An experimental study of boiling in calandria tubes

SRDC Project JCU021

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Australian Government
Sugar Research and Development Corporation

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Executive Summary:

Raw sugar processing relies heavily on process equipment employing calandria-based heating systems to concentrate highly viscous sugar solutions, such as evaporators or vacuum pans. The design of these unit operations is based largely on experience and lacks a rigorous basis. Due to the high capital cost of these components, this situation is highly undesirable. The main aim of this project is to develop an experimental apparatus that can be used to measure viscous boiling phenomena in a single calandria tube, boiling molasses and massecuites. Data gathered will be an invaluable resource to assist with the development of models that can be used to assist with the design of full-scale equipment.

The single tube boiling circuit that resulted from this project was developed using sound engineering principles. The mechanical design of the circuit itself was complemented with a user-friendly control and data acquisition system that assists the experimenter in controlling various aspects of the equipment. While most of the work was done by JCU staff and undergraduate students, collaborations with SRI staff were instrumental in finishing the project.

The main deliverable of this project is the commissioned boiling circuit apparatus. This equipment is currently being used on a follow-up project, SRI129, to evaluate the boiling behaviour of viscous fluids, such as molasses and high-grade massecuites.

It is anticipated that there will be a significant financial benefits to the Australian sugar industry, since more rigorous designs of vacuum pans will be possible for the first time. It is hoped that further research can be supported in order to continue the present studies.

Background:

Calandria heat exchangers are found in a variety of unit operations used within raw sugar mills. A calandria is essentially a bank of parallel tubes with a central downcoming section. The cross section of a typical vacuum pan calandria is shown below. Massecuite, or other materials, flow upward through the calandria tubes and downward through the central downcoming section. This is pictured below in Figure 1.

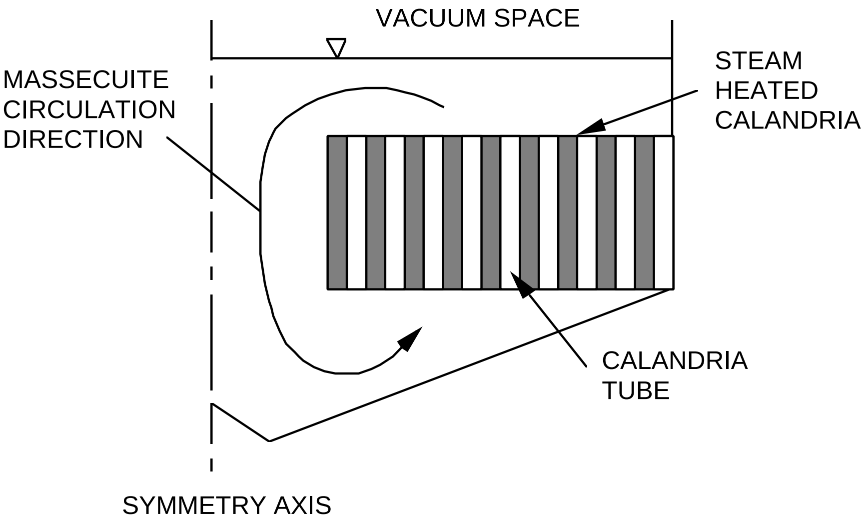

Figure 1: Cross section of a typical vacuum pan calandria

Upward flow through the calandria tube is driven by a heat exchange process. Steam, supplied to the calandria, condenses on the outer surface of the calandria tubes. The heat liberated by this condensation process transfers to the massecuite, due to a temperature gradient, through the wall of the calandria tube. Subsequently, the material within the calandria tube boils. Vapour formation creates a condition whereby the material within the tube has a lower density, compared with the material outside of the calandria. This results in buoyancy driven flow, in the upward direction, which is pictured in Figure 2.

In order to optimise the design of a full-scale vacuum pan, it is necessary to understand the underlying boiling process occurring within each calandria tube. For example, questions such as "What is the optimum calandria tube diameter?" or "How long should the calandria tube be?" cannot be answered based on fundamental understanding. Until now, these questions have been answered by trial and error, which is expensive and highly uncertain. It would be highly desirable to design vacuum pans, or other vessels using calandria heating sections, in a more rigorous manner.

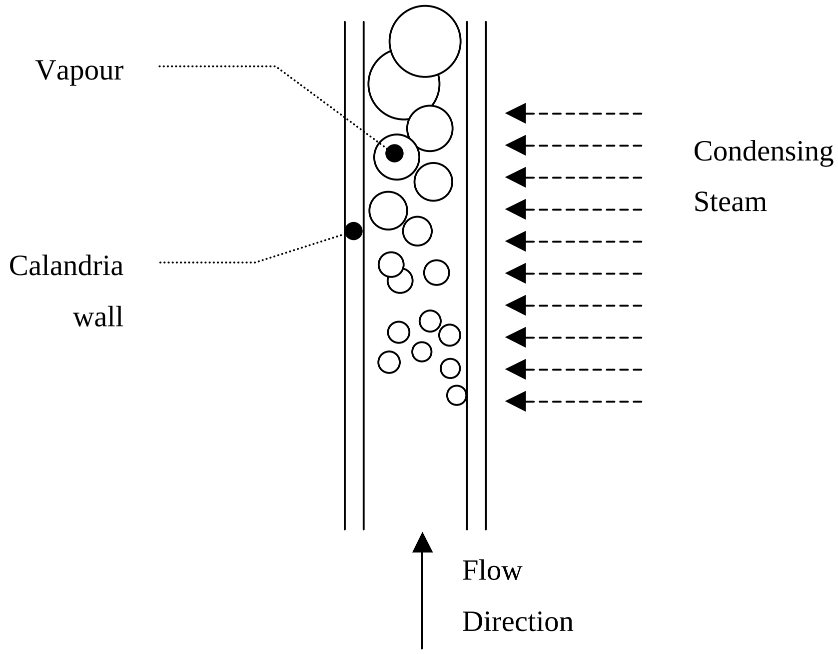

Figure 2: Schematic of boiling and multiphase flow within a calandria tube

The development of a single calandria boiling circuit would shed experimental light on the fundamentals of the boiling process, enabling more rigorous calandria designs for vacuum pans. The main thrust of the current project was to design, build and commission a boiling circuit that could be used to gather detailed experimental data, leading to a better understanding of viscous, convective boiling phenomena.

Objectives:

The objectives of this investigation, as stated in the original proposal, are as follows.

Objective 1 - To design, construct and commission an experimental calandria tube apparatus for laboratory studies of boiling viscous fluids such as molasses and massecuite.

Objective 2 - To undertake detailed measurements of temperature, void fraction and pressure for flows of molasses and high-grade massecuite under conditions spanning the range found in industrial vacuum pans.

Objective 3 - To develop improved correlations for heat transfer coefficients, evaporation rates, void fractions and pressure drops that are applicable to molasses and high-grade massecuite.

Objective 4 - To determine the implications of the experimental results for the design and performance of calandria tube heat exchangers in the Australian sugar industry.

Due to the loss of project research personnel (Mr Bruce Atkinson), and since subsequent funding could not be sourced (from the SRDC or other sources), the project's scope was reduced to include only Objectives 1 and 2 above. Consequently, the final project milestone, Milestone 5, was excised from the project.

Objectives 3 and 4 are currently the subject of a current SRDC-funded project (SRDC SRI129).

The final project milestone (Milestone 4.4) Achievement Criteria and the extent to which they have been completed are described below.

Boiling circuit operational

The boiling circuit was tested for the first time late in 2001. Mr Drew Penny, a JCU undergraduate engineering student, did this as part of his final year thesis project. While detailed measurements of the operation of the equipment were not made, it was clear that the boiling circuit was fully operational boiling both water and synthetic molasses, under varying levels of vacuum and calandria tube heat fluxes. From that time to the present the boiling circuit has operated with very few problems, which is a testament to the engineering design that went into its development.

Instrumentation and data acquisition functioning

The table below highlights the instrumentation installed on the boiling circuit. All sensors have been calibrated and/or processes have been developed to enable their calibration, in order to monitor the process as faithfully as possible.

Table 1: Process sensors attached to boiling circuit.

Sensor	Number	Location	Measurement of…
RTD[1] probes	6	Embedded within wall of calandria	Calandria wall temperature distribution
Thermocouple probes	11	Positioned along length of calandria	Massecuite temperature distribution (within, above and below calandria)
	4	Heat exchange condenser	Inlet/outlet cooling water, steam and condensate temperatures
Radiation gauge	1	Movable yoke, traversing boiling tube	Density distribution of boiling massecuite/ molasses along calandria tube
Magnetic flow meters	1	Return line of boiling circuit	Return volumetric flow rate of massecuite/ molasses
	1	Cooling water supply line	Cooling water volumetric flow rate to heat exchange condenser
Pressure transducers	5	Mounted along length of boiling tube	Massecuite pressure during boiling
	1	Head space above boiling massecuite	Overhead pressure
Power transmitters	5	In series with resistive heating bands	Power supplied to resistive heating elements, heating the calandria tube

All process sensors are connected to a supervisory control and data acquisition (SCADA) system, located within the Chemical Engineering Research Bay at James Cook University, Townsville. Project JCU021 was the first significant deployment of this SCADA system, which was secured

[1] Resistive Temperature Device

through a combination of JCU internal and external funding. The SCADA system is fully operational and has been used extensively by Mr Darryn Rackemann for his MSc research work as part of SRDC SRI129.

Preliminary measurements have been performed

Preliminary measurements have been performed on the boiling circuit, using a variety of process fluids, including water, high-grade molasses and synthetic massecuites. Mr Rackemann has performed a significant number of experimental runs on the boiling circuit, in order to assess the boiling circuit's range of operation. As such, his work to date clearly exceeds the requirements of this achievement criterion.

Methodology:

The methodology employed in the development of the boiling circuit experimental apparatus involved two distinct phases. These are the mechanical engineering design of the apparatus and the development of a supervisory control and data acquisition system to enable experiments to be performed.

Mechanical Design of the Boiling Circuit

The mechanical design of the boiling circuit was facilitated through the use of a mathematical model that predicted the flow behaviour within a single calandria tube. This model predicts the net pressure driving force and the evaporation rate produced in the tube as a function of parameters such as heat input, mass flow rate, liquid height above the calandria, vacuum level and boiling point elevation.

Mathematical modelling was also employed to assist in the selection of pipe work components for the boiling circuit. A CFD model (CFX 4.2) was employed to predict the pressure drop and resistance to circulation in the downcomer pipe, bends and magnetic flow meter and associated pipe transitions.

Due consideration was also given to various health and safety aspects of the boiling circuit apparatus. A HAZOP was carried out in order to identify and quantify any risks associated with the operation of the equipment. Risk associated with the procurement and deployment of the radiation gauge, used for density determination, was managed according to Queensland Radiation Health's policies and practices. A Radiation Safety and Protection Plan was developed to specifically address the conditions in and around the boiling circuit apparatus. All certifications for the source, its installation and storage requirements have been met.

The mechanical design of the apparatus, the support structures and instrumentation fit-out was undertaken using IDEAS Master Series software. This software allowed modelling of the apparatus in three dimensions, so that the apparatus could be built in virtually. This process delivered a very smooth construction phase, with very few "surprises" along the way.

The experimental apparatus has been located within the Chemical Engineering laboratory, within the School of Engineering. This location is ideal, since it is fitted with three-phase power, vacuum, hot water and other important utilities.

A photograph of the completed boiling circuit apparatus are shown below in Figure 3.

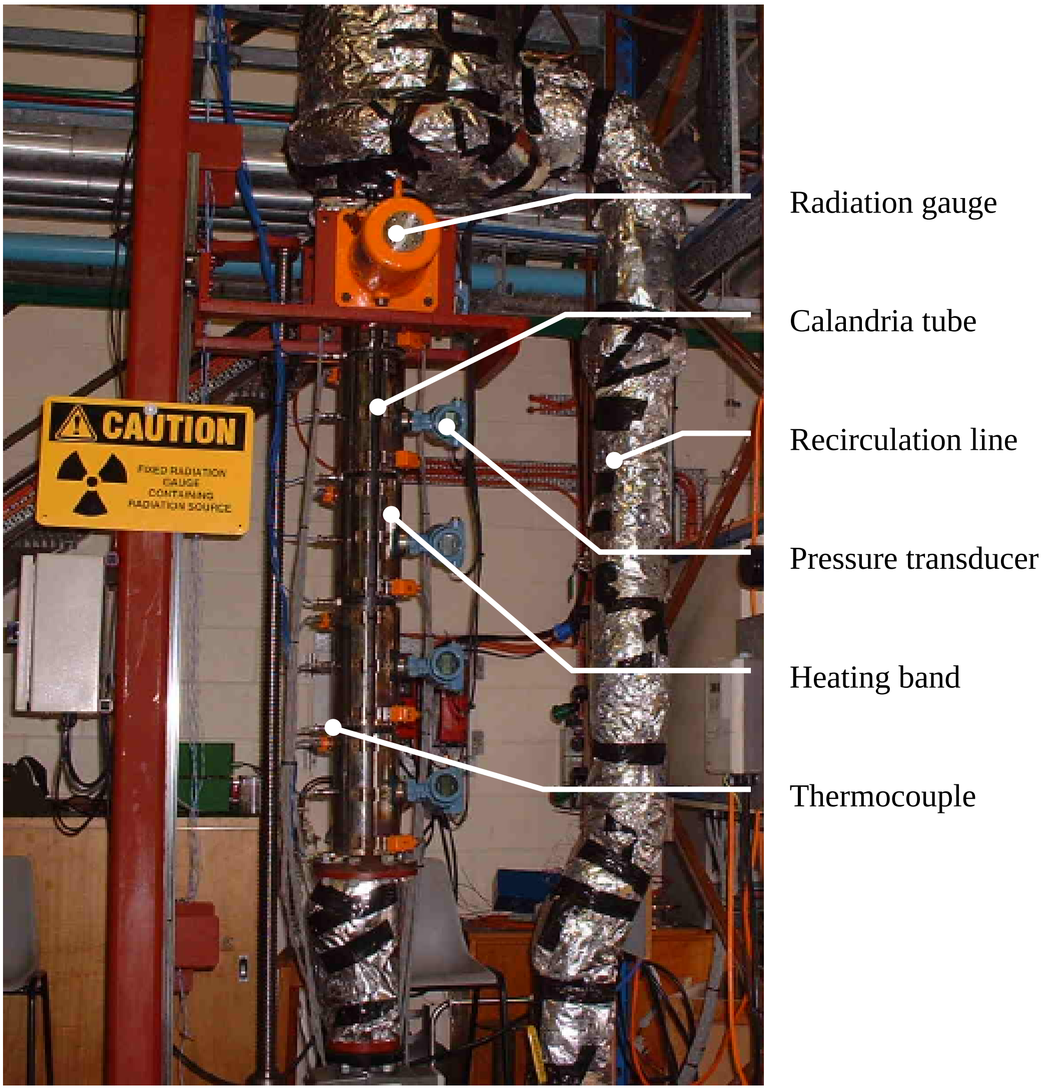

Figure 3: Completed boiling circuit apparatus

SCADA System Development

The SCADA system is a key component of the viscous boiling apparatus. The SCADA system is a hierarchy of integrated subsystems, designed to carry out specific tasks, pictured in Figure 4.
At the level immediately above the boiling circuit is the MTL8000 plant input/output system. This system handles data transfer between the boiling circuit sensors and actuators and the computer controller system, located above it.

The control system, designed using the software-based system ProcessACT[2], is responsible for maintaining control of various aspects of the boiling circuit's operation, such as wall temperatures of the calandria tube. An example of a ProcessACT schematic is displayed below, showing its "building block" nature. ProcessACT was chosen because of its power and flexibility, enabling rapid prototyping of a control system for the boiling circuit. It was also possible to custom design

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[2] ProcessACT kindly donated by Matrikon Australia for this and other projects requiring process control

blocks for tasks specific to the boiling circuit. The best example of this is the development of the control system for the yoke, which accurately positioned the radiation gauge according to commands issued by the experimenter.

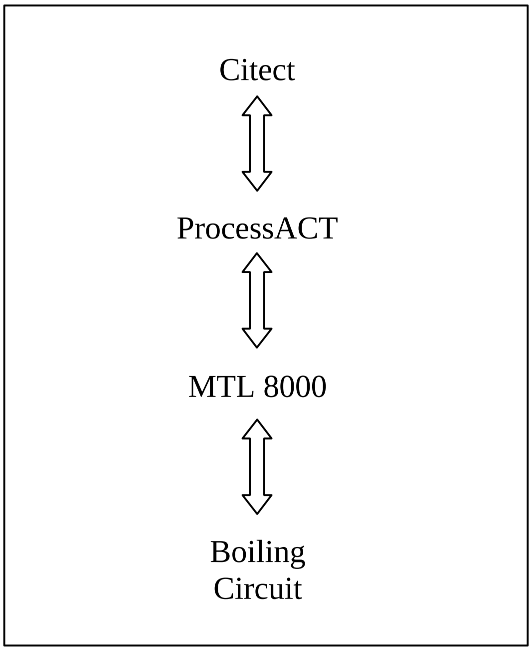

Figure 4: Schematic of SCADA system hierarchy

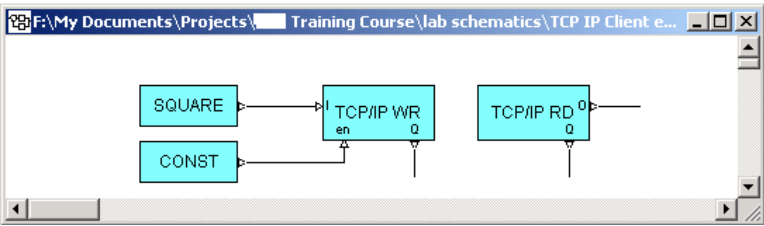

Figure 5: ProcessACT schematic showing its "building block"nature.

While ProcessACT has the ability to trend and log data, it has a relatively poor man-machine interface. For this reason a Citect interface was developed to give experimenters better control of the boiling circuit and easier access to process data. Citect is a graphical system that allows a user to indirectly interact with the ProcessACT control configuration. Typical Citect displays are shown below in Figure 6 and Figure 7, showing the system overview of the boiling circuit and its ancillary components. In most cases, the user can simply "point and click" in order to interact with the boiling circuit.

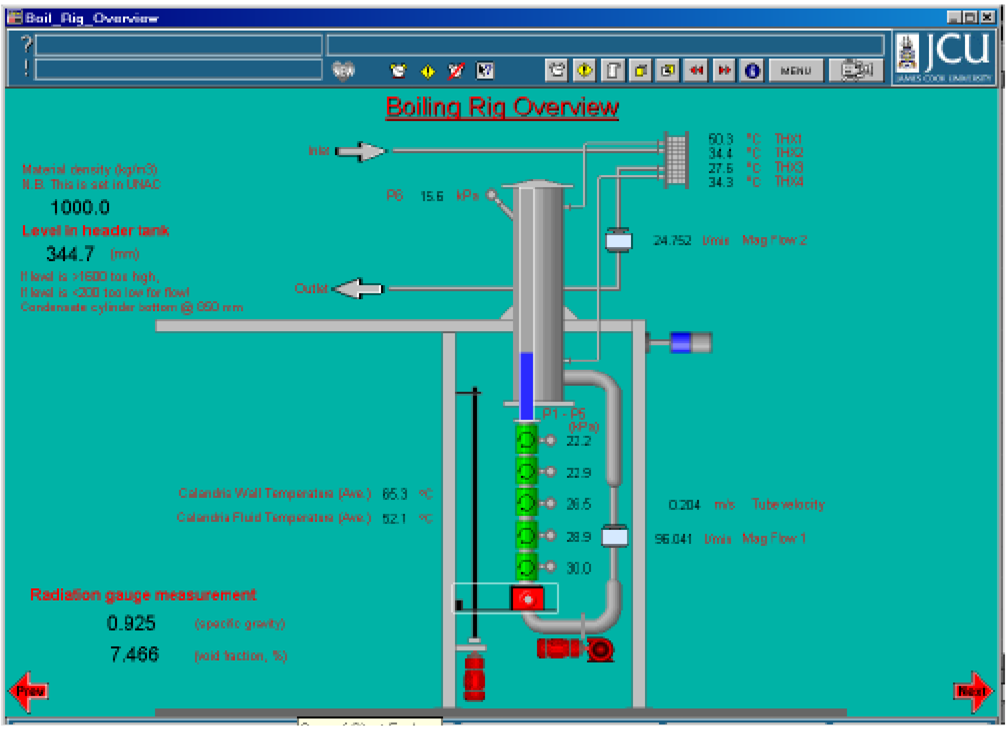

Figure 6: Citect overview of boiling circuit controller

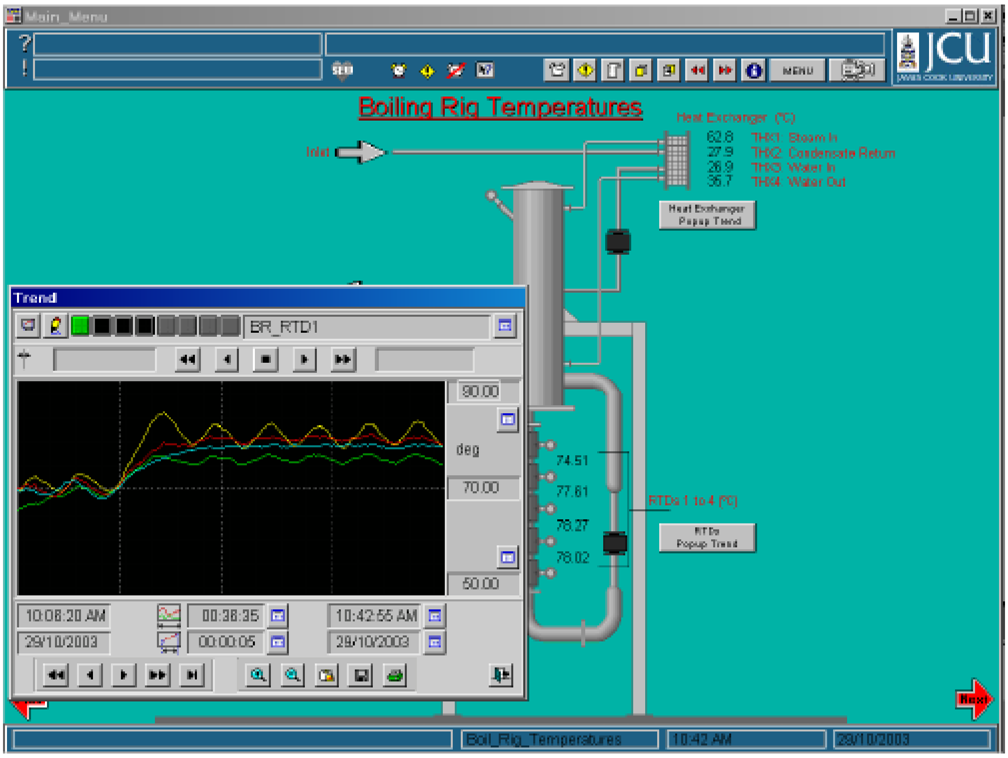

Figure 7: Citect display, showing details of a heating band controller

Figure 8 shows the physical layout of the boiling circuit, including the various components that make up the SCADA system. The Citect display PC is physically located in another part of the Chemical Engineering Research Bay.

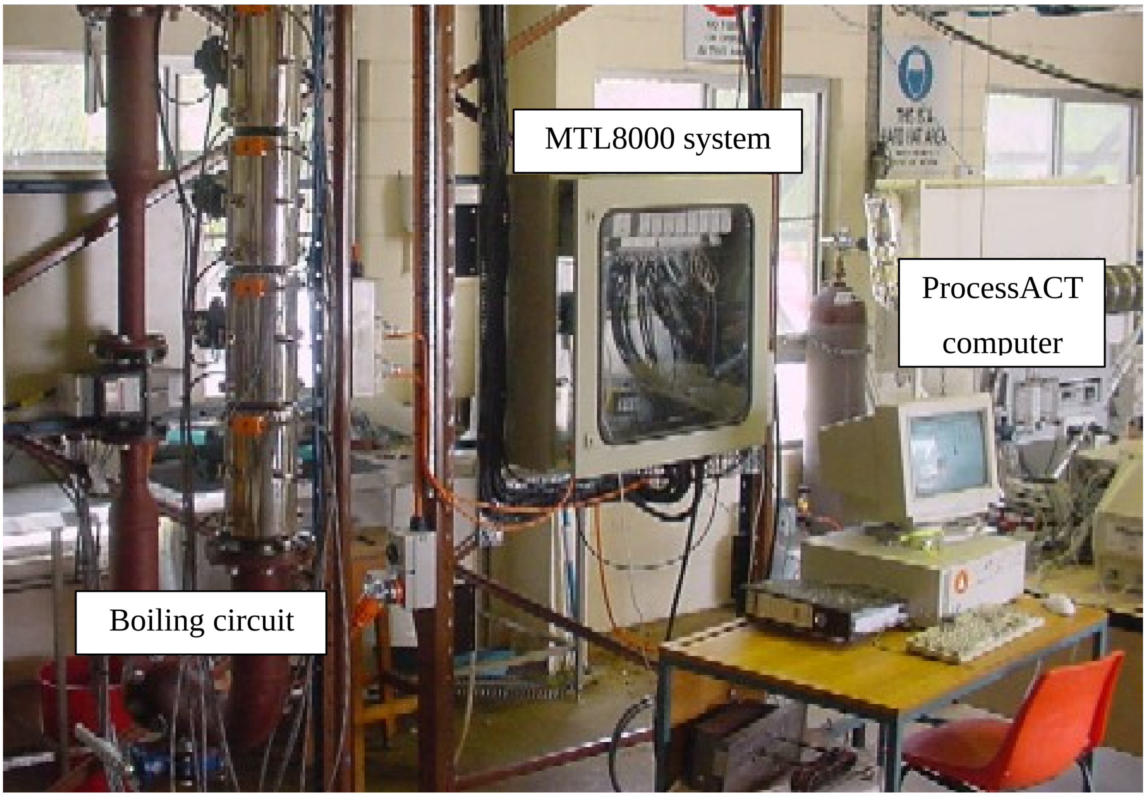

Figure 8: Layout of the boiling circuit and SCADA system components

Due to the loss of project personnel, a series of thesis projects were conceived to develop the SCADA system. Three JCU undergraduate engineering undergraduate students were involved with this process, as part of their respective final year thesis projects. Their contributions to the successful completion of the project, detailed below, are gratefully acknowledged.

1. Mr Drew Penny – initially commissioned the boiling circuit, developed the MTL8000 system and coupling it to ProcessACT.
2. Mr Jarrod Giese – developed a customised controller within ProcessACT for the radiation gauge positioning system, greatly increasing the utility of the boiling circuit.
3. Mr Geoff Devin – developed the Citect interface, which again was a very important contribution to the effective operation of the boiling circuit.

Outputs:

The boiling circuit with its associated SCADA system is the most significant output from this project. This system is a world-class facility that has started to make a positive impact on the Australian sugar industry. This facility is a fully instrumented experimental facility that can be used to study convective boiling in viscous fluids found in the sugar industry, including juice, molasses and massecuites.

Another key output from this project is the emerging body of data related to boiling phenomena of molasses and massecuites. This database of experimental results is currently under review as part of SRDC project SRI129, and will enable a much clearer understanding of convective boiling in vacuum pans.

A paper resulting from the current project was presented at the 2000 ASSCT conference, and is referenced below.

Intellectual Property:

There are no issues related to intellectual property for JCU021.

Expected Outcomes:

There are a variety of important outcomes that result from this work. For the first time in Australia, it is now possible for technicians to take highly accurate and detailed measurements of viscous boiling in calandria tubes. An important outcome from this is that convective boiling of viscous materials, such as molasses and massecuite, will be better understood.

The other expected outcome of this project is that predictions of full-scale calandria behaviour can now be made, using data generated from the experimental boiling circuit facility. This will enable a more rigorous experimental evaluation of calandria tubes of differing materials and geometry to be made. The cost savings of this, compared with full-scale evaluations, is significant.

It is also now possible to experimentally validate the various CFD models of convective boiling in viscous, two-phase fluids. Without this important validation step, CFD predictions of process behaviour are of questionable value. The benefit of model validation is that the CFD predictions for improved pan design can now be made with greater assurance.

Future Research Needs:

The experimental boiling circuit could be modified to use different calandria tube geometries. It would be of great interested to evaluate the effects of tube length and diameter on the two-phase flow characteristics of massecuites. Furthermore, alternative materials for the calandria tube could be evaluated in terms of their impact on flow. In order to carry out these experiments, further funding would be required.

Recommendations:

It is recommended that further experimental work be carried out on the viscous boiling apparatus, in order to further elucidate the behaviour of viscous boiling in massecuites and molasses. A wide range of experiments should be carried out to elucidate the effects of various process parameters on two-phase flow in the calandria tube.

It would also be of interest to evaluate the effect of flow additives to massecuites, which are used to improve boiling heat transfer on the interior surface of the calandria.

It is also recommended that a CFD study of the boiling circuit be carried out, so that comparisons can be made against the emerging set of experimental data. A positive outcome of this would be a more accurate model of boiling two-phase flow in a single calandria tube, which could be used to supplement the modelling efforts of projects such as JCU010. In this way, more accurate CFD models of full-scale vacuum pans could be realised, making rigorous design of these unit operations possible.

List of Publications:

Atkinson, B.J., Stephens, D.W., Harris, J.A. and Schneider, P.A., "The net pressure driving force due to boiling in calandria tubes," *Proc. of the Australian Society of Sugar Cane Technologists*, **22**, pp. 449-455, 2000.