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Improved batch pan monitoring, control and optimization - a soft sensor approach

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Improved Batch Pan Monitoring and Control – a soft sensor approach

by
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Contents

1. SUMMARY	ii
2. INTRODUCTION	1
3. BACKGROUND	1
4. OBJECTIVES.....	1
5. METHODOLOGY.....	4
6. RESULTS.....	7
7. OUTPUTS.....	8
8. EXPECTED OUTCOMES	9
9. FUTURE RESEARCH NEEDS.....	9
10. RECOMMENDATIONS	10
11. PUBLICATIONS.....	10
APPENDIX.....	11

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1. Summary

Cane sugar is manufactured in process vessels called vacuum pans, which are closely supervised by operating personnel, known as *pan boilers*. Traditionally, the pan boiler's job has been made easier through the use of a control system based on electrical conductivity. However, conductivity-based vacuum pan control is far from perfect, since it requires continual attention from the pan boiler to ensure that the vacuum pan is running efficiently.

Existing and emerging technologies are now available which should allow for more advanced monitoring and control schemes to be developed for vacuum pans. The ultimate goal for these technologies is to develop a control system that can run the pan closer to its optimal operating point, with less operator intervention.

The main aim of this project is to develop optimal operating policies for an industrial vacuum pan and implement them on a production scale. Rather than use conductivity as the control variable, it is proposed that more process relevant variables should be considered. These variables are the molasses sucrose oversaturation, or OS, and the massecuite crystal content, or CC.

Once these policies have been developed, they need to be implemented. Before that can happen, the OS and CC variables need to be available to the controller. The problem is that the variables cannot be measured directly – there are no devices that can measure either of these variables. However, a technique called *soft sensing* can be used to estimate the values of OS and CC in the vacuum pan. A soft sensor is actually a computer model of the vacuum pan that uses other available process measurements to predict the values for the OS and CC in the pan. This project's second aim is to develop a soft sensor that can be implemented on a factory vacuum pan, so that the OS and CC variables are available for process control purposes.

The third aim of the project is to evaluate the effectiveness of controlling the vacuum pan by using OS and CC, in place of electrical conductivity.

The final aim of this project is to control the full-scale vacuum pan in such a way that it follows the predicted optimal operating policies.

This final aim is very important to the Australian sugar industry, since it can help to make each vacuum pan operate faster and therefore be more productive. An extension of this goal is that the vacuum pan might also run with less operator intervention, giving them more time to see to other, more pressing tasks in the factory.

The testing phase of this project was carried out in partnership with Macknade Mill, who have availed a 120 tonne batch vacuum pan. This pan is unique, since it has a number of high quality process sensors attached to it. This makes it an ideal testing ground for the evaluation of alternative process control techniques.

The main outcomes from this work are that while advanced monitoring and control are possible on the 100 tonne vacuum pan, it is currently not feasible to operate the vacuum pan to the predicted optimal operating policies.

However, it has been clearly demonstrated that controlling the pan using a massecuite Brix sensor is efficacious. The advantage of using this for process control, instead of conductivity, is that this device is much less sensitive to changes in cane purity. As a result, it can be argued that this method of control requires much less operator intervention, which could lead to cost savings for the industry.

If the findings of this study are applied to the Australian sugar industry, it is likely that productivity will improve through batch time reductions and potential reductions in plant operating personnel.

In summary, this project has succeeded in evaluating the applicability of advanced process control to the operation of batch vacuum pans. A great deal of knowledge has been gained in terms of what level of advanced control is practicable. Furthermore, it proposes a new method of pan control, based on massecuite Brix, that could be used in place of conductivity control.

2. Introduction

This final report completes the requirements for SRDC project JCU018. The report presents background information, which leads naturally into the objectives of the project. Research methodologies are presented in order to clarify how the research was executed. Results of the work undertaken then follow. Project outputs and expected outcomes are delineated in the next two sections. Recommendations for further work are presented in the next section. Finally, copies of papers published as a result of this research appear in the last section of the report.

3. Background

For the last several decades the Australian Sugar Industry has clung to a simple, conductivity-based pan control scheme, given its low installed cost, simplicity and high reliability. The main hurdle to overcome in this type of control scheme was in determining the setpoint for the conductivity controller; since this measurement is not fundamentally process relevant. Initially, this did not present a problem, since skilled operators were on hand to make that determination.

Paradoxically, the problem of pan control really isn't the problem at all. In fact the control problem is actually a measurement problem. If the molasses oversaturation (OS) and massecuite crystal content (CC) in the pan can be measured (or estimated) then it is a trivial exercise to control them. The main difficulty lies in knowing the setpoint trajectories (or ramps) to choose for these process variables throughout the duration of the strike.

The overriding goals of this project were as follows:

- to develop a reliable scheme that would estimate, in real time, the OS and CC process variables.
- to determine the best operating policy for a batch vacuum pan through a computer optimisation study

In order to pursue the above goals, a series of objectives were established and are presented in the next section.

4. Objectives

The objectives of this investigation, as stated in the original proposal, and a statement of the extent to which the project has achieved them is summarised below.

To develop practical batch pan monitoring and control strategies based on a soft sensor approach

A soft sensor was developed in order to predict two key process variables on-line and in real time

- molasses sucrose oversaturation (OS)
- massecuite crystal content (CC)

on a 120-tonne industrial batch vacuum pan.

This sensor proved to be useful in terms of process monitoring, since it gave operating personnel an alternative way of evaluating the process. However, it must be said that the uptake of information was only slight. This is explained by the fact that pan boilers lack a deep understanding of the process fundamentals involved.

Trying to control the pan using the above two derived process variables was not as successful. This is due in part to errors in the two predicted process variables. This was further complicated by the fact that the operating policies predicted by computer simulation did not stand-up to industrial implementation. In other words, what worked well in computer simulation, did not work well on the actual process.

To evaluate these schemes in simulation and on a 120 tonne production vacuum pan

In simulation, the proposed batch pan monitoring and control scheme worked extremely well. By incorporating newly available process measurements (such as the microwave Brix device), it was straightforward to develop a reliable soft sensor for monitoring and control purposes.

In terms of actual process monitoring, a soft sensor set-up to run in parallel with a 120 tonne batch vacuum pan, located at CSR's Macknade Mill. This soft sensor was able to predict reasonable values for the molasses oversaturation and massecuite crystal content, which gave operating personnel a completely new view of the process. It is of interest to note that operating personnel were hesitant to use this information, most likely since they lacked sufficient training to fully utilise this information.

It was demonstrated that controlling the molasses oversaturation and massecuite crystal content led to the control the full-scale batch vacuum pan. This represents an important departure from traditional control schemes that rely on process outputs, such as conductivity.

To revisit, and consequently redefine, the optimal control problem first presented by Frew, but in a more practical and direct manner.

The Postdoctoral Fellow attached to this project, Dr Linh Vu, revisited the optimal control problem of the batch vacuum pan. The objective of the optimisation method was to reduce the time required to grow the seed crystals to their target size.

Dr Vu's work in this area was significant, since she was able to incorporate various real-world operating features into her optimisation studies, including:

- **A-molasses boilback** - The optimum switching time for the commencement of A-molasses boilback was determined by this approach, determined by setting a target molasses purity for the end of the strike.
- **Process constraints** – Constraint handling was incorporated into the optimisation scheme, including limits on sucrose oversaturation, massecuite crystal content and the flow of steam and feed to the pan. Constraint handling on the state variables (like oversaturation and crystal content) has not been achieved to date.
- **Uncertainties** – The effect of plant-model mismatch and uncertain operating conditions (footing conditions, feed composition) could also be handled by the approach developed by Dr Vu, which makes the optimisation process more robust.

To implement these optimal control policies on the 120 tonne batch vacuum pan

The operating policies predicted by the computer-based optimisation studies were implemented on the same 120 tonne batch vacuum pan located at CSR's Macknade Mill.

It became evident very early in these trials that the predicted optimum operating policies were not superior to current pan operation. This was a rather discouraging result, to say the least. Many attempts were made to overcome this issue, but to no avail.

The reasons for this implementation failure are most likely related to some combination of the following effects:

- **a poor heat transfer model** – modelling heat transfer across the calandria is a key requirement to solving the optimal control problem posed by Dr. Vu (and others before her).
- **no model of pan circulation** – the model employed in Dr. Vu's optimal control study assumed that the mixing behaviour of the pan is perfect. It is possible that the sensors being used in the soft sensor were not indicative of average conditions in the pan. In this case, the control policies being implemented would be compromised.
- **a poor thermodynamic model** – the model of the batch pan employs rather coarse relations describing the sucrose solubility in the mother molasses. The relations employed were chiefly developed for lower purity molasses, since no relations exist for high purity molasses.
- **inaccurate crystal growth model** – the model description of the crystal growth rate kinetics is far from perfect. However, the sensors selected for measurement feedback to the soft sensor should afford some protection against this problem.
- **calibration errors** – the sensors used for measurement feedback may have been inaccurately calibrated. The net effect of this is that the estimated OS and CC values would be biased away from their true values.

Based on the mediocre performance of the plant-based soft sensor experiments, additional project funds were requested, and subsequently granted, in order to pursue one final objective.

To evaluate alternative control schemes based on direct measurement of the process

Given that the optimal control of the pan by the soft sensor approach did not live up to expectations, it was decided to attempt control of the vacuum pan using novel process sensors.

A simulation study was carried out in which the molasses and massecuite Brix were controlled, by manipulating the feed and steam flows to the pan. This approach was successful in computer simulation.

During the 2002 crushing season, a series of trials were carried out at Macknade Mill in which the output from a microwave Brix device¹ was controlled for almost the entire period of the strike.

¹ pro-M-tec Theisen GmbH, Pforzheimer Str. 162, D – 76275 Ettlingen

Operator acceptance of this scheme was high. During the 2002 crush, Macknade Mill took on factory make-up water with brackish water (due to tidal effects on the creek adjacent to the plant). At these times automatic pan operation was effectively impossible, since the conductivity probes were driven off-scale, due to the high conductivity of the incoming liquor streams, concentrated in salt. At these times the pan boilers requested that the microwave-based control system be switched on, freeing them from the need to monitor this pan closely. Since the microwave device is not influenced by the presence of salts, ongoing adjustment of setpoint trajectories would no longer be necessary.

By the end of the 2002 crush, the pan was being controlled using the microwave device at least as well as it was under traditional conductivity control. Unfortunately, due to time restrictions and issues related to the batch automation structure, it was not possible to optimise the pan for microwave Brix control. However, it is anticipated that batch optimisation based on microwave Brix control would be straightforward.

In summary, the project objectives were largely met. It is apparent that the more complex pan control system, based on soft sensing, is not ready for factory implementation. However, it is clear that improved output base control is feasible and should lead to more uniform and effective batch pan control.

5. Methodology

The methodologies for this research project were diverse and fell into three distinct categories. They are described in turn.

Soft Sensor Development

The first area of research investigated the design of a feasible soft sensor for factory implementation. The ultimate goal of the soft sensor is to run in real-time, in parallel with the process that it is monitoring. Its development was achieved by first implementing the soft sensor on a computer simulated batch pan. Next, the soft sensor was set up to process data logged from the full-scale factory pan. The third stage was to implement the soft sensor in real-time, in step with the factory vacuum pan. An advanced control prototyping and development package, called UNAC², was employed for all soft sensor development.

The soft sensor was formulated using a modified version of Wright's model, which assumed a point crystal size distribution. The model employed flow and temperature data in order to make predictions of the OS and CC in the pan. Measurement feedback from the process was based on massecuite Brix (microwave probe), molasses Brix (process refractometer) and massecuite level (? P cell). This choice of measurement feedback affords excellent feedback to the soft sensor, since it is receiving information that is highly process relevant. These soft sensor input and feedback measurements are highlighted in Table 1 below.

² Matrikon Inc., PO Box 516, Mayfield NSW 2304

Table 1: Soft sensor input and feedback measurements

Soft Sensor Inputs		Soft Sensor Feedback	
Variable	Device	Variable	Device
feed	mag flow	molasses Brix	refractometer
steam	ΔP cell/orifice plate mag flow	massecuite Brix	microwave
movement water	mag flow	massecuite level	ΔP cell
temperature	100ohm RTD	-	-

Vacuum Pan Optimisation

The second area of research involved the development of the batch pan optimisation codes. All optimisation work was carried out using GAMS³, which is specifically designed for modelling linear, nonlinear and mixed integer optimisation problems. To avoid solving the ODEs required for each iteration step, which is computationally expensive, the state variables are approximated by the Lagrange interpolation polynomial. These were then differentiated and back substituted into the state equations, converting them to a set of algebraic equations. The approximating problem now becomes a normal nonlinear programming problem and can be solved by existing optimisation techniques. The approximating method of Orthogonal Collocation on Finite Elements is especially advantageous for this type of optimal control problem, since it is solved for not only the minimum operating time but also the duration of each stage of the whole batch pan process. Any number of finite elements can be specified for each stage; it is the lengths of these elements that are decision variables in the optimisation problem. The advantage of this approach was that events, such as A-molasses boilback, could be determined based on a specified target purity for the mother molasses at the end of the strike.

Factory Implementation

The final area of this research involved the implementation of the proposed control schemes on the 120 tonne batch vacuum pan at Macknade Mill. Again UNAC was employed for this task, since the soft sensor was commissioned using UNAC. The first step in this process was to merge the soft sensor with the existing pan control scheme. Macknade Mill employs a reasonably complex set of batch sequencing to effect very good control of their pans. These batch sequences are complex and difficult to account for when attempting to monitor the pan with the soft sensor, since all of the possible events need to be built into the soft sensor code. The complexity of this task should not be underestimated, since it plays a key role in the success of a *robust* the soft sensor.

The next stage in the factory implementation involved the development of the control system that employed either the soft sensor outputs (OS and CC) or the microwave Brix device. Below is a screen shot of a portion of the UNAC-based control system,

³ GAMS Development Corporation, 1217 Potomac Street, NW, Washington, DC 20007

showing details of the microwave controller. It should be noted that a significant amount of this configuration is devoted to bullet-proofing, so that the controller could be implemented with confidence. This bullet-proofing was also required on the existing factory control system, in case UNAC froze-up for some reason.

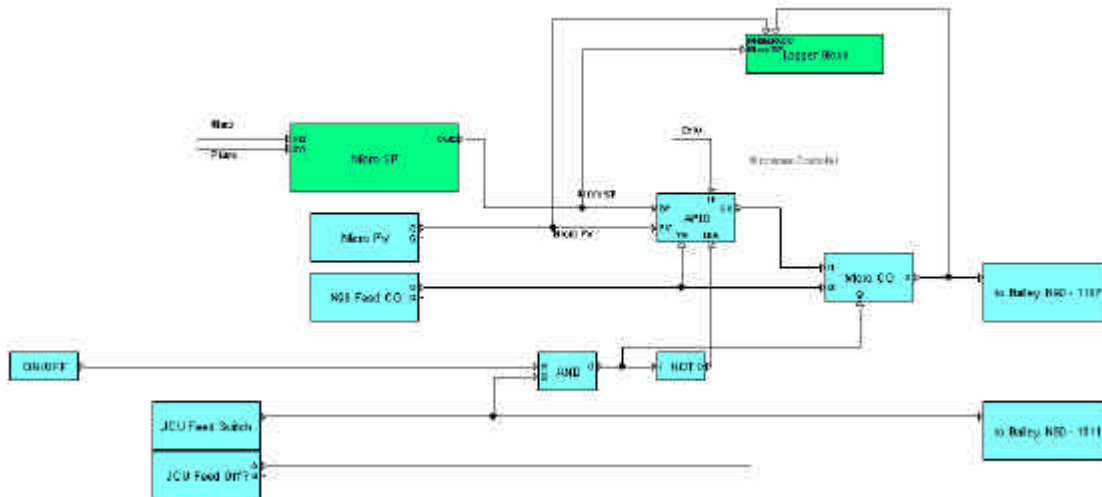


Figure 1: UNAC implementation of a PID feedback controller

Feedback control was affected using simple PID formulations. In fact, only PI control was required for the OS and CC control, while P-only control was required for the microwave Brix control. In all cases, some kind of setpoint trajectory was required. The computer optimisation worked performed by Dr Vu was used to generate these trajectories.

The table below shows the different configurations considered in this study for the control of the batch vacuum pan.

Table 2: Controller configurations considered for this study

Option	Controlled variable(s)	Manipulated variable(s)	
		Feed	Steam
1	OS CC	✓	✓
2	CC	✓	
3	OS	✓	
4	microwave Brix refractometer Brix	✓	✓
5	microwave Brix	✓	

6. Results

As stated above, it was possible to estimate the OS and CC in the 120-tonne factory batch pan. A variety of factory experimental trials were run in order to determine the efficacy of the soft sensor. The estimated OS and CC were repeatable and reasonable.

Effective process control these variables was also achieved. The first three options shown in the table above were evaluated at the factory. While it was possible to control the pan using these options, it became clear that the predicted optimum profiles for the OS and CC did not produce optimal factory results. In fact, many of the trials had to be aborted, due to concerns expressed by the operator (and shared by the author!). The reasons for this have been explained in the Objectives section above. While this is a disappointing result, it is nonetheless valuable, since it is the first time that such a study has been carried out and a great deal of insight into this problem has been gained.

The last two options (4,5) were considered in simulation. The detailed results of this study have been published (Schneider, 2003) and appear in the Appendix.

Factory trials were carried out evaluating only option 5 in the table above, whereby the microwave Brix signal was controlled by manipulating the feed flowrate to the pan. These results are shown below in Figure 2. In this case the microwave signal was controlled to a constant profile of 86.5 Brix. Clearly the pan is under tight control.

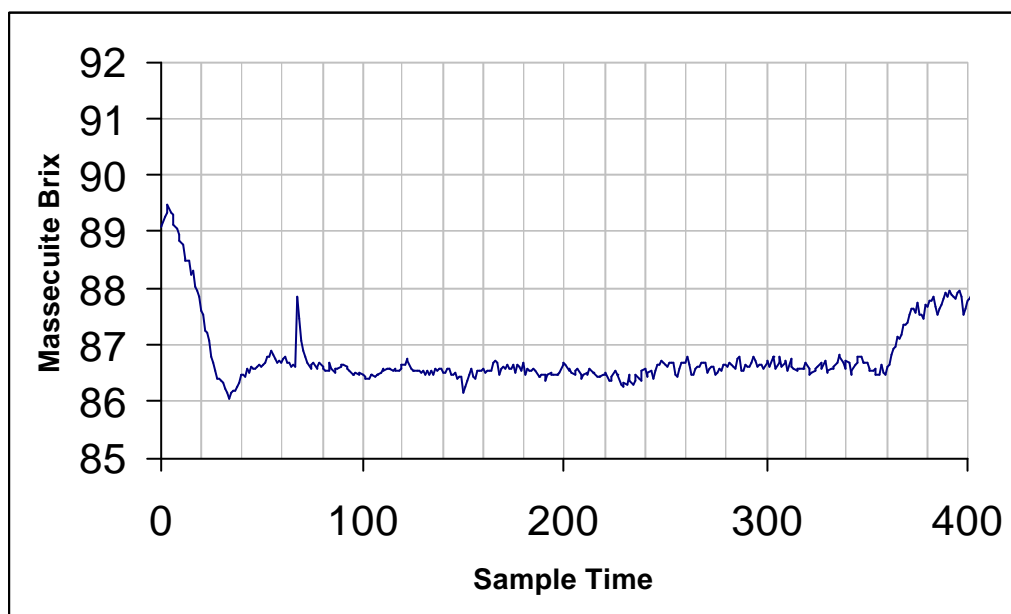


Figure 2: Control of microwave Brix on 120 tonne batch vacuum pan

The departures from setpoint in the early and late stages of the strike are not due to the alternative control scheme. At the start of the strike (i.e. the first 40 sample times), the pan was being controlled by the factory's existing batch sequencing code. Late in the strike (i.e. between 360 and 400 sample time) the pan was cutting masecuite out to a receiving pan. The microwave signal changes during this time, since temperature compensation was not being used. Therefore, when the pan drops vacuum (to motivate flow to the receiving pan) the pan temperature rises, biasing the signal.

Figure 3 shows the flowrate of feed to the pan during the same period. It is of interest to note that very good control of the massecuite Brix could be achieved, despite the fact that a simple proportional mode controller was employed. Clearly this result is encouraging, since it means that a more process relevant and potentially more robust measurement is available for the control of batch vacuum pans.

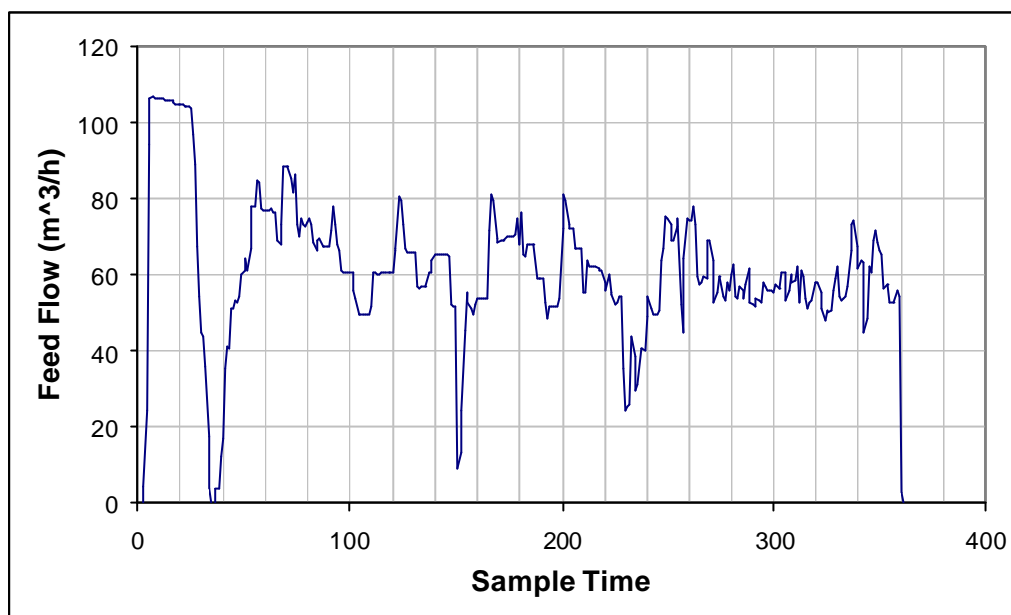


Figure 3: Feed flow to the 120 tonne vacuum pan under microwave Brix control

7. Outputs

There are a variety of important outputs resulting from this research.

- The batch pan optimisation studies, carried out by Dr Vu, demonstrate that it is possible to optimise the operating policy of a pan, while honouring various state constraints, such limits on OS and CC. This is important, since it delivers a more realistic picture of what can be achieved on the real process. This optimisation work also includes the determination of when the pan should commence Amolasses boilback, which is a significant step forward in pan stage optimisation.
- It is possible to run a soft sensor on a 120 tonne batch vacuum pan without interfering with its routine operation. Derived process variables, like OS, CC and others, can be reported to operating personnel in real time as a pan control advisory tool. The soft sensor developed in this project produces valid estimates of these process variables.
- It was also demonstrated that the outputs from the soft sensor running on the full-scale vacuum pan can be controlled, replacing traditional conductivity-based control schemes.
- The predicted optimal setpoint trajectories derived from the computer optimisation study lead to relatively poor control of the pan, compared with traditional conductivity control. This failing is most likely due to errors in the model employed within the soft sensor and/or errors in calibration of the sensors used for measurement feedback to the soft sensor.

- A simulation study indicates that Brix-based control is an alternative to conductivity control.
- Plant studies carried out on a 120 tonne batch pan demonstrate that massecuite Brix control (manipulating feed flowrate) is a highly effective way in which to control a pan. The controller structure is simple and very effective. It could be argued that Brix-based control is superior to conductivity control, since it is not sensitive to inorganic salts, which tend to obscure conductivity measurements.

8. Expected Outcomes

There are a variety of potential outcomes from this research. Key outcomes are highlighted below.

- The work of Dr Vu indicates that it is now possible to more rigorously optimise the operation of a batch vacuum pan. The obvious outcome of this study is that factories could benchmark their pan operations against the predicted optimum. In this way, each pan on the stage could be assessed in terms of its overall productivity. There is clearly an economic incentive to carry out such benchmarking programs, although it is difficult to estimate the net dollar value benefit to the Australian industry.
- Another key outcome is that this project has clearly demonstrated that massecuite Brix control of the pan is feasible. In fact, it could be argued that this approach is superior to the conductivity paradigm. Based on its reliability, it might be possible to run batch vacuum pans with much less supervision. This would have a significant economic impact on the Australian and world sugar industry.

9. Future Research Needs

The main goal of this project was to evaluate the applicability of advanced process control theory to the operation of an industrial vacuum pan. Further research work should be carried out in the following areas.

- to recast the batch pan optimisation work in terms of molasses and massecuite Brix. It is clear, from the preceding discussion, that optimal control of the OS and CC are not feasible at this time. However, the development and implementation of optimal Brix profiles should have a much higher chance for success, since the soft sensor would not be used. This type of project is ideally suited to a PhD student.
- assuming that optimal control of an individual pan is achievable, the next step is to carry out an optimisation study on the entire pan stage. While optimising a single pan is important, it is critical to ensure that the pan stage is operated such that it capitalises fully on the optimal operation of each pan. Due to the advanced nature of this work, it would be best left to a Postdoctoral Research Fellow.
- it is also necessary to better understand heat transfer in batch vacuum pans. If this problem can be fully addressed, improved optimal control policies can be developed. Presently research is being carried out by Mr Darryn Rackemann in the area of pan circulation at the Masters level. It is felt that another postgraduate student, at Masters level, would be required to evaluate and model heat transfer in a mill-based study.

- finally, it is highly recommended that a study commence, evaluating the utility of advanced process control applied to continuous vacuum pans. Given the significance of these units in the Australian sugar industry, this research would be well justified.

10. Recommendations

It is recommended that the following steps be taken to maximise potential benefits stemming from this research.

- extension work is recommended in order to more fully develop microwave Brix control of industrial batch vacuum pans. A participating mill is required to see host this work. Macknade Mill would make an ideal candidate for this work.
- carry out an industry-wide survey in order to determine the level of interest in adopting the use of massecuite Brix control.

11. Publications

The following papers resulted from this research project. Full copies are found in the Appendix.

Schneider, P.A., "Evaluation of an alternative vacuum pan control scheme" Proceedings of the Australian Society of Sugar Cane Technologists, Vol. 25, 2003.

Vu, T.T.L. and Schneider, P.A. "Improving the Control of an Industrial Sugar Crystalliser: a Dynamic Optimisation Approach", Proceedings of the European Symposium on Computer Aided Process Engineering - 12, Computer Aided Chemical Engineering, Vol. 10, p 571-576, Elsevier, 2002

Vu, T.T.L. and Schneider, P.A., "Controllability Analysis of an Industrial Crystalliser", Proceedings of the 6th World Congress in Chemical Engineering, Melbourne, September 2001.

Vu, T. T. L. and Schneider, P. A., 2000, 'Operability Analysis of an Industrial Crystalliser – An Optimal Control Approach', CHEMECA Proceedings 2000.

Appendix