FINAL REPORT APPENDIX 2015/043

Impact of low pressure vapour on pan stage productivity: Appendix 6 for Develop a blueprint for the introduction of new processing technologies for Australian factories: final report 2015/043

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Impact of low pressure vapour on pan stage productivity
Appendix 6 of SRA Final Report

by

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Summary

Australian pan stages predominantly use large unstirred batch pans which make it difficult to reduce the process steam consumption of the factory to below 38 to 40% on cane, as these pans typically require process steam (at 200 kPa abs) or vapour 1 (at a minimum of 180 kPa abs) for efficient operation. Continuous pans can operate effectively on vapour 2 (at say 120 kPa abs) or even vapour 3 on certain duties, and so substantial savings in process steam can be obtained through the use of continuous pans.

In general, unstirred batch pans of the conventional design in Australian factories cannot operate on low pressure vapour without incurring major operational problems such as poor exhaustions and long cycle times (or reduced capacity). Poor exhaustion of high grade massecuites results in increased massecuite production loadings because of the increased recirculation of sucrose in the A and B molasses. Poor exhaustion of C massecuite results in increased sucrose loss to final molasses and reduced shipment sugar production.

The overseas sugar factories that operate with process steam%cane (SOC) of below 35% invariably use vapour 3 for batch pan operation and in almost all cases these pans are stirred and often utilise conditioned (slightly superheated) molasses feed. Evaporator modelling shows that changing the vapour use on a pan stage from vapour 1 to vapour 3 reduces the SOC by ~6%, *e.g.* from 40% to 34%. The ability to operate the pan stage efficiently on vapour 3 is therefore an essential requirement to reduce the SOC of the factory to very low levels.

The work undertaken in this phase of the project investigates the expected changes in batch pan productivity, through changes in cycle times and exhaustions, when the typical Australian batch pans are operated with vapour supplied at a range of pressures. This work is the first step in a planned major study to determine the preferred changes that Australian factories can make to their current suite of unstirred batch pans to allow effective operation with lower pressure vapour.

A dynamic model using SysCAD software has been developed for a batch pan of 100 m^3 massecuite volume. This model incorporates the control loops of head space pressure, steam flow control and syrup/molasses feed rate control to a defined crystal content profile and so replicates the actual controls on a factory pan. The model runs at 1/600 of the speed of a factory batch pan and so provides trends of data from a run at a specified vapour supply pressure in less than 30 seconds.

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Control logic has been incorporated in the model to activate termination conditions for (1) the feed of syrup/molasses when the feed on rate or crystallisation rate is uneconomically slow and (2) the heavy up step when the rate of brix increase in heavy up or crystallisation rate is uneconomically slow.

No data have been found in the literature to define the evaporation rate (or heat transfer coefficient) for a natural circulation batch pan for a range of supply vapour pressures including low pressure vapour. A correlation developed in a pilot vacuum pan over 30 years ago has been modified based on the expected performance in factory pans for operation with vapour through a range of supply pressures.

Modelling of typical A, B and C massecuite strikes was undertaken for vapour supply at 200, 140, 100 and 70 kPa abs. The results are a good approximation of industrial behaviour, for the known performance with steam supply at 200 kPa abs. The modelling results have reinforced the practical observations that, when using lower pressure vapour, reduced evaporation rates slow the crystallisation rates, increase boil on times, slow the heavy up process, increase the total cycle times and lead to reduced exhaustion of the product massecuite (depending on the specified termination conditions). With low pressure vapour supply the boil on rates and heavy up rates may become so slow that these operations are terminated prior to reaching pan full or a target dropping brix, in order to maintain the productivity of the whole pan stage.

A follow on major study is planned to identify the most appropriate changes to pan stage equipment, operating procedures and control to minimise the capital investment required to allow operation of existing batch pans with low pressure vapour, while maintaining production performance with respect to rate, sugar recovery and sugar quality.

The assistance of KWA staff Dr John McFeaters and Ms Merry Huang in developing the dynamic model in SysCAD is greatly appreciated.

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Impact of low pressure vapour on pan stage productivity
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1. Introduction

Australian pan stages predominantly use large unstirred batch pans which make it difficult to reduce the process steam consumption of the factory to below ~40% on cane, as these pans typically require process steam (at 200 kPa abs) or vapour 1 (at a minimum of 180 kPa abs) for efficient operation. Continuous pans can operate effectively on vapour 2 (at say 120 kPa abs) or even vapour 3 on certain duties, and so substantial savings in process steam can be obtained through the use of continuous pans.

In general, unstirred batch pans of the conventional design in Australian factories cannot operate on low pressure vapour without incurring major operational problems such as poor exhaustions and long cycle times (or reduced capacity). Poor exhaustion of high grade massecuites results in increased massecuite production loadings because of the increased recirculation of sucrose in the A and B molasses. Poor exhaustion of C massecuite results in increased sucrose loss to final molasses and reduced shipment sugar production.

The overseas sugar factories that operate with process steam%cane (SOC) of below 35% invariably use vapour 3 for batch pan operation and in almost all cases these pans are stirred and often utilise conditioned (slightly superheated) molasses feed. In some cases the batch pans are started on vapour 4 and finish off the strike with vapour 3. Vapour 3 is typically at 91 kPag (saturation temperature 97 °C) and vapour 4 at 56 kPag (saturation temperature 84 °C). In some factories continuous pans such as the stirred module VKT from BMA operate on vapour 4.

As continuous pans are expensive capital items and will not be installed readily to replace batch pans in Australian factories it is desirable that the capabilities of existing batch pans are (1) defined for operation on lower pressure vapours and (2) extended as much as possible, *e.g.* by the supply of superheated (conditioned) molasses feed, use of mechanical agitators, and use of jigger systems etc. No suitable references have been found that provide answers to these issues.

A dynamic model using the SysCAD software has been developed to simulate batch pan operation and used to investigate the changes in pan cycle times and exhaustion of massecuites at pan drop as a function of vapour supply pressure. The modelling is considered to be a preliminary study as little data are available on the changes in evaporation rates (and hence crystallisation rates) that result when a low pressure vapour is used. The model was used to investigate typical duties for the A, B and C massecuite strikes.

The work undertaken in this phase of the project investigates current operation of batch pans and when the feed syrup/molasses is hotter and/or of higher brix. It is clear that a much larger study is required to fully define the capabilities of existing batch pans and explore options to improve operation on low pressure vapour.

## 2.	Advantages of having pans operating on low pressure vapour

The primary reason for operating pans on low pressure vapour is to reduce the process steam consumption of the factory. As stated, process steam consumptions below 35% on cane cannot be achieved unless the pans utilise vapour of low pressure (say vapour from effect #3 or later). From a steam economy point of view the benefit of operating the pan stage on lower pressure vapour is demonstrated by application of the Rillieux principles (Wright, 2000; Broadfoot, 2001). Changing pan stage operations from vapour 1 to vapour 3 would achieve a 6% unit reduction in process steam consumption, *e.g.* from steam%cane of 40% to 34%.

There are several additional advantages in having a pan stage that operates effectively on lower pressure bleed vapour as described below:-

- Reduce the heat load on the cooling water system which would:
    - Reduce capital (cooling towers, spray ponds); and
    - Reduce power requirements for circulating water pumps, fans.
- Allow (maybe) lower pressure exhaust steam to be used which would:
    - Reduce the steam/power ratio of the STG; and
    - Reduce the temperature of boiling in effect #1 (giving a further reduction in process steam consumption and reduced sucrose loss in the early effects).

## 3.	Typical profile of processing conditions in a batch pan in an Australian factory

During the early stages of the strike it is common to maintain a constant steam flow rate to the calandria (controlled to set point). As the massecuite level increases through the strike several changes occur which adversely affect the heat transfer performance and the ability of the calandria to maintain a desired rate of condensation of steam/vapour. As the massecuite level increases:-

- The massecuite temperature inside the tubes increases due to the increased head of massecuite above the tubes;
- The crystal content and brix of the massecuite are most likely increasing steadily. As a consequence the boiling point elevation increases and this also increases the boiling temperature of the massecuite inside the tubes;

- The viscosity of the massecuite increases and the heat transfer coefficient on the massecuite side reduces;

- The pressure on the vapour bubbles produced inside the calandria tubes increases thus reducing the size of the bubbles within the tube and the turbulence created by the bubbles. These changes reduce the heat transfer efficiency at the tube surface; and

- The relative difference in density of the massecuite under the calandria and at the base of the downtake is reduced due to the smaller fraction of the massecuite column occupied by vapour bubbles. As a consequence the buoyancy effects are reduced and the motive force for natural circulation is reduced. The velocity of the massecuite entering the base of the heating tubes is reduced which further reduces the heat transfer efficiency.

Thus the calandria pressure increases as the level of massecuite in the pan increases and the steam flow valve slowly opens during the early part of the strike in order to maintain the steam flow rate at the set point. Once the steam valve is fully open the calandria pressure reaches its maximum value, *i.e.* the pressure of the steam/vapour supply. Subsequent increases in massecuite level or heavying of the pan causes the steam flow rate to reduce as heat transfer efficiency is reduced. The steam flow rate no longer holds at set point.

Figure 3.1 shows a typical example of how the operating parameters change over the strike (data are scaled 0 to 100%). This example is for a well designed pan, boiling an A massecuite using exhaust steam (200 kPa abs). As the massecuite level increases the calandria pressure increases and when the calandria pressure reaches its maximum value (at a massecuite level of ~85% of pan full), the steam flow rate starts to slowly reduce (*i.e.* steam flow is no longer being controlled to set point). The steam flow rate continues to reduce as the massecuite level builds to 100% full. Subsequently the reduction in steam flow rate (and hence heat transfer) is accelerated when the massecuite is heavied to a higher dry substance, higher crystal content and higher viscosity prior to completion of the strike as shown by the sharp reduction in the measured conductivity during heavy up.

Figure 3.1 also shows a measurement of velocity (taken with a hot film anemometer probe) in the region underneath the calandria close to the downtake. The velocity measurement shows a significant decline in velocity as the boiling level in the pan increases. The trend data for this pan shows a sharp decline in velocity when the massecuite level reaches 80 to 85% of pan full. Very low velocities exist during the 'heavy up' phase when the heat transfer rate is low.

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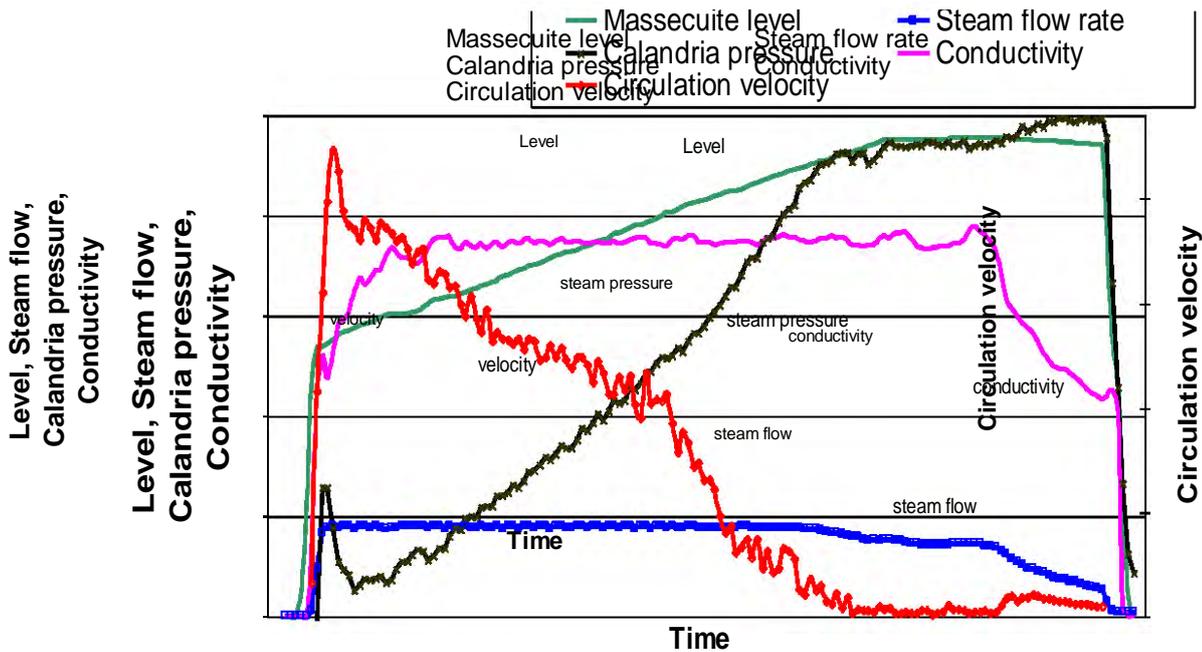
Figure 3.1   Operating parameters over a batch pan strike using exhaust steam boiling A massecuite

Most Australian factories use exhaust steam from the turbines (LP steam) which is typically at 200 kPa abs (saturation temperature ~120 °C). Those factories operating cogeneration plants typically use a higher exhaust steam pressure and vapour 1 (typically at 185 kPa abs; saturation vapour temperature 117.8 °C) for pan boiling. Condong Mill uses vapour 2 at ~145 kPa abs (saturation vapour temperature 110.4 °C) and this is the lowest pressure currently used on a pan stage in an Australian factory.

4.   Information from the literature review

4.1   General comments

The key requirement to quantifying the effect of supplied vapour pressure on a pan's performance is to be able to define the change in heat transfer coefficient or evaporation rate with the changes in massecuite level and massecuite properties (brix *etc*). A detailed examination of the literature has been undertaken to try to source suitable information.

The investigations have provided information on measurements of circulation in pans, CFD modelling of the flow profiles of massecuite in pans and measurements of heat transfer coefficients. Most of the data are for natural circulation batch pans while work by SRI also included investigations into the performance of a stirred pan. The available data are for the use of exhaust steam at 200 kPa abs.

Work by Rouillard (1985) on measuring evaporation rates in a pilot rig to replicate a vacuum pan provides a correlation that appears most suitable for the investigations in this project. This correlation is described in section 4.5.

4.2   Circulation measurements in pans

Information is available for circulation measurements in batch and continuous pans for a steam supply at 200 kPa abs (Wright, 1966; Rackemann and Stephens, 2002; Rackemann, 2004; Rein, 2014). No data are available where circulation velocities or heat transfer performance have been measured for pans operating with a range of vapour supply pressures.

The measurement of circulation velocities in the base of several batch pans was undertaken by SRI using calibrated 'hot film' anemometers (Rackemann, 2004; Rackemann and Stephens, 2002). Despite the uncertainties with aligning the probes exactly to obtain the radial measurement of the flow and the tedious calibration procedure, the technique was able to give good repeatability of velocity profiles. A couple of test results are described that demonstrate typical circulation velocity profiles in pans and the large extent to which the velocity of massecuite reduces with increasing massecuite level.

The data given are for No 6 pan at Macknade Mill which is a 110 t fixed calandria pan which boils high grade seed to 105 t, cuts out half to another pan and completes an A massecuite with 10 t A molasses boilback and drops 108 t.

Figure 4.1 shows data for four tests on high grade seed massecuite production using two anemometer probes with each probe located in its same position for the four tests (Rackemann, 2004). Probe 1 was mid-way underneath the calandria with 100 mm insertion and Probe 2 was inserted 600 mm into the downtake from the base of the pan. It should be noted that Run 13 in Figure 4.1 had a steam flow set point 2 t/h lower than for the other runs which explains the slightly lower circulation velocities.
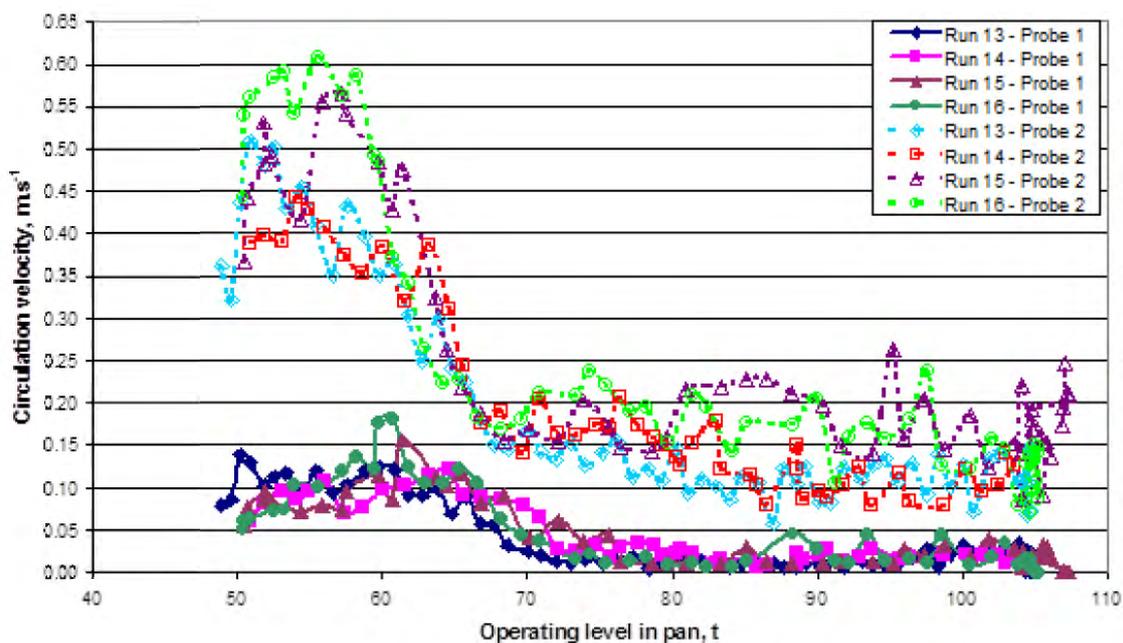
Figure 4.1   Velocity profiles for four pan cycles for high grade seed production in Macknade No 6 pan

Figure 4.2 shows the logged parameters for a high grade seed and A massecuite production cycle of No 6 pan at Macknade Mill where three probes recorded the massecuite velocity. The probe locations were:- Probe 1 – half way under the calandria (insertion depth 100 mm); Probe 2 – into the downtake from under the pan (insertion depth 600 mm); Probe 3 – 100 mm above the top tube plate (insertion depth 60% across the calandria from the wall).

The data in Figure 4.2 are typical data for the operating conditions in this well designed batch pan. The steam flow is held at set point through to pan full in both cycles. At pan full in both cases the calandria pressure is 50 kPag. During the A massecuite heavy up the calandria pressure rises to the mains pressure of 110 kPag. It is clear that the circulation velocity is much stronger when the massecuite level is low but declines rapidly when the high grade seed and the A massecuite reaches ~65% full.

This same pattern is observed in several pans although the level at which the velocity declines depends strongly on the boiling duty and the pan design.
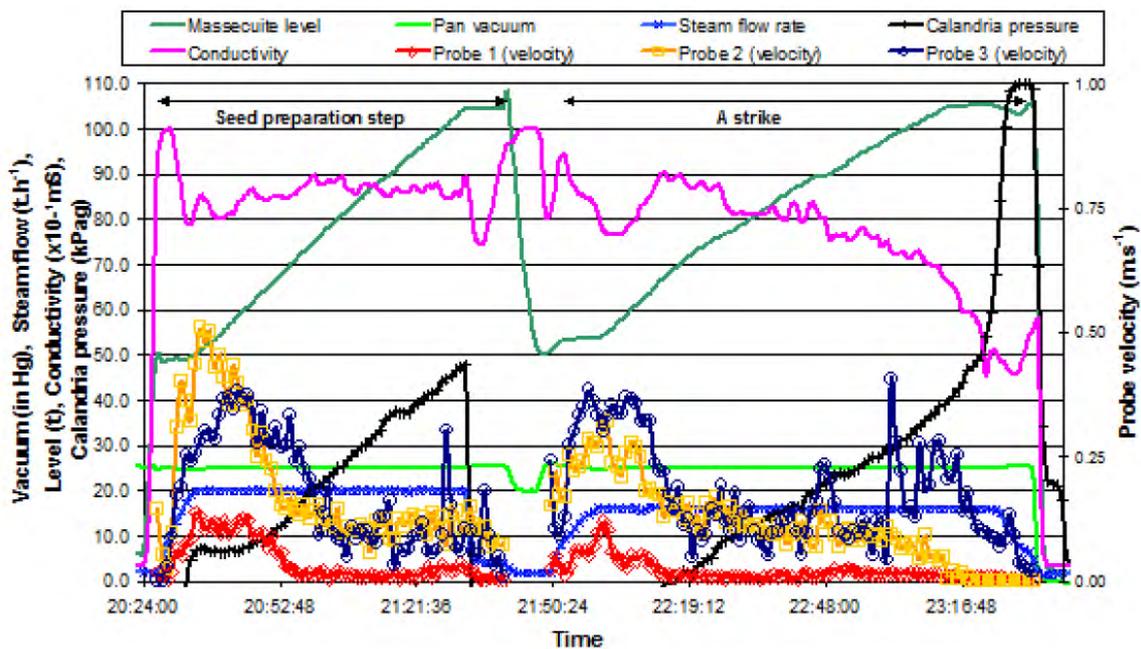
Figure 4.2   Logged parameters on No 6 pan at Macknade Mill for high grade seed and A massecuite production

It is clear from the results of pan circulation measurements that for well designed batch pans the nominated set point for steam flow rate can be maintained till the pan is full or near full when exhaust steam is used to boil the pans. However, the circulation measurements show a rapid decline in velocity when the pan level is still relatively low. It is common that the peak circulation velocity exists when the pan level is ~65 % of pan full.

Circulation velocities in B and C massecuite pans are lower than for high grade seed and A massecuite pans because of the higher viscosity and greater density of massecuite in these massecuites.

4.3   CFD modelling of circulation

Several investigations have been undertaken using CFD modelling to predict circulation flows and pan performance (Rackemann *et al.*, 2006a; Echeverri *et al.*, 2005; Echeverri *et al.*, 2007).   These studies have been very beneficial in providing an improved understanding of the massecuite flow patterns and locations of the generated vapour bubbles within the pans. The main findings have been:-

- Recirculation zones exist at the outer wall of a batch pan and at the edge near the downtake;

- For a flared batch pan the velocity in the recirculation zone at the outer wall is slower and larger in volume than for a straight sided pan. However the increased circulation resulting from the reduced massecuite level for the same strike quantity compensates to a large extent for the weaker circulation in the flared section of the pan;

- When the massecuite is of lower viscosity and at lower level, shorter smaller diameter tubes produced stronger circulation movement. However, when the massecuite is of higher viscosity and at higher massecuite level longer larger diameter tubes produced a better result; and

- For simulations of lower viscosity massecuites less condensation of vapour produced within the calandria tubes takes place immediately above the calandria and this vapour rises to the surface. For high viscosity conditions (and with the same evaporation rate imposed) the vapour produced in the calandria is almost totally condensed above the calandria tubes before flashing as the flow nears the massecuite surface. This latter arrangement causes lower massecuite circulation rates.

Some deficiencies were noted in the CFD modelling compared with observations from circulation velocity measurements using anemometers. Notably the CFD modelling predicted fairly uniform flow into the base of all the calandria tubes. However factory measurements generally show a bias to stronger flows in the tubes near the downtake.

None of these CFD modelling studies considered the effects of a change in vapour supply pressure.

4.4   Heat transfer coefficients

Rackemann (2004) calculated the heat transfer coefficient for boiling in several batch pans in Australian factories. The overall heat transfer coefficient is defined as:

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$$U* = \frac{Q}{A \ \Delta T_{eff*}}$$

where U is the overall heat transfer coefficient (W.m^{-2}.K^{-1})

Q is the heat flux (W)

A is the area available for heat transfer (m^2)

ΔT_{eff*} is the temperature difference (K) between the condensing steam in the calandria and the boiling temperature of the massecuite in the pan which is estimated from the operating pressure in the head space plus the boiling point elevation plus superheat which may be generated due to the slow movement of massecuite away from the surface of the calandria tubes.

Table 4.1 summarises the HTC data determined by Rackemann (2004).

Table 4.1   HTC data from studies by Rackemann (2004)

Mill and Pan	Apparent Heat Transfer Coefficient, U* (W/m²/K)				Decline in HTC per m of head
	Initial	Entire cycle	During heavy up	Start of heavy up	
Proserpine No. 2 pan. A massecuite.	455-495	350-360	280-315	310-325	130 (run up) 45 (last stage of run up)
Proserpine No. 3 pan. A massecuite.	420	320	245	270	80
Macknade No 6 pan. HG seed massecuite.	700	600	500 (end of cycle)		165
Macknade No 6 pan. A massecuite.	550	465	280*	415	85 (run up) 23 (last stage of run up)
Plane Creek No 1 pan. B massecuite. Strike when surfactant used)**	680	500	205	315	295 (period before surfactant added)
Plane Creek No 1 pan. B massecuite. Strike when surfactant not needed.	650	505	240	375	278

* End of heavy up HTC is < 100 W/m²/K.
** Data prior to surfactant being added (usually ~90 t).

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Figure 4.3 shows the HTC data calculated for the Proserpine No 2 pan (A massecuite). Of note Run 10 was run up with a lower steam rate due to slow crushing at the time and the need to slow the boil-on rate. The steam rate for the majority of the runs was 25 t/h and for Run 10 ~18 t/h.
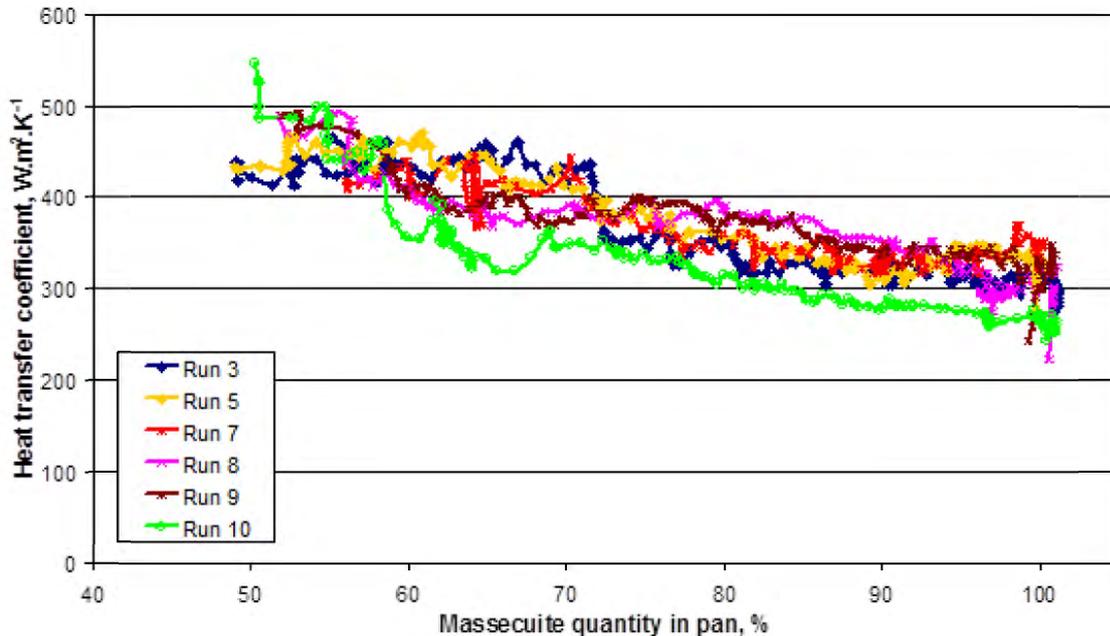
Figure 4.3   HTC data for Proserpine No 2 pan on A massecuite boiling

Figure 4.4 shows the HTC data for Macknade No 6 pan which boils a high grade seed and, after cut out of some of the high grade seed, boils an A massecuite. The steam rate for the high grade seed boiling is 24 t/h and for the start of the A massecuite boiling is reduced to 16 to 18 t/h. The pan is largely boiled in fully automatic control and the tight repeatability of the data is apparent. These data were collected when the cane supply was of high CCS and fresh cane was available. If the cane supply was of low purity, stale or perhaps standover cane was being supplied then lower HTC values would be expected. Of note Figure 4.4 shows:-

- The rate of decline of HTC with increasing level in the final run up stage on A massecuite is slower than for the earlier stage of run up. During heavy up the HTC declines markedly to a very low value (< 100 W/m^2/K) prior to discharge of the massecuite; and

- The HTC of the high grade seed at pan full (1600 mm above the calandria) at 24 t/h steam rate is 520 W/m^2/K. Whereas for the start of the A massecuite boiling (200 mm above the calandria) the HTC is ~550 W/m^2/K for a steam rate 18 t/h.
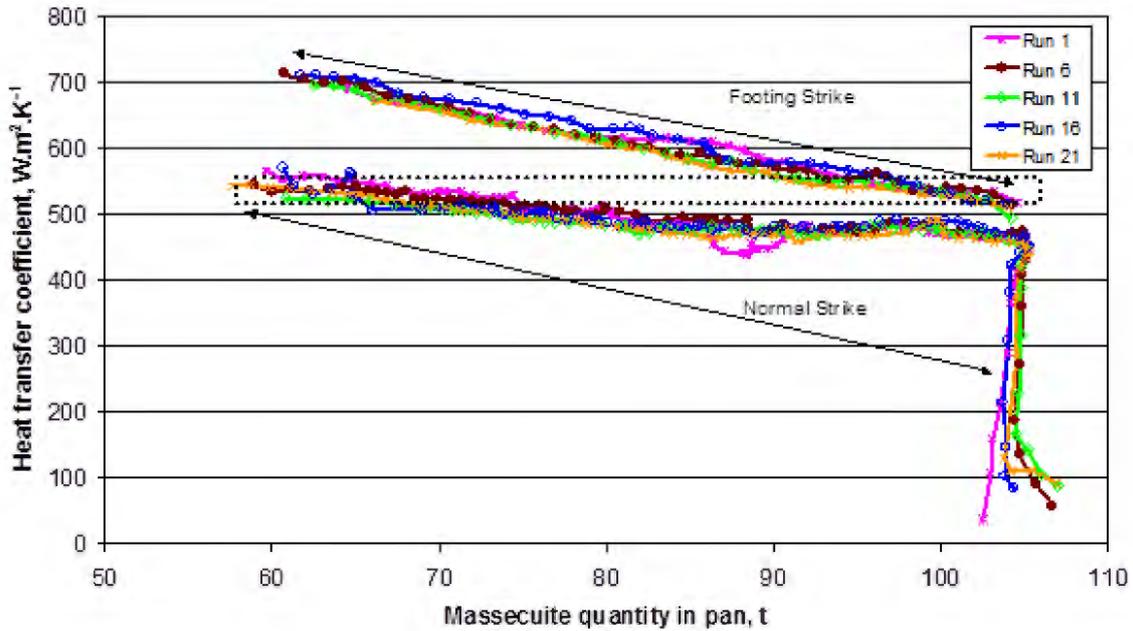
Figure 4.4   HTC data for the Macknade No 6 pan boiling high grade seed followed by an A massecuite

The HTC data for Plane Creek No 1 pan boiling B massecuite are shown in Figure 4.5 (Rackemann, 2004). These data are for runs where surfactant was not needed to be added (often added at the 90 t level). Interestingly the data in Figure 4.5 are for three rates of water addition (6, 8 and 10 t/h) but at the same steam rate (18 t/h). Unexpectedly the varying rates of water addition did not alter the HTC values. Of course runs with additional balance water reduced the boil-on rates.
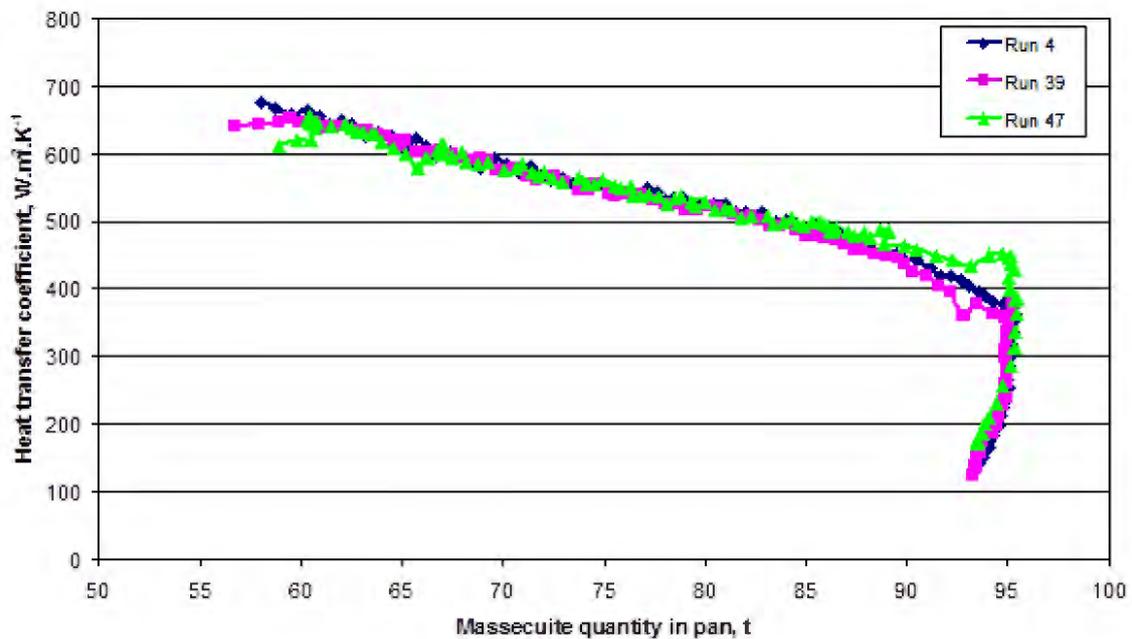
Figure 4.5   HTC data for Plane Creek No 1 pan boiling B massecuite (runs with no surfactant required)

The HTC analysis for boilings of HG seed (one pan), A massecuite (three pans) and B massecuite (one pan) showed the following:-

- The lower steam rate for the A massecuite boiling in the Proserpine No 2 pan produced a lower HTC. The reduction in the steam rate alters the circulation velocity in the pan and thus indirectly influences the heat transfer coefficient;

- The highest HTC values existed for the high grade seed boiling. The low viscosity of this boiling compared with the A and B massecuite strikes would be a factor producing the high HTC. The viscosity of massecuite affects the ability of the massecuite in the calandria to transfer heat from the tube surface. As well the high grade seed boiling used a steam rate of 24 t/h compared with 16 to 18 t/h for the A massecuite cycle;

- The rate of decline of the HTC with height of massecuite for the high grade seed boiling was faster than the rate of decline of the HTC with height of massecuite for the A massecuite boiling. It is postulated that, with the low viscosity high grade seed boiling, the circulation is stronger in the inner region of the calandria throughout the run up whereas for the A massecuite boiling which would be at higher viscosity a stronger circulation flow to the outer regions of the calandria occurs through the run up of the cycle; and

- The rate of decline of HTC with increasing boiling level for the B massecuite was much faster than for A massecuite (~280 $W/m^2/K$ per m of head above the calandria compared with 85 $W/m^2/K$ per m of head above the calandria). The result is attributed to the higher viscosity of the B massecuite boiling. However differences in pan design between the two pans would also be a factor affecting this assessment.

4.5   Correlation for evaporation rate

4.5.1   Rouillard expression for evaporation rates in A, B and C massecuites

Rouillard (1985) investigated the boiling of C seed massecuite in a pilot vacuum pan in which the velocity of the massecuite entering the base of the tube was regulated by using a circulating pump. The length of the sub-cooled region (section at the base of the tube) was found to be a function of the heat flux and the velocity up the tube. For some boiling conditions the sub-cooled region was calculated to extend to the top of the tube.

Rouillard (1985) also undertook factorial experiments in boiling A, B and C massecuites in a pilot vacuum pan to assess the effect of a range of process variables. It appeared that pumped circulation was not employed in this apparatus. The specific evaporation rate $(kg/h/m^2)$ was measured for tubes of 0.6, 1.0, 1.4 and 1.8 m. Each tube was of 100 mm diameter and contained its own steam jacket. The range of data for the experimental trials is shown in Table 4.2. No data were obtained for the high operating levels as experienced at the end of a batch strike and the minimum vapour pressure in the steam chest was 125 kPa abs.

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Table 4.2   Range of data investigated by Rouillard (1985)

Massecuite	Vapour pressure in the steam chest, kPa abs	Vacuum, kPa abs	Head of massecuite above top tube plate, m
A	125-195	9-25	0.20-0.94
B	127-195	9-20	0.25-0.91
C	130-180	10	0.24-0.87

Rouillard (1985) proposed a correlation for the heat transfer coefficient in terms of the various processing variables. The factorial experiment showed that shorter tubes provide a higher evaporation rate per unit heating surface area. From the factorial experiment Rouillard (1985) developed the following correlation to predict the evaporation rate.

$$\text{Ln (E)} = 15.92 - 0.165 * \text{Ref Brix} - 0.0601 * \text{Head space P} + 0.0311 * \text{Purity (App)} + 0.00639 * \text{Press} - 0.321 * \text{Length of tube} - 0.298 * \text{Head}$$

Where E = evaporation rate (kg/h/m^2)

Ref Brix = refractometer brix of the massecuite

Head space P = head space pressure in the pan (kPa abs)

Purity (App) = apparent purity of the massecuite

Press = vapour pressure in the calandria (kPa abs)

Length of tube = Length of the heating tube in the calandria (m)

Head = Height of massecuite above the top tube plate (m)

In total 254 sets of data were analysed to provide the above correlation with a correlation coefficient of 0.81.

This correlation is used in the dynamic model to predict the evaporation rate for the set of nominated conditions although several modifications have been made to some of the dependencies based on available HTC values for factory pans (see section 4.4) and intuitive changes that would be expected if the vapour pressure was as low as 58 kPa abs (85 °C saturation temperature). Ideally a large data set for evaporation rates from factory pans when operating for a range of vapour pressures in the steam chest would be used to improve the correlation. This data set should include evaporation rates when low pressure vapour is used.

4.5.2   *Modifications to the Rouillard expression*

Based on available HTC data from factory pans the Rouillard expression was found to be unsuitable in the proposed form and modifications were incorporated.

Generally for A and B massecuite boilings the calandria pressure at the start of the strike, with massecuite at a low boiling level above the top tube plate, the pressure in the calandria

is below the supply pressure and the steam flow rate is controlled to a set point value. This set point value is typically lower than that corresponding to the evaporation rate predicted by the Rouillard expression using the supply pressure.

The procedure used to modify the Rouillard expression makes use of available factory HTC values and observed changes in calandria pressure through the strike as massecuite level increases. The procedure for adjusting the Rouillard expression is summarised below for A massecuite:-

- Using the HTC data for Macknade No 6 pan and making adjustments based on HTC data for other A massecuite pans in the industry, the variation in HTC ($W/m^2/K$) was assumed to be:

Status in strike	HTC, $W/m^2/K$
Shortly after start run up	520
At pan full but before heavy up	420
At massecuite ready for pan drop	100

- Estimate the calandria pressure at different boiling heights in industry pans.

- Calculate the evaporation rate at different boiling heights within the pan using the estimate of calandria pressure and HTC value. Modify the dependency of the terms in the Rouillard expression to obtain an improved match of the Rouillard values to these calculated industry values. At early stages of the strike the evaporation rate will still be limited by the control of the steam rate to the set point value. As an approximation, taking into account differences in latent heats of vapour in the calandria and head space, heat losses and sensible heating of the feed streams, the steam rate to the calandria is assumed to be 1.1 times the calculated evaporation rate. This factor will be lower when vapour supply to the calandria is at lower pressure.

Table 4.3 lists the modifications made to the Rouillard expression to better match the 'expected' industry evaporation rates. These modifications should be considered as being a 'stop gap' only till reliable factory data are available. The largest discrepancy in estimating the evaporation rates is for operation at low pressure vapour (say lower than 130 kPa abs) for which there is currently no industry data.

Steam rates have been estimated for A, B and C massecuite boilings based on the pan described in section 5.2.1 (100 m^3 pan volume, 655 m^2 heating surface area, tubes 1 m length). For these estimates the calandria pressure used in the modified Rouillard expression is the estimated pressure based on the boiling level above the top tube plate. For example, for a 200 kPa abs steam supply in an A massecuite pan a calandria pressure of 130 kPa abs is assumed for a boiling level below 0.5 m above the top tube plate. The refractometer brix of the massecuite has been assumed to increase in line with industry values as the boiling level increases in the pan. Pan full is at 1.63 m above the top tube plate.

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Table 4.3   Modifications made to the Rouillard expression

Parameter	New term	Value of factor
Refractometer brix of massecuite	-0.165 * Ref Brix ^ D1	D1 = 1.003
Steam pressure supply	+0.00639 * D2 * Press ^ D3	D2 = 0.7 D3 = 1.0
Head of massecuite	- 0.298 * Head ^ D4.	D4 = 0.4
Overall value of evaporation rate	Overall value * D5	D5 = 1.0 for A and B massecuite D5 = 1.7 for C massecuite

Figure 4.6 shows the estimated values of steam rate for the pan boiling A massecuite. Figure 4.7 and Figure 4.8 provide the steam rate data for the B and C massecuite boilings respectively. The reduced influence of boiling height at low boiling heights in these figures is attributed to the estimated calandria pressure at these boiling levels being lower than the supply pressure.
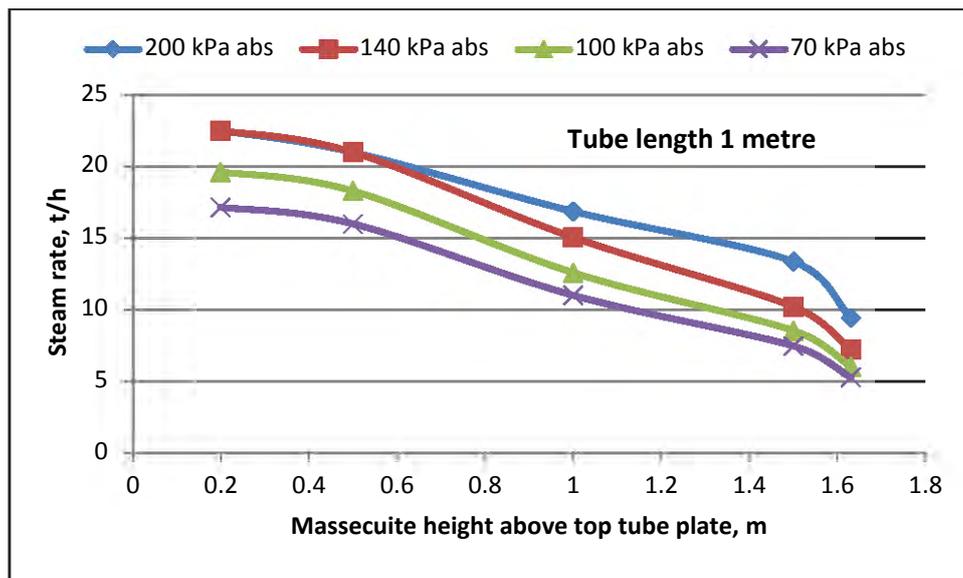
Figure 4.6   Estimate of steam rate for A massecuite boilings using the modified Rouillard expression
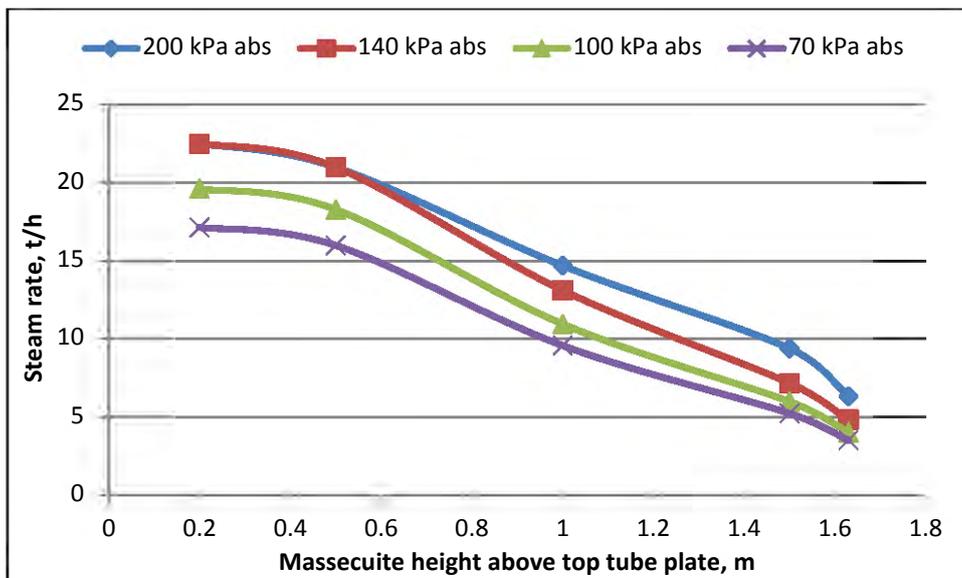
Figure 4.7   Estimate of steam rate for B massecuite boilings using the modified Rouillard expression
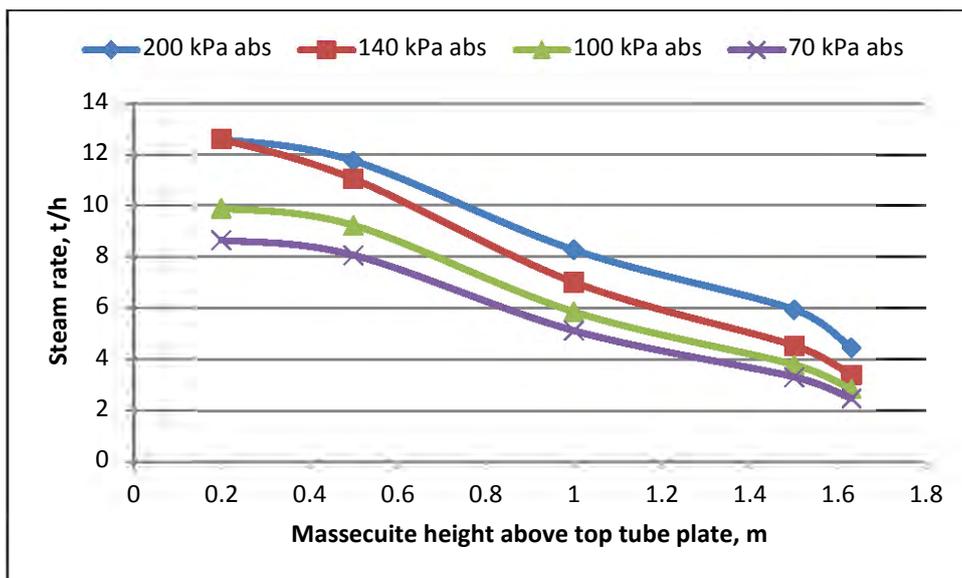
Figure 4.8   Estimate of steam rate for C massecuite boilings using the modified Rouillard expression

5. Methodology to investigate the effects of vapour supply pressure on the productivity of a batch pan

5.1 Selection of the model and objectives

The investigations into batch pan operation using low pressure vapour were undertaken using the modelling software SysCAD (Mann *et al.*, 2015). The team at KWA (developers of SysCAD) has assisted greatly with this project. Consideration was given to either developing a SysCAD steady state model of a batch pan that would be progressed incrementally through the pan cycle or to a full dynamic model in SysCAD. KWA advised of the advantages of a dynamic model and this model has been developed. Subsequently the dynamic model was developed owing to the significant advantage that, once validated, the model could be used to investigate the dynamic responses for various control methodologies and so determine the preferred control parameters for the nominated input conditions, such as supply vapour pressure. It is likely that the control responses and the preferred massecuite viscosity profile (function of crystal content and supersaturation of the mother molasses) will be different for vapour supplies of different pressures.

For this study the primary aim of the model was to determine the cycle time to complete a boiling duty at a specified massecuite dropping condition (*e.g.* brix, crystal content, and massecuite level in the pan) for a defined duty (*e.g.* A, B or C massecuite) and defined pressure of the vapour supply. Thus application of the model allowed the effects of using vapour at different supply pressures to be determined for the different boiling duties.

5.2 Description of the model

5.2.1 Batch pan design

The model is based on the dimensions for a well designed, straight sided, centre well, unstirred batch pan of 100 m^3 massecuite capacity at pan full. Table 5.1 provides the key dimensions for the pan. By industry standards this pan is considered to be one that provides strong circulation and heat transfer performance. Operating data for this type of pan (with steam supply at 200 kPa abs) has been used to modify the Rouillard expression.

Table 5.1   Key dimensions for the batch pan

Parameter	Value
Capacity at pan full, m^3	100
Pan internal diameter, m	7.0
Height above top tube plate at pan full, mm	1630
Footing volume to start the pan (at 200 mm above the top tube plate), m^3	45.3
Run up volume per metre of height above the top tube plate, m^3	38.5
Heating surface area, m^2	655
Heating tubes in the calandria:	
Length, mm	1000
Diameter (outside), mm	114.3
Thickness, mm	6.0

5.2.2   Control loops in the dynamic model

During operation, the batch process is controlled by the vapour rate, the feed rate to the pan and the head space pressure. The two main variables being controlled in the pan were crystal content and supersaturation (or conductivity as an inferred measure of both supersaturation and crystal content).

There were several strategies investigated for controlling vapour and feed rates. The available control loops incorporated into this model are:-

- Head space pressure. A constant set point was used throughout the cycle. The effect of head space pressure could be investigated if required.

- Vapour rate to the calandria. The vapour rate to the calandria could be controlled in one of several ways with the overriding constraint of an operator set upper limit or a rate corresponding to the maximum evaporation rate determined by the modified Rouillard expression:-

    o   Manually set fixed vapour rate (user adjustable during the cycle);

    o   Control to a pre-set supersaturation profile; or

    o   Control to a pre-set conductivity profile.

- Feed rate control. The feed rate of syrup/molasses onto the pan could be regulated according to selectable procedures:-

    o   To a pre-set conductivity profile. This option can replicate the conductivity control methodology commonly used in batch pans;

o   To a pre-set supersaturation level nominated as a fraction of the oversaturation at which nucleation would occur; and

o   To a crystal content profile while limiting the supersaturation to be at or below a nominated fraction of the oversaturation at which nucleation would occur.

The strategy chosen for this study was to measure crystal content and control it with feed rate and to measure supersaturation and control it, at or below the nominated fraction of oversaturation at which nucleation would occur, with vapour rate. The conductivity profile is an output from this control method.

5.2.3   Selection of the pan termination condition

The massecuite conditions (brix and crystal content) at which a pan strike is terminated have a large influence on the yield of sugar per strike, on the quantity of sucrose recycled with the molasses and the management of the pan stage and subsequent strikes. If the B molasses purity increases as a result of poor exhaustion of the high grade strikes then the overall sugar production from the syrup will be reduced. For the model a target termination condition is defined which, when reached in the heavy up step, will terminate the strike and set the total cycle time for the pan.

When using supply vapour at a lower pressure the rate of evaporation, circulation and crystallisation rate in the run up stage will be slower and, during the heavy up stage, the rate of brix increase and crystallisation rate will also be slower. Either of these conditions can be so detrimental to pan stage throughput that the strike must be terminated to allow the next round of operations to commence. Thus, two conditions exist which cause the procedure for a pan strike to be terminated prematurely *viz.*, not at the defined target pan full condition of 100% full and/or not at the target massecuite conditions for dropping/discharge of the pan contents.

Figure 5.1 shows the control logic used for running the dynamic model for a set of defined conditions. This flow scheme incorporates the termination conditions that would apply either during run up to full or during heavy up.
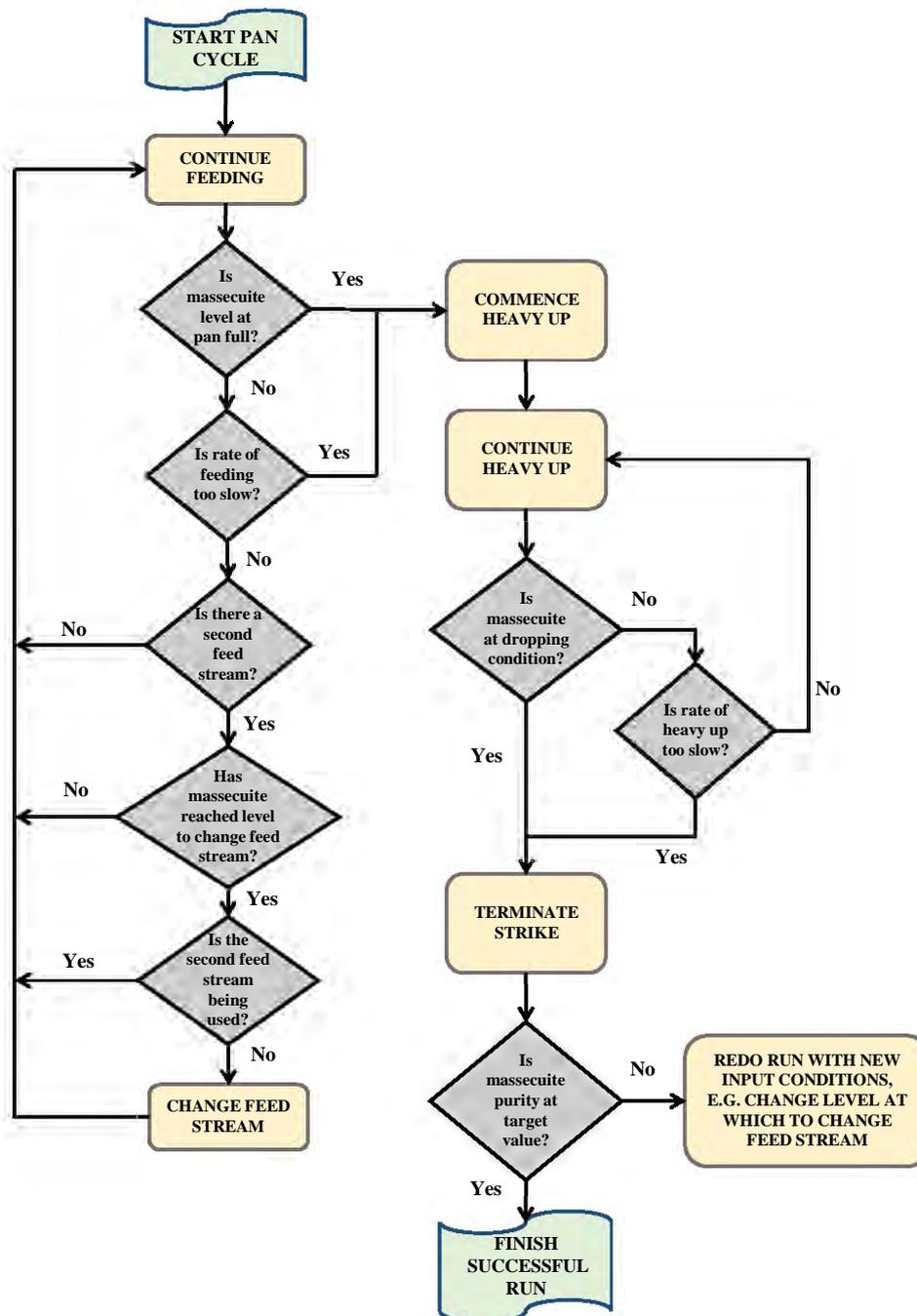
Figure 5.1   Logic flow diagram for conducting a modelling run

The conditions for premature termination are:-

- *Premature termination of feed of syrup/molasses.* The rate of increase in level has slowed to below a defined minimum acceptable rate of increase. This condition indicates that the sucrose deposition rate during run up is so slow to be not economical. The feeding of syrup or molasses is then terminated and the massecuite quantity in the pan is below the 'pan full' capacity. The pan is placed in the heavy up mode which is undertaken, either successfully or unsuccessfully.

- *Premature termination of the heavy up step.* The rate of increase in brix or crystal growth rate has slowed below a defined value and termination of heavy up is enacted.

For situations where a run is terminated at a level lower than 100% the target massecuite purity is not reached (*e.g.* through not supplying the required amount of A molasses boilback for an A strike) then the run will need to be repeated with the switch level for changing the feed stream adjusted to suit so that the massecuite at drop is at the nominated purity. As well the footing volume may need to be reduced (or the seed size increased) if the reduction in product crystal size is unacceptable.

If the heavy up step is not successfully completed, *i.e.* the defined massecuite conditions for completion of heavy up are not satisfied, the run is classified as completed but with a lower yield of sugar.

When either premature termination point is enacted the mass of crystal production in the strike is less than would be achieved for good exhaustion performance in an uninterrupted run. However this objective has been sacrificed because the reduced productivity of this pan would have adverse consequences for other pans in the schedule and the productivity of the whole pan stage.

5.2.4   Description of the SysCAD dynamic model

The dynamic SysCAD model was developed and the termination procedures incorporated. The model allowed use of any one of the control procedures described in section 5.2.2. The procedure which uses a crystal content profile for control of the feed was favoured as it provided a more stable progression of conditions through the strike.

Figure 5.2 shows the screenshot of the interface to the dynamic model.
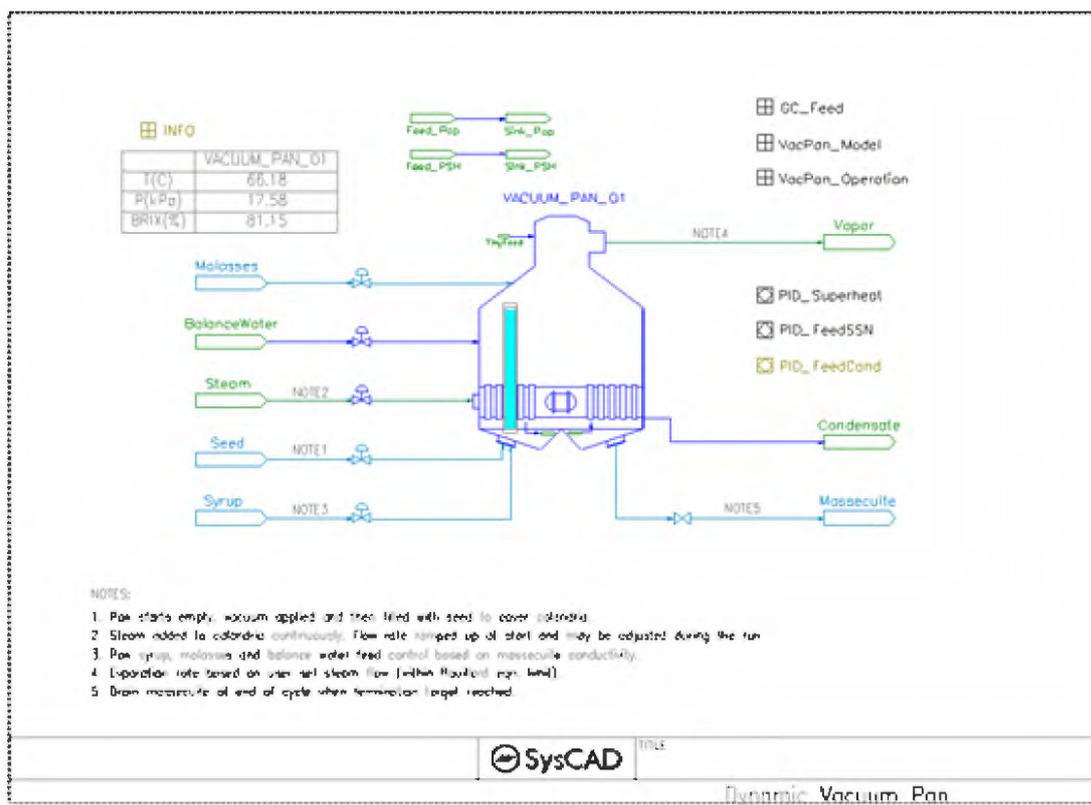
Figure 5.2   Screenshot of the interface to the SysCAD dynamic model

The main input and output parameters for the model are shown in Table 5.2. The inputs are provided under different worksheets. The model includes ramp factors for raising vacuum, for drawing in the footing massecuite to the pre-set level, ramping of steam to start boiling the footing, and a delay time prior to commencing heavy up and holding on balance water.

Table 5.2   List of the main input and output parameters for running a pan strike in the SysCAD model

Function	Worksheet	Parameter
Steam	Feeder sink	Maximum steam flow rate Pressure of vapour supply
Syrup	Feeder sink	Pressure and temperature Maximum flow rate
	DSp	Composition
Molasses	Feeder sink	Pressure and temperature Maximum flow rate
	DSp	Composition
Seed	Feeder sink	Mass flow rate for providing footing Pressure and temperature
	DSp	Seed composition (crystal content and mother molasses composition)
	DSSA	Seed mean aperture
Balance water	Feeder sink	Pressure and temperature Maximum flow rate
Massecuite	Sp	Massecuite composition (crystal content and mother molasses composition) Product massecuite mean aperture
Vapour	Feeder sink	Vapour flow rate Pressure and temperature of vapour from head space
Condensate	Feeder sink	Condensate flow rate Pressure and temperature of condensate
QC-FEED	Composition	Used to input compositions of seed and feed streams Temperature and composition of the seed massecuite Temperature and composition of syrup feed Temperature and composition of molasses feed
VAC PAN 01	SP	Output massecuite composition
	DSSA	Output crystal size
	Settings	Height in pan Volume in pan
VACUUM PAN OPERATION	QControl	pgm*
	Status	Time for strike from when start to raise vacuum to drop massecuite
	Termination	Brix of massecuite to terminate in heavy up
		Crystallisation rate to terminate during run up
		Heavy up % change in dry substance per minute

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		Delay time for start of heavy up
	Pressure heat	Vacuum pumping rate
		Operating headspace pressure target
		Superheat value
		Footing level
		Footing flow rate
		Massecuite level to start steam
		Maximum steam rate
		Steam ramp period, h
		Target steam rate
	Pan feed	Pan massecuite conductivity – syrup feed, molasses feed and heavy up
		Supersaturation limits – syrup feed, molasses feed and heavy up
		Crystal content – fall till syrup feed starts, change from syrup to molasses feed, at change over from stop molasses to start of heavy up
		Maximum syrup feed rate
		Stop level for syrup (level for change from syrup to molasses
		Maximum molasses flow rate
		Molasses feed rate too slow (change over to heavy up)
		Pan level to stop molasses feed
		Balance water feed maximum rate
		Stop level for balance water (101%)
VAC PAN MODEL	Qcontrol	pgm*
	Pan	Pan dimensions
	Contents	Vacuum pan contents (massecuite, mother molasses)
	Evap rate	Factors for Rouillard expression (K1, K2)
		Maximum specific evaporation rate
	Xtal growth	Growth rate parameters for HG and LG
		Growth rate parameters Factor and exponent for supersaturation)
		Seed CV
PID_Superheat		Control parameters to regulate superheat in massecuite
PID_FeedSSN		Control parameters for using supersaturation control to regulate feed rate
PID_FeedCond		Control parameters for using conductivity control for regulating feed rate

* Programmable module.

6. Results of the investigations

6.1 Comments on the test procedure

The dynamic SysCAD model was used to investigate the effect of different supply steam pressures on the operation of typical strikes for A, B and C massecuites in the Australian three massecuite boiling scheme. In each case the investigations were undertaken for the supply of exhaust steam at 200 kPa abs (saturation temperature 120.2 °C), vapour at 140 kPa abs (saturation temperature 109.3 °C), vapour at 100 kPa abs (saturation temperature 99.6 °C) and for vapour at 70 kPa abs (saturation temperature 90 °C). A head space pressure of 14 kPa abs was used for each run. Superheat in the massecuite is adjustable in the model and was set at 5 °C although superheat is likely to be greater when using low pressure vapour because of the slower massecuite circulation at the lower evaporation rate.

6.2 A and B massecuite investigations

6.2.1 Test conditions for the A and B massecuites

The test conditions for the A and B massecuite runs are shown in Table 6.1.

Table 6.1 Data for simulation runs for A and B massecuites

Stream	Parameter	Value
High grade seed massecuite	Massecuite purity	89
	Massecuite dry substance	85.4
	Crystal content%massecuite	35
	Mean size, mm	0.55
	CV	0.30
	Temperature, °C	60
A massecuite	Seed footing volume% pan volume	40
	Volume % pan full at which change from syrup feed to A molasses feed	90
	Volume % pan full at which A molasses feed stops and heavy up commences	100
	Limit of supersaturation (% of oversaturation at nucleation limit)	90% throughout the strike
	Crystal content profile	36% at start of syrup feed 43% at change from syrup to A molasses 46% at pan full
	Target massecuite purity	88
	Target dry substance of massecuite at end of heavy up	91.0

	Minimum growth rate to terminate a run, μm/h	40
	Target mean crystal size, mm	0.87
B massecuite	Seed footing volume% pan volume	40
	Volume % pan full at which change from syrup feed to A molasses feed	55
	Volume % pan full at which A molasses feed stops and heavy up commences	100
	Limit of supersaturation (% of oversaturation at nucleation limit)	90% throughout the strike
	Crystal content profile	36% at start of syrup feed 37% at change from syrup to A molasses 42% at pan full
	Target massecuite purity	82.0
	Target dry substance of massecuite at end of heavy up	91.8
	Minimum growth rate to terminate a run, μm/h	20
	Target mean crystal size, mm	0.85
Syrup feed	Purity	90
	Dry substance	69
	Temperature, °C	60
A molasses feed	Purity	74
	Dry substance	70
	Temperature, °C	50

6.2.2   Results for the A massecuite simulations

Time step size in the model was set between 5 and 10 seconds. The model ran at about 600 times real time (although the speed is adjustable and, if required, the software can be set to run in real time). A single run for a batch A massecuite boiling which takes 180 min in practice is run with full trending of data in 18 seconds.

Figure 6.1 shows the trends of data from a run of the dynamic model on A massecuite with steam supply at 200 kPa abs. The complete set of trends for A massecuite boiling at 200, 140, 100 and 70 kPa abs vapour pressure are provided in Appendix A.

The trend data shows that the modified Rouillard evaporation rate was much higher than the input set point value in the early stages of the A massecuite boiling. This is because the modified Rouillard expression is using the steam supply pressure (200 kPa abs) even though the calandria pressure in this phase of the cycle will be much lower (possibly

130 kPa abs). The modified Rouillard evaporation rate reduces rapidly as the massecuite level and massecuite brix increase during the run up.

The trend data in Figure 6.1 show cyclic response of supersaturation in the early stages of the run and the subsequent cyclic variation to crystal growth rate, steam rate and conductivity. The cyclic variation then stabilized to tight control. A disturbance to supersaturation is also introduced in the changeover from syrup to A molasses feed. The cyclic variations are a consequence of the control loop settings (the model uses PID controllers and there is room to optimise tuning) and also the simplicity of the control functions used to date in the model.
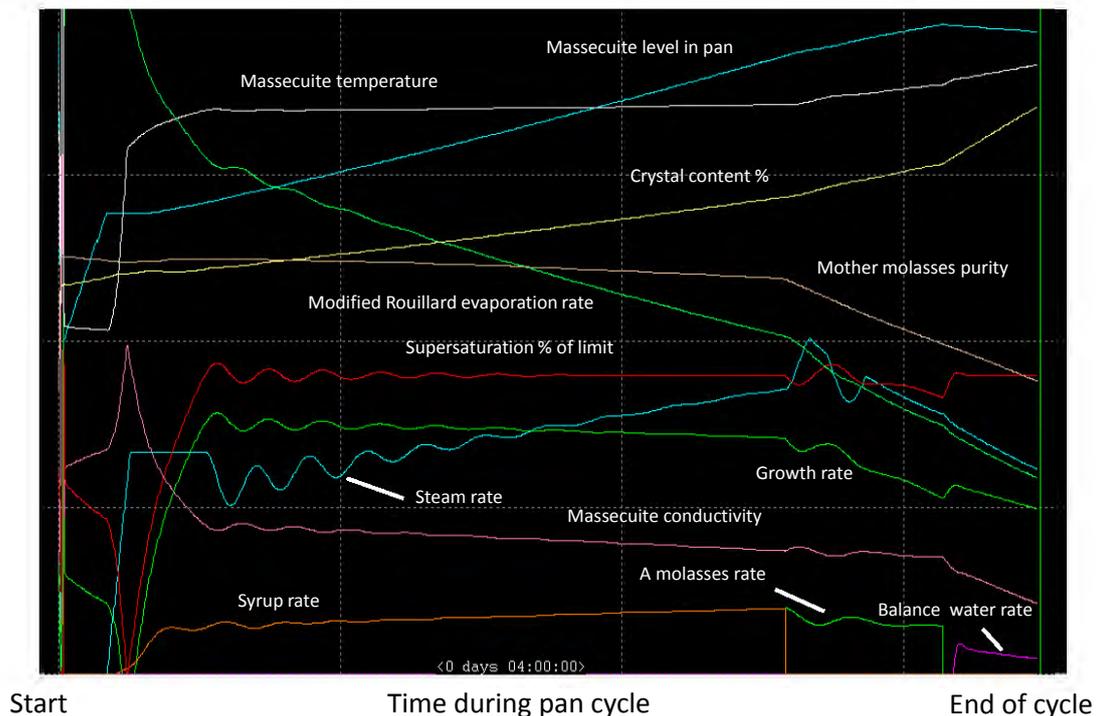
Figure 6.1   Trended data for A massecuite simulation for a vapour supply pressure of 200 kPa abs

Figure 6.1 shows the modified Rouillard rate is higher than the supersaturation limited steam rate through most of the cycle. During this period the supersaturation increased and was maintained at the target value (90% of the nucleation limit) until part way through A molasses feed where the evaporation rate became limited by the conditions in the pan (determined by the modified Rouillard expression). For this run the supersaturation held at close to the 90% limit (the target value) as the available evaporation rate was sufficiently high. During the heavy up stage some balance water was fed to control the supersaturation at the target value.

For the A massecuite boilings the pan completed the strike for all four vapour supply pressures to the pan full condition (100%) and to the nominated dry substance (91.0) for

terminating the strike massecuite. For all supply vapour pressures, the pan drop massecuite was 87.7 purity, 51.6% crystal content with mean size of crystals 870 µm. Table 6.2 shows the cycle times for the simulations of A massecuite boilings for the supply of steam/vapour at different pressures. These cycle times include the time to raise vacuum, draw in the footing high grade seed massecuite, and ramp steam to the required set point steam rate. At the start of the run the steam rate is held at set point till the supersaturation has reached the nominated % of oversaturation. From this point onwards the steam rate is the lesser of that required to hold at the supersaturation level or match the steam rate corresponding to the modified Rouillard evaporation rate.

Table 6.2   Cycle times for A massecuite strikes using vapour at different supply pressures

Supply pressure of vapour, kPa abs	Cycle time, h
200	3.47
140	3.57
100	3.80
70	4.06

The following observations are made from these results and from inspection of the trend data for the modelling runs at the different supply pressures.

- The increase in cycle time when operating with a lower vapour supply pressure was smaller than expected compared with limited observations on factory pans. This is because for all cases the available evaporation rate by the modified Rouillard expression was sufficiently high to allow the supersaturation to be increased to the limiting value for a reasonably large section of the run up.

  For all scenarios the supersaturation increased to the limiting value (90%) from the start of the syrup boil-on period and controlled at this supersaturation level until the modified Rouillard evaporation limit was reached. The level of massecuite in the pan, in combination with the vapour pressure, determined the point at which the supersaturation could no longer be maintained as the Rouillard evaporation limit was reached and was subsequently declining in further run up of the pan. The level in the pan when the supersaturation reduced from the nominated limit is shown in Table 6.3 for each of the supply pressures.

  Up to the level in the pan when the supersaturation reduced from the limiting value the required steam rate increases to hold the supersaturation at the nominated value. The increase in steam rate is attributed to the increasing crystal surface area in the pan as the mass of crystals increases. Eventually the steam rate is limited by the Rouillard value and the supersaturation starts to fall.

  The increasing steam rate through the strike is most evident for the 200 kPa abs vapour supply. The control function to increase steam rate through the cycle has

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been promoted previously by SRI as being beneficial for well designed A massecuite pans operating with a high steam supply pressure.

Table 6.3   Level in A massecuite pan when supersaturation reduced below limiting value

Vapour supply pressure, kPa abs	Level when supersaturation reduced from the limiting value
200	Pan full including heavy up
140	90%; start of A molasses feed
100	75%; part way through syrup feed
70	65%; part way through syrup feed

- The crystal growth rate is ~100 to 105 µm/h during the syrup feed period at the 90% supersaturation limit which is in general agreement with growth rates in A massecuite boilings. The growth rate declines during the A molasses feed section and heavy up as the supersaturation is limited by the Rouillard evaporation rate.

- When steam is supplied at 200 kPa abs balance water is used in the heavy up stage as the evaporation rate exceeds that required to reach the 90% supersaturation limit. For the lower vapour supply pressures no balance water is used and the supersaturation during heavy up is below the 90% limit.

- Overall the trend data is in good agreement with typical boilings of A massecuite in well designed batch pans when operated with 200 kPa abs steam supply. In practice operators may target higher supersaturation levels in the heavy up stage which will increase crystal growth rates in the final stage and shorten the overall cycle. The use of balance water would then be reduced.

- The conductivity profile is observed to be different for the scenarios at the different supply pressures. The main effect is the change in operating supersaturation as imposed by the limiting evaporation rate. Simply, the conductivity declines slightly as the pan is being run up while the supersaturation is being held at the nominated limit (constant supersaturation and increasing crystal content).   When the supersaturation declines owing to the limited evaporation rate the conductivity increases.   During heavy up the conductivity declines steeply.   The changing profiles for conductivity can be seen in the trends in Appendix A.

6.2.3   Effects of varying A massecuite feed conditions

Simulations run for A massecuite boiling with vapour supply at 100 kPa abs were examined for the following two scenarios:-

- Both syrup and A molasses feed heated to 70 °C instead of supplying syrup at 60 °C and A molasses at 50 °C (no change to the dry substance of the syrup or A molasses); and

- Syrup supplied at 72 dry substance instead of 69. Both syrup and A molasses supplied at 70 °C. A molasses dry substance unchanged at 70.

The trends for these two simulations are also shown in Appendix A. The cycle times for these two runs are shown in Table 6.4 together with the data for vapour supply at 100 kPa abs for the base test conditions. The main changes that occur relative to the base conditions are:-

- The level in the pan during syrup feed when the supersaturation starts to reduce below the supersaturation limiting value is higher; and

- The supersaturation is slightly higher during A molasses feed as during this period the evaporation rate is limited to the value given by the modified Rouillard expression.

Both these changes result in slightly reduced cycle times.

Table 6.4   Effect of changing the feed conditions on pan cycle times for A massecuite boilings for a vapour supply at 100 kPa abs

Case	Cycle time, h	Level when supersaturation reduced from the limiting value
Base test conditions	3.80	75%; part way through syrup feed
Syrup and A molasses at 70 °C	3.71	79%; part way through syrup feed
Syrup at 72 dry substance. Syrup and A molasses at 70 °C	3.65	90%; at end of syrup feed

6.2.4   Results for the B massecuite simulations

Figure 6.1 shows the trends of data from a run of the dynamic model on B massecuite with steam supply at 200 kPa abs. The complete set of trends for B massecuite boiling at 200, 140, 100 and 70 kPa abs vapour pressure are provided in Appendix B.

Start   Time during pan cycle   End of cycle
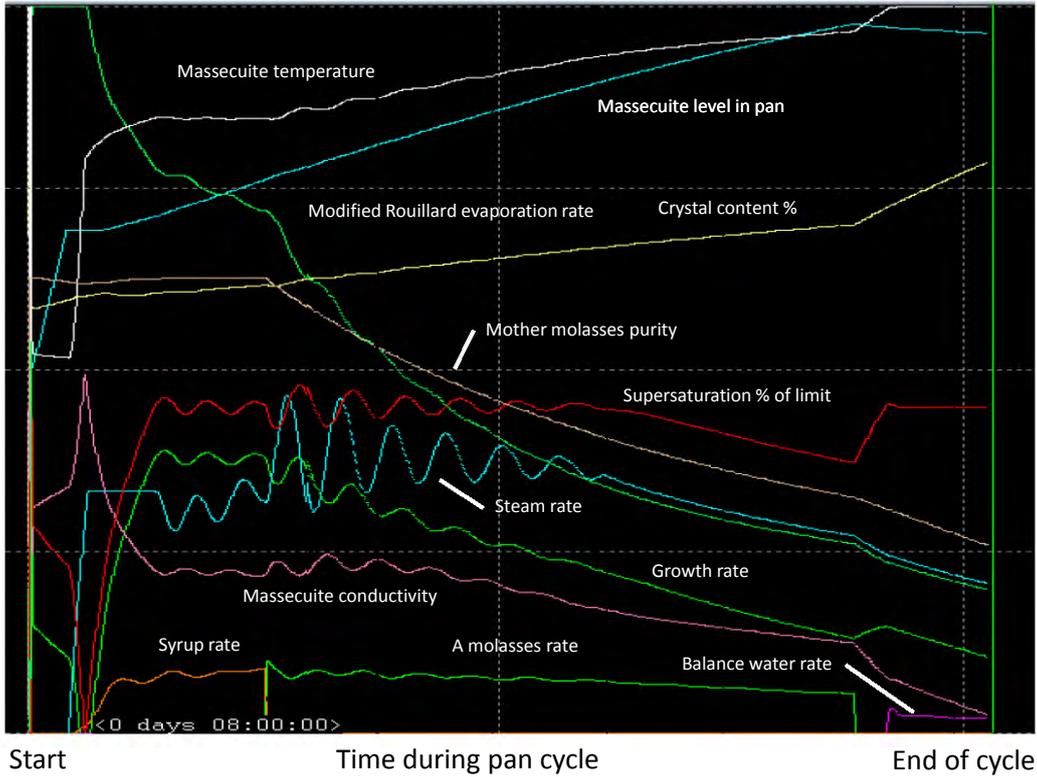
Figure 6.2   Trended data for B massecuite simulation for a vapour supply pressure of 200 kPa abs

For the B massecuite boilings the pan completed the strike to the pan full condition (100%) and to the nominated dry substance (91.8) for terminating the strike massecuite, for the full range of vapour supply pressures. For all supply vapour pressures, the pan drop massecuite was 82.0 purity, 47.5% crystal content with mean size of crystals 845 µm. Table 6.5 shows the cycle times for the simulations of B massecuite boilings for the supply of steam/vapour at different pressures.

Table 6.5   Cycle times for B massecuite strikes using vapour at different supply pressures

Supply pressure of vapour, kPa abs	Cycle time, h
200	4.10
140	4.43
100	4.92
70	5.38

Whether or not the strike is completed without being terminated depends on the selected termination dry substance value and the specified minimum crystal growth rate. For the B massecuite boilings the minimum crystal growth rate was set at 20 µm/h which would likely be regarded as not financially justifiable. Setting the minimum growth rate at say

40 µm/h would have terminated the runs for 100 kPa abs and 70 kPa abs prematurely, *i.e.* not run up to 100% and dropped at a lower massecuite dry substance than 91.8.

Overall the cycle times for the B massecuite boilings are slightly longer than experienced in practice when using steam at 200 kPa abs. A substantial increase in cycle time is required when the vapour supply pressure is reduced. It is likely that in practice use of vapour at lower than 140 kPa abs would be problematic in terms of maintaining productivity on the pan stage.

The conclusions for the B massecuite boilings are similar to those for the A massecuite boilings. In summary:-

- For all scenarios the supersaturation increased to the limiting value (90%) for the start of the syrup boil-on period and controlled at this supersaturation level into the period of A molasses feed until the modified Rouillard evaporation limit was reached.

  The level in the pan when the supersaturation reduced from the nominated limit is shown in Table 6.6 for each of the supply pressures.

  Table 6.6   Level in the B massecuite pan when supersaturation reduced below limiting value

Vapour supply pressure, kPa abs	Level when supersaturation reduced from the limiting value
200	82%; during A molasses feed
140	72%; during A molasses feed
100	63%; early in period of A molasses feed
70	59%; shortly after start of A molasses feed

  Up to the level in the pan when the supersaturation reduced from the limiting value the required steam rate increases to hold the supersaturation at the nominated value.

- The crystal growth rate is ~100 to 105 µm/h during the syrup feed period at the 90% supersaturation limit and then declines steadily during the A molasses feed section, in agreement with industrial practice.

- When steam is supplied at 200 kPa abs, balance water is used in the heavy up stage as the evaporation rate exceeds that required to reach the 90% supersaturation limit. For the lower vapour supply pressures no balance water is used and the supersaturation during heavy up is below the 90% limit.

- For all supply pressures the conductivity profile reduces steadily during the latter period of A molasses feed and declines sharply during heavy up. This pattern agrees with industry practice. The conductivity profile differs in the early part of the cycle for the different supply pressures. For vapour supply at above 140 kPa abs the conductivity profile is flat initially before declining. For lower vapour supply

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pressures the conductivity is flat initially and then rises steadily into the A molasses feed section before declining. The changing profiles for conductivity can be seen in the trends in Appendix B.

6.2.5   *Effects of varying B massecuite feed conditions*

Simulations runs for B massecuite boiling with vapour supply at 100 kPa abs were examined for the following two scenarios:-

- Both syrup and A molasses feed heated to 70 °C instead of supplying syrup at 60 °C and A molasses at 50 °C (no change to the dry substance of the syrup or A molasses); and

- Syrup supplied at 72 dry substance instead of 69 and A molasses supplied at 74 dry substance instead of 70. Both syrup and A molasses supplied at 70 °C.

The trends for these two simulations are also shown in Appendix B. The cycle times for these two runs are shown in Table 6.7 together with the data for vapour supply at 100 kPa abs for the base test conditions. The main changes that occur relative to the base conditions are

- The level in the pan during A molasses feed is higher at the time when the supersaturation reduces below the supersaturation limit; and

- The supersaturation is slightly higher during A molasses feed as during this period the evaporation rate is limited by the value given by the modified Rouillard expression.

Both these changes result in reduced cycle times. As expected the magnitude of the reductions in cycle times are greater for B massecuite than for A massecuite. The use of A molasses of higher dry substance provides a substantial increase in crystal growth rate (and reduction in cycle time) by allowing the A molasses run up to be undertaken at a higher supersaturation. The conductivity profile reduces at a steeper rate during A molasses run up when A molasses of higher dry substance is used.

Table 6.7   Effect of changing the feed conditions on pan cycle times for B massecuite boilings for a vapour supply at 100 kPa abs

Case	Cycle time, h	Level when supersaturation reduced from the limiting value
Base test conditions	4.92	63%; part way through A molasses feed
Syrup and A molasses at 70 °C	4.69	66%; part way through A molasses feed
Syrup at 72 dry substance; A molasses at 74 dry substance. Syrup and A molasses at 70 °C	4.38	74%; part way through A molasses feed

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6.3 C massecuite investigations

6.3.1 Test conditions for the C massecuites

The test conditions for the C massecuite runs are shown in Table 6.8.

Table 6.8 Data for simulation runs for C massecuites

Stream	Parameter	Value
C seed massecuite	Massecuite purity	68
	Massecuite dry substance	87.3
	Crystal content%massecuite	23
	Mean size, mm	0.18
	CV	0.33
C massecuite	Seed footing volume% pan volume	42.5
	Volume % pan full at which B molasses feed stops and heavy up commences	100
	Limit of supersaturation (% of oversaturation at nucleation limit)	90% throughout the strike
	Crystal content profile	23% at start of B molasses feed 26% at pan full
	Target massecuite purity	66
	Target dry substance of massecuite at end of heavy up	92.5
	Minimum growth rate to terminate a run, μm/h	5
	Target mean crystal size, mm	0.260
B molasses feed	Purity	64.5
	Dry substance	72
	Temperature, °C	50

6.3.2 Results for the C massecuite simulations

Figure 6.3 shows the trends of data from a run of the dynamic model on C massecuite with steam supply at 200 kPa abs. The complete set of trends for C massecuite boiling at 200, 140, 100 and 70 kPa abs vapour pressure are provided in Appendix C.

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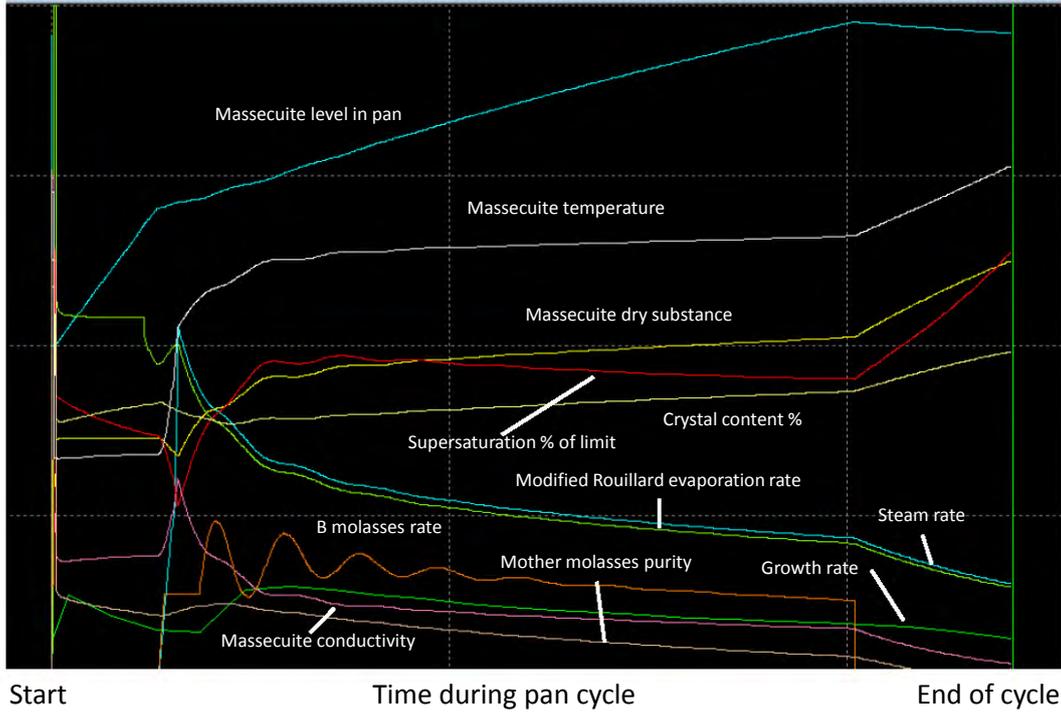
Figure 6.3   Trended data for C massecuite simulation for a vapour supply pressure of 200 kPa abs

For the C massecuite boilings the pan completed the strike to the pan full condition (100%) and to the nominated dry substance (92.5) for terminating the strike massecuite, for the full range of vapour supply pressures. In practice C massecuites are unlikely to be boiled with low pressure vapour to 100 % full and to complete the heavy up to the target dry substance at an acceptable rate. If the minimum acceptable growth rate was changed to 7 µm/h instead of 5 µm/h the runs at 70 and 100 kPa abs would not have completed the heavy up and the run would have terminated the cycle at a lower crystal content.

For all supply vapour pressures, the pan drop massecuite was of 65.9 purity, 30 % crystal content with mean size of crystals 260 µm. Table 6.9 shows the cycle times for the simulations of C massecuite boilings for the supply of steam/vapour at different pressures.

Table 6.9   Cycle times for C massecuite strikes using vapour at different supply pressures

Supply pressure of vapour, kPa abs	Cycle time, h
200	4.82
140	5.85
100	6.72
70	7.49

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For the C massecuite boilings the cycle times are strongly affected by the supply vapour pressure. The cycle time for C massecuite boiling when using steam at 200 kPa abs is of the same order of time (perhaps slightly shorter) as experienced in factory pans. As for the B massecuite it is likely that in practice use of vapour at lower than 140 kPa abs would be problematic for C massecuite boilings in terms of maintaining productivity on the pan stage.

The main observations from the C massecuite simulations are:-

- The steam rate to the pan is limited by the modified Rouillard evaporation rate throughout the whole cycle. As a result the supersaturation does not reach the nominated supersaturation limit of 90% of the nucleation. For example, for use of 200 kPa abs steam, the supersaturation during the feed on of B molasses was limited to 35% to 45% of the nucleation limit.

  For runs with lower supply vapour pressure the supersaturation level is lower and hence crystal growth rate is also lower.

  For all supply vapour pressures the supersaturation increases during the heavy up stage.

- For vapour supply at 200 kPa abs the crystal growth rates varied between 28 µm/h at the start of the run to 8 µm/h at the end of heavy up. These growth rates are comparable to growth rates in factory C massecuite boilings at this supply pressure.

- The conductivity profile for the C massecuite boilings at all supply pressures reduced steadily during the run up stage to pan full and then decreased more rapidly during the heavy up. The rate of decline in the conductivity during run up was slightly steeper for the cases using lower pressure vapour than for 200 kPa abs vapour supply.

6.3.3   Effects of varying C massecuite feed conditions

Simulations runs for C massecuite boiling with vapour supply at 100 kPa abs were examined for the following two scenarios:-

- The B molasses feed was heated to 70 °C instead of supplying at 50 °C (no change to the dry substance of the B molasses); and

- B molasses was supplied at 74 dry substance instead of 72 and at 70 °C.

The trends for these two simulations are also shown in Appendix C. The cycle times for these two runs are shown in Table 6.10 together with the data for vapour supply at 100 kPa abs for the base test conditions. Both these changes reduce the cycle time as the operating supersaturation is slightly higher as a consequence of the evaporation rate being limited to the modified Rouillard value.

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Table 6.10 **Effect of changing the feed conditions on pan cycle times for C massecuite boilings for a vapour supply at 100 kPa abs**

Case	Cycle time, h
Base test conditions	6.72
B molasses at 70 °C	6.27
B molasses at 74 dry substance and at 70 °C	6.07

6.4 Discussion on the results of the simulations

The simulations have shown, as expected, that when using lower pressure vapour longer cycle times are required. With lower pressure vapour a greater proportion of the run up of the pan is evaporation limited, and hence longer run up times are required. During the heavy up, when using lower pressure vapour, the supersaturation is lower and hence the crystal growth rate and rate of increase in brix is slower. Longer heavy up times are required.

The results showed that the use of low pressure vapour has a greater influence on the productivity of pans boiling massecuites of higher viscosity, *i.e.* C massecuite more than B massecuite and B massecuite more than A massecuite. This observation is in line with industrial experience and expectations.

While reasonable approximations to industrial practice were obtained for the runs with high pressure vapour (200 kPa abs) the ability to operate with 100 kPa abs or 70 kPa abs vapour for all three grades of massecuite to the nominated termination conditions is considered to be incorrect. Factories commonly experience reductions in pan stage productivity if the pressure of the vapour supply reduces by more than 10 to 20 kPa, say from 180 to 160 kPa abs. Most likely B and C massecuites could not be boiled satisfactorily in terms of run up rate and heavy up rate for vapour at lower pressure than 140 kPa abs. It is also likely that most A massecuite batch pans in the industry would find difficulty is achieving adequate heavy up performance when operating with vapour supply pressure below 140 kPa abs.

There are two main reasons why the termination conditions (pan filled to 100% and massecuite at the nominated dry substance for completing the strike) were able to be reached for all three grades of massecuite, even with vapour supply as low as 70 kPa abs pressure:-

- The termination growth rates (40 µm/h for A massecuite, 20 µm/h for B massecuite, 5 µm/h for C massecuite) were most likely set lower than factories would accept in a production environment; and

- The sole use of an evaporation rate limit (modified Rouillard expression) is a gross simplification of the requirements to achieve adequate boiling. In a natural circulation pan the ebullition provides not only evaporation of water from the massecuite but affects:

o Extent of mixing of the massecuite within the pan and hence the uniformity of contents;

o Velocity of massecuite into the base of the tubes which affects heat transfer and evaporation rate; and

o Superheat that may generate within the massecuite by virtue of slow movement of massecuite from the tube surface. Increased superheat reduces the temperature difference between the vapour in the calandria and the massecuite, and so contributes to reduced heat transfer.

There is a need to develop a parameter that defines limiting circulation movement in the pan as an additional descriptor of the effectiveness of a pan to undertake a boiling duty.

For runs with steam supply at 200 kPa abs (typical of current operation), the profiles of conductivity from the model were similar to those used by factories for current control of batch pans *viz.*, for A massecuites the conductivity profile is flat while syrup is fed, ramp down of conductivity while A molasses is fed and steep decline in conductivity during heavy up. The conductivity profiles for the B and C massecuites showed conductivity ramping down during run up to pan full and then a steep decline during heavy up.

The conductivity profiles alter when lower pressure vapour is used as the supersaturation profile is altered. The change is most pronounced for the A and B massecuite boilings.

7. Recommendations to improve the productivity of existing pans and the pan stage when supplied with low pressure vapour

The assessments have determined that several equipment and procedural changes are likely to be required to ensure the productivity of the stage can be maintained for all steps of C seed production, high grade seed production, and the A, B and C massecuite production, when operating with vapour of low pressure. The appropriate measures for a specific factory will vary among factories depending on the pressure of the vapour supply, the designs and capacities of the equipment already installed, the cane quality, the pol of the sugar to be produced and the target sugar recovery from final molasses.

Several measures can be implemented for improving the productivity of the stage and these are described below (not in any order of priority):-

- *Feed entry arrangements.* The entry of the feed syrup/molasses should ensure that the feed materials provide a boost to the natural circulation movement. The preferred location for feed entry is where feed molasses or syrup will promote movement of massecuite up the tubes close to the extremities of the circulation path. These locations are defined on the basis that the feed is lighter than the massecuite and will rise from the feed entry point with minimal transverse flow. Thus, for a fixed calandria pan, the feed entries should be located on the underside of the calandria near the outside wall. For floating calandria pans the feed entries should

be under the calandria near the centre of the pan. Physical restrictions to locations, and the need to ensure that the feed provides maximum benefit and symmetrical enhancement to circulation, must be considered in selecting the preferred arrangement for the feed system.

- *Conditioning of the feed.* The supply of feed material that has been suitably conditioned can assist the boil-on operation and boost circulation. Conditioning refers to treating the feed material so that it is supplied to the pan consistently at the preferred brix and temperature. Conditioning to provide a slight superheat of the feed material (*e.g.* by about 3 °C) so that subsequent light flashing of vapour when the feed enters the pan assists the circulation movement.

  The appropriate brix of the feed material will depend on the circulation characteristics of the pan. From a purely mass balance point of view the supply of a higher brix feed (syrup or molasses) will reduce the evaporation requirement and boost the productivity. However in practice the supply of lower brix feed may generate greater heat transfer, evaporation rate and hence circulation. These practical benefits are likely to be of greater importance in natural circulation pans compared with stirred pans. A well stirred batch pan will likely benefit from the supply of feed of higher brix as the required evaporation rate will be reduced. A poorly designed natural circulation pan may benefit from the supply of a lower brix feed as the circulation may be improved through a higher evaporation rate being achieved.

  Several options exist for conditioning the feed. These include:-

  o Brix control of the molasses in the tanks at the fugal stage followed by a heating step on the pan stage prior to supplying the pan. Heating could be in a non-contact heat exchanger (plate or shell and tube), an open tank with steam injection or a direct contact heater as described in Appendix 4 of the final report for this project;

  o Brix and temperature adjustment in a tank with steam injection. Use of two tanks in series is a more efficient arrangement for this type of pre-conditioning; and

  o Brix and temperature adjustment through the use of a small concentrator (evaporator) on the pan stage. This arrangement is more suited to treating syrup (rather than molasses) when the syrup from the evaporators is at a low brix.

- *Installation of a jigger steam system using the noxious gases from the calandria.* The SRI jigger steam system is effective in increasing the circulation of massecuite in batch and continuous pans (Rackemann and Broadfoot, 2007a) and has been used in numerous pans in Australia and overseas, including A, B and C massecuite pans. The circulation boost is generally greater when massecuites are more viscous.

- *Provide a second vapour supply of higher pressure to the pan for heavy up operations.* The lower pressure vapour is used for the early run up operations until

the boil on rate slows. At this point the change of vapour supply to the higher pressure is made to complete the run up and heavy up steps.

- *Removal of incondensible gases from the calandria.* Adequate removal of incondensible gases from the calandria is more critical when low pressure vapour is used, as the partial pressure of the incondensible gases causes a larger reduction of the saturation temperature of the vapour (and so leads to a larger reduction in the ΔT for heat transfer to the massecuite) compared to the situation when the calandria pressure is higher. The pipe work to vent noxious gases from the calandria may need to be replaced to provide a more effective sweep of noxious gases from the calandria.

- *ESJ wash out of the internals of batch pans.* An effective ESJ spray system in the top of each pan should be provided to thoroughly wash the calandria surface between successive cycles of the pan. The system requires an automated ESJ flush and recovery/drain system to be installed. Most Australian factories already have a suitable system in place. The main benefits of the ESJ flushing system are to:

  (i) Hasten the pan turnround and so maximise the time available for productive operations; and

  (ii) Ensure the calandria surface is consistently clean for each cycle.

  Ideally the ESJ washings would return to a buffer tank from where the washings are pumped at a steady rate to the ESJ tank, rather than flow directly to the ESJ tank. The use of the intermediate tank is to minimise the impact that large surges in the flow of ESJ washings would have on the control of the evaporators.

- *High grade seed production.* The magma preparation/high grade seed production generally shows reasonably strong circulation compared with other pan boiling duties and is expected to be less affected by using low pressure vapour than other pan duties. However this step requires high evaporation rates and so the use of low vapour pressure may substantially reduce the boil-on rate of syrup. The use of the SRI magma preparation system (Broadfoot and Petersen, 2005) eliminates the magma washing and reconcentration step (saving ~25 minutes of the pan's cycle). In addition to increasing the available time for boil-on of syrup an improved quality of high grade seed is expected to be produced which will have flow on benefits to the A and B massecuite boilings and fugalling.

- *Retrofit of stirrers into pans.* The retrofit of stirrers into batch pans should provide a strong boost to the circulation, heat transfer and evaporation rate. The design of the stirrer needs to be considered carefully as several existing designs have been shown to be relatively ineffective in increasing the velocity of massecuite near the outer wall in a fixed calandria pan. SRI has developed an effective design that is well suited to retrofitting into batch fixed calandria pans although it has a high power consumption (Rackemann *et al.*, 2006b; Rackemann and Broadfoot, 2007b).

- *Modifications to calandrias and the base of batch pans.* Some design deficiencies in existing pans include conical bottoms (resulting in near stagnant regions) and a small gap at the outer wall under the (fixed) calandria. A large frictional resistance

in the circulation path adversely affects the circulation flow which in turn reduces the heat transfer in the tubes and the motive force generated by the ebullition. Several large pans in the industry have been modified to include a ring below the calandria in order to increase this gap and assist circulation (Rackemann, 2004).

Replacement of a calandria may be necessary in some instances and this would provide the opportunity to install a calandria design that is better suited to achieve high circulation velocities when fitted with a stirrer. These include the use of a larger downtake.

As is standard in the design of calandrias for batch pans the design is a compromise between provision of adequate heating surface area, circulation ratios (cross sectional area of the tubes/downtake cross sectional area), gaps beneath the calandria, downtake diameter, pan diameter, boiling height above the calandria at pan full and incorporation of a sufficiently small footing volume. The designs of calandrias for batch pans operating on low pressure vapour are expected to be more critical in terms of selecting the dimensions for a suitable compromise.

Rouillard (1985) indicated that shorter tubes provide a larger evaporation rate per unit area. However calandrias with shorter tubes require larger diameter pans for the same total heating surface area. The review of the results from CFD modelling described in section 4.3 concluded that when the massecuite is of lower viscosity and at lower level, shorter smaller diameter tubes produced stronger circulation movement. However, when the massecuite is of higher viscosity and at higher massecuite level longer larger diameter tubes produced a better result.

It is clear that the designs of batch pans and the designs of retrofitted calandrias for operation on low pressure vapour will need to consider many factors and the boiling duty to be undertaken.

- *Installation of additional pan capacity.* The increased cycle times for several pans on the stage as a result of using low pressure vapour will, in many instances, require that additional pan capacity is provided. The requirements for this are very site specific but matters to be considered are:-

    o Suitability of installing a continuous pan or continuous pans. Broadfoot *et al.* (2018) discuss the potential application of vertical continuous pans for strike massecuite production if vapour at very low supply pressure is used;

    o The most appropriate design for a batch pan. Changes to the shape of the base of the pan, the heating surface area, circulation ratio, downtake diameter; and

    o Use of auxiliary equipment such as a syrup concentrator, molasses conditioner, fitting of a mechanical stirrer and/or jigger tubes for noxious gas injection.

- *High grade seed receiver.* For operation of existing batch pans on low pressure vapour the difference in productivity (cycle times, exhaustion) among the pans will likely be accentuated. The installation of a high grade seed receiver (with quick

transfer in and out) will allow independent operation of the product massecuite pans and achieve production efficiencies.

- *Change in the boiling formula from the three massecuite formula to the CBA scheme.* One of the significant production requirements of the three massecuite boiling formula is to boil B massecuites that provide good quality shipment sugar and a B molasses of 64 to 65 purity to suit a high level of sugar recovery in the C massecuite production steps. Boiling B massecuites in batch pans with low pressure vapour is likely to experience substantial reductions in productivity. One option that will alleviate some of these production issues is to change to the CBA flow scheme. In this scheme the B massecuite boiling is required to provide B molasses at the required purity and a B sugar that is a suitable seed for the A massecuite boilings. B sugar of ~94 purity is a suitable target. The purity of the B massecuite is lower than for the three massecuite scheme, *e.g.* 78 to 80 compared to 83. The increase in crystal size in the B massecuite boiling in the CBA scheme is much less than in the three massecuite scheme and the need to achieve high exhaustion levels is reduced. The B massecuite boiling in the CBA scheme is ideally suited to horizontal continuous pans operating on vapour 3 (at saturation temperature of 97 °C or higher).

- *Stock tank capacity.* The stock tank capacity for A and B molasses and syrup may need to be reviewed to better suit operation of the pan stage on low pressure vapour. Ideally sufficient storage capacity is available so that the pans can operate at their inherent productive levels and avoid waiting for feed *etc*.

  Consideration needs to be given to any changes that will be implemented in pan stage operations during the factory's maintenance stops. With the use of low pressure vapour current procedures of continuing to boil massecuite on the pan stage during the maintenance stop may no longer be feasible. The preferred procedure may involve not boiling the pans while the evaporators are being cleaned. If this arrangement is adopted then additional storage capacity may be required for the A and B molasses to allow all completed massecuites to be fugalled.

- *Use of surfactants.* Experience indicates that surfactants such as Kemmat are effective in reinitiating boiling in B massecuite pans when the steam flow reduces sharply (onset of 'pan death'). They are also effective in C massecuite boilings. However their boost to heat transfer is often limited to 20 to 30 mins and a subsequent addition of surfactant may be necessary. Their effectiveness in A massecuite boiling appears to be minimal but this may change when the vapour supply is at much lower pressure than currently used.

- *Adjustment to operating vacuum.* Towards the end of the strike, particularly during the heavy up of the A and B massecuite batch pans, an increased vacuum would assist the evaporation rate and circulation movement. The benefit of this has to be balanced against a slower crystallisation rate (at the same supersaturation) and a more viscous massecuite and mother molasses at pan drop. For several pan stages the scope to increase vacuum on the pans is limited due to the high temperature of the cooling water.

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- *Cleaning of the steam side of calandrias.* Ideally the steam side of calandrias is able to be inspected to check for scale deposits on the outside of tubes and the buildup of rust scale on the bottom tube plate. Chemical cleaning of the steam side should be undertaken when necessary so as to improve the efficiency of heat transfer.

- *Reducing the strike volume of certain batch pans.* For some batch pans that experience difficulties in the final run-up on molasses feed and/or the heavy up step, a higher level of production output and exhaustion may be achieved by terminating the strike at a lower level. The reduction in time for the final stages of the pan cycle would need to outweigh the reduced quantity per strike. Other options such as changes to the feed system, conditioning the feed, installation of a jigger steam system, changes to the incondensible gas venting, retrofitting of a stirrer are likely to be more beneficial.

8. Future development and application of the dynamic model

The development of the SysCAD dynamic model is the first step in a planned major study to determine the preferred changes that Australian factories can make to their current suite of unstirred batch pans to allow effective operation with lower pressure vapour. In order for the factories to be able to make large reductions in process steam consumption (*e.g.* by 6% steam on cane) it will be necessary for pan stages to operate effectively on vapour 3 (pressure at 95 to 100 kPa abs).

The proposed study will involve further development of the dynamic model and importantly incorporate improved evaporation rate data and definitions for the effects of ebullition for operation with lower pressure vapour. Experimental investigations are planned on several batch (stirred and unstirred) and continuous pans to measure vapour rates, production rates (cycle times for batch pans) and exhaustion performance under simulated 'low pressure' conditions and observe other behaviours when using lower pressure vapours. These data will be incorporated into the model.

Another important aspect of the study is to undertake CFD modelling of the circulation in batch and continuous pans using the latest version of commercially available software to simulate operation of specific factory pans with different vapour pressures. The models will be developed using the evaporation data from the factory trials. It is anticipated that the outputs of the CFD modelling will also be utilised in the improved dynamic model to better define the impact of using low pressure vapour. The CFD modelling will also investigate the effects of retrofitting stirrers and/or jigger tube systems.

The improved dynamic model will be used to investigate for different supply vapour pressures and for both stirred and unstirred batch pans:-

- Cycle times and exhaustion for the three strike massecuites (revisit of work undertaken in this preliminary study);
- Run up times for seed pans;

- Preferred control brix (conductivity) profiles for each duty;

- Cycle times and exhaustion when feed streams of different brix and supply temperature are used (more extensive investigation than in this preliminary study);

- Benefit of switching from a low pressure vapour to a higher pressure vapour for the final run up and/or heavy up stage; and

- Benefit of incorporating additional feed streams such as may be supplied by using molasses separation in batch fugals.

The outputs from the dynamic modelling will be utilised in steady state pan stage modelling (SysCAD model and Excel) to determine changes which can be made to the pan stage boiling schemes to mitigate the effects of reduced exhaustion when using low pressure vapour.

It is envisaged that, in order to allow vapour of pressure of 100 kPa abs or lower to be used without major compromise to the pan stage's productivity, several changes will be required including retrofits of stirrers and jiggers to the batch pans, installation of feed conditioning systems, increases in brix of feed materials and changes to the pan stage flow scheme. The dynamic model will help define the appropriate control profiles for operation of the batch pans on the individual duties when using low pressure vapour.

The improved dynamic model may also be useful as a training simulator but that was not the focus of this investigation.

9.   Conclusions

A dynamic model in SysCAD has been developed to allow the syrup/molasses feed on operations and heavy up operations of a batch pan to be modelled to determine the effects of using vapour supply at different pressures. The model is comprehensive in that it incorporates sugar specific physical properties models, detailed geometry, integrated models for crystallisation, heat transfer and evaporation rate, superheat and industrial type PID control. The physical model is solved exactly at every time step.

No data has been found in the literature to define the evaporation rate (or heat transfer coefficient) for a natural circulation batch pan for a range of supply vapour pressures including low pressure vapour. A correlation developed in a pilot vacuum pan over 30 years ago has been modified based on expected performance in factory pans for operation with vapour through a range of supply pressures.

Modelling of typical A, B and C massecuite strikes was undertaken for vapour supply at 200, 140, 100 and 70 kPa abs. The results are a good approximation of industrial behaviour, for the known performance with steam supply at 200 kPa abs. The modelling results have reinforced the practical observations that, when using lower pressure vapour, reduced evaporation rates slow the crystallisation rates, increase boil on times, slow the heavy up process, increase the total cycle times and lead to reduced exhaustion of the

product massecuite (depending on the specified termination conditions). With low pressure vapour supply the boil on rates and heavy up rates may become so slow that these operations are terminated prior to reaching pan full or a target dropping brix, in order to maintain the productivity of the whole pan stage.

It is clear that further improvements to the model, including the use of better estimates of evaporation rates and ebullition conditions in factory batch pans operating with low pressure vapour, are required. The heat transfer in the calandria is a complex phenomenon with viscous high solids content flows that are heavily affected by the geometry. Improved correlations for evaporation rate and ebullition (including the effects of auxiliary circulation aids such as mechanical stirrers and jigger systems) will need to be derived from a combination of factory measurements and CFD analysis.

A follow on major study is planned to identify the most appropriate changes to pan stage equipment, operating procedures and control to minimise the capital investment required to allow operation of existing batch pans with low pressure vapour, while maintaining production performance with respect to rate, sugar recovery and sugar quality.

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Appendix A   Trends for A massecuite boiling
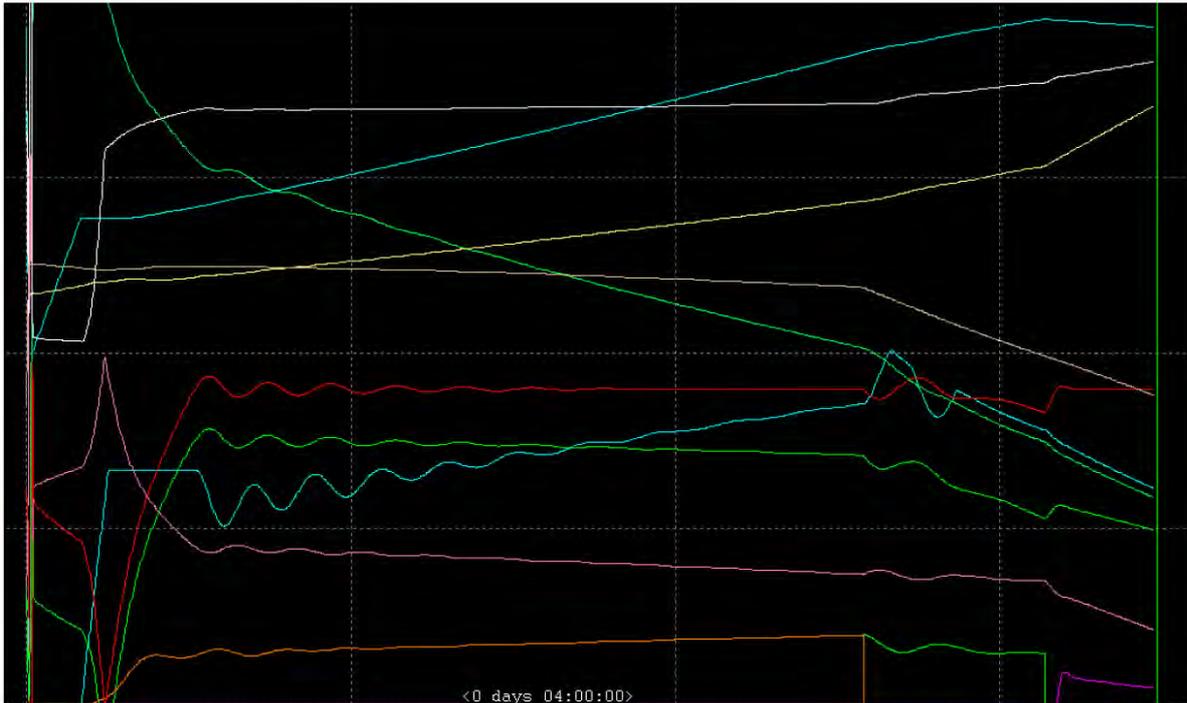
Figure A.1   Trends for A massecuite boiling with 200 kPa abs vapour supply
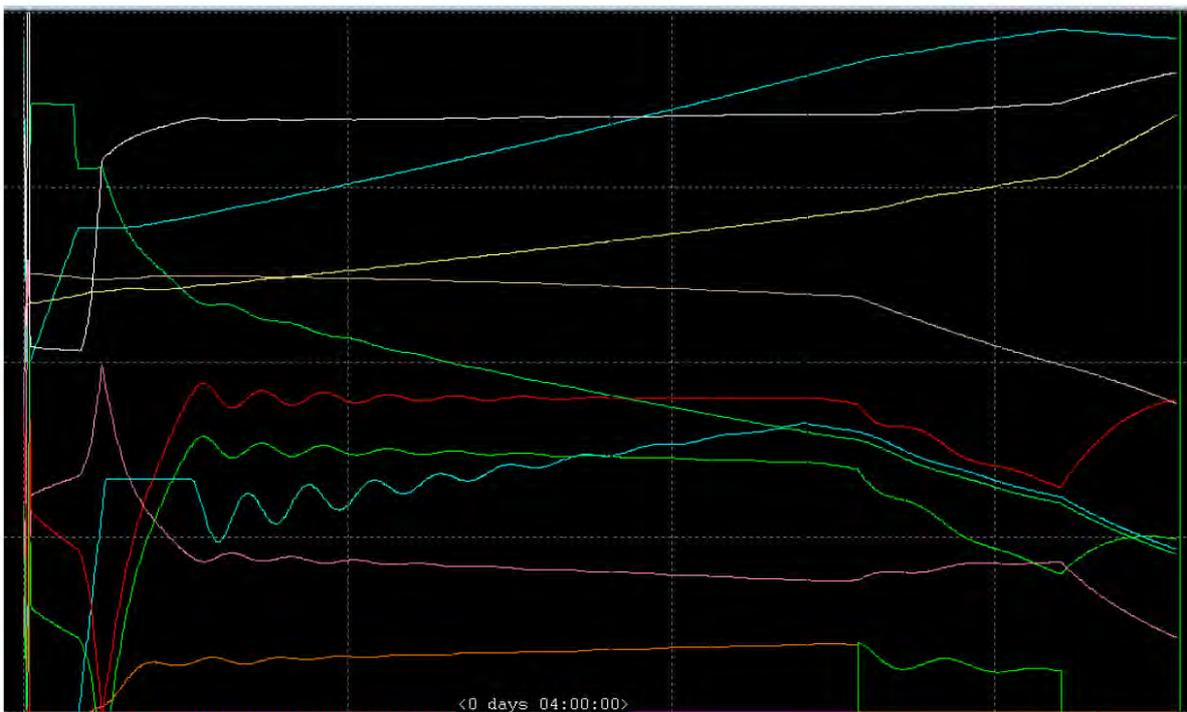
Figure A.2   Trends for A massecuite boiling with 140 kPa abs vapour supply
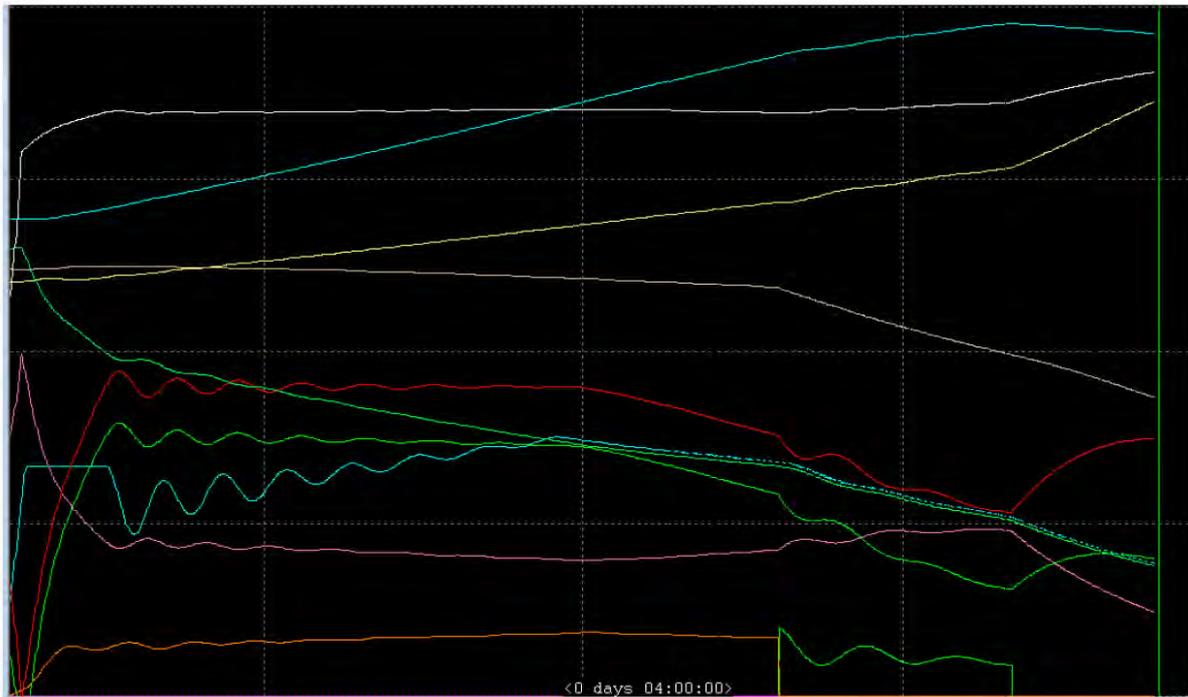
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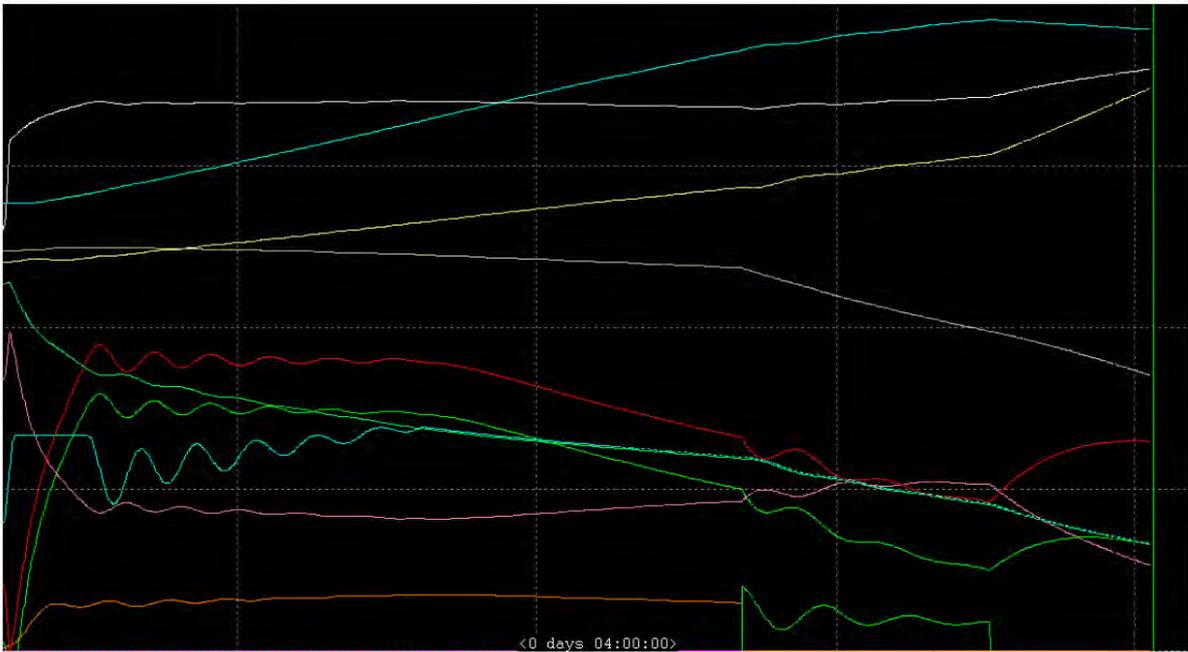
**Figure A.4   Trends for A massecuite boiling with 70 kPa abs vapour supply**
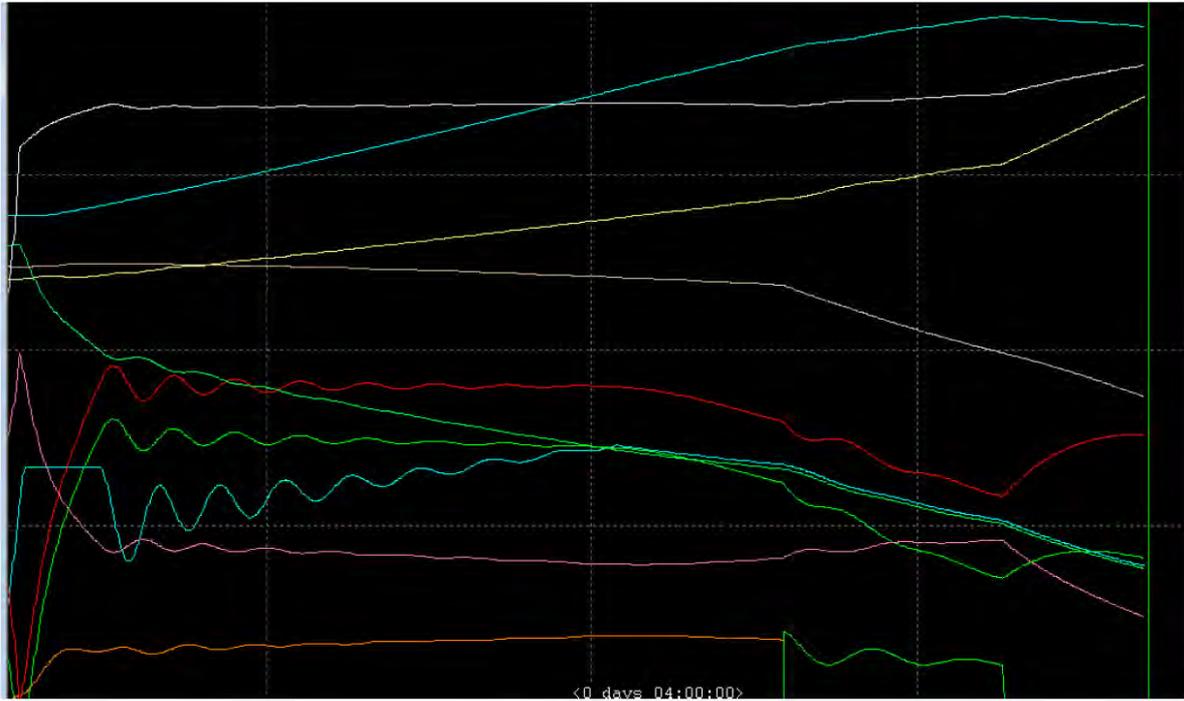
Figure A.5   Trends for A massecuite boiling with 100 kPa abs vapour supply and syrup and A molasses supplied at 70 °C
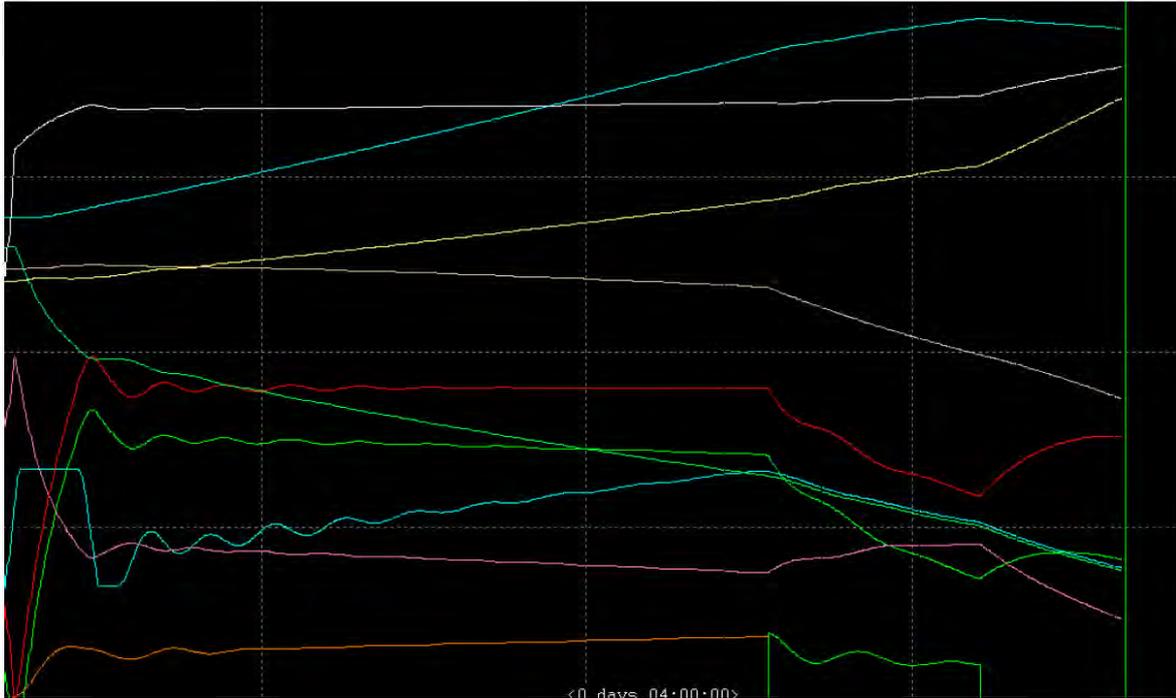

Figure A.6   Trends for A massecuite boiling with 100 kPa abs vapour supply, syrup at 72 dry substance and syrup and A molasses supplied at 70 °C

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**Appendix B   Trends for B massecuite boiling**
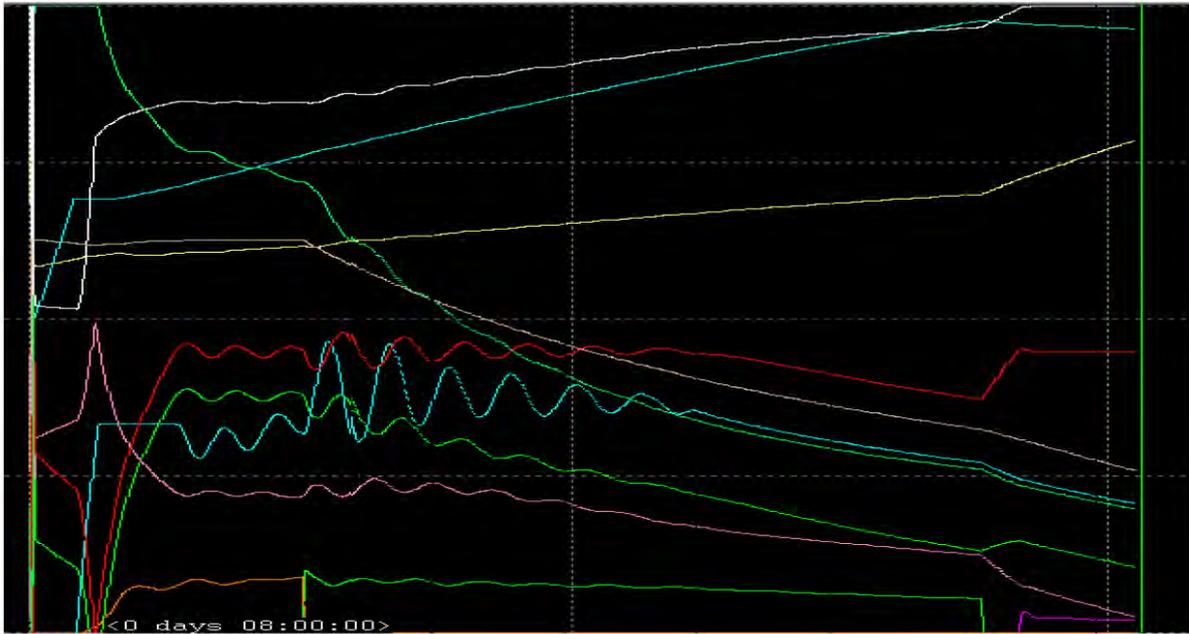
Figure B.1   Trends for B massecuite boiling with 200 kPa abs vapour supply
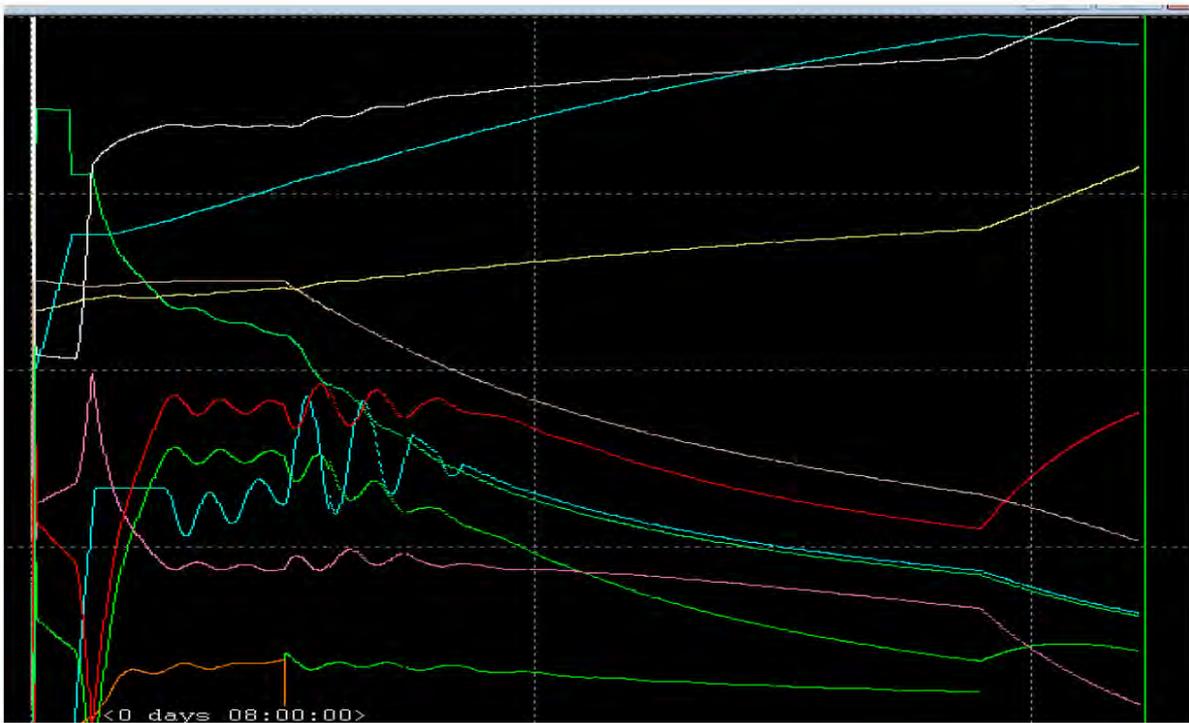
Figure B.2   Trends for B massecuite boiling with 140 kPa abs vapour supply

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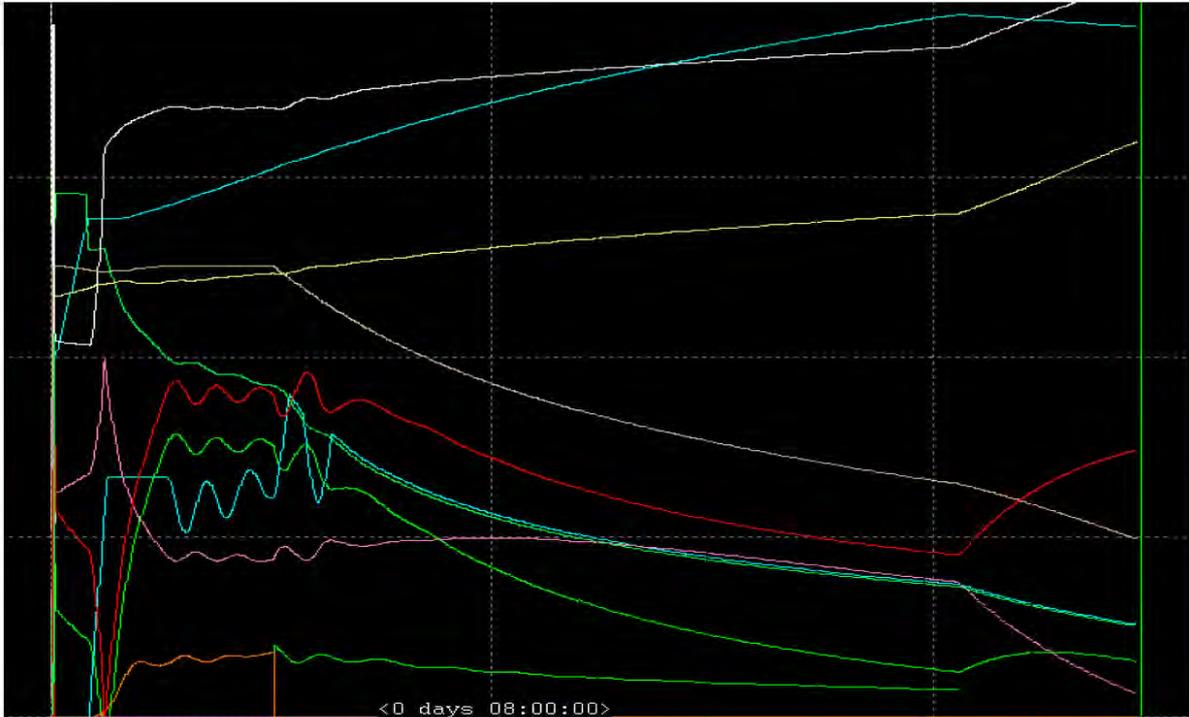
Figure B.3   Trends for B massecuite boiling with 100 kPa abs vapour supply
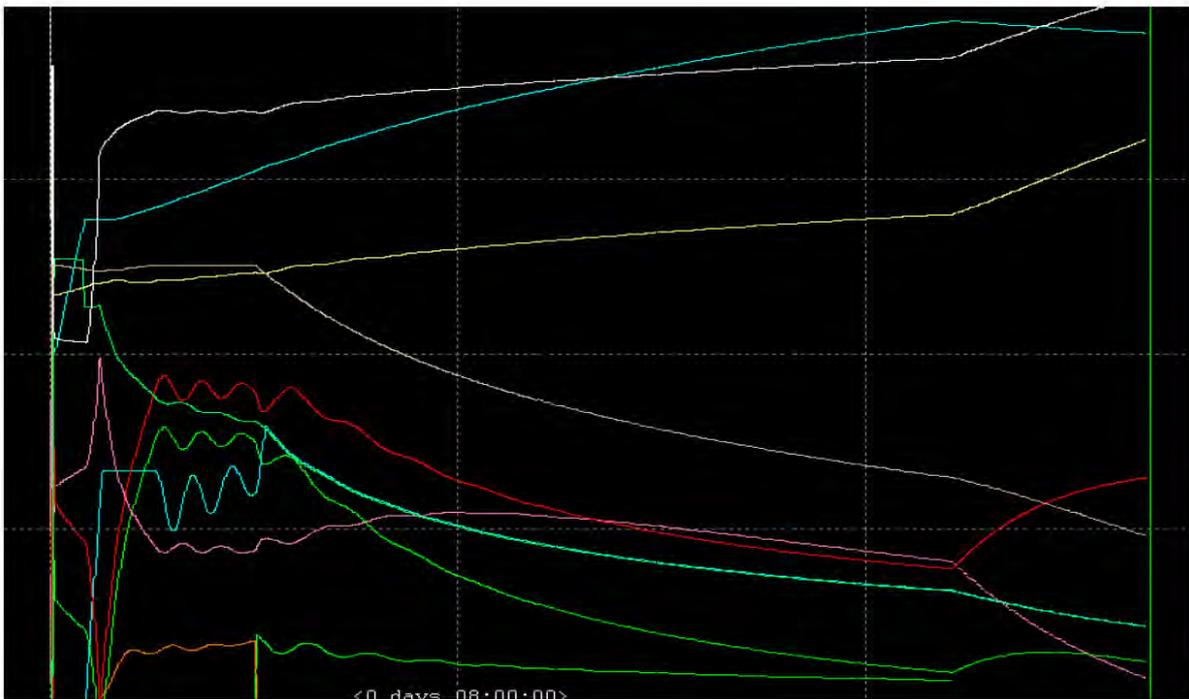
Figure B.4   Trends for B massecuite boiling with 70 kPa abs vapour supply
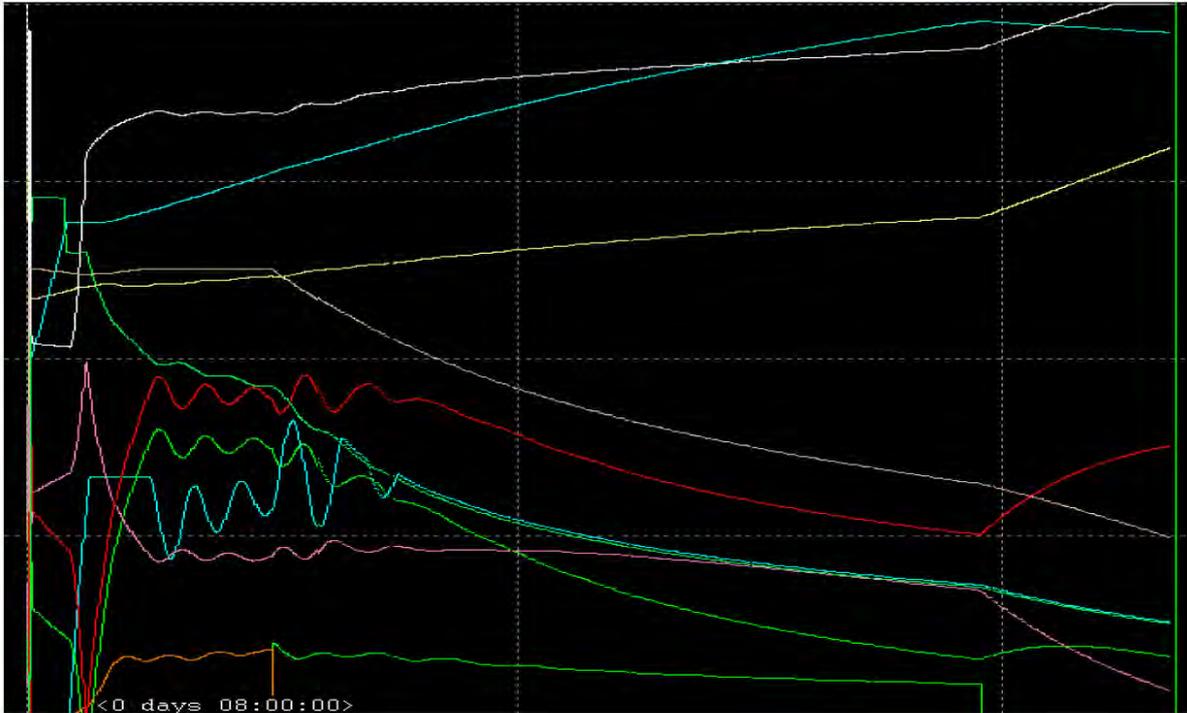
Figure B.5 **Trends for B massecuite boiling with 100 kPa abs vapour supply and syrup and A molasses supplied at 70 °C**
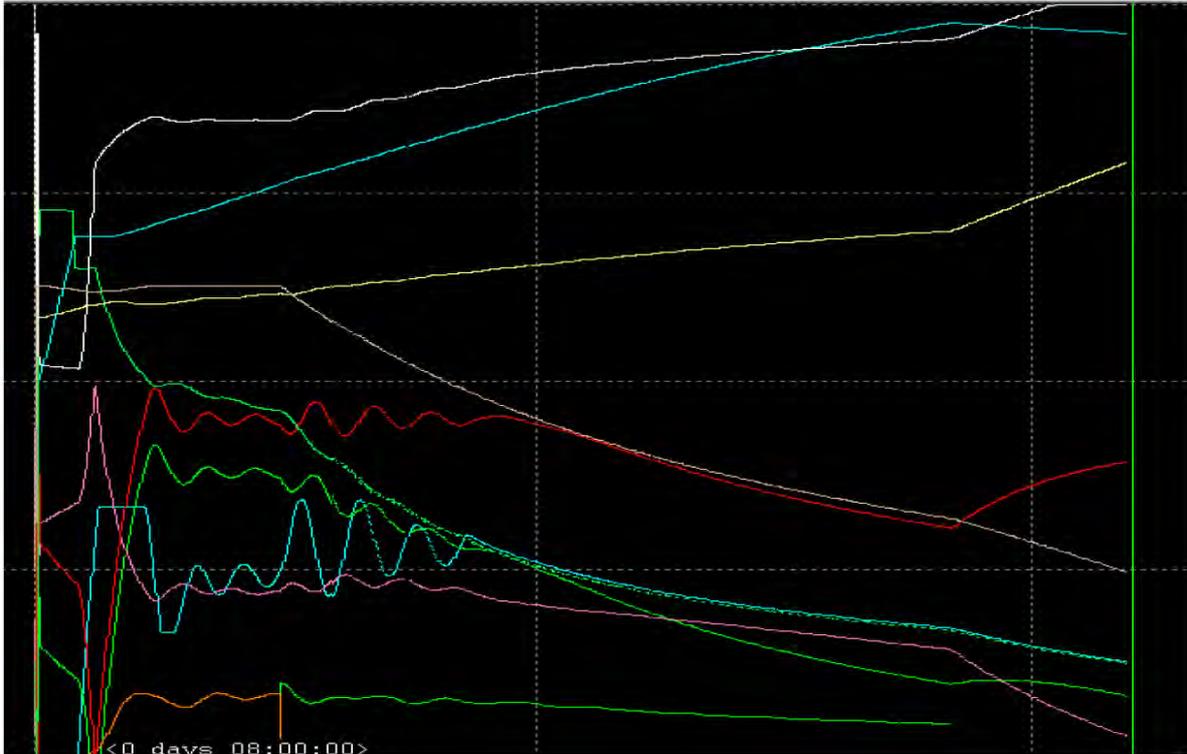
Figure B.6 **Trends for B massecuite boiling with 100 kPa abs vapour supply, syrup at 72 dry substance, A molasses at 74 dry substance and syrup and A molasses supplied at 70 °C**

Appendix C   Trends for C massecuite boiling
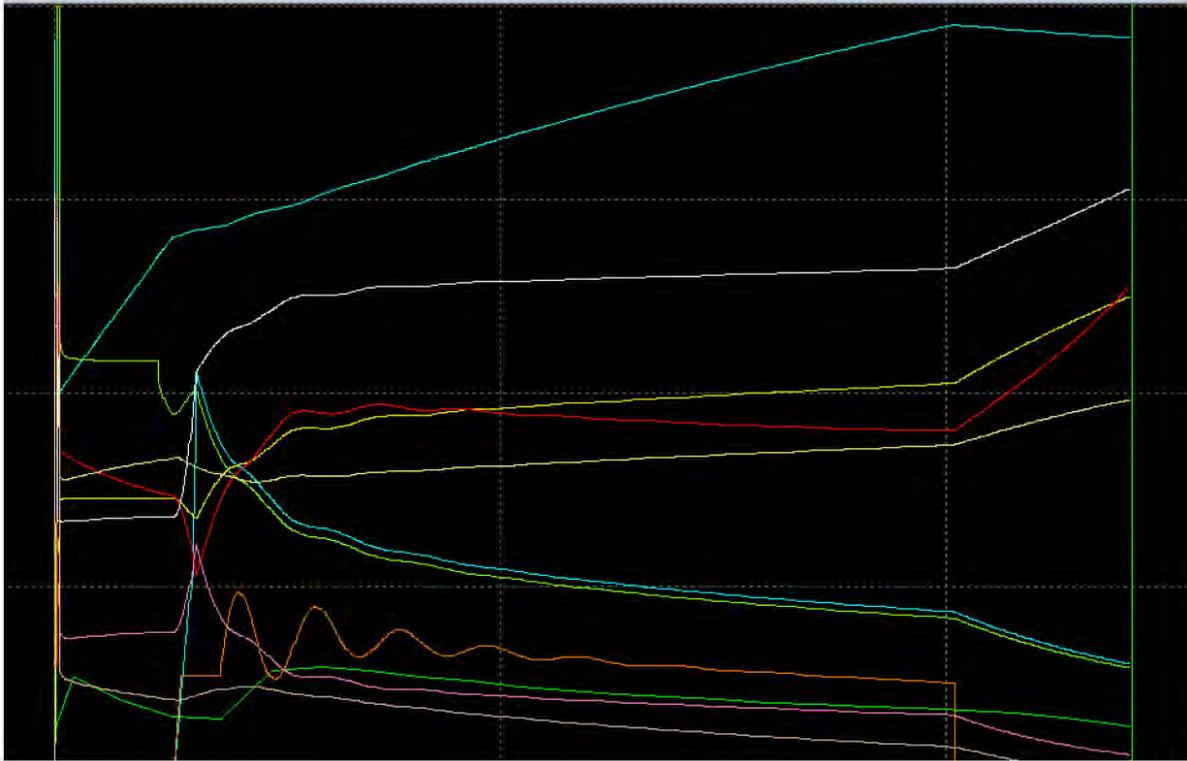
**Figure C.1   Trends for C massecuite boiling with 200 kPa abs vapour supply**
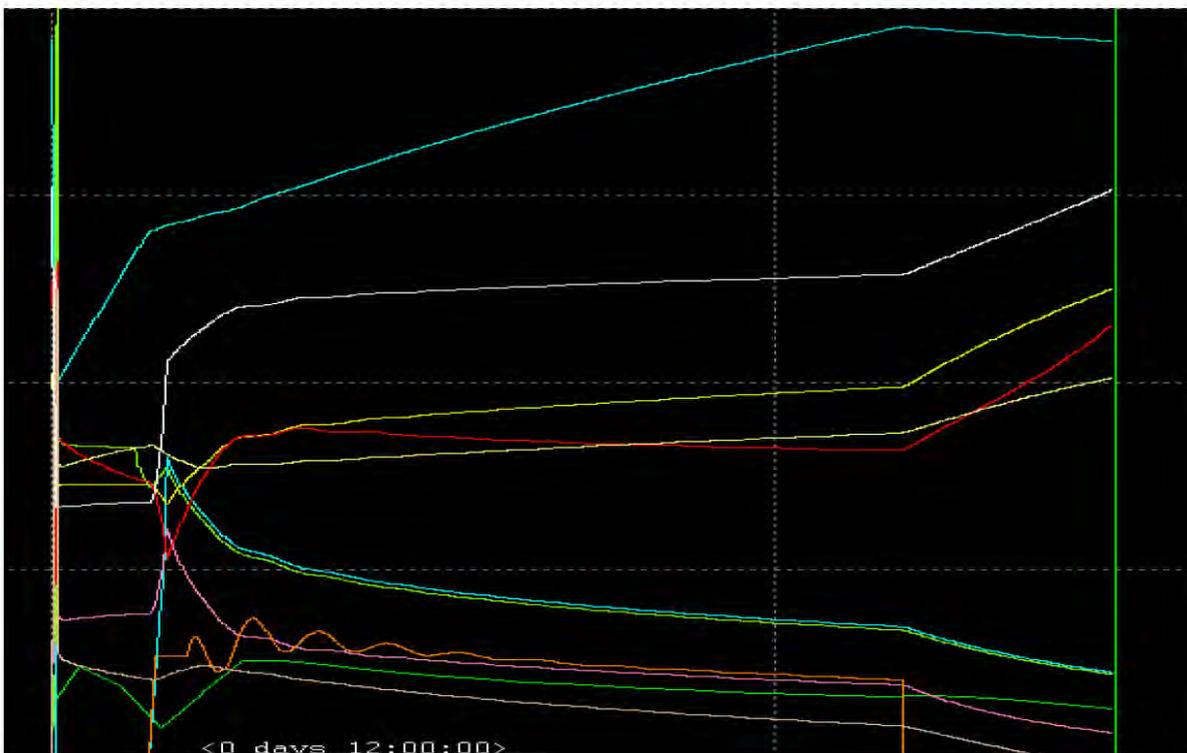
Figure C.2   Trends for C massecuite boiling with 140 kPa abs vapour supply

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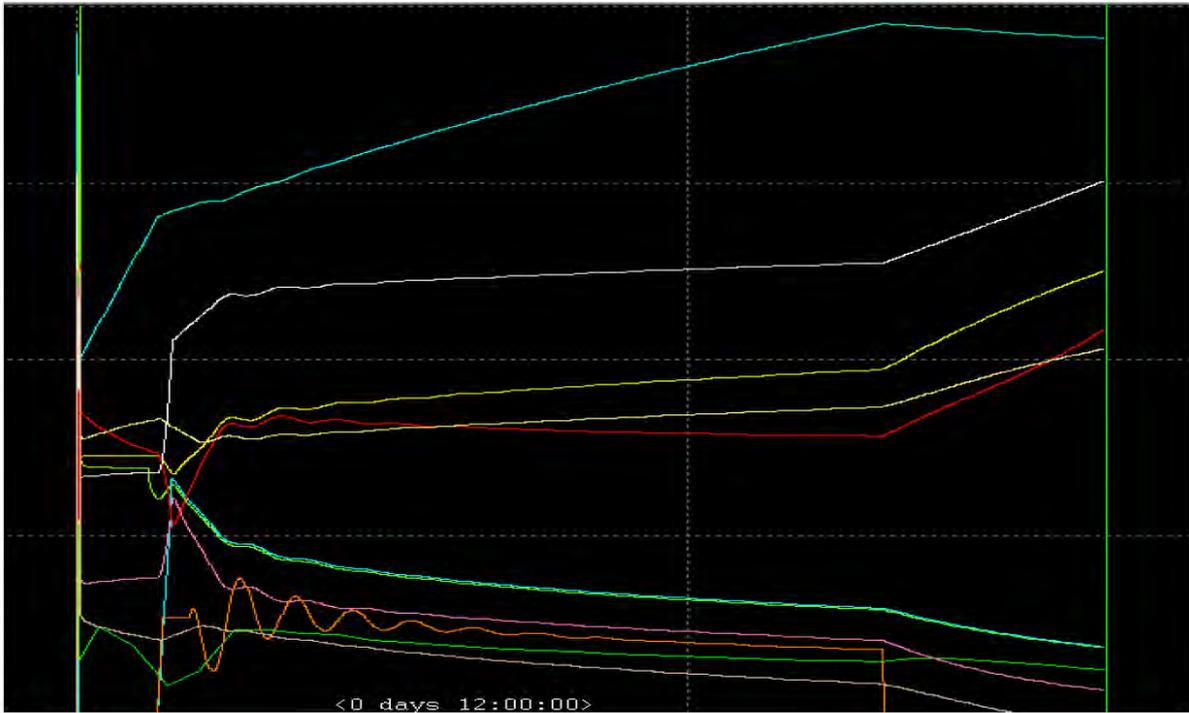
**Figure C.3   Trends for C massecuite boiling with 100 kPa abs vapour supply**
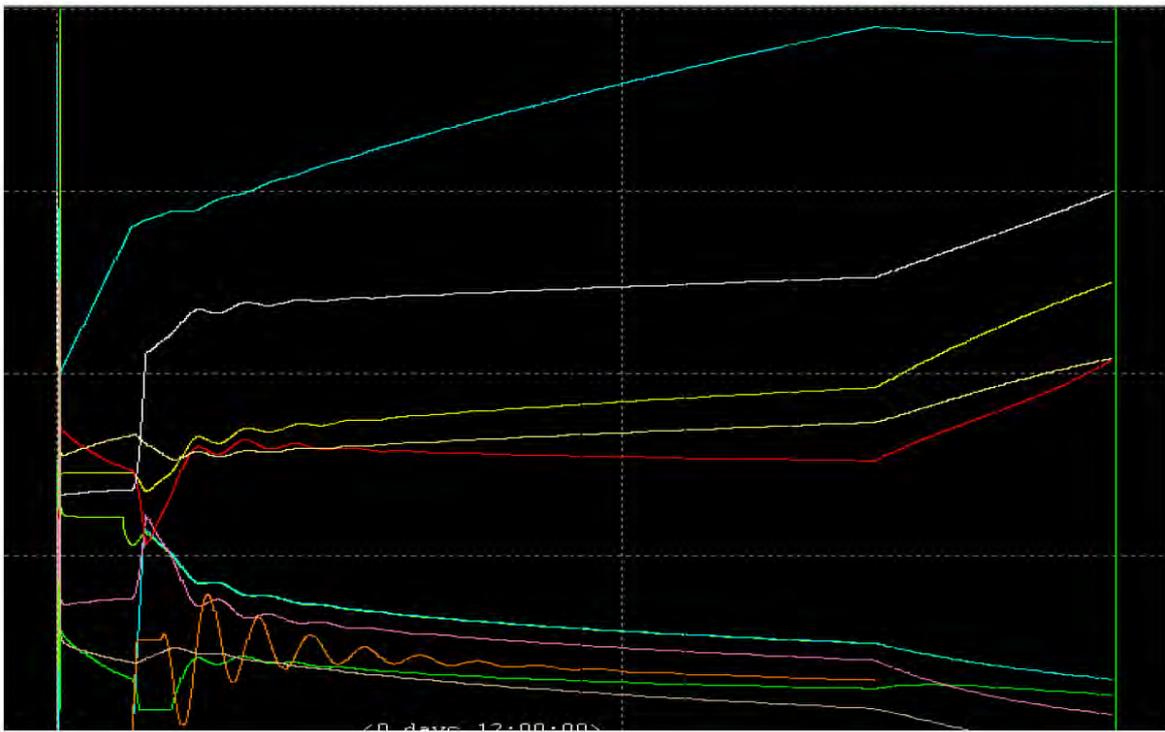
**Figure C.4   Trends for C massecuite boiling with 70 kPa abs vapour supply**
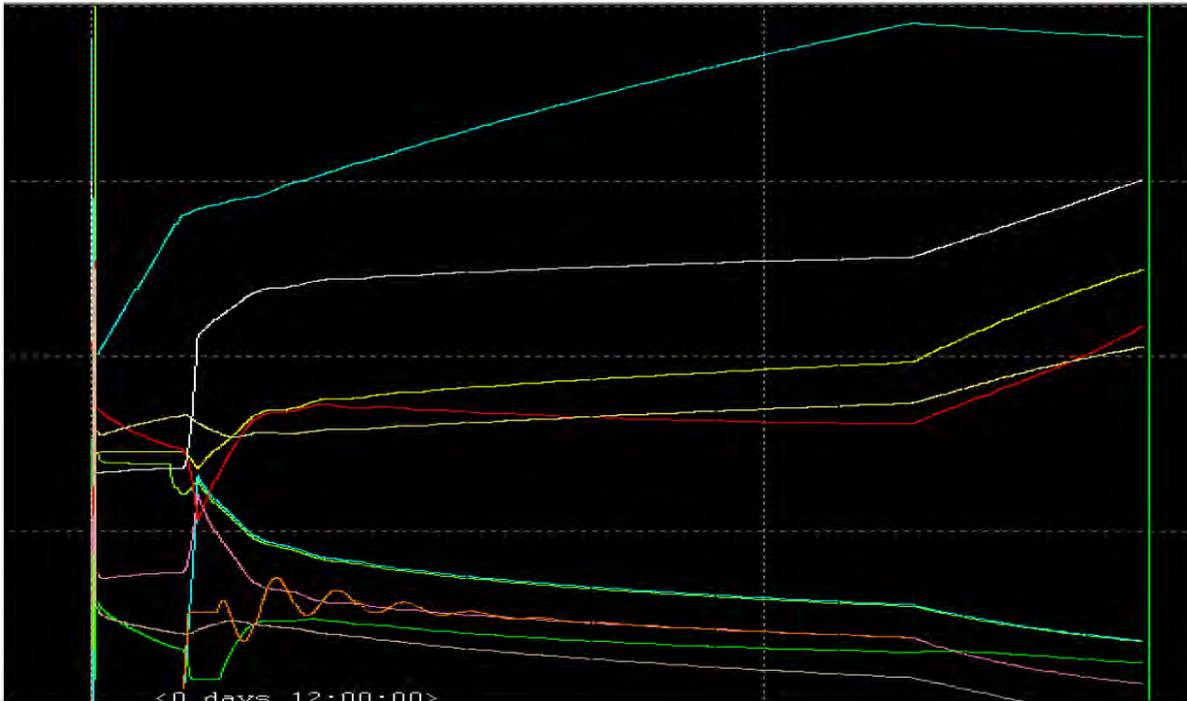
Figure C.5 **Trends for C massecuite boiling with 100 kPa abs vapour supply and B molasses supplied at 70 °C**
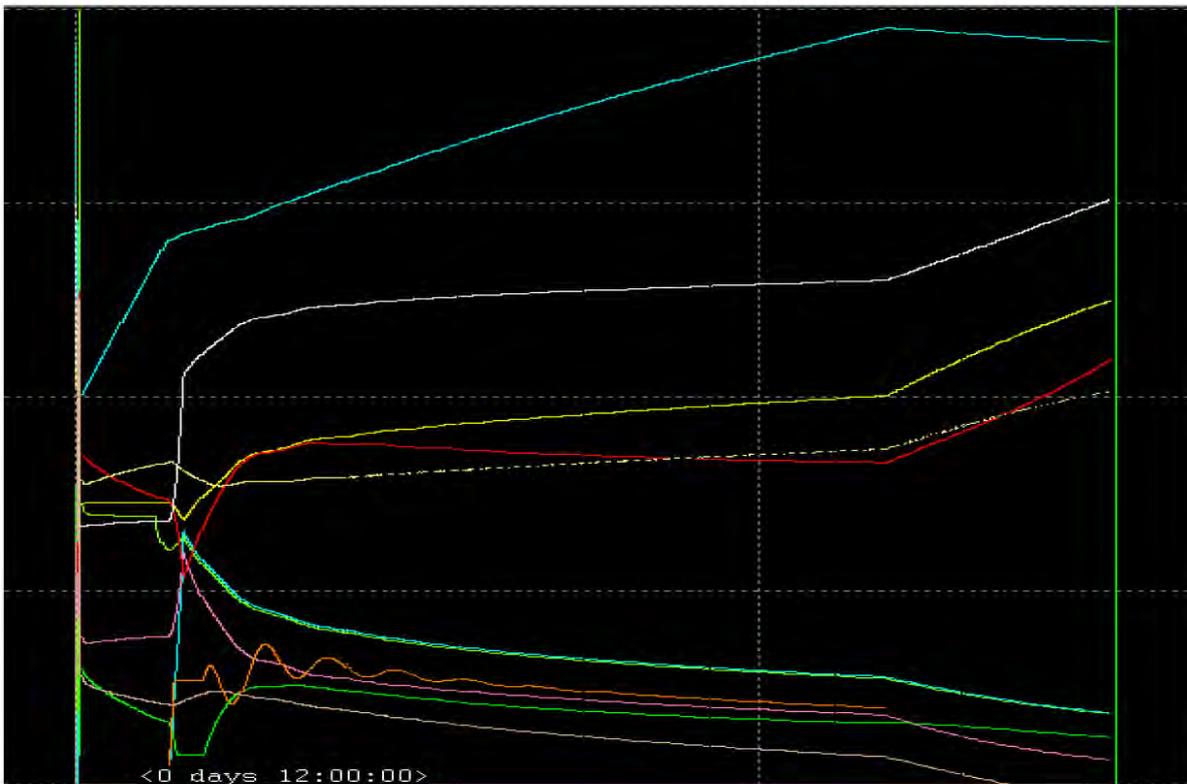

Figure C.6 **Trends for C massecuite boiling with 100 kPa abs vapour supply and B molasses supplied at 74 dry substance and 70 °C**