Pan Stage Steady State Flow Model for Integration within a Knowledge Based Supervisory Support System

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Abstract - **This paper covers the development of a core industrial process model of an expert advisory system and its integration within a knowledge based supervisory support system (KBSSS) for the control and management of a sugar mill crystallization stage. The pan stage steady state flow model predicts the long term steady state flow rates and purities of process materials within the pan stage. The primary topic of this paper will be a description of the steady state flow model for the knowledge based supervisory support system. This paper will focus on: (1) design features, (2) implementation, and (3) results of the proposed model.**

I. Introduction

Sugar production is one of Australias major export industries employing directly in excess of 17,000 people in the areas of growing, milling, storage, marketing and refining of raw sugar with a further indirect employment of 24,000 people [1]. The Australian sugar industry provides a major economic base for rural and regional areas. Australia's sugar producing region stretches from Mossman in far north Queensland to Grafton in northern New South Wales. The sugar industry processes in excess of 35 million tonnes of cane annually, producing in excess of 4.75 million tonnes of sugar. Exports amount to around 80% of the total sugar production. The sugar industry is heavily dependent on achieving cost effective operations in order to compete in the global sugar market.

The production of sugar of very high quality is essential in order for Australia to maintain a favoured market position. Recent financial incentives and changes due to the new raw sugar quality scheme standards [2] introduced for the 2003 sugar season, and beyond, give premium bonuses and add extra financial incentive for the production of high quality sugar.

The low world sugar prices, which currently exist, place further pressure on the industry to find additional avenues for cost saving and increases in revenues. The pressures on the Australian sugar industry to reduce the costs of sugar manufacture and increase the consistency of producing sugar of high quality require a smarter strategy for operations.

The research to develop a KBSSS for sugar mill pan stage processing operations, a portion of which is detailed in this paper, is one such example of the way the industry has responded to these pressures through developing solutions to reduce costs and boost revenue. Such research improves the economic strength of the industry and allows it to remain a competitive force in world trade.

Previous literature [3] acknowledges that no conventional software engineering methods exist in the provision of a KBSSS due to the overall problem complexity, the wide variety of information sources required to be managed, overall pan stage management objectives, lack of adequate sugar mill crystallisation stage industrial process models and requirements for advisory strategies and supporting advice to validate recommendations. Such wide and varied requirements are not easily managed.

Currently, there is no such supervisory control system for pan stage operations neither in the Australian sugar industry nor, as best as known to the collaborators, in the world sugar industry. The KBSSS uses advanced intelligent technologies to provide a standardised approach for pan operations by integrating data from a variety of information sources from different sections of the sugar mill, along with dynamic process models of the pan stage and the collective knowledge and expertise of pan stage operators [4].

In order to forward predict future pan stage operating conditions, fulfill the objectives [5] and system requirements for the KBSSS, the development of a sequence of process models to describe the overall process is necessary. These models collectively work together to quantify the primary pan stage inputs and outputs along with the internal workings of the pan stage itself.

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Modelling pan stage operations requires establishing relationships with the centrifugal station and juice processing sections as well as modelling internal pan stage workings. A pan stage steady state flow model is used to determine long term flow rates and purities of materials for all equipment items in this section.

Models of overall pan stage sugar production [6,7] are available; however they are overly complex and exist only in spreadsheet format. These models do not focus specifically on the three massecuite boiling scheme, rather they are generic models with application to several different boiling schemes. These limitations call for a compact yet flexible pan stage steady state model, focusing specifically on the three massecuite boiling scheme, that can be integrated into the KBSSS and focusing on providing a broad based overview of the pan stage and long term prediction of production quantities under seasonal conditions.

This paper is organised as follows. Section II provides an overview of the sugar crystallisation processes undertaken on the pan stage and highlights some of the specific control and management problems. Section III presents the basic KBSSS framework used and discusses how industrial process models, such as the pan stage steady state flow model, are integrated. Section IV discusses the major features and implementation of the pan stage steady state model. Section V presents results for the model with Section VI then presenting a discussion and conclusions.

II. PAN STAGE PROCESS OVERVIEW

Raw sugar production from cane sugar is essentially a continuous operation. Sugar processing extends through 120-168 hours per week over 20-25 weeks of the harvest season. Cane is crushed to extract juice which is then clarified to remove impurities. The juice is evaporated at reduced pressure and temperature to give a concentrated liquid known as syrup. The syrup is pumped to a liquor storage tank in the crystallisation section of the factory.

From the initial point of unloading of the sugar cane bins through to the syrup tank of the pan stage, the processing operation is essentially continuous. Buffer tanks interspersed between units helps in reducing the effects of flow variations that can occur as a result of many often interacting, factors including the batch and continuous operations on the pan stage.

The crystallisation section, as shown in Fig. 1, is commonly referred to as the pan stage and is the most complex stage of the overall sugar factory process. Several batch wise and continuous crystallisation steps take place concurrently within this part of the process. Feed forward and feedback recycle streams are superimposed on this series of operations. The final stages in the raw sugar factory are the centrifugal station, which separates the sugar crystals from the mother liquor, and the sugar drying station [8].

In current practice, two operators are normally employed on the pan stage and usually their duties extend no further than this section. There is considerable process interaction between the pan stage and centrifugal stage although management of the centrifugals is undertaken by different operators. The overall strategic management of the pan stage is quite difficult because of the large range of process streams of varying compositions and crystal growth rate characteristics that must be managed [9].

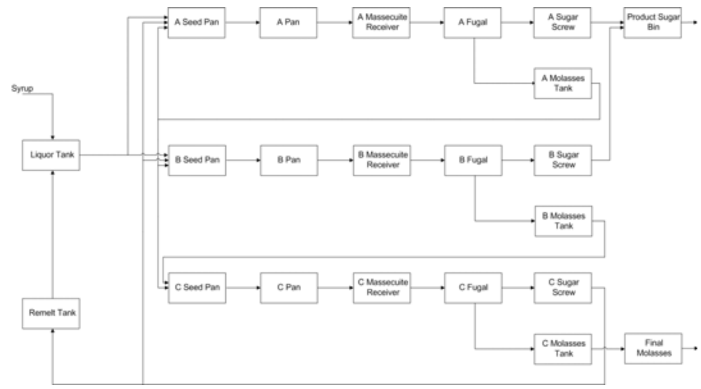

Fig. 1. A simplified model of the pan stage showing process material flows and equipment interactions.

The crystallisation process actually takes place in large batch fed vessels known commercially as "batch vacuums pan"; in continuous vacuum pans; or in batch and continuous stirred cooling vessels referred to as "crystallisers". Typical factories have between six and ten of these pans and about sixteen hours of residence time in the crystallisers. The pan stage has an input stream of syrup and intermediate molasses recycle streams. The resulting output products from the pan stage are raw sugar and final molasses.

The sugar content and purity characteristics of the sugar cane received by a factory also have a strong influence on pan stage operations and in particular the production loadings on different equipment on the pan stage [7]. Often the pan stage is managed in a sub-optimal manner because an overview of operations encompassing various sections – cane receival, juice processing station, the pan stage and centrifugal station – is not available.

Operators are not able to predict future pan stage loadings using existing factory management systems. The only available predictions are the actual forward estimates the operators intuitively carry out. Decisions are often not based upon an analytical approach. Instead decisions are based on and affected by the experience of the current pan stage operators on shift. Inexperienced operators in particular would find it difficult to make well informed decisions for management of the crystallisation process.

III. SYSTEM FRAMEWORK

The KBSSS is essentially a hybrid fuzzy logic based expert system incorporating fuzzy logic, explanatory capabilities and industrial process models of the pan stage. The knowledge base is composed of human operator knowledge coupled with dynamic industrial process models describing the crystallization process. The integration of such features leads to a challenge in the design and development of the KBSSS.

The KBSSSs modular architecture is based upon conventional expert systems [10,11] and conventional IF-THEN fuzzy rule based systems design [12,13]. Fig. 2 provides a representation of the overall system framework [4].

A core feature of this system is a predictive mechanism to quantify future product sugar and molasses production quantities on the pan stage as well as providing supporting information on required C sugar footing quantities for seed pans [3,4,5].

The determination of C sugar footing quantities, through the use of a steady state flow model, will aid in vacuum pan management which form part of the primary system control strategies and is a core component of the dynamic process models of the pan stage expert system framework [4]. This pan stage process model (steady state model) is integrated into and works in tandem with the expert system rule base framework.

IV. Pan Stage Steady State Flow Model: Features and Implementation

The pan stage steady state flow model predicts the long term material flows, and associated purity, for each major equipment item in the pan stage under the three massecuite boiling scheme that is commonly used for sugar production throughout Australian sugar mills. This pan stage steady state model has been developed to calculate the average flow rates and purities of process streams, using mass balances [14], at each vacuum pan, fugal, massecuite receiver, tank, sugar screw and bin. The model determines the average production rates of massecuite, C sugar remelt, molasses and sugar streams given inputs of the syrup flow rate and purity to the pan stage.

Within the KBSSS this model is directly used to provide information in determination of:

- C sugar footings to A/B seed pans which is a core system recommendation for the production of quality sugar of specification size sugar;
- Long term expected final molasses and product sugar rates and purity; and
- Average remelt rate for use in a liquor stock tank model [15].

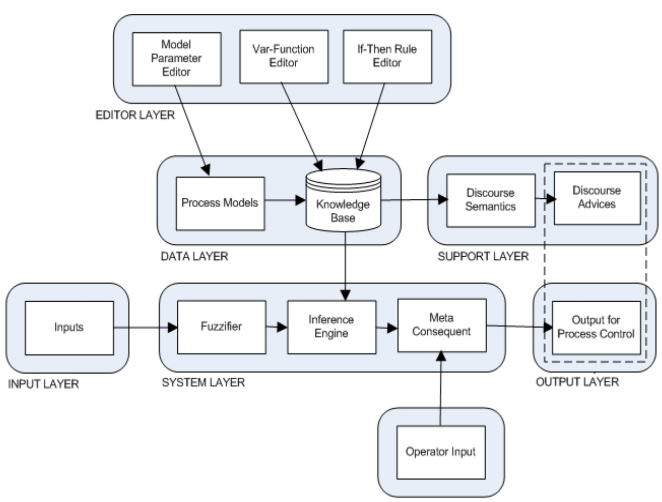

Fig. 2. Smart supervisory control system framework diagram.

The major equipment item sets, as depicted in Fig. 1, utilized in this model are:

Pans {A Seed, B Seed, C Seed, A, B, C}
Fugals {A, B, C}
Massecuite Receivers {A, B, C}
Tanks {Remelt, Liquor, Final Molasses, A molasses, B molasses, C molasses}
Sugar Screws {A, B, C}
Bins {Product Sugar}

The customisable parameter sets, with their initial settings, for this model are:

Sugar Purity {A, B, C} = {99.326, 98.898, 88.0} %
Fugal Sugar Purity Rise {A, B, C} = {1.481, 2.286, 1.723} %
Target Purities {A Massecuite, B Massecuite, C Graining, Final Molasses} = {88.59, 82.0, 70.0, 48.4} %
Target Sugar Crystal Length {A Sugar, B Sugar, C Sugar, Product} = {0.9, 0.85, 0.28, 0.88} mm
Coefficient of Variation of Sugar Crystal Length {A Sugar, B Sugar, C Sugar, Product} = {0.27, 0.35, 0.35, 0.35}
B Sugar Fractions {A Seed, Product, Remelt} = {0.0, 1.0, 0.0}
Graining Fraction {C Pan} = {0.22}
C Sugar Fractions {A Seed, B Seed, Remelt} = {0.11, 0.08, 0.81}
Liquor Tank Fractions {A Seed, B Seed} = {0.5, 0.5}
A Molasses Tank Fractions {A Seed, B Seed, C Seed, Final Molasses} = {0.45, 0.45, 0.1, 0.0}
B Molasses Tank Fractions {B Seed, C Seed, Final Molasses} = {0.0, 1.0, 0.0}
Crystal Content on solids {A Pan, B Pan, C Pan, C Sugar Screw} = {57.6, 51.9, 32.0, 35.0} %
Dry Substance Values {A Massecuite, B Massecuite, C Massecuite, Syrup, Remelt, A Molasses, B Molasses, C Molasses} = {90.66, 91.48, 92.01, 68.0, 67.0, 69.0, 69.0, 77.0} %
Maximum Iterations for Optimisation Loops {Mass Balance, Purity Balance} = {30, 1000}
Tolerance Values {Mass Balance Convergence, Purity Target Convergence, Sugar Size} = {0.01 t/h, 0.01 %, 0.001 mm}

These customizable model parameters are typical of mid seasonal sugar factory conditions for the production of Brand 1 grade sugar [7].

Each equipment item is modeled in software using the object oriented approach. Typically each item has data members for output solids flow rate and purity. The liquor, A molasses and B molasses tanks, B sugar screw and C sugar screw additionally have their output product being fractionally split and consequently have these flows used as feed material for other equipment items on the pan stage. This solids flow information is stored against the producing item along with the fractional values used in splitting these flows. The occurrence of fractional splits to other devices is visually represented in Fig. 1. The model is capable of varying pan stage arrangements under the three massecuite boiling scheme through customization of the product fractions from the major equipment devices.

In following the three massecuite boiling scheme, which is common for pan stage sugar processing within Australian sugar mills, there exists three major process streams within the model. These are the production of A sugar, B sugar and C sugar. C sugar is used as footings for the production of A and B sugar with the excess sent to the remelt tank. A and B product sugar are combined to form the final product sugar. The A molasses and B molasses products result from fugalled A and B massecuite respectively and along with liquor are used as feed products in the A, B and C sugar production segments of the process. C molasses from fugalled C massecuite is sent for storage as final molasses, and sold.

The overall algorithm, as presented in Fig. 3, consists of two main program loops with several conditional branches ensuring purities of the seed pans are achieved through local

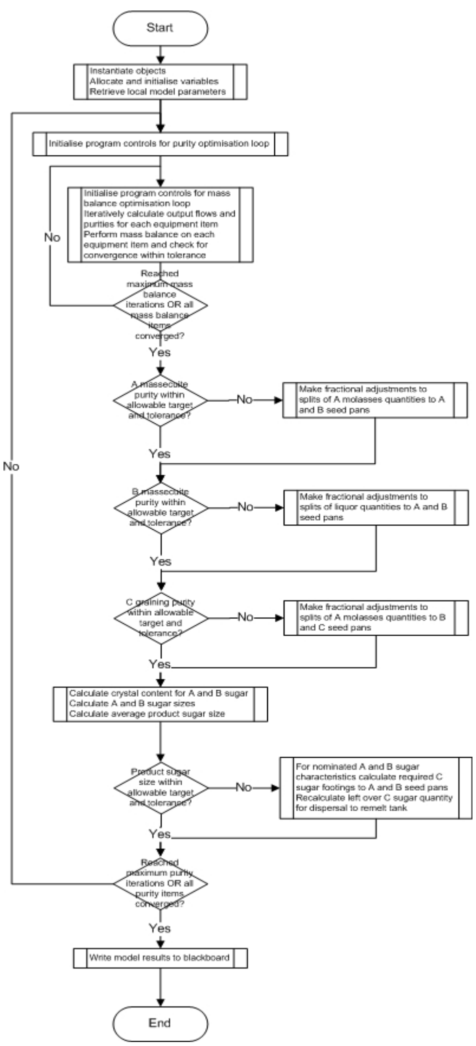

Fig. 3. Pan stage steady state model algorithm.

optimization. Calculations to ensure C sugar footings to the seed pans produce product sugar within the nominated specification size are also performed. All initial flows are set to small positive values to allow calculation of process material flow purities during the first iteration through the flow update loop.

The key model input is the syrup rate and purity to the liquor tank which is the first major item in the overall model. Customizable model parameters are used to establish initial conditions for the model. The setting of key model parameters guides the initial flows and purities on the seed pans and flows are sequentially fed forward throughout the network.

The primary loop controls purity and sugar sizing calculations and contains a secondary loop responsible for calculations of equipment item flows and purities and validation using mass balance checks.

After the primary loop runs the secondary loop it checks to see if the maximum number of iterations for the mass balances has been reached or if all the mass balances have converged to within specified limits. If neither of these conditions has been reached the inner secondary loop is repeated until one is met. Otherwise control moves back to the primary loop.

Within the secondary loop, flow and mixed purity calculations [16] are used to determine process material solids flow rates and associated purities for each equipment item in the model. A mass balance [14] on each equipment device is then conducted to ensure that the quantities of sugar solids entering a device is equivalent to that leaving adhering to a set tolerance value for calculations. Process material flows essentially feed forward through the network, during each iteration of the loop, one device at a time and radiating outwards from the primary syrup input to the liquor tank.

After completion of the secondary loop control passes back to the primary loop. A check is made to see if the A massecuite purity of the A seed pan is within allowable target limits. If this has not occurred fractional changes to the split of A molasses quantities from the A molasses tank to the A and B seed pans are made to incrementally adjust the A masseuite purity towards the target.

Next a check is made to see if the B massecuite purity of the B pan is within allowable target limits. If this has not occurred fractional changes to the split of liquor quantities from the liquor tank to the A and B seed pans are made to incrementally adjust the B massecuite purity towards the target.

One final purity check is made. This is to determine if the C graining purity of the C seed pan is within the allowable target limits. If this has not occurred fractional changes to the split of A molasses quantities from the A molasses tank to the B and C seed pans are made to incrementally adjust the C graining purity towards the target.

After this series of purity checks and calculations are carried out, a check on the sugar sizes is performed through calculation of the A and B sugar sizes as well as the combined product sugar. If the product is not within the allowed limits, for the nominated A and B sugar characteristics, calculation of the required C sugar footings to the A and B seed pans is performed. Since these sugar quantities come from the C fugals the excess quantity of sugar that is not used for footings is calculated for diversion to the remelt tank. The crystal sizing calculations determine the necessary quantities of C sugar needed for the A and B seed pans to ensure final product sugar is within specified size and tolerance.

This sequence of operations with the initial secondary loop operations is iteratively performed as part of the primary loop. This continues until the maximum number of purity iterations has been reached for the optimisation process or all target purities have converged.

The final model results are solids flow rates and purities for each equipment device, and sugar sizing information along with convergence data for target purities and mass balances for each equipment item. The solids flow excludes the quantity of water present in practice. A conversion to actual flows is made at the successful completion of the model. The model results are then written to a blackboard system resulting in algorithm completion.

V. Results

In order to validate the functionality of the proposed steady state flow model algorithm and demonstrate its viability the model is compared to previous research [7] which is used as a reference model for comparative measure. The steady state flow model is run with the parameters presented in Section IV and an input syrup solids rate of 17.59 t/h and purity value of 92.5%.

Due to the large volume of model data results generated, a streamlined representation of the key process material solids flows and their associated purities is presented in Fig. 4. The overall layout is similar to the overall model schematic shown in Fig. 1. In this reduced representation certain equipment items and their associated flows have been clustered together for a compact results display.

Model solids flow rates are presented in Table I and purities are presented in Table II and compared to the reference model with relative difference calculations highlighting the variations between model results.

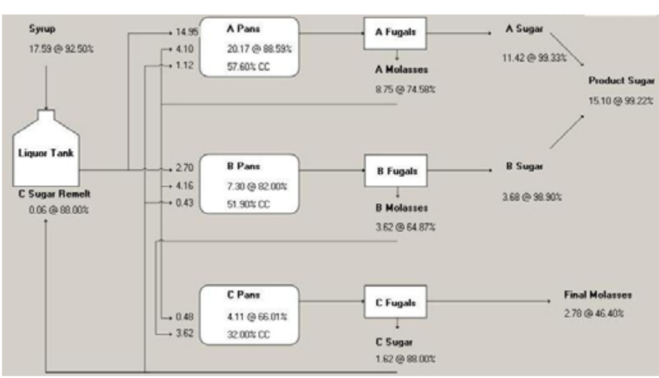

Fig. 4. Solids flow results from pan stage steady state model algorithm.

TABLE I
STEADY STATE MODEL FLOWS COMPARED TO REFERENCE MODEL

Flow from	Flow to	Solids flow (t/h)	Reference model solids flow (t/h)	Absolute difference to reference model (%)
Liquor Tank	A Pans	14.95	15.70	4.78
Liquor Tank	B Pans	2.70	2.90	6.90
A Fugals	A Pans	4.10	4.10	0.00
A Fugals	B Pans	4.16	4.30	3.26
A Fugals	C Pans	0.48	0.50	4.00
B Fugals	C Pans	3.62	3.80	4.74
C Fugals	A Pans	1.12	0.60	-86.67
C Fugals	B Pans	0.43	0.30	-43.33
A Fugals	A Sugar	11.42	11.55	1.13
B Fugals	B Sugar	3.68	3.78	2.65
A/B Sugar	Product Sugar	15.10	15.33	1.50
C Fugals	Final Molasses	2.78	2.26	-23.00
A Pans	A Fugals	20.17	20.44	1.32
B Pans	B Fugals	7.30	7.54	3.18
C Pans	C Fugals	4.11	4.24	3.07

VI. Discussion and Conclusions

The majority of solids flows presented in Table I closely match production quantities for the reference model. The major

TABLE II
STEADY STATE MODEL FLOW PURITIES COMPARED TO REFERENCE MODEL

Flow from	Purity (%)	Reference model purity (%)	Absolute difference to reference model (%)
Liquor Tank	92.48	92.20	-0.30
A Pans	88.59	88.59	0.00
B Pans	82.00	82.00	0.00
C Pans	66.01	66.09	0.12
A Fugals	74.58	74.60	0.03
B Fugals	64.87	65.00	0.20
C Fugals	88.00	88.00	0.00
A Sugar	99.33	99.33	0.00
B Sugar	98.90	98.90	0.00
Product Sugar	99.22	99.22	0.00
Final Molasses	46.40	46.80	0.85

differences between the two approaches exist for the C sugar footing quantities for the seed pans. The cause of the difference is attributed to the population balance calculation, which needs to be investigated further. As a result solids flows for the C sugar quantities from the C fugals to the seed pans differ from their counterparts in the reference model.

The purities presented in Table II match reference model results very closely with an extremely low relative difference. This close matching of purity values is to be expected within the model. Once the target purities for the seed pans are correctly reached within the model, through the optimization of the fractional values for feed materials to the equipment items, consistent purity values in the remainder of the model should follow.

The innovation introduced in this paper is in the development of a key process model to be used in the KBSSS to quantify the interactions for pan stage process with the juice processing and centrifugal sections of the sugar mill and provide a long term overview of pan stage production rates and internal flows. The major features of the model have been presented along with the method used in the provision of advice in C sugar footing quantities to seed pans, quantifying long term production rates of product sugar and final molasses and long term C sugar remelt rates for use in liquor tank level prediction [15]. Further innovation is introduced in the method of implementation. A spreadsheet style modelling approach was undertaken in previous research [6,7]. Instead the proposed model is a dynamic component in a KBSSS and not a stand alone static object. This allows it to work in tandem with additional models, as presented in Section III, to collectively quantify the pan stage and its future operating conditions as part of a future forecast of operations.

The model uses the object oriented paradigm and methodologies for implementation. This provides a compact and flexible representation of the pan stage and its major equipment items. Furthermore, the model is tailored specifically to the three massecuite boiling scheme. This steady state forward flow model integrates a reverse chaining mechanism to work backwards within the flow model to calculate and then set the initial C sugar footings flows to the A and B pans. Feed forward networks do not act in reverse fashion but this is essentially what was required in order to ensure product sugar was of the nominated target size leading to innovation in the approach.

The developed model can be extended with further improvements as part of future research. Such changes could include the incorporation of sucrose losses over the pan stage. The current model assumes no such losses. The presented model can also be linked with average syrup production rates from the syrup prediction [17] working in tandem with dynamic forecasting for a specified horizon to provide the average syrup production rate as the primary model input. In order to verify the viability of the steady state flow model such input was not used in this paper. Input conditions instead matched previous research [7] to allow for model comparisons.

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