test rig was fitted with a means of controlled dye injection to the water at the inlet of the model and for test purposes water was passed through the annulus with the contents of the central core being static.

The dimensions of the model were generally in accordance with Figure 4.1. The leading dimensions of 1 200mm high and 600mm diameter were those proposed for a production unit and suited to standard plate sizes with the minimum of cutting and wastage.

The diameter of the inner cylinder was 575mm thus leaving an annular width of 12,5mm. This gap was maintained by the use of spacing lugs at the top and base of the inner cylinder, positioned to avoid interference with the flow. The thin material necessitated a number of swages to the inner and outer shells, but these swages were located opposite each other so as not to cause restrictions.

A further smaller cylinder was positioned so as to take up approximately 2/3 of the inner cylinder water volume and thus reduce both the weight and heating time of the appliance.

The inner cylinder was painted white behind the observation panels in order that discoloration on the introduction of blue dye could be more easily observed. Thermometer mounting brackets were attached to the outside shell in the positions indicated in Figure 4.2 and ultimately thermometers sealed into the holes with flexible sealant.

The dosing of dye was effected with a valved dosing assembly as indicated in Figure 5.1 and comprising a clear water by pass valve (red) and two dosing valves (yellow) with a removable glass container for the dye cubes.

4.3 Limitations

The method of construction introduced certain inconsistencies in the annular dimension which would not occur in a production model having machined end plates to correctly locate the shells.

The concept design proposed an external heat source, storage tank and hot water pump instead of the static heated water used in the model. The former would have been more easily monitored, while the latter was much cheaper to manufacture.

In the experiment water temperatures were checked at the top and bottom of the heated core and an arithmetic mean determined for use in calculations.

The heat balance of the model was such that the heat lost by the immersion heaters was gained by the working fluid in the annulus. The extent of this gain was studied both in convection assisted and convection opposed flow. In relation to the concept design, convection assisted flow in the model approximated parallel flow, and convection opposed flow approximated counter flow.

In temperature detection, economics determined that mercury in glass thermometers be used in place of multi-point electronic instruments and it was considered that the specified accuracy of within 0,5°C was adequate for the experiment.

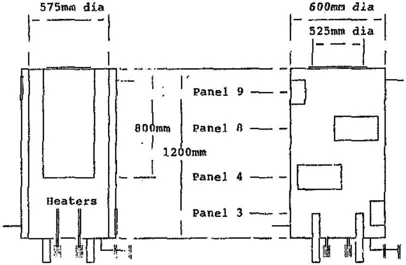


Figure 4.1 Section and elevation of Model

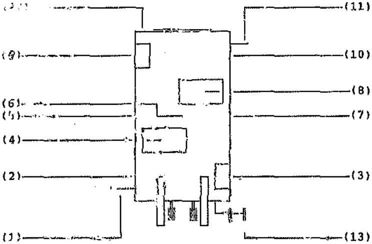


Figure 4.2 Location and *Numbers of Thermometers*

The purchase of an SABS certified thermometer for calibration purposes was considered and rejected. Calibration of twelve thermometers was carried out against the thirteenth thermometer which was found to have a mean of the range of readings of all the thermometers at ambient temperature.

The Ricketts Blue dye cubes used in the test had the disadvantage that they do not dissolve uniformly thus making the use of an accurate comparator impossible. Also, irregular dissolution of the cubes brought about changes in density of the dyed liquid.

CHAPTER 5

TEST OF MODEL

5.1 General

This chapter contains the consolidated results obtained from the experiments described under section 5.2, and derives certain mathematical relationships from these results. These relationships are then compared with established theoretical or experimental data given by earlier workers in this field.

The test results for flow in the annulus are collated in the following forms:-

Convection assisted with central core heated.
Convection opposed with central core heated.
Bottom flow connection with central core unheated.
Top flow connection with central core unheated.

for each of the following:-

Sequence of panel corruption, Tables C1, C2
Sequence of panel clearing, Tables C3, C4
Time taken to corrupt from zero base, Tables C5, C6
Time taken to clear from zero base, Tables C7, C8
Time taken to corrupt per panel, Tables C9, C10
Time taken to clear per panel, Tables C11, C12
Temperature distribution, Figures C1 to C5

From the experimental data it was possible to make certain observations on flow patterns, cycle times

25x10

and retention times and then to investigate the following:-

5.1.1 Flow State

The Reynolds Number and flow condition were confirmed for the specific annular gap and diameter of the experimental model.

5.1.2 Decay Time

An expression for the decay time of the clearing of a panel was derived and the residual concentration after a given period calculated.

5.1.3 Transfer Area

The theoretical heat transfer areas for both parallel and counter flow modes were calculated.

5.1.4 LMTD Factor

LMTD factors for the experimental model in both convection assisted and convection opposed flow modes were derived.

5.1.5 Nusselt Number

The Nusselt Number for the experimental model was derived and the actual and theoretical heat transfer co-efficents compared.

5.1.6 Comparison with Established Data

The mathemetical relationships derived from the experimental results were compared with other relationships documented in Volume II of the

HEDH[2] for convection assisted and convection opposed laminar flow. The validity of these alternatives in this application is discussed.

5.2 Test Method

The arrangement of the test rig and the method of testing are outlined in the following sections.

5.2.1 Thermometers

The thirteen mercury in glass thermometers were checked at an ambient temperature of approximately 13,5°C. The thermometer reading 13,3°C was chosen as a standard since it was the approximate mean of all the thermometer readings. The deviations of the other twelve against this thermometer are tabulated in Appendix B.

The thermometers were numbered with No 1 being the standard thermometer and deviations were again compared in a warm water bath at approximately 40°C.

5.2.2 Annular Thickness

The thickness of the annular space was measured with a vernier at each thermometer entry point and the average found to be 12,1mm. These measurements are tabulated in Appendix B.

5.2.3 Test Rig

The test rig was connected as shown in Figure 5.1 for convection assisted flow, the water supply being provided from a centrifugal pump maintained at constant suction head by a reservoir. This was necessary as no mains water supply was available.

Flow rate was determined by recording the time taken for the discharge to fill a 4 litre container.

The discharge was taken through a glass jar against a white background to facilitate identification of the presence of any dye.

5.3 Procedure

Tests were undertaken to record the temperature distribution for given flow rates under stable conditions with the water heaters on. These were both for convection assisted flow as in Figure 5.1, and convection opposed flow with the connections reversed.

In each case, as shown in Figure 5.1, the red clear water valve was closed and yellow dye by-pass valves opened to observe, through the clear inspection panels, the rate and pattern of corruption of the annulus by the dye.

The time was recorded on the first entry of dye into each panel and again when each panel was full of dye. The time at which dye was first observed in the discharge was also noted.

The tests were then repeated with the yellow dye valves closed and the red clear valve open. The time of decay of the dyed panels was recorded from the start of decay until the panels were substantially clear of dye. The time of clear discharge was also recorded.

The flow pattern through the annulus without the heaters on was observed and times recorded as previously.

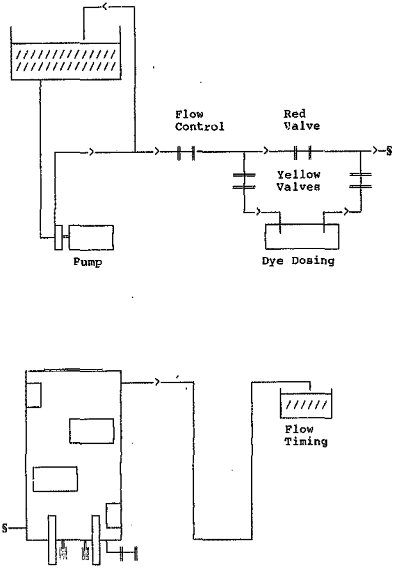


Figure 5.1.Test Rig with convection assisted flow

This section comprises the Test Sheets numbered 01 to 17 completed during the flow and temperature distribution tests and contained in Appendix B.

Significant observations made during the testing programme were as follows:-

With bottom feed and no primary heating, the flow was, as anticipated, generally diagonally helical with the appearance of stagnation zones at Panels 3 and 9.

With top feed and no primary heating, the flow was vertically down from inlet to bottom of the annulus, with dye discharge occurring immediately after contamination of Panel 3 and before contamination of Panels 4 and 8 was complete.

With bottom feed and primary heating, the flow was convection assisted, and it was observed that the convection forces were such that they were predominant, causing the flow to be vertical fairly evenly distributed around the circumference. Convective clearing was such that stagnation zones did not occur. The temperature gradient was even.

With top feed and primary heating, the flow was convection opposed, resulting in a flow of entering cold water directly to the bottom of the annulus, with partial mixing and convective migration upwards. This resulted in an uneven temperature gradient with fluctuations and hot spots. Clearing in this mode was difficult to assess due to the even and gradual convective diffusion of the clear water upwards through Panels 4, 8 and 9. This flow pattern is depicted in Figure 5.2.

5.4 Observations on Test Results

In general terms the test results appeared sufficiently consistent, given that the experimental equipment was basic by laboratory standards, and that problems were experienced with only two operators attempting to accurately record the rapidly changing results. For ease of reference Tables C5 to C12 have been averaged arithmetically to indicate mean readings and the associated accuracy of individual tests.

The nature of the test programme did not justify expanded discussion on statistical error measurement.

In certain cases, readings were missed through interruptions and difficulty was experienced in maintaining a consistent level visually at which a panel was declared to be 99,5% clear.

Uneven dissolution of the Rickets Blue Dye precluded the use of a test tube comparator as originally intended. In retrospect it would have been useful to have had a small sealed section of annulus containing clear water behind each observation panel, against which the adjacent liquid could have been compared.

The use of a stopwatch would have simplified time keeping rather than the cumulative method used with an ordinary clock.

In the top flow connection configurations, the discharge pipe had to be raised to empty above the height of the unit to ensure complete filling of the annulus. With a simple loop in the discharge pipe the syphoning effect tended to draw air into the annulus through minor leaks.

Since the clearing of dye from panels tended towards asymptotic, with large changes of time occurring for very small changes in concentration, it was reasonable to take the arithmetic average of results in each case and use these as a basis for calculation.

5.4.1 Corruption and Decay Sequence

Tables C1 to C4 indicate the sequence with which the panels were corrupted by the introduction of dye, and cleared on the re-introduction of clear water.

In Table C1 the sequence of corruption is the same for both bottom and top flow connections. This appeared to have been caused by a slight density difference between the cold dyed water entering the top of the annulus and the water existing in the annulus. This density difference was assumed to have been due to the inclusion of the denser dye material in the flow, possibly assisted by thermally induced currents in the annulus from ambient or solar gains. The occurrence, while noteworthy, is of no relevance to a milk flow condition.

Regrettably temperature gradients were not recorded where no primary water heating was applied.

The similarity of results in sequence of filling show the flow of entering cold water in convection opposed mode directly to the bottom of the annulus at Panel 3, with the separation of the convective rolls rising to corrupt Panels 4, 8 and 9, while in the convection assisted mode the corruption is horizontally even from the bottom up.

Comparable corruption in convection opposed flow would thus have been 9, 8, 4, 3 and this would be expected with a sufficient increase in mechanically induced flow rate. It was noted that with bottom connection the flow tended to be helical at Panels 4 and 8.

The sequence of clearing of panels with no heat, when compared with the similarities of the sequences of corruption, indicate that the primary cause of density difference was due to the inclusion of the dye, since the entering clear water more readily cleared to the top point of the annulus with the top entry.

The same principle applies to the clearing with heat applied in convection opposed mode. The change in sequence of the results in convection opposed mode was ascribed to a reduction in flow rate for Tests 15 and 17 with an associated possible predominance of convective forces. The denser dye material collected in Panel 3.

5.4.2 Time taken to Corrupt from Zero Base

Tables C5 and C6 indicate the average times for corruption from the start of each test.

Table C5 shows that, for conditions of no heat, cycle times of 8 minutes 12 seconds for bottom connection at a flow rate of 4,090 l/m and 7 minutes 33 seconds for a top connection and flow rate of 3,356 l/m are similar. The slight difference indicating that the denser dyed water clears more readily when the flow is in a downward direction.

Table C6 compares the filling times from a zero base for opposed flows.

From an inspection of Tables C5 and C6, the even horizontal corruption of convection assisted flow, and the rapid corruption of Panel 3 in convection opposed flow is apparent. The convective migration upwards from the bottom, first to Panel 4 and then to Panels 8 and 9 can also be noted. These flow patterns are indicated in Figure 5.2.

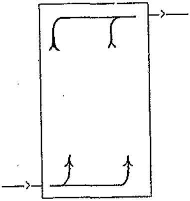
The average cycle times are similar in both cases at approximately 5 minutes 30 seconds each.

5.4.3 Time Taken to Clear from Zero Base

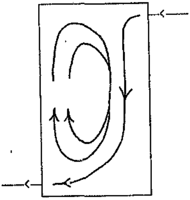
Tables C7 and C8 indicate the average times for clearing from the start of each test.

Table C8 compares the clearing times from zero base for covection assisted and convection opposed flows. The significance of these results is in the cycle times where convection assisted mode is on average 3 minutes 15 seconds less than the convection opposed mode, with cycle peaks having a difference of 6 minutes 25 seconds.

With pasteurisation in mind this indicates the advantage of employing convection assisted flow in a milk to milk regenerative heat exchanger. Both cycle times are well within the accepted maximum cooling time of one hour to reach 7°C. This is normal for batch pasteurisers, but the project design is required only to cool to 15°C, with sub-cooling to 7°C taking place in an external tank. However, even taking this into account the cycle times are acceptably short.



Convection Assisted



Convection Opposed

Figure 5.2 Flow Patterns

5.4.4 Times to Corrupt and Clear per Panel

Tables C9 to C12 indicate the times taken to fully corrupt and to fully clear each panel under various flow conditions.

The relevance of these results is in the investigation of retention times at panels having different temperatures, particularly those that would occur in the milk to milk regenerative heat exchanger.

Under these circumstances Panels 4 and 8 would be those most likely to be at a mean temperature conducive to the propagation of residual bacteria and these retention times of 9 minutes 45 seconds and 7 minutes 04 seconds for clearing in convection assisted mode are within acceptable limits based on a linear cooling rate of 1°C per minute and thus approximately 10 minutes to cool from 45°C to 35°C.

Assessment of the value of the maximum retention time per panel was made in conjunction with the average cycle time, to obtain a true reflection of the suitabilty of the proposed method for pasteurisation.

In any event the ultimate test is in the quality of milk finally produced when standard quality control measures are applied.

The theoretical concentration of original milk retained after a given period can be calculated using a decay equation and this is discussed later in this chapter.

5.4.5 Temperature Distribution

A comparison of the actual temperature distributions for convection assisted flow, being bottom entry parallel flow and convection opposed flow, being top entry counter flow are shown in Figures C1 and C2. The data in each case was recorded for 3 tests having similar flow rates so that the average temperature could be taken at any point.

The horizontal, diagonal and vertical temperature gradients are represented graphically in Figures C3, C4 and C5. Using existing correlations it is possible to calculate, from Figures C2 and C2, the theoretical heat transfer area required for the actual heat transferred under the test conditions. From this the correction factors applicable in each case can be calculated.

The graphical representations in Figures C3, C4 and C5 show clearly the even temperature distribution of convection assisted flow when compared to convection opposed flow. The horizontal temperature gradient for convection opposed flow in Figure C3 between points 10 and 9 demonstrates the result of convective migration upwards in rolls, similar to those found by Stork & Mullem(8), even though the main stream is downwards. This is highlighted further in the diagonal and vertical gradients shown in Figure C4 and C5 which figures also indicate the effect of cooling in the flow between mid point and discharge.

In each experiment the thermostats on the immersion heaters were set at 70°C and as such never switched off. This had the advantage that the heat input to the core was constant and not cyclical for calculation purposes. However, it had the disadvantage that the control cycle for annular discharge temperature, when operating about a thermostat set point in the primary heating water, could not be evaluated. The annular gap of 25,0mm in the primary water vessel was assumed to be sufficiently wide to approximate an infinite vessel for the primary heat source.

5.5 Determination of Flow Condition

The flow is shown to be laminar with a Reynolds Number of 141 at a flow rate of 3,545 l/m and an average annular gap of 12,1mm. Calculations are contained in Appendix D.

5.6 Derivation of Decay Time

The calculation in Appendix E indicates that the probable residual concentration of original milk in a panel would be 0,00001% after 30 minutes. While this is an approximation, it does indicate the level of dilution within the risk period for propagation of residual bacteria in the outflowing pasteurised milk. It can reasonably be assumed that the level of contamination with this dilution would not affect the commercial acceptability of the milk.

5.7 Derivation of LMTD Factor

The calculations in Appendix F show the LMTD for convection assisted flow to be 5,77°C and for convection opposed flow to be 14,20°C.

According to Kern$^{(4)}$, in conditions where the viscosity is in the region of one centipoise (10^{-3} Ns/m^2) at the cold terminal and the temperature range is below 40°C with a difference of below 10°C. The arithmetic mean of the inlet and outlet temperatures can be used to evaluate fluid properties.

For convection assisted flow, the above criteria apply and the arithmetic mean temperature in the annulus can be taken from Figure C2 as:-

$$T \text{ mean} = \frac{33,9 + 13}{2} = 23,45°C$$

For convection assisted parallel flow, the flow rate from Figure C1 was 3,157 l/min or 189,42 kg/h for a temperature rise from 13°C to 33,9°C.

Thus taking c_p @ 23,45°C = 4180 J/kg K according to ASHRAE[3]

$Q = mc_p\Delta T$

$= 189,42\text{kg/h} \times 4180 \times (33,9 - 13)$

$= 16547,78$ kJ/h

$= 4,5966$ kW

and for convection opposed counter flow, the flow rate from Figure C2 was 3,025 l/min or 181,48 kg/h for a temperature rise from 13°C to 21,5°C.

Then

$Q = 1,7911$ kW

The heat transfer surface available in each case is identical as:-

$A = \text{Annulus ID} \times \pi \times \text{length}$

$= 2,171\ m^2$

Neglecting radial conduction due to the small difference in radii, then the heat transfer to the annulus is:-

$Q = uA\ LMTD$

or more specifically, allowing for changes in film co-efficient for convection assisted and convection opposed flows then:-

$Q = uA\ C\ LMTD$

where C is a dimensionless factor specifically related to the performance of the test model under certain parameters of flow condition, flow rate and temperature gradient. C also serves as a measure of the efficiency of the usage of the heat exchanger surface available, when compared with an ideal theoretical exchanger having the same 'u' value and LMTD.

Thus for convection assisted flow:-

$4596{,}6\ W = uC \times 2{,}171 \times 5{,}77$

and

$$C = \frac{366{,}94}{u}$$

and for convection opposed flow:-

$1791{,}1\ W = uC \times 2{,}171 \times 14{,}2$

and

$$C = \frac{58{,}09}{u}$$

thus, if it is considered that for an ideal theoretical heat exchanger C = 1,0, then decreasing values of C are associated with falling efficiency and

$$C \text{ assisted} = \frac{366,94}{58,09} \text{ C opposed}$$

$$= 6,3167 \text{ C opposed}$$

Assuming the galvanising of the heat transfer surface to be 0,075 mm thick and

$$\text{Resistivity } R = \frac{1}{k}$$

k for zinc = 112 W/m K
k for steel = 45 W/m K
thermal resistance of zinc:-

$$R = \frac{0,075 \times 10^{-3}}{112} = 0,667 \times 10^{-5} \text{ m}^2\text{K/W}$$

thermal resistance of steel:-

$$R = \frac{0,8 \times 10^{-3}}{45} = 0,17 \times 10^{-4} \text{ m}^2\text{K/W}$$

$$u = R_{mi} + R_{wall} + R_{mo}$$

Fouling factors are not to be considered as a production unit would be cleaned between each 4 hour cycle.

It can then be assumed that the resistance of the annulus inner wall is so low that it can be neglected and the value of 'u'can be based on surface co-efficients h_{mi} and h_{mo} only, thus:-

$$u = R_{mi} + R_{mo}$$

and

$$u = \frac{1}{h_{ci}} + \frac{1}{h_{co}}$$

$$= \frac{h_{ci}h_{co}}{h_{ci} + h_{co}}$$

Since the experimental apparatus approximates, in convection assisted flow, two vertical flat plates, the correlation suggested by ASHRAE Fundamentals Vol 1977[3] Section 2.12 Table 5 for natural convection can be used as follows:-

$Nu = 0,56\ (Gr\ Pr)^{0,25}$

This being applicable for laminar flow with (Gr Pr) between 10^4 and 10^9.

Calculations included in Appendix G indicate:-

The Grashof Number:-
$Gr = 2,226108 \times 10^6$

The Prandtl Number at 23,45°C:-
$Pr = 6,405$

The value of (Gr Pr) then becomes:-
$(Gr\ Pr) = 1,4258221 \times 10^7$

which is $\leq 10^9$ and thus within the limits of the correlation:-

$Nu = 0,56\ (Gr\ Pr)^{0,25}$

$= 34,412$

and

$$Nu = \frac{h\ D_m}{k}$$

$$h = \frac{34,412 \times 0,6}{0,0494}$$

$$= 417\ W/m^2K$$

This compares reasonably with the experimentally derived overall heat transfer of:-

$uC = 366,94\ W/m^2K$

The value of 'h' calculated, is equal to the overall transfer co-efficient 'u' since the LMTD was used to compute the Grashof Number instead of the mean wall and annular fluid temperatures.

The value of 'C' can be calculated for convection assisted parallel flow from:-

$uC = 366,94\ W/m^2K$

where

$u = 417\ W/m^2K$

$$C = \frac{366,94}{417} = 0,879952$$

and for convection opposed counterflow:-

$$C = \frac{58,09}{524} = 0,110859$$

where 524 W/m²K is the value computed using the Grashof number corrected for an LMTD of 14,27°C.

Both values relative to the correlation:-

$Nu = 0,56\ (Gr\ Pr)^{0,25}$

If, however, a direct application of the LMTD were required without the use of a 'C' factor, then a suitable correlation for the test model can be derived as follows:-

If

$h = 366,94\ W/m^2K$

$$Nu = \frac{366,94 \times 0,0494}{0,6} = 30,21$$

and

$30,21 = K\ (Gr\ Pr)^{0,25}$ where 'K' is a constant

$$K = \frac{30,21}{61,4492} = 0,491626$$

Thus for the test model:-
$Nu = 0,491626\ (Gr\ Pr)^{0,25}$
at 200 litres per hour in convection assisted mode.

Assuming then that the wall resistance is negligible and the surface resistances on either side of the wall are equal, then from:-

$$u = \frac{h_{mi}\ h_{mo}}{h_{mi} + h_{mo}}$$

$$u = \frac{h_m^2}{2h_m} \qquad \text{where } h_m = h_{mi} = h_{mo}$$

$h_m = 2u$

and for convection assisted flow

$h_m = 2 \times 366,94 = 733,9\ W/m^2K$

5.8 Comparison with Alternative Correlations

5.8.1 Sieder Tate

On the assumption that the flow through the annulus is laminar forced convection, then both Kern[4] and ASHRAE[3] propose the Sieder Tate relationship:-

$$\frac{hD_e}{k} = 1,86 \left[\left[\frac{D_eG}{\Gamma} \right] \left[\frac{C\Gamma}{k} \right] \left[\frac{D_e}{l} \right] \right]^{1/3} \left[\frac{\Gamma}{\Gamma_w} \right]^{0,14}$$

For the experimental model the value of $\left[\frac{\Gamma}{\Gamma_w} \right]^{0,14}$

can be taken as 1,0 and ,

$$Nu = 1,86 \left[Re\ Pr\ \frac{D_e}{l} \right]^{1/3}$$

$$= 1,86 \left[141 \times 6,405 \times \frac{49,418}{1200} \right]^{1/3}$$

$$= 6,2078$$

which is very much less than the actual value of:-

Nu = 34,412

This correlation is also proposed in the APV (Pty) Ltd Heat Exchange Handbook[5] with the clarification that for the term:-

$$\left[\frac{r}{r_w} \right]^n$$

The exponent 'n' is a function of plate type varying between 0,1 and 0,2 while the constant of 1,86 can vary between 1,86 and 4,5 depending on the plate type.

Clearly in the experimental model, the value of the constant would appear to be closer to 10,0 if the correlation were to be valid.

5.8.2 Heat Exchanger Handbook

The HEDH(2) expands this evaluation in sections 3,7,4 and 3,7,5 as follows:-

Based on normally experienced flow through a plate exchanger, the flow would be expected to be laminar at:-

$Re \leq 10$

and turbulent at:-

$Re \geq 1000$

It states further that the transition area between these values of Re is difficult to predict without accurate testing and lies between plate heat exchanger and flat plate theory.

It proposes that for flow in this region the heat transfer can be calculated by interpolation between the laminar value of:-

$$Nu = 1,68 \left[Re \; Pr \frac{D_e}{l} \right]^{0,4} \left[\frac{\Gamma}{\Gamma_w} \right]^{0,1}$$

and turbulent of:-

$$Nu = 0,2(Re)^{0,67}Pr^{0,4} \left[\frac{\Gamma}{\Gamma_w} \right]^{0,1}$$

for values of 'l' between 0,7 - 2,0m and D_e between 4,0 and 7,0mm with an l/w aspect ratio of more than 1,8.

To compare these two values for Pr = 6,405 and Re at both 1000 and 10, then critical Nusselt numbers would be:-

Nu = 42,84
Nu = 2,476
and by interpolation for Re = 141
Nu = 7,8
which is also invalid for the test model.

5.8.3 Cheremisinoff

It is proposed in Chapter 10 of Heat Transfer Equipment[6] by Cheremisinoff, that for spiral plate heat exchangers:-

$$\frac{h}{c_pG} = 1,86 \; (Re)^{-2/3}(Pr)^{-2/3} \left[\frac{D}{l} \right]^{1/3} \left[\frac{\Gamma}{\Gamma_w} \right]^{0,14}$$

where D = the spiral dia
and G = mass velocity

c_p = specific heat

which, when calculated for the test model gives a more realistic value of:-

$h = 200\ W/m^2K$

and

$Nu = 16,5$

However, this is still half the correct value.

5.8.4 Pohlhausen

It is proposed by Pohlhausen in HEDH[2] section 2.5.1 that for parallel plates:-

$$Nu = c\sqrt[3]{\frac{PeS}{l}}$$

where

$$c = 1,468 \text{ for } \frac{PeS}{l} \geq 10^3$$

and

$$c = 3,78 \text{ for } \frac{PeS}{l} \leq 10^2$$

where Pe is the Peclet Number

$Pe = Re\ Pr$

and S is the equivalent diameter then:-

$$\frac{PeS}{l} = 37,19$$

and

$Nu = 12,6$

5.8.5 Stephan

For annular ducts the HEDH(2) gives the following correlation developed by Stephan for:-

$0{,}1 \leq Pr \leq 10^3$

$0 \leq d_i/d_o \leq 1{,}0$

$Re \leq 2\ 300$

$$Nu = Nu_\infty + f\left[\frac{d_i}{d_o}\right]\frac{0{,}19[Pe(d_h/l)]^{0{,}8}}{1{,}0+0{,}117[Pe(d_h/l)]^{0{,}467}}$$

Using the chart in the HEDH(2) of Nu_∞ against d_i/d_o, Nu_∞ was taken as 4,7 and $f(d_i/d_o)$ calculated from:-

$$f\left[\frac{d_i}{d_o}\right] = 1 + 0{,}14\left[\frac{d_i}{d_o}\right]^{1/3}$$

$Nu = 7{,}06$

which is invalid for the test model.

5.8.6 Martinelli

For free convection in annuli, Martinelli, in HEDH(2), derived the following correlation:-

$$Nu = 1{,}6\left[Pe\ \frac{d}{l} + 0{,}0919\ AF\left[Gr\ Pr\ \frac{d}{l}\right]^{0{,}75}\right]^{1/3}$$

where A = +1,0 for convection assisted flow

and A = -1,0 for convection opposed flow

and F is evaluated from a graph as a function of

1/4 (Ped/l) where 'F' becomes asymptotic at a value of approximately 0,05.

The equation yields Nu = 8,2 for convection assisted flow and a negative Nu when the Grashof Number was corrected for the convection opposed LMTD. Clearly this is an invalid solution for this experiment and HEDH(2) does suggest that the relationship should be used with care.

However, it is also suggested in HEDH(2), that the effects of the free convection could increase the rate of heat transfer to a value of three or four times that of the forced convection alone, and this would appear to be borne out by the Nusselt Numbers derived from various correlations in this section.

5.9 Regenerative Heat Exchanger

Based on a derived value for 'u' of 366,94 W/m²K, the area required for the regenerative milk to milk heat exchanger can be calculated approximately, assuming a cold fluid entering temperature of 4°C and a pasteruised milk leaving temperature of 15°C, with a uniform temperature difference of 11°C.

If losses are ignored then the heat lost by the warm fluid equals the heat gained by the cold fluid.

The heat lost by the warm fluid in cooling from the pasteurisation temperature of 72°C down to 15°C is:-

$$
\begin{aligned}
Q &= mc_p\Delta T \\
&= 189 \times 4180 \times (72 - 15) \\
&= 10\ 773\ \text{kJ/h} \\
&= 12\ 528\ \text{J/s}
\end{aligned}
$$

and

$Q = uA\ LMTD$

$12528 = 366,94\ A\ 11$

$A = 3,10\ m^2$ being the surface area required for regeneration.

The available heat transfer area in one pass of the annulus is $2,1\ m^2$.

5.10 Summary and Conclusions

The experimental process has established some clearly defined conclusions relative to the original project proposal and cast some doubt on the validity of certain established correlations when used in the test application.

5.10.1 Concept

It is concluded that the original concept design with the central annulus of the pasteuriser in a convection opposed counter flow mode would not work, due to the unexpectedly high influence of convective forces at low flow rates. However, in the convection assisted parallel flow mode, the concept of an annular heat exchanger with heated central core is valid.

5.10.2 Stagnation Zones

The stagnation zones as originally envisaged in the concept design do not appear in the convection assisted parallel flow mode and the dilution rate of residual milk would be such that the risk of bacterial propagation in the pasteurised milk would not present a hazard.

5.10.3 Practicability

The surface area envisaged for the regenerative section in the concept design was inadequate and a commercial prototype would have to have a double annulus in order to increase the heat transfer area.

Certainly, practical modifications such as corrugating the heat transfer surface could be introduced to enhance the heat transfer rate and area, but within the terms of design reference for simplicity and ease of cleaning, it is preferable to have a double annulus.

5.10.4 Mathematical Relationships

It has been shown that the relationship:-

$$Nu = 0{,}491626(Gr\ Pr)^{0.25}$$

is valid for the test model at the flow rate of approximately 200 l/h. Since this correlation is independent of Reynolds Number, it will also be valid for the regeneration exchanger with a revised Grashof Number.

It has also been shown that if the standard correlation of:-

$$Nu = 0{,}56\ (Gr\ Pr)^{0.25}$$

were used to calculate the heat transfer co-efficient then a dimensionless factor of:-

$$C = 0{,}879952$$

should be applied to the LMTD when calculating the area required in the convection *assisted flow mode*.

5.10.5 Existing Data

Comparison with the existing experimental data of others, indicates that correlations which include the Reynolds Number are less likely to be accurate than those which are based on the Grashof Number.

Presumably this is because the effect of natural, *free convection distorts the relationships* at low flow rates and values of Reynolds Number. This would also account for the invalidation of the Martinelli relationship, where a higher value of Reynolds Number would have yielded more realistic figures.

The HEDH(2), cautions the reader to *exercise care* in the use of the Martinelli equation but does not give the limiting criteria within which the equation can be reasonably applied. It is suggested that some relationship between Reynolds Number and buoyancy forces are these limiting criteria.

5.10.6 Temperature Distribution

It has been shown experimentally that the *temperature gradients through the annulus are evenly* distributed in convection assisted parallel flow, and very irregular in convection opposed counterflow.

CHAPTER 6

PROTOTYPE DESIGN

6.1 General

This chapter outlines the design and manufacturing concepts for a prototype milk pasteuriser based on the findings of previous experimental work. The final arrangement of the pasteuriser is shown in Figure 6.1.

6.2 Shells

It was deduced in section 5.9 that a heat transfer area of 3,10m² is required for the regeneration section of the heat exchanger. Assuming that the height of the exchanger is fixed at 1 200mm by standard plate size, then a mean annular diameter for half the area required would be 411mm, and taking an annular gap of 12,5mm then the outside annulus would be 417,25mm, and the inside 404,75mm. However, allowing a 10% margin of error to accommodate the effects of possible over-heating, then the surface area of each annulus becomes 1,705m², and the mean becomes 450,2mm diameter, making an outside shell of 458,45mm. For simplicity of manufacture and taking into account the surface requirements of the heating section, this value is taken as 500mm, thus:-

outside annulus diameter = 500mm
second annulus diameter = 475mm
third annulus diameter = 450mm

fourth annulus diameter = 425mm

This completes the regeneration heat exchanger. The milk input is between the second and third annuli and the milk output between the first and second and third and fourth annuli.

If the fifth annulus, being the final heating section, follows a similar spacing, then its diameter would be 400mm. However, there is a strong case to have $\pi D \leq 1,2$m for the heating shells so that the two shells could be made from one sheet of 1 200mm x 2 400mm.

Thus the outer heating cylinder can be 395mm diameter and the inner hot water cylinder 370mm diameter, both being cut from a single sheet without wastage.

Assuming a milk leaving temperature from the regeneration sections of 61°C, the temperature rise in the heating section will be 72°C - 61°C = 11°C and the heat input required, assuming a specific heat of 4180 J/kg K and flow 200 l/h.

$$
\begin{aligned}
Q &= mc_p \Delta T \\
&= 200 \times 4180 \times 11 \\
&= 9\ 196 \text{ kJ/h} \\
&= 2\ 559 \text{ J/s}
\end{aligned}
$$

Thus, for a heat transfer rate of 366,94 W/m²K and an inner annular area of 1,395m²:-

$$\text{LMTD} = \frac{2559}{366,94 \times 1,395}$$

$$= 4,999°\text{C}$$

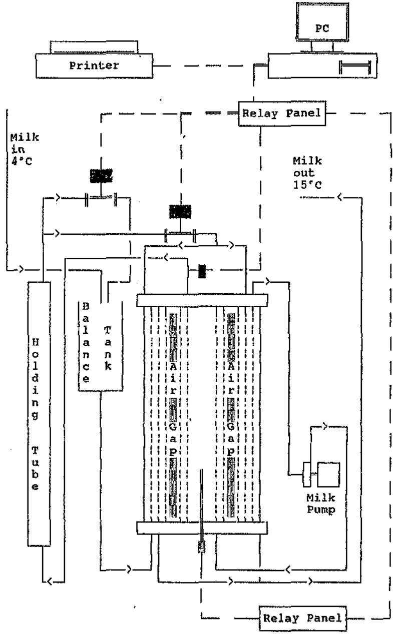


Figure 6.1 General Arrangement of Pasteur.ser

The LMTD can be manipulated by adjustment of the thermostats in the case of fixed heaters, or with forced circulation hot water at four times the milk flow rate, the temperature fall in the water would be about 3°C, thus having an entering temperature of approximately 76°C and a leaving temperature of 73°C.

$$\text{Then LMTD} = \frac{(76-61) - (73-72)}{\text{Ln}\,\frac{15}{1}}$$

$$= \frac{14}{\text{Ln}15}$$

$$= 5{,}18\text{°C}$$

This difference of 1°C at the pasteurised milk leaving point would be ideal for an optimum control condition of approximately 0,5°C.

The shells would be manufactured from 304 grade stainless steel 0,9mm thick in a standard 2B finish with one longitudinal weld.

6.3 End Plates

End plates are to be manufactured from food quality polyethylene, an attractive milky white material, easily machined and resistant to temperatures up to 120°C. The material is heat weldable for fully sealed piping connections and an end plate of 25mm thick and 600mm diameter will not easily deform when tightened against the annuli.

The end plates are to be machined with concentric grooves having centre lines of the diameters of the annuli and sufficient clearance to enable the annuli to be earily located. The grooves would each have a gasket manufactured of food quality rubber forming a moderately compressible seal at each end of the annuli. The space between each pair of grooves would be drilled and tapped, or heat welded, with a suitable 10mm nominal bore connection and the bottom plate would be drilled and tapped for the fitting of the three electric heaters and drain. The end plates would have an outside diameter of 600mm, thus allowing an overlap of 50mm all round for the fitting of four tie rods on the outside of the annulii between the end plates with which to draw up the ends on the annuli. The bottom end plate would be fitted with four adjustable feet.

6.4 Holding Tube

The purpose of the holding tube is to ensure that all particles of milk entering from the heating section of the pasteuriser at 72°C, remain at that temperature for a period of at least 15 seconds before cooling commences. Based on a flow rate of 250 l/h, the maximum envisaged for the project, and a vertical holding tube of 1 200mm long, then the velocity necessary for a 15 second pass would be:-

$$\frac{1\ 200}{15 \times 1\ 000} = 0{,}08\text{m/s}$$

This would necessitate a pipe of 33,23mm diameter. However, taking into consideration the pipework leading into the holding tube, which in itself would form an extension of the holding tube, the commercial size of 32mm nominal bore could be selected. The diameter should not be excessive as this would allow too much cooling and also in the vertical position would allow separation of the flow pattern due to reduction in mechanically induced velocity with a proportional increase in the significance of convection forces. The holding tube would be connected with bottom entry to ensure even convection assisted flow. Clearly this holding tube does not meet the criteria recommended by Kessler(7) in the DF Bulletin, but will suffice for this application.

6.5 Piping

All piping, in accordance with good practice, would be constructed from dairy tubing in 304 stainless steel. Piping would be fitted with adequate unions for easy dismantling to clean and, while a diameter of 10mm would theoretically be suitable, with a velocity of 0,5 m/s and a pressure drop of 420 Pa/m at 250 l/h a practical minimum size for cleaning would be 15mm diameter. Entering and discharge piping would have to be higher than the heater exchangers in order to flood the annuli and pump. In practice the entering pipework would be connected to a high level balance tank and the discharge pipework would feed a pasteurised milk tank at approximately 2 500mm level. This is located for gravity filling of the bottling machine.

The layout of the pipework is generally as shown in Figure 6.1. Provision to be made in the pipework for drains and venting as required and a 0C° - 100°C glass thermometer will be fitted in a pocket at the entrance to the holding tube.

6.6 Pump

The pump head can be calculated using the CIBSE(9) equivalent length method and the equivalent hydraulic diameter of the annuli as follows:-

From tables for thin wall copper piping to BS 3931.

The pressure drop in a 10mm diameter pipe at 0,069 kg/s is 420 Pa with an equivalent length EL of 0,5. The pressure drop in a 15mm diameter pipe with an EL of 0,5 is 200 Pa/m. The pressure drop in the 32mm diameter holding tube is approximately 4 Pa/m with an EL of 1,0.

The pressure drop through the annuli having an equivalent diameter of 24,0mm can be taken from tables for 25mm pipe as 9,0 Pa/m with an EL of 0,9 for full flow and 4,0 Pa/m with an EL of 1,0 for the regeneration section where the flow is reduced.

Thus, assuming a total pipe length to the pasteurised milk tank of 20 metres, including the integral piping of the unit and assuming that the inlet to the pasteurised milk tank at a height of 3 500mm then:-

20,0m	15mm pipe at 200 Pa/m	4 000 Pa
1,2m	32mm pipe at 4 Pa/m	5 Pa
2,4m	25mm pipe at 9,0 Pa/m	22 Pa
1,2m	25mm pipe at 4,0 Pa/m	5 Pa

18 bends at K = 0,8	EL = 0,5	900 Pa
Entry to Holding Tube at K = 0,7	EL = 0,5	70 Pa
Exit for Holding Tube at K = 0,4	EL = 0,5	40 Pa
Entry to annuli at K = 0,3	EL = 0,5	126 Pa
Exit for annuli at K = 0,4	EL = 0,5	168 Pa
Entry from Tank at K = 0,4	EL = 0,5	40 Pa
Exit to Tank at K = 1,0	EL = 0,5	100 Pa

Total Frictional Resistance = 5 476 Pa
Static head is 3 500mm - 1 200mm
or approximately 23 000 Pa.

The total pump head is then 23 000 Pa + 5 476 Pa 28 476 Pa, or 2,9 metres of water.

The pump selected is a Little Giant, 3 MD, single phase unit with hygienic magnetic drive, and easily dismantled polypropylene head. The motor would be 2 800 r/m 112 W.

The pump would be mounted on a suitable base attached to the feet of the pasteuriser.

6.7 Diversion valves

The proposed polysulfone air operated valves can be adapted for solenoid operation by the manufacture of a suitable bracket and the modification of a standard Burket 24 volt solenoid. The 15mm valves are manufactured in Israel by SAE AFIKIM for milking machines and meet all international food standards.

6.8 Assembly

The general arrangement of the pasteuriser is shown in Figure 6.1. Suitable brackets would be provided for the holding tube and balance tank and the feet would be adjustable. The pasteuriser could be cleaned in place by the use of a hot caustic solution in the balance tank circulated in diversion mode and later discharged to the pasteurised milk tank. To clean by dismantling, the four knurled nuts at the top of the end plate would be undone and the top end plate lifted off after disconnection of the unions in the pipework. The annuli could then be lifted off and cleaned individually, as could be end plates. The pasteuriser could then be reassembled in the reverse order.

6.9 Pasteuriser Control System

The control system is required to maintain the required milk pasteurising temperature and divert for reprocessing any milk leaving the heating section of the pasteuriser below that temperature.

The criteria require that milk must be heated to at least 72°C and, held at that temperature for 15 seconds. Should the pasteurising temperature fall below 72°C then the milk must be recycled.

The pasteurising temperature is measured after the hot water to milk heating section of the pasteuriser and before the holding tube. Measurement at this point with the diversion valves located after the holding tube, effectively allows a 15 second safety margin. Any rise in temperature above 72°C results in a proportional rise of unpleasant burnt flavour in the product which is undesirable from a consumer point of view.

There are various ready made controller/recorders on the market that would meet the above requirements, but the intention of this project is to develop a simple system of control, via a PC, so that a farmer could use his pasteurising facility alongside his other software for milking and feed control as part of an overall farming concept.

It is envisaged that the printer of the PC will serve as the recording system required in terms of the Standard Milk By Laws(1), and that the option of using a PC will be more cost effective than a controller/recorder bought off the shelf.

6.9.1 Control Parameters

The basic control cycle required for a milk pasteuriser is a simple proportional system of heat input to the primary heating water against rise or fall of milk temperature around a set point of 72°C. While not specified in the Milk By Laws(1), it is generally accepted, and reference can be made to Chapter XI of the IDF Bulletin No 200(7), that the recording instrument should have a span of about 17°C. 7°C of which should be either side of the Pasteurising temperature in divisions of 0,5°C. In practice, commercial plants can control to 0,1°C, but this control accuracy is clearly related to the narrowness of the leaving temperature difference between heated milk and heated water.

In a system having forced circulation of the hot water at, say, four times the milk flow rate, the accuracy of control will be vastly superior. The simplicity of the plant proposed does however mean that there is unlikely to be any sudden change either in flow rate or incoming milk temperature, so the possibility of needing rapid control response is minimised. With this in mind, and taking into account the experimental model tests, it is proposed to use a static water container as a primary heater, rather than forced circulation.

6.9.2 Process Control System

The diagramatic arrangement of the process control is as shown in Figure H1.

Valves X and Y are the 24 volt solenoid operated diversion and flow valves respectively, and H_1, H_2 and H_3 are heating elements each 3kW 220 V. R_1 to R_4 are low voltage normally open relays for the computer output to 24 volt interface.

T is a PT 100 thermocouple. Of the three heaters, H_1, H_2 and H_3, H_1 and H_2 are control heaters and H_3 serves to provide additional input when starting from cold.

R_5 and R_6 are 24 volt/220 volt normally open relays for heater control. Each heater has an intergral overheat thermostat which would be set at approximately 68°C to suit the temperature gradient of the primary heating water under stable flow conditions.

As a process technique, in common with other pasteurisers, water would be circulated through the system until the pasteurising temperature is reached. The primary control requirements are depicted in Figure H2.

6.9.4 Logic Definition

The logic definition is outlined in Figures H3 and H4 which indicate the control logic and time logic respectively.

The time cycle has been taken as 10 seconds, since with a holding time of 15 seconds this frequency would ensure that diversion would take place before any milk having a lower temperature than Set Point reached the diversion valve.

6.9.5 Control Software

The logic defined in section 6.9.4 has been presented in a simple BASIC programme in Table H1.

While this programme does not purport to be commercially acceptable software, it nevertheless serves to illustrate the type of simple programme that can be written for the control cycle. All variables such as set point, cycle times and intermediate switching levels are easily adjustable in the software to facilitate the reduction of hunting; this being an inherent problem associated with the use of a static water supply.

The draft programme employs only simple programming techniques and assumes inputs readily available in a convenient form. In practice however, an analogue 1/0 Board such as the Dascon -1, manufactured by Metra Byte Corp has its own language symbols for inputs and outputs. For example MD% = mode, CH% = Channel No, DIO% = A data 1/0 integer array. BASADR% = Base address of DASCON 1 accessed.

For the purpose of this report the draft programme depicts the interpretation of the logic in terms acceptable to a PC. On production of a prototype pasteuriser a card will be custom built and the final programme developed around this card.

The software takes a time input, stores it, compares it every 10 seconds to current time and completes a control cycle of temperature checks and actions.

Every 60 seconds the programme initiates a PRINT of time and milk temperature also recording both a DIVERSION MODE and audible alarm on milk temperature fall

The subroutine in the programme, for simplicity, assumes a linear output of 4 - 20 mA from a temperature detector and converts this to a temperature reading in degrees centigrade.

This oversimplification of the input to the PC is introduced to demonstrate the need for such a conversion in the final programme, the complexity of which would depend on the type of card ultimately incorporated.

The programme would continue looping for the duration of the pasteurising run until the system were switched off and the flow manually diverted.

CHAPTER 7

SUMMARY OF CONCLUSIONS

7.1 General

The contents of this chapter summarise the conclusions outlined in each of the preceding chapters.

7.2 Validity

It has been shown experimentally that the original concept of a pasteuriser with a counter flow heating section, as depicted in figure 1.1, is invalid due to the unexpectedly high role played by convective forces in mechanically induced laminar flow conditions. It has, however, been further shown that the concept of laminar flow milk pasteuriser, with an annular, convection assisted, heating section, as shown in Figure 6.1, is valid and innovative.

7.3 Existing Data

From the literature survey, it was apparent that there is a dearth of works relating to heat transfer in concentric annuli, with either convection assisted or convection opposed flow. Certain doubts have been cast on the validity of existing equations. It is suggested that this area might offer scope for further research to establish the limits within which existing data can be applied and to develop further mathemetical relationships for practical application.

7.4 Experimental Data

Extensive experimental data was obtained from a series of tests carried out on a full size model of one annulus, with primary heating, manufactured for the project.

7.5 Stagnation

It has been shown that in the convection assisted mode, due to the even temperature gradients, the anticipated propagation of stagnation zones at risk temperatures is not likely to occur.

7.6 Heat Transfer

From experimental data, mathematical relationships have been derived for the heat transfer, namely:-

$Nu = 0{,}491626\ (Gr\ Pr)^{0{,}25}$

or that a factor of 0,879952 should be applied to the LMTD when using the Fourier equation.

The overall heat transfer co-efficient was determined as 417 W/m^2k.

The reader is referred to Chapter 5 for expanded conclusions.

7.7 Controls

The analysis in Chapter 6 has shown that the concept of using a PC to control the milk pasteuriser and record the data is viable and in keeping with current trends in the farming industry. There is no doubt, however, that the question of control system stability has not been adequately addressed in the project report and will only be resolved through experiments on a prototype machine.

7.8 Practical Application

The original concept has, as a result of the project research, been modified in three major ways. The regeneration section has been doubled, the flow pattern in the heating section of the pasteuriser has been reversed from counter to parallel flow and the overall diameter of the pasteuriser has been reduced from 600mm to 500mm.

The design concepts are based on ease of manufacture, with maximum local content, avoiding the use of expensive imported plates, and with the small scale of daily milk throughput envisaged, practical considerations have taken precedence over heat exchanger efficency.

7.9 Commercial Application

In the light of the project results a patent application has been filed, Appendix I refers, and commercial manufacture appears economically viable.

7.10 Summary

The writer is conscious that many areas of the design, such as film co-efficients, limiting conditions of validity, control stability and correlations relating to convection within the primary heating medium, have not been fully explored. This has been firstly because of the practical need to draw a line somewhere in the research and secondly to limit the research to that necessary to validate commercial manufacture, while nevertheless satisfying the requirements of the six month project report.

APPENDIX A

INITIAL CALCULATIONS

The conceptual calculations contained in this Appendix are presented uncorrected in their original form converted from imperial units.

Mass flow rate required 250kg/h.

Milk Specific Heat taken as 0,95 times that of water.

Regeneration Section; Milk to Milk.

T_1	in	4,4°C	
T_1	out	50,0°C	approx
T_2	in	72,2°C	
T_2	out	21,1°C	or less

Heat rejected = Heat gained (Losses ignored)

$$Q = 250 \times 0,95 \times (72,2-21,1) \times 1,163$$
$$= 14\ 089\ J/s$$

at a mean temperature difference of 15,6 degC
and
based on 567,8 W/m^2K for concentric cylinders the Area:-

$$A = 1,6\ m^2$$

Heating section; Water to Milk.

Milk in	50,0°C
Milk out	72,2°C

Heat gain = (72,2 - 50) x 0,95 x 250 x 1,163

= 6 131 J/s

Assume a water temperature rise of 5,6 degC and an arithmetic mean temperature difference under counterflow conditions of:-

$$\text{AMTD} = \frac{(79{,}4 - 73{,}9) + (73{,}9 - 50)}{2}$$

= 14,7 degC

and surface area required at 851,7 W/m^2K (for serpentine plates).

A = 0,489m^2

State of Flow

250 kg/h approximately 0,25m^3/h

Assume gap between cylinders of 12,7mm
Equivalent diameters = 2 x 12,7mm
= 25,4mm

Assume 609,6mm diameter inner cylinder. Then perimeter of annulus is 1,915mm and

CSA = 0,0239m^2

thus velocity = 0,00286 m/s

Viscosity of milk = 1,5 centipoise

Re = 52,5 and Flow will be laminar

TEST RESULTS

Annular Thickness

The following annular thicknesses were measured through thermometer pockets:-

Table B.1 Annular Thickness

Pocket No	Thickness (mm)
1	14.6
2	14.6
3	11.5
4	12.8
5	13.5
6	8.8
7	10.4
8	13.1
9	13.3
10	10.7

Discrepancies in dimensions appear to have arisen during manufacture, apart from No 6 which was caused through damage in transit.

Thermometer Corrections

Table B.2 Thermometer Corrections

Thermometer Number	Test 1 Ambient °C	Correction °C	Test 2 40°C °C	Correction °C
1	13,3	0,0	42,3	0,0
2	13,0	+0,3	42,2	+0,1
3	13,1	+0,2	42,2	+0,1
4	13,7	-0,4	42,1	+0,2
5	13,1	+0,2	42,6	-0,3
6	13,1	+0,2	42,3	0,0
7	13,7	-0,4	42,6	-0,3
8	12,9	+0,4	41,7	+0,6
9	13,0	+0,3	42,0	+0,3
10	12,9	+0,4	42,0	+0,3
11	13,9	-0,6	42,1	+0,2
12	13,5	-0,2	42,0	+0,3
13	13,4	-0,1	42,3	0,0

Thermometer No 1 taken as base thermometer with zero correction in terms of Chapter 5, section 5.2.1.

TEST REPORT

Test No.: 01

Date: 7/07/88

Time: 12.06.00

Ambient Temp.: 14°C

Status: Convection ~~Opposed~~/Assisted/~~Nil~~

Primary Water Heating: Yes/~~No~~

Flow Measurement: 4 litres 63 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 16	50.[illegible]	[illegible]	55.10
1	13,8	Panel No 3 visible	50.30	No 3 Start to Clear	56.30
2	14,5	Panel No 3 full	51.25	No 3 Clear 17	01.25
3	15,0	Panel No 4 visible	51.30	No 4 Start to Clear	56.20
4	21,9	Panel No 4 full	52.00	No 4 Clear	58.25
5	24,5	Panel No 8 visible	52.20	No 8 Start to Clear	57.15
6	23,0	Panel No 8 full	53.[illegible]	No 8 Clear	02.20
7	24,8	Panel No 9 visible	53.22	No 9 Start to Clear	58.00
8	25,5	Panel No 9 full	54.05	No 9 Clear	07.00
9	29,0				
10	28,0	Dye Discharge Visible	54.30	Dye Discharge Clear	03.30
11	33,0				
12	30,1	Close Dye	55.10		
13	---				

Notes: Time change 16.00.00 to 17.00.00

TEST REPORT

Test No.: 02
Date: 7/07/88
Time: 17.10.00
Ambient Temp.: 14°C
Status: Convection ~~Opposed~~/Assisted/~~Nil~~
Primary Water Heating: Yes/~~No~~
Flow Measurement: 4 litres 62 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 17	15.10	Open Water	22.35
1	13,5	Panel No 3 visible	15.43	No 3 Start to Clear	24.20
2	14,0	Panel No 3 full	16.40	No 3 Clear	35.05
3	14,5	Panel No 4 visible	16.53	No 4 Start to Clear	23.25
4	20,8	Panel No 4 full	18.23	No 4 Clear	32.10
5	23,4	Panel No 8 visible	18.05	No 8 Start to Clear	25.20
6	22,8	Panel No 8 full	20.15	No 8 Clear	33.55
7	23,8	Panel No 9 visible	19.30	No 9 Start to Clear	38.40
8	24,2	Panel No 9 full	21.40	No 9 Clear	38.40
9	27,9				
10	27,0	Dye Discharge Visible	20.20	Dye Discharge Clear	36.15
11	31,3				
12	36,5	Close Dye	22.35		
13	---				

Notes:

TEST REPORT

Test No.: 03

Date: 12/07/88

Time: 14.00.00

Ambient Temp.: 13°C

Status: Convection ~~Opposed~~/~~Assisted~~/Nil

Primary Water Heating: Yes/No

Flow Measurement: 4 litres 59 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 14	07.30	Open Water	16.20
1		Panel No 3 visible	07.55	No 3 Start to Clear	23.57
2		Panel No 3 full	08.23	No 3 Clear	55.17
3		Panel No 4 visible	09.02	No 4 Start to Clear	18.00
4		Panel No 4 full	10.16	No 4 Clear	50.30
5		Panel No 8 visible	10.07	No 8 Start to Clear	20.00
6		Panel No 8 full	12.14	No 8 Clear	39.27
7		Panel No 9 visible	13.08	No 9 Start to Clear	18.08
8		Panel No 9 full	15.45	No 9 Clear	35.18
9					
10		Dye Discharge Visible	13.26	Dye Discharge Clear	40.13
11					
12		Close Dye	16.15		
13					

Notes: Panel 9 half full when discharge started blue. Flow is laminar spiral. To clear flow is vertical spiral. Clearing is 9/8/4/3.

TEST REPORT

Test No.: 04

Date: 12/07/88

Time: 14.58.00

Ambient Temp.: 13°C

Status: Convection ~~Opposed~~/~~Assisted~~/Nil

Primary Water Heating: ~~Yes~~/No

Flow Measurement: 4 litres 59 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 15	01.00	Open Water	10.10
1		Panel No 3 visible	01.32	No 3 Start to Clear	17.57
2		Panel No 3 full	03.17	No 3 Clear	41.20
3		Panel No 4 visible	02.54	No 4 Start to Clear	10.47
4		Panel No 4 full	04.26	No 4 Clear	33.30
5		Panel No 8 visible	05.26	No 8 Start to Clear	11.35
6		Panel No 8 full	06.24	No 8 Clear	24.28
7		Panel No 9 visible	06.54	No 9 Start to Clear	10.33
8		Panel No 9 full	09.50	No 9 Clear	22.25
9					
10		Dye Discharge Visible	07.55	Dye Discharge Clear	23.35
11					
12		Close Dye	10.10		
13					

Notes: One cube of dye only. Flow is vertical to Panel 9

TEST REPORT

Test No.: 05

Date: 12/07/88

Time: 15.44.00

Ambient Temp.: 13°C

Status: Convection ~~Opposed~~/~~Assisted~~/Nil

Primary Water Heating: ~~Yes~~/No

Flow Measurement: 4 litres 58 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye	15.48	Open Water	55.50
1		Panel No 3 visible	48.34	No 3 Start to Clear	01.30
2		Panel No 3 full	49.43	No 3 Clear	30.14
3		Panel No 4 visible	49.59	No 4 Start to Clear	56.43
4		Panel No 4 full	51.04	No 4 Clear	25.16
5		Panel No 8 visible	51.49	No 8 Start to Clear	57.50
6		Panel No 8 full	52.46	No 8 Clear	21.09
7		Panel No 9 visible	53.02	No 9 Start to Clear	56.19
8		Panel No 9 full	55.32	No 9 Clear	12.27
9					
10		Dye Discharge Visible	54.16	Dye Discharge Clear	13.16
11					
12		Close Dye	55.50		
13					

Notes: Two dye cubes used. 15.50.27 photograph of Panel 4 was taken, then photograph of 8.

TEST REPORT

Test No.: 06

Date: 13/07/88

Time: 12.56.00

Ambient Temp.: 14°C

Status: Convection ~~Opposed~~/Assisted/~~Nil~~

Primary Water Heating: Yes/~~No~~

Flow Measurement: 4 litres 60 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 13	07.15	Open Water	13.45
1	11,5	Panel No 3 visible	07.50	No 3 Start to Clear	14.40
2	13,0	Panel No 3 full	08.53	No 3 Clear	26.23
3	13,5	Panel No 4 visible	08.50	No 4 Start to Clear	14.23
4	20,0	Panel No 4 full	11.33	No 4 Clear	23.45
5	22,0	Panel No 8 visible	10.21	No 8 Start to Clear	15.37
6	21,5	Panel No 8 full	12.58	No 8 Clear	24.44
7	22,8	Panel No 9 visible	10.50	No 9 Start to Clear	17.23
8	23,0	Panel No 9 full	13.20	No 9 Clear	27.19
9	27,0				
10	26,0	Dye Discharge Visible	12.41	Dye Discharge Clear	27.09
11	30,0				
12	36,0	Close Dye	13.45		
13	20,0				

Notes: Two dye cubes used. Flow is laminer/ vertical.

TEST REPORT

Test No.: 07

Date: 13/07/88

Time: 13.40.00

Ambient Temp.: 14°C

Status: Convection ~~Opposed~~/Assisted/~~Nil~~

Primary Water Heating: Yes/~~No~~

Flow Measurement: 4 litres 76 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 14	04.00	Open Water	09.50
1	12,5	Panel No 3 visible	04.38	No 3 Start to Clear	11.10
2	13,8	Panel No 3 full	06.15	No 3 Clear	22.42
3	14,8	Panel No 4 visible	05.30	No 4 Start to Clear	10.50
4	23,3	Panel No 4 full	---	No 4 Clear	21.32
5	26,0	Panel No 8 visible	06.40	No 8 Start to Clear	12.17
6	24,5	Panel No 8 full	---	No 8 Clear	18.50
7	26,5	Panel No 9 visible	---	No 9 Start to Clear	14.55
8	27,0	Panel No 9 full	---	No 9 Clear	23.50
9	30,0				
10	30,5	Dye Discharge Visible	09.16	Dye Discharge Clear	23.04
11	34,5				
12	37,5	Close Dye	09.50		
13	21,2				

Notes: Test aborted - dye problems. Restarted 14.04.00
Telephone! 14.09.16 all panels full and blue discharge.

TEST REPORT

Test No.: 08

Date: 13/07/88

Time: 14.26.00

Ambient Temp.: 15°C

Status: Convection ~~Opposed~~/Assisted/~~Nil~~

Primary Water Heating: Yes/~~No~~

Flow Measurement: 4 litres 76 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 14	30.00	Open Water	38.15
1	13,0	Panel No 3 visible	30.27	No 3 Start to Clear	39.53
2	15,0	Panel No 3 full	31.58	No 3 Clear	52.48
3	17,0	Panel No 4 visible	32.14	No 4 Start to Clear	39.37
4	22,8	Panel No 4 full	34.10	No 4 Clear	51.02
5	24,5	Panel No 8 visible	34.04	No 8 Start to Clear	42.22
6	24,0	Panel No 8 full	36.10	No 8 Clear	48.18
7	26,8	Panel No 9 visible	35.52	No 9 Start to Clear	43.53
8	26,2	Panel No 9 full	38.58	No 9 Clear	55.14
9	28,8				
10	30,5	Dye Discharge Visible	37.00	Dye Discharge Clear	54.07
11	33,5				
12	37,5	Close Dye	38.15		
13	20,5				

Notes: Flow is vertical/laminar. Panel 8 late call 14.42.22
Dye solution on low speed test is unsatisfactory

TEST REPORT

Test No.: 09

Date: 13/07/88

Time: 3.01.00

Ambient Temp.: 15°C

Status: Convection ~~Opposed~~/Assisted/~~Nil~~

Primary Water Heating: Yes/~~No~~

Flow Measurement: 4 litres 76 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 14	01.00	Open Water	08.45
1	13,5	Panel No 3 visible	01.25	No 3 Start to Clear	09.51
2	15,0	Panel No 3 full	02.45	No 3 Clear	26.55
3	16,0	Panel No 4 visible	03.00	No 4 Start to Clear	09.35
4	23,0	Panel No 4 full	06.27	No 4 Clear	22.03
5	25,2	Panel No 8 visible	05.13	No 8 Start to Clear	11.58
6	24,2	Panel No 8 full	07.18	No 8 Clear	19.05
7	26,5	Panel No 9 visible	06.52	No 9 Start to Clear	13.23
8	27,5	Panel No 9 full	08.27	No 9 Clear	27.50
9	29,2				
10	30,0	Dye Discharge Visible	07.53	Dye Discharge Clear	24.16
11	33,3				
12	37,0	Close Dye	08.45		
13	23,0				

Notes: Convection forces dye spearation into vertical stings. (Additional dye) Better results

TEST REPORT

Test No.: 10

Date: 14/07/88

Time: 10.55.00

Ambient Temp.: 11°C

Status: Convection ~~Opposed~~/~~Assisted~~/Nil

Primary Water Heating: ~~Yes~~/No

Flow Measurement: 4 litres 59 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 10	56.30	Open Water	04.45
1		Panel No 3 visible	57.15	No 3 Start to Clear	06.29
2		Panel No 3 full	59.22	No 3 Clear	11.29
3		Panel No 4 visible	57.20	No 4 Start to Clear	05.39
4		Panel No 4 full	59.33	No 4 Clear	10.29
5		Panel No 8 visible	58.32	No 8 Start to Clear	05.24
6		Panel No 8 full	59.58	No 8 Clear	09.58
7		Panel No 9 visible	02.44	No 9 Start to Clear	07.44
8		Panel No 9 full	04.17	No 9 Clear	10.52
9					
10		Dye Discharge Visible	59.00	Dye Discharge Clear	12.54
11					
12		Close Dye	04.45		
13					

Notes: No leaks from dye system.

TEST REPORT

Test No.: 11

Date: 14/07/88

Time: 11.37.00

Ambient Temp.: 12°C

Status: Convection ~~Opposed~~/~~Assisted~~/Nil

Primary Water Heating: ~~Yes~~/No

Flow Measurement: 4 litres 70/74 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 11	39.00	Open Water	46.50
1		Panel No 3 visible	39.40	No 3 Start to Clear	49.38
2		Panel No 3 full	40.04	No 3 Clear	53.40
3		Panel No 4 visible	40.17	No 4 Start to Clear	49.10
4		Panel No 4 full	41.33	No 4 Clear	51.13
5		Panel No 8 visible	39.45	No 8 Start to Clear	47.46
6		Panel No 8 full	45.00	No 8 Clear	50.10
7		Panel No 9 visible	44.30	No 9 Start to Clear	49.47
8		Panel No 9 full	46.30	No 9 Clear	51.30
9					
10		Dye Discharge Visible	41.15	Dye Discharge Clear	54.52
11					
12		Close Dye	46.50		
13					

Notes: Panel 9 vertually no corruption 11.44.00. Flow is from 10 straight down to 3. Dye discharge dark blue. Dye line drops horizontally. Leak from dye system.

TEST REPORT

Test No.: 12

Date: 14/07/90

Time: 12.33.00

Ambient Temp.: 13°C

Status: Convection ~~Opposed~~/~~Assisted~~/Nil

Primary Water Heating: ~~Yes~~/No

Flow Measurement: 4 litres 87 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 12	33.00	Open Water	40.00
1		Panel No 3 visible	33.42	No 3 Start to Clear	42.43
2		Panel No 3 full	34.13	No 3 Clear	47.43
3		Panel No 4 visible	33.46	No 4 Start to Clear	42.03
4		Panel No 4 full	34.48	No 4 Clear	46.30
5		Panel No 8 visible	33.35	No 8 Start to Clear	41.09
6		Panel No 8 full	38.27	No 8 Clear	44.40
7		Panel No 9 visible	38.27	No 9 Start to Clear	41.43
8		Panel No 9 full	39.21	No 9 Clear	46.11
9					
10		Dye Discharge Visible	34.48	Dye Discharge Clear	48.32
11					
12		Close Dye	40.00		
13					

Notes: Leak from dye system.

TEST REPORT

Test No.: 13

Date: 14/07/88

Time: 14.48.00

Ambient Temp.: 13.5°C

Status: Convection ~~Opposed~~/~~Assisted~~/Nil

Primary Water Heating: ~~Yes~~/No

Flow Measurement: 4 litres 70 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 14	56.15	Open Water	02.00
1	21,8	Panel No 3 visible	56.40	No 3 Start to Clear	02.50
2	23,5	Panel No 3 full	57.05	No 3 Clear	15.45
3	22,3	Panel No 4 visible	56.50	No 4 Start to Clear	03.09
4	26,5	Panel No 4 full	58.00	No 4 Clear	14.58
5	28,2	Panel No 8 visible	57.44	No 8 Start to Clear	03.32
6	28,0	Panel No 8 full	59.00	No 8 Clear	13.58
7	23,0	Panel No 9 visible	53.48	No 9 Start to Clear	05.27
8	27,2	Panel No 9 full	01.22	No 9 Clear	17.58
9	31,0				11.26
10	13,8	Dye Discharge Visible	57.44	Dye Discharge Clear	
11	13,5				
12	39,3	Close Dye	02.00		
13	28,5				

Notes: Convection is vertical - esp Panel 4. Flow is 10/3 Convection is 4/8/9. 3.07.30 even defused blue. General defusion remains. Thermometer No 7 fluctuates +- 1°C

TEST REPORT

Test No.: 14

Date: 14/07/88

Time: 15.24.00

Ambient Temp.: 14°C

Status: Convection Opposed/~~Assisted~~/~~Nil~~

Primary Water Heating: Yes ~~No~~

Flow Measurement: 4 litres 74 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 15	30.00	Open Water	35.10
1	22,8	Panel No 3 visible	30.28	No 3 Start to Clear	37.05
2	23,8	Panel No 3 full	30.37	No 3 Clear	46.45
3	22,0	Panel No 4 visible	30.40	No 4 Start to Clear	37.10
4	28,0	Panel No 4 full	31.35	No 4 Clear	47.39
5	28,5	Panel No 8 visible	31.30	No 8 Start to Clear	37.30
6	29,0	Panel No 8 full	32.27	No 8 Clear	46.08
7	24,0	Panel No 9 visible	32.43	No 9 Start to Clear	39.26
8	27,5	Panel No 9 full	34.55	No 9 Clear	52.59
9	31,0				
10	14,0	Dye Discharge Visible	31.28	Dye Discharge Clear	47.49
11	13,8				
12	39,5	Close Dye	35.10		
13	29,0				

Notes: Thermometer No flucuates +-1°C. Convection began at 15.31.20. At 15.38.55 photograph, general light blue. At 15.39.52 pump/dye system/very even difusion. When 'clear' there was slight defusion of dye - Test 13 too. Valve seeting for Tests 13 & 14 as per unheated test and no leaks from dye system.

TEST REPORT

Test No.: 15

Date: 14/07/88

Time: 15.59.00

Ambient Temp.: 13°C

Status: Convection Opposed/~~Assisted~~/~~Nil~~

Primary Water Heating: Yes/~~No~~

Flow Measurement: 4 litres 79 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 16	05.00	Open Water	11.30
1	21,5	Panel No 3 visible	05.24	No 3 Start to Clear	12.40
2	23,2	Panel No 3 full	05.35	No 3 Clear ?	20.50
3	21,5	Panel No 4 visible	05.50	No 4 Start to Clear	13.23
4	26,8	Panel No 4 full	06.59	No 4 Clear	23.00
5	27,5	Panel No 8 visible	06.50	No 8 Start to Clear	13.38
6	28,0	Panel No 8 full	08.02	No 8 Clear ?	21.00
7	23,0	Panel No 9 visible	07.55	No 9 Start to Clear	16.38
8	26,8	Panel No 9 full	11.10	No 9 Clear	28.10
9	30,0				
10	14,2	Dye Discharge Visible	06.40	Dye Discharge Clear	24.10
11	13,8				
12	39,0	Close Dye	11.30		
13	28,2				

Notes: Thermometer No 7 fluctuates +- 1°C. At 16.06.14 photograph of Panel 4. Rolls - strings - convective. System set at maximum flow available.

TEST REPORT

Test No.: 16

Date: 14/07/88

Time: 16.35.00

Ambient Temp.: 12°C

Status: Convection Opposed/~~Assisted~~/~~Nil~~

Primary Water Heating: Yes/~~No~~

Flow Measurement: 4 litres 79 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 16	43.00	Open Water	48.30
1	21,5	Panel No 3 visible	43.25	No 3 Start to Clear	49.16
2	23,5	Panel No 3 full	43.37	No 3 Clear	00.16
3	21,5	Panel No 4 visible	43.40	No 4 Start to Clear	49.40
4	26,0	Panel No 4 full	44,51	No 4 Clear	00.40
5	27,5	Panel No 8 visible	43.55	No 8 Start to Clear	50.01
6	27,5	Panel No 8 full	45.31	No 8 Clear	59.10
7	21,0	Panel No 9 visible	46.03	No 9 Start to Clear	52.22
8	21,5	Panel No 9 full	48.08	No 9 Clear	05.05
9	30,5				
10	13,2	Dye Discharge Visible	46.00	Dye Discharge Clear	01.32
11	13,5				
12	38,3	Close Dye	48.30		
13	28,2				

Notes: Maximum flow available. Thermometer No 3 fluctuates +-,5°C and Thermometer No 7 +- 1°C. Flow down then rising. Convection is spiral left/right. Discharge deep blue, panels light blue. All clearing slowly, fairly evenly.

TEST REPORT

Test No.: 17

Date: 14/07/88

Time: 17.08.00

Ambient Temp.: 11°C

Status: Convection Opposed/~~Assisted~~/~~Nil~~

Primary Water Heating: Yes/~~No~~

Flow Measurement: 4 litres 80 secs

Therms.		Dye Status			
No.	Deg C		Time		Time
		Open Dye 17	15.00	Open Water	20.20
1	21.5	Panel No 3 visible	15.28	No 3 Start to Clear	21.03
2	22.8	Panel No 3 full	15.34	No 3 Clear	32.55
3	21.5	Panel No 4 visible	15.56	No 4 Start to Clear	21.38
4	26.5	Panel No 4 full	17.05	No 4 Clear	35.54
5	27.2	Panel No 8 visible	15.18	No 8 Start to Clear	22.27
6	27.5	Panel No 8 full	17.51	No 8 Clear	33.47
7	20.0	Panel No 9 visible	18.13	No 9 Start to Clear	25.15
8	26.5	Panel No 9 full	19.55	No 9 Clear	45.30
9	30.8				
10	13.0	Dye Discharge Visible	16.35	Dye Discharge Clear	33.31
11	13.5				
12	38.5	Close Dye	20.20		
13	28.5				

Notes: Thermometer No 7 fluctuates +- 1°C. Vertical convection slightly left to right. Convection strands between 1 and 1,5cm apart, and 1cm wide. 17.19.39 air leak.

CONSOLIDATED TEST RESULTS

Table C1 Sequence of Panels Filled

Bottom Flow Connection - No Heat

TEST No	PANEL No	PANEL No	PANEL No	PANEL No
3	3	4	8	9
4	3	4	8	9
5	3	4	8	9

Top Flow Connection - No Heat

TEST No	PANEL No	PANEL No	PANEL No	PANEL No
10	3	4	8	9
11	3	4	8	9
12	3	4	8	9

Table C2   Sequence of Panels Filled

Convection Assisted

TEST No	PANEL No	PANEL No	PANEL No	PANEL No
1	3	4	8	9
2	3	4	8	9
6	3	4	8	8
7	no result	--	--	--
8	3	4	8	9
9	3	4 8	8	9

Convection Opposed

TEST No	PANEL No	PANEL No	PANEL No	PANEL No
13	3	4	8	9
14	3	4	8	9
15	3	4	8	9
16	3	4	8	9
17	3	4	8	9

Table C3 Sequence of Panels Cleared

Bottom Flow Connection - No Heat

TEST No	PANEL No	PANEL No	PANEL No	PANEL No
3	9	8	3	4
4	9	8	4	3
5	9	8	4	3

Top Flow Connection - No Heat

TEST NO	PANEL No	PANEL NO	PANEL No	PANEL No
10	8	4	9	3
11	8	4	9	3
12	8	9	4	3

Table C4 . Sequence of Panels Cleared

Convection Assisted

TEST No	PANEL No	PANEL No	PANEL No	PANEL No
1	4	8	3	9
2	4	8	3	9
6	4	8	3	9
7	8	4	3	9
8	8	4	3	9
9	8	4	3	9

Convection Opposed

TEST No	PANEL No	PANEL No	PANEL No	PANEL No
13	8	4	3	9
14	8	4	3	9
15	3	8	4	9
16	8	3	4	9
17	3	8	4	9

Table C5 Time Taken for Filling from Zero Base

Bottom flow Connection - No Heat

TEST No	PANEL 3		PANEL 4		PANEL 6		PANEL 9		CYCLE	FLOW
	Start	Finish	Start	Finish	Start	Finish	Start	Finish		
	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	l/m
3	00-25	01-53	01-32	02-46	02-37	04-45	05-38	08-15	08-15	4,067
4	00-32	02-17	01-54	03-26	04-26	05-24	05-24	08-50	08-50	4,067
5	00-34	01-41	01-59	03-04	03-44	04-46	05-02	07-32	07-32	4,137
AVERAGE	00-30	01-58	01-48	03-05	03-37	04-58	15-21	08-12	08-12	4,090

Top Flow Connection - No Heat

TEST No	PANEL 3		PANEL 4		PANEL 6		PANEL 9		CYCLE	FLOW
	Start	Finish	Start	Finish	Start	Finish	Start	Finish		
	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	l/m
10	00-45	02-52	00-50	03-03	02-02	03-28	06-14	08-47	08-47	4,067
11	00-40	01-04	01-17	02-33	00-45	06-00	05-30	07-30	07-30	3,243
12	00-42	01-13	00-46	01-48	00-35	05-27	05-27	06-21	06-21	2,758
AVERAGE	00-42	01-43	00-58	02-28	01-07	04-58	05-44	07-33	07-33	3,356

Table C6 Time Taken for Filling from Zero Base

Convection Assisted

TEST No	PANEL 3		PANEL 4		PANEL 8		PANEL 9		CYCLE	FLOW
	Start	Finish	Start	Finish	Start	Finish	Start	Finish		
	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	l/m
1	00-30	01-25	01-30	02-00	02-20	03-05	03-22	04-05	04-30	3,000
2	00-33	01-30	01-43	03-13	02-55	05-05	04-20	06-30	06-30	3,999
6	00-35	01-38	01-35	04-18	03-06	05-43	03-35	06-05	06-05	4,000
7	00-38	02-15	01-30	---	02-40	---	---	---	---	3,157
8	00-27	01-58	02-14	04-10	04-04	06-10	05-52	08-58	08-58	3,157
9	00-25	01-45	02-00	05-27	04-13	06-18	05-52	07-27	07-27	3,157
AVERAGE	00-31	01-45	01-45	03-11	03-13	04-23	03-50	05-31	05-35	3,545

Convection Opposed

TEST No	PANEL 3		PANEL 4		PANEL 8		PANEL 9		CYCLE	FLOW
	Start	Finish	Start	Finish	Start	Finish	Start	Finish		
	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	l/m
13	00-25	00-50	00-35	01-45	01-29	02-45	03-33	05-07	05-07	3,428
14	00-28	00-37	00-40	01-35	01-30	02-27	02-45	05-55	04-55	3,243
15	00-24	00-35	00-30	01-39	01-58	03-03	02-55	06-10	06-18	3,037
16	00-25	00-37	00-40	01-51	00-55	02-31	03-03	05-08	05-08	3,037
17	00-28	00-34	00-56	02-05	00-18	02-36	02-58	04-40	04-40	3,000
AVERAGE	00-26	00-39	00-44	01-31	01-12	02-40	03-03	05-24	05-24	3,149

Table C7 Time Taken to Clear from Zero Base

Bottom Flow Connection - No Heat

TEST No	PANEL 3		PANEL 4		PANEL 8		PANEL 9		CYCLE	FLOW
	Start	Finish	Start	Finish	Start	Finish	Start	Finish		
	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	l/m
3	07-37	28-57	01-40	34-10	03-10	23-07	01-48	18-58	34-10	4,067
4	07-47	31-10	00-37	23-20	01-25	14-18	00-23	12-15	31-10	4,067
5	05-40	34-24	00-53	29-26	02-00	25-19	00-29	16-37	34-24	4,137
AVERAGE	03-01	31-30	01-03	28-59	02-12	20-55	00-53	15-57	3. 15	4,090

Top Flow Connection - No Heat

TEST No	PANEL 3		PANEL 4		PANEL 8		PANEL 9		CYCLE	FLOW
	Start	Finish	Start	Finish	Start	Finish	Start	Finish		
	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	l/m
10	01-44	06-44	00-54	05-44	00-39	05-33	02-55	06-07	06-44	4,067
11	02-48	06-50	02-20	04-23	00-56	03-20	02-57	04-40	06-50	3,243
12	02-43	07-43	02-03	06-30	01-09	04-40	01-43	06-11	07-43	2,758
AVERAGE	02-25	07 06	01-46	05-32	00-54	04-24	02-32	05-39	07-06	3,356

Table C8 Time Taken to Clear from Zero Base

Convection Assisted

TEST No	PANEL 3		PANEL 4		PANEL 8		PANEL 9		CYCLE	FLOW
	Start	Finish	Start	Finish	Start	Finish	Start	Finish		
	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	l/m
1	01-20	06-15	01-10	03-15	02-05	07-10	02-50	11-50	11-50	3,800
2	01-45	17-30	00-50	09-35	02-45	11-20	03-55	16-05	16-05	3,999
6	00-55	12-38	00-38	10-00	01-52	10-59	03-38	13-34	13-34	4,000
7	01-20	12-32	01-00	11-42	02-29	09-00	05-05	14-00	14-00	3,157
8	01-38	15-33	01-22	12-47	04-06	10-03	05-38	16-59	16-59	3,157
9	01-06	18-10	00-50	13-18	03-13	10-20	04-38	19-05	19-05	3,157
AVERAGE	01-21	12-56	00-58	14-06	02-45	09-57	04-17	15-15	15-15	3,345

Convection Opposed

TEST No	PANEL 3		PANEL 4		PANEL 8		PANEL 9		CYCLE	FLOW
	Start	Finish	Start	Finish	Start	Finish	Start	Finish		
	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	min-sec	l/m
13	00-50	13-45	01-09	12-58	01-32	11-58	03-27	15-58	15-58	3,428
14	01-55	11-35	02-00	12-29	02-20	10-58	04-16	17-49	17-49	3,243
15	01-10	09-20	01-53	11-30	02-00	09-30	05-08	16-40	16-40	3,037
16	00-46	11-40	01-10	12-18	01-31	10-40	03-52	16-35	16-35	3,037
17	01-03	12-55	01-38	15-54	02-27	13-47	05-15	25-30	25-30	3,000
AVERAGE	01-09	11-51	01-34	13-02	02-00	11-23	04-24	18-30	18-30	3,149

Table C9 Time to Corrupt per Panel

Convection Assisted

TEST	PANEL 3	PANEL 4	PANRL 8	PANEL 9	FLOW
No	min-sec	min-sec	min-sec	min-sec	l/m
1	00-55	00-30	00-45	00-43	3,000
2	00-57	01-30	02-10	02-10	3,999
6	*01-03*	*02-43*	*02-37*	*02-30*	4,000
7	01-37	--	--	--	3,157
8	01-31	01-56	02-06	03-06	3,157
9	01-20	03-27	02-07	01-35	3,157
AVERAGE	01-14	02-01	01-57	02-01	3,545

Convection Opposed

TEST	PANEL 3	PANRL 4	PANEL 8	PANEL 9	FLOW
No	min-sec	min-sec	min-sec	min-sec	l/m
13	00-25	01-10	01-16	01-34	3,428
14	00-09	00-55	00-57	02-10	3,243
15	00-11	01-09	01-12	03-15	3,037
16	00-12	01-11	01-36	02-05	3,037
17	00-06	01-09	01-18	01-42	3,000
AVERAGE	00-13	01-07	01-16	02-09	3,149

Table C10 Time Taken to Corrupt per Panel

Bottom Flow Connection - No Heat

TEST	PANEL 3	PANEL 4	PANEL 8	PANEL 9	FLOW
No	min-sec	min-sec	min-sec	min-sec	l/m
3	01-28	01-14	02-08	02-37	4,067
4	01-45	01-32	00-58	02-56	4,067
5	01-09	01-05	00-56	02-30	4,137
AVERAGE	01-27	01-17	01-21	02-41	4,090

Top Flow Connection - No Heat

TEST	PANEL 3	PANEL 4	PANEL 8	PANEL 9	FLOW
No	min-sec	min-sec	min-sec	min-sec	l/m
10	02-07	02-13	01-26	02-33	4,067
11	00-24	01-16	05-15	02-00	3,243
12	00-31	01-02	04-52	00-54	2,758
AVERAGE	01-01	01-30	30-51	01-49	3,356

Table C11 Time Taken to Clear per Panel

Convection Assisted

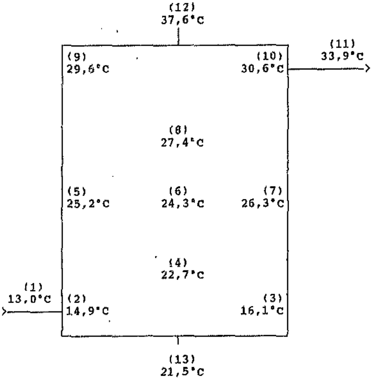
TEST No	PANEL 3 min-sec	PANEL 4 min-sec	PANEL 8 min-sec	PANEL 9 min-sec	FLOW l/m
1	04-55	02-05	05-05	09-08	3,800
2	10-45	08-45	06-35	12-10	3,999
6	11-43	09-22	09-07	09-56	4,000
7	11-12	10-42	06-33	08-55	3,157
8	13-55	11-25	05-59	11-21	3,157
9	17-04	12-29	07-07	14-27	3,157
AVERAGE	11-26	09-45	07-04	10-58	3,545

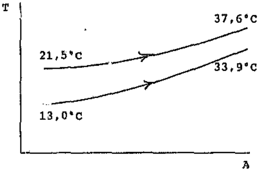
Convection Opposed

TEST No	PANEL 3 min-sec	PANEL 4 min-sec	PANEL 8 min-sec	PANEL 9 min-sec	FLOW l/m
13	12-55	11-49	10-26	12-31	3,428
14	09-40	10-29	08-38	13-33	3,243
15	08-10	09-37	07-22	11-32	3,037
16	10-54	11-08	09-09	12-43	3,037
17	11-52	14-16	11-20	20-15	3,000
AVERAGE	10-42	11-28	09-23	14-07	3,149

Figure C1

Corrected Mean Temperatures - Tests 7,8 and 9





Temperature Distribution, Convection Assisted Flow

Table C12 *Time Taken to Clear per Panel*

Bottom Flow Connection - No Heat

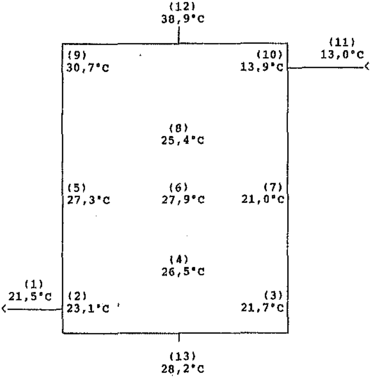
TEST	PANEL 3	PANEL 4	PANEL 8	PANEL 9	FLOW
No	min-sec	min-sec	min-sec	min-sec	l/m
3	21-20	32-30	19-27	17-10	4,067
4	23-26	22-43	12-53	11-52	4,067
5	28-44	28-33	23-19	16-08	4,137
AVERAGE	24-30	27-55	18-33	15-03	4,090

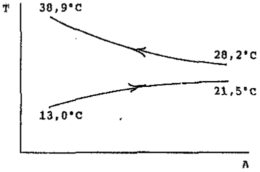
Top Flow Connection - No Heat

TEST	PANEL 3	PANEL 4	PANEL 8	PANEL 9	FLOW
No	min-sec	min-sec	min-sec	min-sec	l/m
10	05-00	04-50	04-34	03-12	4,067
11	04-02	02-03	02-24	01-43	3,243
12	05-00	04-27	03-31	04-28	2,758
AVERAGE	04-41	03-47	03-30	03-06	3,356

Figure C2

Corrected Mean Temperatures - Tests 15,16 and 17

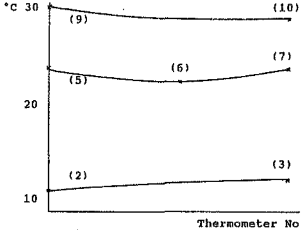




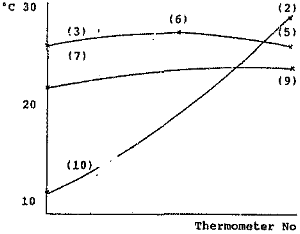
Temperature Distribution, Convection Opposed Flow

Figure C3

Horizontal Temperature Gradients



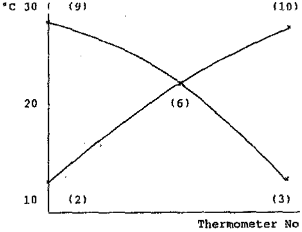
Convection Assisted Flow



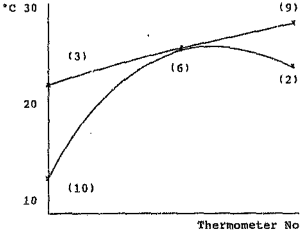
Convection Opposed Flow

Figure C4

Diagonal Temperature Gradients



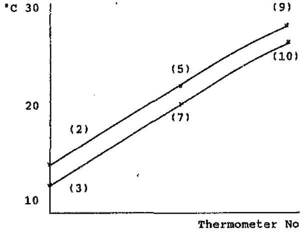
Convection Assisted Flow



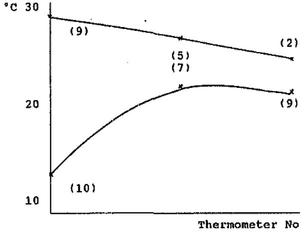
Convection Opposed Flow

Figure C5

Vertical Temperature Gradients



Convection Assisted Flow



Convection Opposed Flow

DETERMINATION OF FLOW CONDITION

The average annular gap was calculated at 12,1mm, Chapter 5, section 5.2.2 refers.

The outside diameter of the annulus was 600mm.

Thus inside diameter (600 - 24,2) = 575,8mm. The equivalent diameter of the annulus is calculated:-

$$D_e = \frac{4 \text{ x flow area}}{\text{wetted perimeter}}$$

$$= \frac{4\pi(D_o^2 - D_i^2)}{4\pi D_i}$$

$$= \frac{D_o^2 - D_i^2}{D_i}$$

where D_o and D_i are the inner and outer diameters of the annulus:-

$$D_e = \frac{600^2 - 575{,}8^2}{575{,}8}$$

$$= 49{,}418 \text{ mm}$$

taking absolute viscosity of water 'Γ' at 23°C

$\Gamma = 0{,}000919$ kg/m s

and density of water 'ρ' at 23°C

ρ = 995,9 kg/m^3

Flow rate taken as 3,545 l/m

= 0,003545 m^3/m

or = 0,000059 m^3/s

Flow area = $\frac{\pi}{4}$ $(D_o^2 - D_i^2)$

= 0,022351 m^2

and velocity 'v' = 0,0026397 m/s

$$Re = \frac{D_e v \rho}{\Gamma}$$

$$= \frac{0{,}049418 \times 0{,}0026397 \times 995{,}9}{0{,}000919}$$

Re = 141

The flow therefore is laminar.

APPENDIX E

DERIVATION OF DECAY TIME

Based on the results of Table C11 and taking the longest time to clear per critical panel as 9 min 45 secs, the rate of decrease in concentration 'Ci ' of residual material is proportional to 'Ci'.

Thus

$$\frac{dCi}{dt} = kCi \qquad \text{,where k is a constant}$$

and

$$\frac{dt}{dCi} = \frac{1}{kCi}$$

$$dt = \frac{dCi}{kCi} = \frac{1}{kCi}\, dCi$$

$$t = \int \frac{1}{kCi}\, dCi + c \qquad \text{where c is a constant}$$

$$t = \frac{1}{k} \log Ci + c$$

$$\log Ci = k(t - c)$$

and

$$Ci = e^{k(t - c)} = e^{kt}e^{-kc}$$

$$Ci = Ae^{kt} \qquad \text{where A is an arbitary constant}$$

Thus if the concentration of the dye is:-

100% at t = 0,0 minutes

and

0,5% at $t = 9{,}75$ minutes

then at $t = 0$

$Ci = 100 = Ae^{(k \times 0)}$

and at $t = 9{,}75$ minutes

$Ci = 0{,}5 = Ae^{k9{,}75}$

$Ae^{(k \times 0)} = 200\ Ae^{k9{,}75}$

$100 = Ae^{(k \times 0)}$

$A = 100$

$100e^{(k \times 0)} = 200 \times 100e^{k9{,}75}$

$100 = 20000e^{k9{,}75}$

$e^{k9{,}75} = 0{,}005$

$e = (0{,}005)^{1/9{,}75\,k}$

and concentration at a time 't' is given by

$Ci = Ae^{kt}$

$= A\left[(0{,}005)^{1/9{,}75k}\right]^{kt}$

$= A\ (0{,}005)^{t/9{,}75}$

$Ci = 100\ (0{,}005)^{t/9{,}75}$

Thus concentration of original milk residual in a panel after 30 minutes would be:-

$$Ci = 100\ (0{,}005)^{30/9{,}75}$$

$$= 100\ (0{,}005)^{3{,}0769}$$

$$= 0{,}00001\ \%$$

APPENDIX F

DERIVATION OF LMTD

Based on convection assisted flow and the temperatures indicated in Figure C1.

$$\text{LMTD} = \frac{\Delta T \text{ max} - \Delta T \text{ min}}{\text{Ln} \dfrac{\Delta T \text{ max}}{\Delta T \text{ min}}}$$

$$= \frac{8,5 - 3,7}{\text{Ln} \dfrac{8,5}{3,7}}$$

$$= \frac{4,8}{0,8317}$$

$$= 5,77°\text{C}$$

For convection opposed counterflow and using the data from Figure C2

$$\text{LMTD} = \frac{25,9 - 6,7}{\text{Ln} \dfrac{25,9}{6,7}}$$

$$= \frac{19,2}{1,3523}$$

$$\text{LMTD} = 14,20°\text{C}$$

DETERMINATION OF DIMENSIONLESS GROUPS

ne Grashof Number

$$Gr = \frac{D_m^3 \rho^2 g\beta\Delta T}{\Gamma^2}$$

and to determine the co-efficient of expansion β between T_1 and T_2:-

$$\beta = \frac{\rho^2_1 - \rho^2_2}{2(2T_2 - T_1)(\rho_1\rho_2)}$$

For water expanding from 23.4°C with an LMTD of 5,77°C

$$\beta = \frac{997{,}5^2 - 995{,}9^2}{2(5{,}77)\ 997{,}5 \times 995{,}9}$$

$$= 0{,}0002782/°C$$

Thus the Gr No based on the LMTD becomes:

$$Gr = \frac{0{,}0494^3 \times 995{,}9^2 \times 9{,}8 \times 0{,}0002782 \times 5{,}77}{0.000919^2}$$

where

D_e = 0,0494 m

ρ = 995,9 kg/m^3

g = 9,8m/s^2

β = 0,2782 x 10^{-3}/°C

ΔT = LMTD

Γ = 919 x 10^{-6}kg/m s

with all values taken at mean fluid temperature of 23,45°C

Gr = 2,226108 x 10^6

The Prandtl Number at 23,45°C

$$Pr = \left[\frac{c_p \Gamma}{k} \right]$$

$$= \frac{4181,5 \times 919 \times 10^{-6}}{0,6}$$

Pr = 6,405

when

c_p = 4181,5 J/kg K

k = 0,6 W/m^{2}K

APPENDIX H

Table H1

Draft Control Software

```
100   REM PASTEURER CONTROL CYCLE
110   REM DAIRY ENGINEERING (SA)
120   REM TEMPERATURE ACCESS TEMP FILE
130   REM VALVE X OUTPUT CHANNEL 001
140   REM VALVE Y OUTPUT CHANNEL 002
150   REM HEATER 2 OUTPUT CHANNEL 003
160   REM HEATER 3 OUTPUT CHANNEL 004

170   LPRINT "ABC DAIRY CO - PASTEURISING RUN"
180   LPRINT DATE$
190   LPRINT TIME$
200   LET TIME$ = A$
210   DATA A TIME$
220   LET B$ = VAL A$
230   READ TIME$
240   FOR TIME$ = B$ TO B$ + 00:01:00, STEP
      00:00:10,
250   OPEN TEMP FILE
260   INPUT I$
270   CLOSE TEMP FILE

280   REM SUB CONVERTS INPUT TO TEMP
290   GOSUB 6000
300   INPUT T$
310   IF T$ > 70 THEN 360
320   LPRINT "DIVERT MODE"
330   OUT 001,003,004
```

Table H1 cont

```
340   REM AUDIBLE ALARM
350   BEEP
360   IF T$ ≥ 72 THEN 400
370   OUT 001, 003
380   LPRINT "DIVERT MODE"
390   BEEP
400   IF T$ ≥ 72.5 THEN 430
410   REM MILK FLOW BEGINS
420   OUT 002, 003
430   OUT 002
440   NEXT TIME$
450   STOP
460   LPRINT T$
470   GOTO 200

6000  FOR I$ = 04 TO 20 STEP 0.1,
6001  REM LINEAR THERMOCOUPLE ASSUMED
6002  T$ = M*I$ + C
6003  REM M AND C THERMOCOUPLE CONSTANTS
6004  RETURN

9999  END
```

Figure H1 General Arrangement of Control System

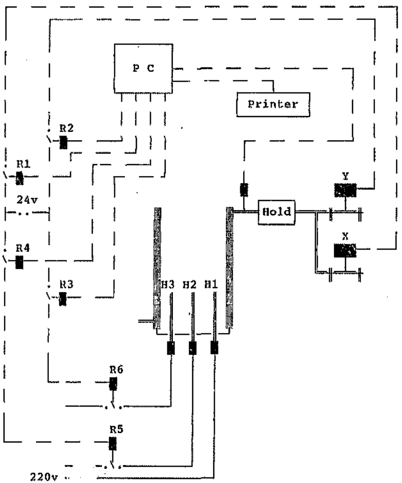


Figure H2 Primary Control Requirements

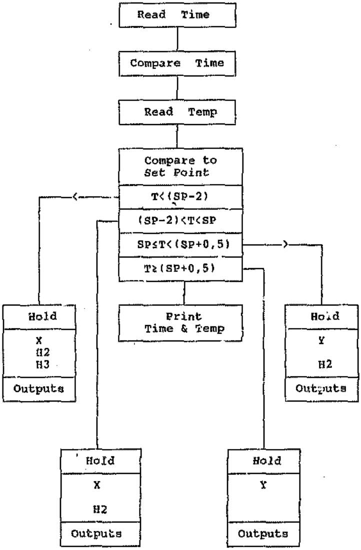


Figure H3 Temperature Control Cycle Logic

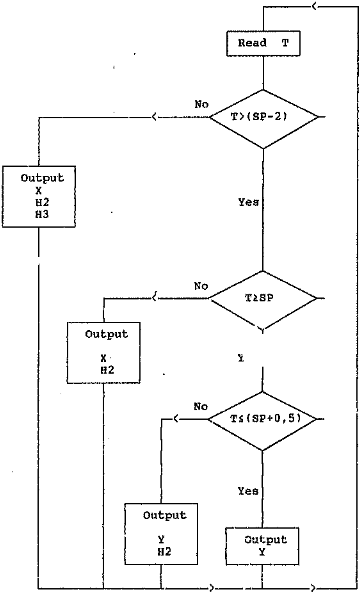
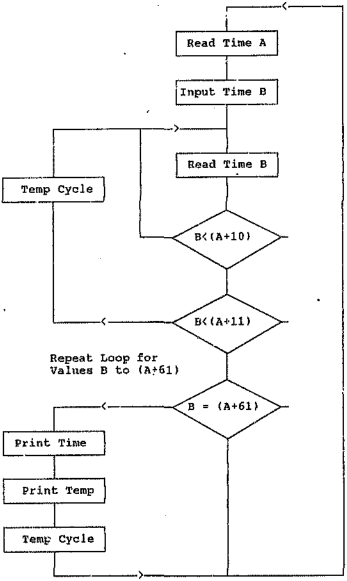


Figure H4 Time Control Cycle Logic



PATENT REGISTRATION

D.M. KISCH INC., Johannesburg

Form P.1

REPUBLIC OF SOUTH AFRICA
PATENTS ACT, 1978

APPLICATION FOR A PATENT AND ACKNOWLEDGEMENT OF RECEIPT

(Section 30(1) — Regulation 22)
The grant of a patent is hereby requested by the undermentioned applicant on the basis of the present application filed in duplicate.

PATENT APPLICATION NO.	APPLICANT'S OR AGENT'S REFERENCE
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MIDRAND

TITLE OF INVENTION

54 MILK PASTEURISER

	THE APPLICANT CLAIMS PRIORITY AS SET OUT ON THE ACCOMPANYING FORM P.2	
	THIS APPLICATION IS FOR A PATENT OF ADDITION TO PATENT APPLICATION NO.	21 01
	THIS APPLICATION IS A FRESH APPLICATION IN TERMS OF SECTION 37 AND BASED ON APPLICATION NO.	21 01

THIS APPLICATION IS ACCOMPANIED BY:

X	1	A single copy of a provisional ~~XXXXXXXXXXXXXXXXX~~ specification of 13 pages.
X	2	Drawings of 1 sheets.
	3	*Publication particulars and abstract (Form P.8 in duplicate).*
	4	A copy of Figure of the drawings (if any) for the abstract.
	5	An assignment of invention.
	6	Certified priority document(s) (State number).
	7	Translation of the priority document(s).
	8	An assignment of priority rights.
	9	A copy of the Form P.2 and the specification of S.A. Patent Application No. 21 01
X	10	A declaration and power of attorney on Form P.3
	11	Request for ante-dating of Form P.4
	12	Request for classification on Form P.9
	13	

DATED THIS 21st DAY OF September 19 88

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