SOME IDEAS ON THE DESIGN OF BATCH AND CONTINUOUS PANS

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Abstract

This paper proposes a method by means of which it is possible to calculate the circulation and evaporation rates and thus optimise the design of pans. It is shown that when designing batch pans there is an optimum combination of tube length, diameter and circulation ratio to produce maximum circulation for a given graining volume and heating surface/volume ratio. Similarly when designing continuous pans there is an optimum tube length and diameter depending on the heating surface/volume ratio.

Introduction

The principal objective of pan design has been to obtain good evaporation and circulation rates so as to maximize the production of the pan and because low crystallization rates and sugar of inferior quality result from insufficient massecuite movement. Experience has shown that the factors that affect circulation in pans are:

(a) The depth of massecuite above the tubes.

(b) The tube length.

(c) The tube diameter.

(d) The ratio of the sectional area of the tubes to that of the downtake, also called circulation ratio.

(e) The ratio of the heating surface to the volume of massecuite.

Ideally a pan should have a low hydrostatic head,[1,2] short tubes[3,4] and a circulation ratio of about 2,0.[4] However, there are difficulties in including all these desirable characteristics into the design, because a batch pan also requires a graining volume which should not exceed a set value, while the design of a continuous pan is restricted because of the necessity of achieving a vessel of manageable proportions.

This paper proposes a method by means of which it is possible to calculate the circulation and evaporation rates using equations derived experimentally and thus optimize the design of pans.

Method of Calculation

Pan circulation is caused by the difference in hydrostatic head between a two-phase mixture of massecuite and vapour flowing up the boiling tubes and single phase massecuite flowing down the downtake. The rate at which this movement takes place is affected by the resistance to fluid flow resulting from the dimension and arrangement of the flow channel, by the physical properties of the liquid phase and by the amount of vapour formed and retained in the two-phase mixture. Calculation of circulation velocity for a given fluid then entails finding the velocity at which the hydrostatic differential head equals the friction losses.

In order to establish this method of calculation it was necessary to determine what are the variables that influence the heat transfer, friction losses and vapour holdup while boiling massecuite, and to combine these variables into equations so that these parameters could be evaluated for different boiling conditions.

A series of experiments done on a pilot vacuum pan[5] showed that the boiling heat transfer coefficient can be represented by the following equation with a correlation coefficient of 0,963

$$\frac{h_{TP}D}{k_f} = 4{,}48\,(Re_{TP})^{0{,}386}\,(\rho_l/\rho g)^{0{,}202}\,(D/L)^{0{,}333} \qquad (1)$$

(The meaning of the symbols is given in the nomenclature). The efffect of the tube length and diameter on the boiling heat transfer coefficient is thus the same as that in the Sieder and Tate equation for heat transfer in laminar flow without change of phase.

It was found that the friction loss of the massecuite-vapour mixture rising in the tubes can be estimated by a modified Hagan-Poiseuille equation as suggested by Griffith and Wallis.[6]

$$\Delta P_F = \frac{32\,\rho_l U_l^2 L}{gD\,Re_{TP}} \qquad (2)$$

in which the velocity of the liquid phase is corrected for the voidage due to the gas phase.

Knowledge of the void fraction is essential in calculating the heat transfer coefficient, the friction loss and the differential head which produces circulation in the pan. It is also the most difficult to predict, because it is a transient phenomenon. Subcooled boiling generally prevails when boiling massecuite, and under these conditions the liquid and vapour phases are not in thermal equilibrium across a section of the tube. It was found that for subcooled boiling the local void fraction can be calculated from the equation[5] with a correlation coefficient of 0,914

$$\alpha = 0{,}00\,649\,\frac{h_{TP}\cdot k_l}{h_{fo}^2\cdot D}\,(Pr)^{0{,}351}\,(\rho_l/\rho_g)^{0{,}414} \qquad (3)$$

Since the parameters that affect boiling do not vary linearly with distance from the tube inlet it is necessary to do a stepwise calculation. The calculations must also be done iteratively until the friction loss in the flow channel equals the hydrostatic differential head. These calculations are done using a desk top computer.

The accuracy of the method was verified by calculating the evaporation rates for the conditions of a factorial experiment done on an experimental vacuum pan.[7] The measured and calculated values are given in Table 1 for B-massecuite and in Table 2 for C-massecuite.

The average difference between the measured and calculated evaporation rates is thirty-nine percent for B-massecuite and 13 % for C-massecuite. This difference results from both the inaccuracy of the results on which Tables 1 and 2 are based and on the inaccuracy of the calculations. The procedure used for the calculations is summarized in the Appendix. They involve two main assumptions.

Table 1

Measured and calculated evaporation rates (kg/m²-h) for B-massecuite (Bx = 91,5; Pty = 66,4)

Steam pressure (kPa)	Vacuum (kPa abs)	Head (m)		Tube length (m)			
				0,6	1,0	1,4	1,8
195	9	0,25	Meas.	23	21	24	21
			Calc.	17	14	12	10
195	9	0,91	Meas.	19	13	15	14
			Calc.	16	13	11	10
195	20	0,25	Meas.	18	16	15	13
			Calc.	23	19	17	15
195	20	0,91	Meas.	15	12	10	9
			Calc.	22	18	16	15
127	9	0,25	Meas.	17	15	13	14
			Calc.	10	8	7	7
127	9	0,91	Meas.	16	11	11	10
			Calc.	10	8	7	6
127	20	0,25	Meas.	11	9	7	7
			Calc.	13	11	9	8
127	20	0,91	Meas.	11	9	6	6
			Calc.	12	10	9	8

Table 2

Measured and calculated evaporation rates (kg/m²-h) for C-massecuite (Bx = 93,9; Pty = 59,4)

Steam Press (kPa)	Head (m)		Tube length (m)			
			0,6	1,0	1,4	1,8
180	0,24	Meas.	9,0	7,8	6,2	5,5
		Calc.	8,2	7,8	7,6	7,3
180	0,87	Meas.	8,2	7,0	6,4	5,5
		Calc.	7,7	7,4	7,2	7,0
130	0,24	Meas.	7,5	5,6	5,0	4,9
		Calc.	5,9	5,7	5,5	5,3
130	0,87	Meas.	6,7	6,1	4,3	4,8
		Calc.	5,6	5,4	5,2	5,1

(a) All the potential energy due to the differences in hydrostatic head between the downtake and the tubes produces flow through the circulation channel.

(b) When the massecuite begins its descent into the downtake the disengagement of the vapour bubbles is complete and bubbles are not entrained into the downtake.

In actual pan operation some of the potential energy is lost as a result of massecuite being projected into the vapour space across the liquid-gas interphase, and also some vapour bubbles are carried down into the downtake. Therefore the circulation velocities obtained by these calculations are high, particularly at low viscosities when projection of massecuite is severe.

Optimization of Batch Pan Design

The main parameters to be considered in designing a batch pan with natural circulation are the graining volume, the heating surface to volume ratio, the circulation ratio and the tube diameter. It will be seen in turn how each of them affect the evaporation rate and the circulation in the pan. The effect of the angle of the saucer and of the low-head design will also be assessed.

The basic shape of the pan is as shown in Figure 1. It is assumed that the passage under the bottom tube plate is not obstructed by feed pipes or steam injection pipes. The friction losses for flow in and out of the downtake, under the lower tube plate and in and out of the tubes is calculated as explained in the Appendix, but losses due to flow across the upper tube plate are neglected. A heating surface/volume ratio of 5,8 m^{-1} is assumed. This corresponds to the mean value of the batch pans now in use in South Africa.

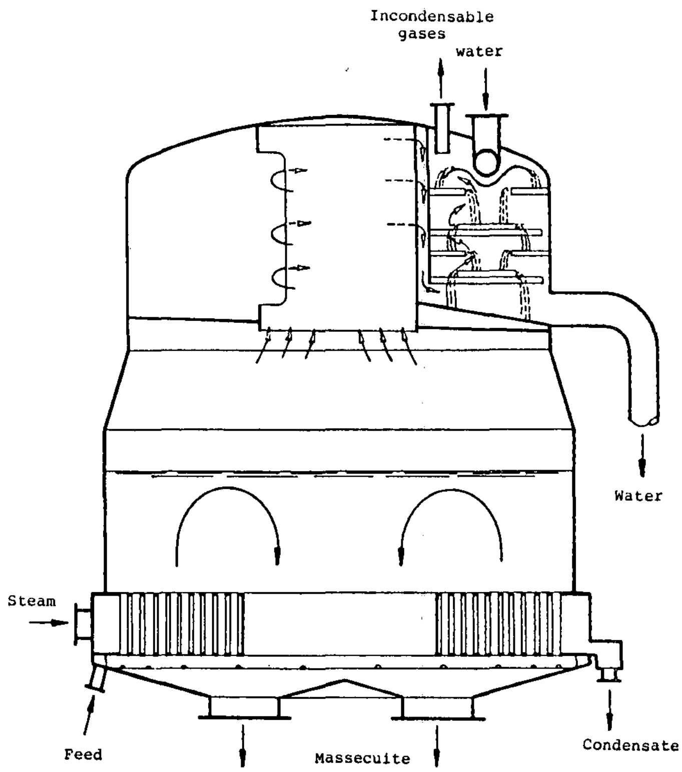

FIGURE 1 Natural circulation batch pan.

The circulation is expressed as the time necessary for the nominal volume of the pan to flow through the downtake. Therefore, the shorter the time the better the circulation.

The physical properties of the massecuites and the operating conditions assumed for the calculations are shown in Table 3.

Table 3

Assumed physical properties of massecuites and operating conditions

	B-massecuite	C-massecuite
Dry substance	91,66	94,65
Purity	72,00	58,60
Purity nutsch	49,33	42,31
Consistency	$K = 1{,}15 \times 10^{-7} e^{\frac{7050}{T}}$	$K = 3{,}37 \times 10^{-3} e^{\frac{3621}{T}}$
Flow behaviour index	0,85	0,836
Steam pressure-kPa	35	35
Vacuum . kPa abs.	10	10

In high grade pans a graining volume of about 35% is needed to reduce the number of cuttings required to achieve the grain size desired. The tube lengths and head of massecuite above the upper tube plate as a function of the tube diameter and circulation ratio is given in Table 4 for this graining volume and the heating surface/volume ratio mentioned above.

The evaporation and circulation rates were calculated for the different geometries given in Table 4, using the properties of B-massecuite. The results are shown graphically in Figure 2 and Figure 3. It can be seen that both the evaporation and circulation improve as the tube diameter increases. However, the effect levels off with the increase in diameter, and there would be little to be gained in using tubes bigger than 0,124 m.

Table 4

Pan characteristics for a graining volume of 35 % and a heating surface volume ratio of 5,8 m^{-1}

Tube diam. (m)	0,085 (3,5")	0,098 (4")	0,111 (4,5")	0,124 (5")	0,086 (3,5")	0,098 (4")	0,111 (4,5")	0,124 (5")
Circ. ratio	Tube length (m)				Head (m)			
2,0	0,63	0,82	1,10	1,53	1,38	1,59	1,88	2,34
2,5	0,58	0,75	0,98	1,29	1,35	1,52	1,75	2,07
3,0	0,56	0,71	0,91	1,18	1,33	1,48	1,67	1,94
3,5	0,54	0,69	0,87	1,10	1,32	1,45	1,63	1,86
4,0	0,53	0,67	0,84	1,05	1,31	1,43	1,60	1,80

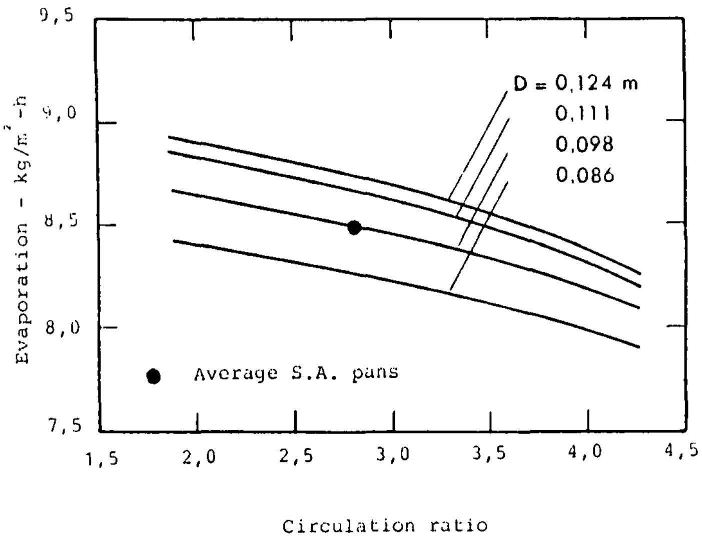

FIGURE 2 Effect of tube diameter and circulation ratio on evaporation rate of B-massecuite. (Graining volume 35 %. Heating surface/volume 5,8 m^{-1}).

The evaporation rate decreases when the circulation ratio increases between 2,0 and 4,0. However, the circulation shows an optimum point at a circulation ratio of 3,5.

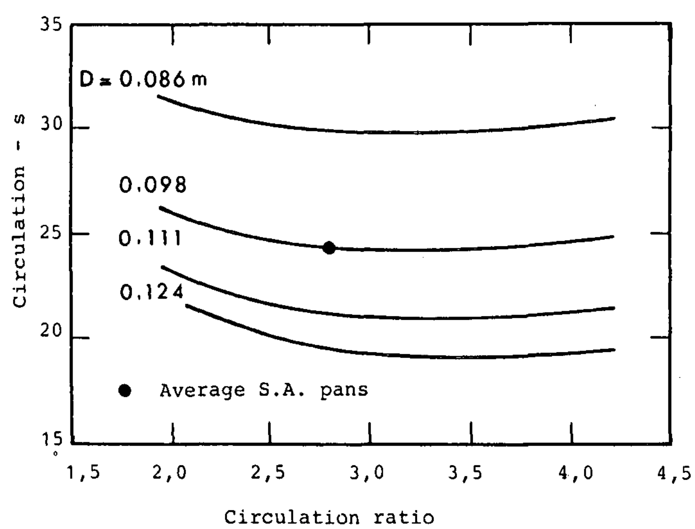

FIGURE 3 Effect of tube diameter and circulation ratio on circulation of B-massecuite (graining volume 35 %. Heating surface/volume 5,8 m^{-1}).

Indicated on Figure 2 and Figure 3 are the evaporation and circulation rates for 0,098 tubes and a circulation ratio of 2,8 which is the average for batch pans in this country. The use of 0,124 m tubes with a circulation ratio of 3,0 would thus result in an improvement of about 2 % in the evaporation and an increase of twenty percent in the circulation.

The above results agree with the conclusions of Hugot and Jenkins[8] based on calculations using single-phase heat transfer and friction losses. Their conclusions were that small relative tube diameters give poor circulation and they added "We feel justified in predicting that the pan of the future will have tubes of greater diameter than those in use at present".

The higher evaporation rates produced by larger tubes was also confirmed by boilings done in an experimental vacuum pan.[9] The results obtained which are shown in Figure 4 show that the evaporation rate produced by 0,124 m diam. tube is higher than that for a 0,0722 tube for a range of viscosities between 2 and 200 Pa.s.

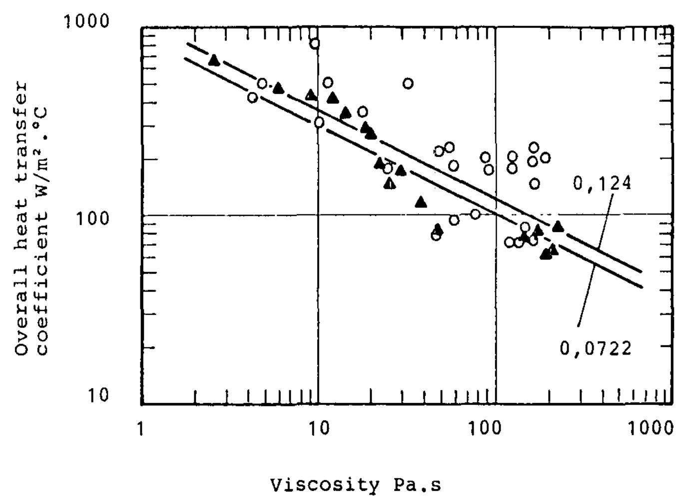

FIGURE 4 Overall heat transfer coefficient for 1,4 m tube and 50°C temperature difference as a function of viscosity (O 0,124 m diam; Δ 0,0722 m diam)

These results can be represented by the equation

$$\text{Overall HTC} = 1{,}36\,(\mu)^{-0{,}47}(\Delta T)^{1{,}9}(D)^{0{,}31}(L)^{-0{,}38} \quad (4)$$

with a correlation coefficient of 0,842, thus confirming the effect of tube length and diameter of equation (1).

Table 4 shows that a pan using the tube diameter and circulation ratio recommended would operate at a massecuite height of 1,94 m above the upper tube plate. Both Venton[1] and Perk[2] have stressed the importance of limiting the boiling height to prevent excessive overheating of the massecuite near the bottom of the tube. The use of the "low-head" type of pan with an expanded belt above the calandria as proposed by Hamill[10] would reduce the height to 1,63 m and decrease the boiling temperature by 2,3°C. At the same time the evaporation would increase by another 2 %, but the circulation would remain unchanged.

The temperature distribution in the pan is probably as follows: In subcooled boiling because of the low thermal conductivity of the massecuite only the fluid adjacent to the tube surface is heated to the boiling point. Thus, in the above pan the temperature of the massecuite throughout the pan would be close to 60,7°C. Because of the hydrostatic head, the massecuite boiling at the bottom of the tubes would be at 108°C and 86° at the top, but the temperature at the tube centre line would still be close to 60,7, for it is calculated that the average temperature at the tube outlet would be 60,9°C. The temperature distribution was determined experimentally by Webre[11] who observed that at the tube outlet the temperature close to the wall was as much as 30° higher than that at the centre. Therefore only a small fraction of the massecuite in the pan is subjected to high temperatures at any one time.

The effect of tube diameter calculated for B-massecuite also applies to C-massecuite. The effect of changing the graining volume on the evaporation and circulation of C-massecuite is shown in Figure 5 and Figure 6. As the graining volume increases there is an increase in both the evaporation and circulation rates. Therefore it is advisable to design pans for low grade high viscosity strikes, where the circulation is usually very sluggish, with a graining volume of about 40%. Of course the penalty to pay would be that more cuttings would be necessary to drop the purity to the desired value.

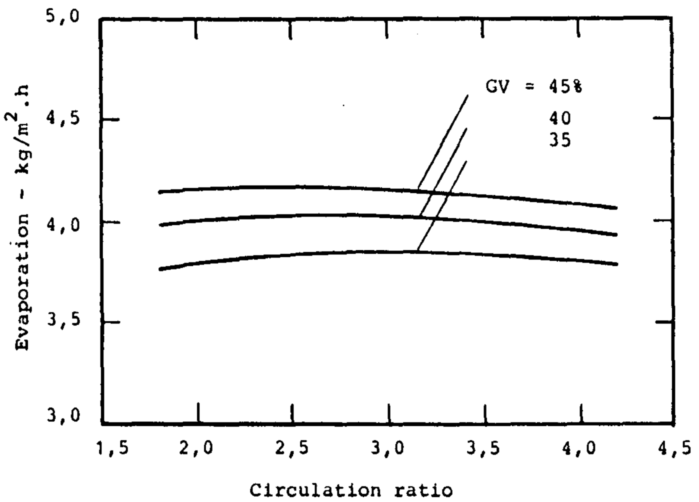

FIGURE 5 Effect of graining volume and circulation ratio on evaporation rate of C-massecuite (0,124 m diam. tube)

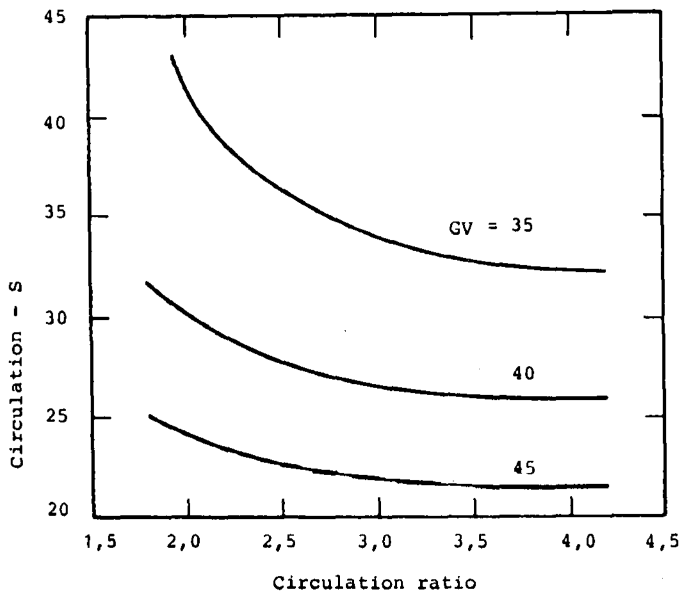

FIGURE 6 Effect of graining volume and circulation ratio on circulation of C-massecuite (0,124 m diam. tube).

However, a survey of the local industry has shown that in most factories low grade strikes are terminated before the design level of the pan is reached, so that in effect the graining volume, expressed as a percentage of the strike volume, is greater than what was originally intended when the pan was designed. The effect of varying the graining volume on the geometry of a pan fitted with 0,124 m tubes is given in Table 5.

Table 5

Pan characteristics for a heating surface/volume ratio of 5,8m⁻¹ and 0,124 m (5") diam. tubes

Graining volume %	35	40	45	35	40	45
Circulation ratio	Tube length (m)			Head (m)		
2,0	1,53	1,07	0,84	2,34	1,51	1,09
2,5	1,29	0,96	0,77	2,07	1,41	1,05
3,0	1,18	0,89	0,73	1,94	1,36	1,02
3,5	1,10	0,85	0,71	1,86	1,33	1,01
4,0	1,05	0,82	0,69	1,80	1,30	0,99

The use of 0,124 m tubes with a circulation ratio of 3,5 and a graining volume of 50% would result in an increase in evaporation rate of about 4% and an increase in circulation of about 26% compared to those of a pan with a graining volume of 35%. Table 4 shows that such a pan would have tubes 0,85 m long and boil with a head of 1,33 m above the upper tube plate.

Although increasing the heating surface/volume ratio produces a higher evaporation rate per unit volume of massecuite it also reduces the circulation rate as illustrated in Figure 7.

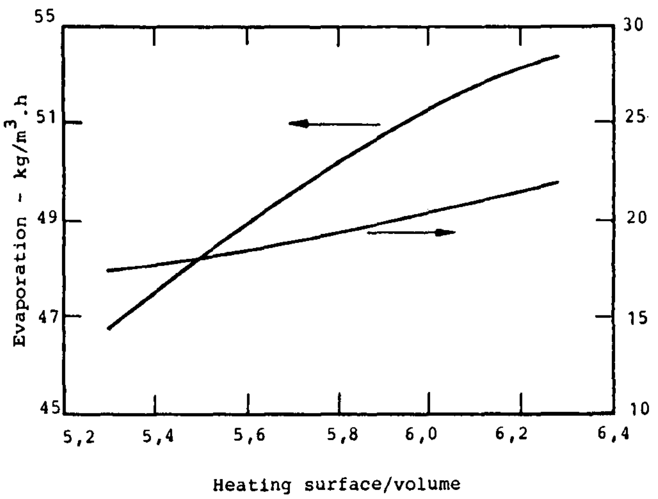

FIGURE 7 Evaporation and circulation in batch B-pans as a function of heating surface/volume ratio (Graining volume 35 %. Tube diam. 0,124 m)

The pan optimization presented is based on a bottom angle of 15°. This angle is used in many of the more recent batch pans installed locally. It has been said that the lack of slope increases the time required to empty the pan and that massecuite does not drain entirely. Increasing the angle to 20° would necessitate lengthening the tubes by 18% and increasing the height above the tube plate by the same percentage to maintain the same graining volume. This would produce a decrease of 8% in the circulation rate. A solution would be to provide two discharge valves as shown in Figure 1.

It is important to note that there is a significant friction loss as massecuite flows under the tube plate. For example for a pan with 0,124 m diam. tubes and a 40 % graining volume the head loss in the tubes including entrance, exit, acceleration and friction loss represents 93 % of the total loss. The entrance, exit and friction loss in the downtake amounts to 1 %, while the friction in the bottom with an angle of 15° amounts to 6 %. It is therefore important to keep the bottom clear of all obstructions such as feed and steam injection pipes.

Optimization of Continuous Pan Design

The significant parameters of continuous pan design are the heating surface to volume ratio, the tube diameter and length and the overall dimensions of the pan. The circulation ratio will vary depending on the choice of these three parameters.

A compartmented linear horizontal continuous pan is assumed for this optimization, a section of which is shown in Figure 8. The pan is assumed to have a tubular calandria with all the tubes of equal length. The calculations are based on a compartment having a volume of 10 m³ with a width of 2,42 m and a heating surface/volume ratio of either 8,8 m^{-1} or 10 m^{-1}. The massecuite head above the upper tube plate is assumed to be 0,5 m. Calculation of the circulation and evaporation rates was done using the properties of B-massecuite given in Table 3. These properties are those of a typical B-massecuite at strike.

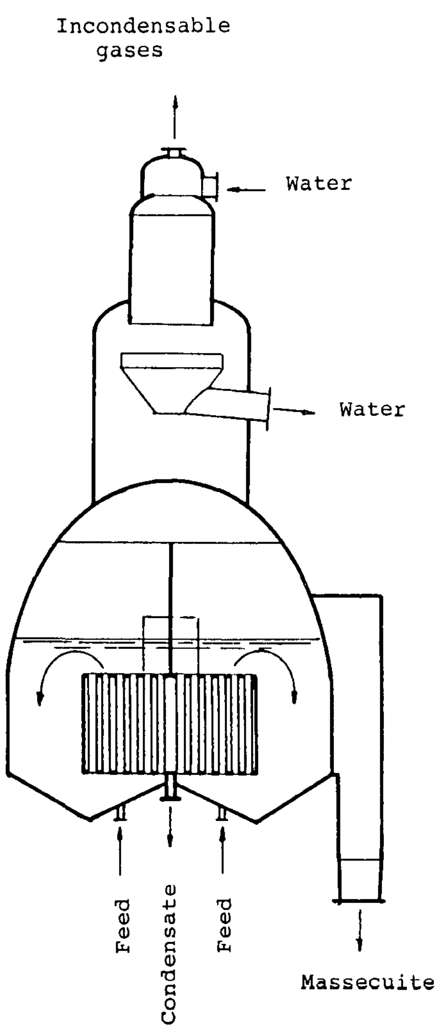

FIGURE 8 Cross section of continuous pan.

The effect of tube length and diameter and heating surface/volume ratio on the evaporation and circulation rates are shown in Figure 9 and Figure 10. For a given heating surface/volume ratio the evaporation rate increases with larger tube diameters and as the tube length is reduced. Decreasing the tube length, however, reduces the size of the downtake, and a point is reached where the friction loss in the downtake slows down the circulation and with it the evaporation. Similarly the circulation improves with increasing tube diameters and decreasing lengths. The heating surface/volume ratio has little effect on the evaporation rate expressed per unit surface area, but the evaporation per unit volume of massecuite will be roughly proportional to the heating surface/volume ratio, as will the circulation rate. Lower values of heating surface/volume, however, allow the use of shorter tubes as can be seen in Figure 8 and Figure 9. For a heating surface/volume ratio of ten, tubes of 0,124 m diameter 1,5 m long would give an increase of 7 % in the evaporation rate and double the circulation rate as compared to 0,098 m tubes. Using 0,124 m instead of 0,098 m diameter tubes would cause only a slight increase in the overall dimensions of the pan.

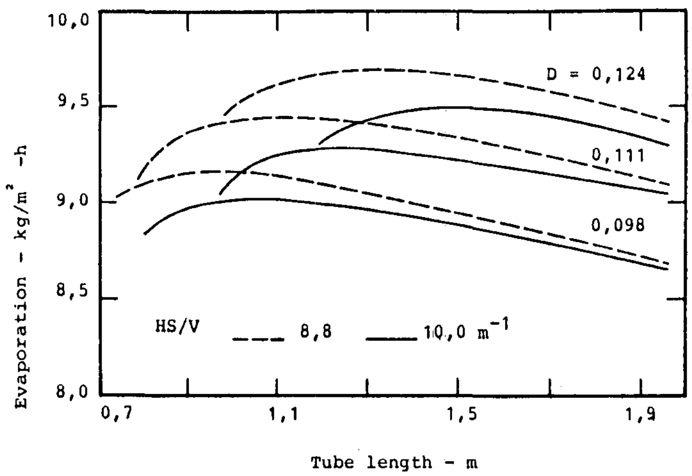

FIGURE 9 Effect of tube length and diameter and heating surface/volume ratio on evaporation rate of continuous pan.

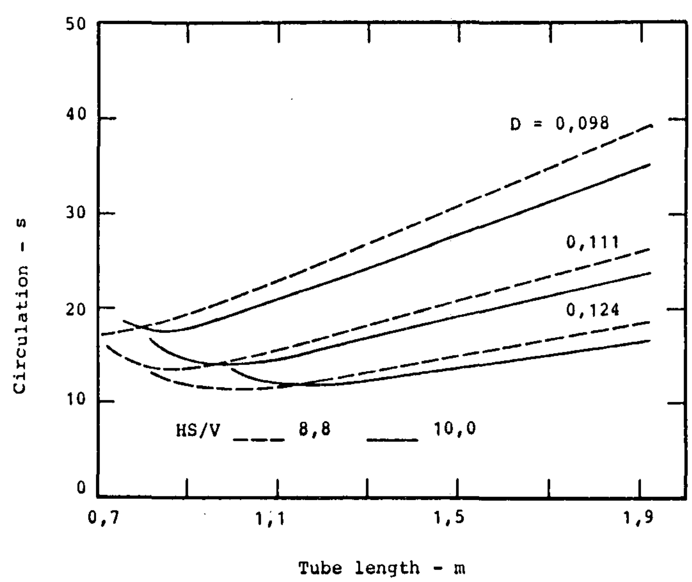

FIGURE 10 Effect of tube length and diameter and heating surface/volume ratio on circulation in continuous pan.

Conclusions

These calculations show that when designing batch pans for maximum circulation there is an optimum combination of tube length and circulation ratio that must be used for the graining volume and heating surface/volume ratio desired. It is interesting to note that this corresponds neither to the shortest tube nor to the lowest circulation ratio. The use of tubes with a diameter larger than 0,098 m is advisable.

Similarly it is shown that when designing continuous pans there is an optimum tube length depending on the heating surface/volume ratio. Here again the use of tubes with a diameter larger than that now generally used would result in improved evaporation and circulation.

Nomenclature

D tube diameter
g acceleration due to gravity
h heat transfer coefficient
k thermal conductivity
L tube length
u velocity of flow
T absolute temperature
α void fraction
μ viscosity
ρ density
ΔP_A pressure difference due to acceleration
ΔP_F pressure difference due to friction
ΔP_z pressure difference due to static head
Pr Prandtl number
Re Reynolds number

Subscripts
f film conditions
fo total flow assumed liquid
g vapour
l liquid
TP two phase
GV graining volume

REFERENCES

1. Venton, CB (1950). A comparative study of some vacuum pans. *Int Sugar j. 52* 63–66, 96–98.
2. Perk, CGM (1952). Coil and calandria vacuum pans. *Proc S Afr Sug Technol Ass* 26 48–53.
3. Claasen, H (1938). *Evaporation and vertical tube evaporators.* Schallehn and Woolbruck, Magdeberg.
4. Jenkins, GH (1958). Heating surface arrangement and circulation in vacuum pans. *Proc GSSCT 25* 199–200.
5. Rouillard, EEA (1986). A study of boiling parameters under conditions of laminar non-Newtonian flow with particular reference to massecuite boiling. PhD. Thesis University of Natal.
6. Griffith, P and Wallis, GD (1961). Two phase slug flow J. Heat Transfer, *Trans ASME 83* 307–320.
7. Rouillard, EEA (1985). Massecuite boiling. *Proc S Afr Sug Technol Ass 59* 43–47.
8. Hugot, E and Jenkins, GH (1959). Circulation in vacuum pans. *Proc Int Soc Sug Cane Technol 10* 232–241.
9. Rouillard, EEA (1987). Factors affecting the evaporation rate of massecuite. SMRI Technical Report No. 1472.
10. Hamill, J. (1965). Vacuum pan design in relation to performance. *Proc Int Soc Sug Cane Technol 9* 76–81.
11. Webre, AL (1962). Mechanical circulation in vacuum pans. *Sugar y Azucar 57* (1) 38–42.
12. Metzner, AB and Reed, JC (1955). Flow of non-Newtonian fluids – correlation of the laminar, transition and turbulent flow regions. *AIChE J. 1* 434–440.
13. Perry, RH and Chilton, CH ed (1973). *Chemical Engineer's Handbook.* McGraw Hill Kogenkusha Ltd. Tokyo.
14. Weltmann, RN and Keller, TA (1957). NACA Tech. Note 3889.
15. Skelland, AHP (1967). *Non-Newtonian flow and heat transfer.* John Wiley and Sons, Inc., New York.
16. Butterworth, D and Hewitt, GFD (1977). *Two phase flow and heat transfer.* Oxford University Press.
17. Genotelle, J (1980). Etude des tables relatives a la vapeur d'eau. *Sucrerie Francaise. 121* 357–367.
18. Batterham, RJ and Norgate TE (1975). Boiling point elevation and superheat in impure cane sugar solutions. *Int Sug J. 77* 359–364.

APPENDIX

Calculation of circulation in pan

The following data inputs are required:

(a) The specifications of the pan which include the diameter of the pan and of the downtake, the number of tubes, their length, internal and external diameters.

(b) The operating conditions which include the steam pressure, vacuum and height of massecuite above the upper tube plate.

(c) The physical properties of the massecuite including the rheological constants, surface tension and brix. Also the dry substance and purity of the mother liquor.

The calculations are done by iteration. A flowchart of the program is given in Figure 11. The iteration is initiated by assuming an arbitrary circulation velocity. The friction loss in the downtake is calculated by the method of Metzner and Reed[12] which is applicable to time-independent non-Newtonian fluids. The same method is used to estimate the friction loss under the tube plate, but in this case it is done by integration since both the flowrate and sectional area vary along the flow path. Calculation of the loss of the entrance to the downtake and of the tubes is done using the equation given by Perry and Chilton[13] for Newtonian fluids which has been shown by Weltmann and Keller[14] to apply also to non-Newtonian fluids, while the expansion loss at the exit of the downtake and of the tubes is calculated as suggested by Skelland.[15]

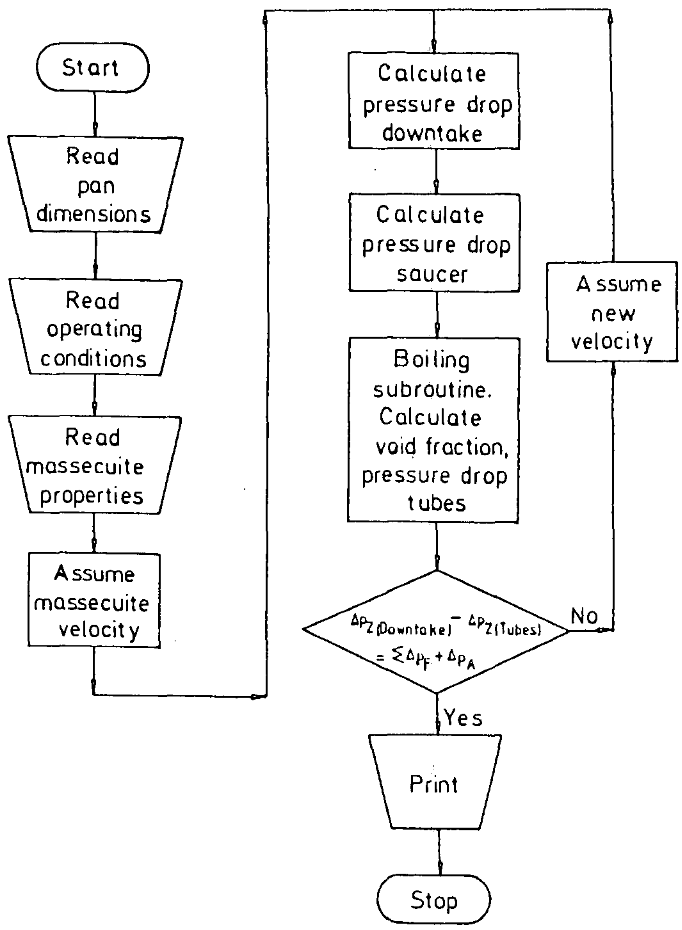

FIGURE 11 Flowchart of circulation program.

A sub-routine in the program is used to calculate the friction and acceleration losses for the boiling tubes. It also gives the tube exit velocity by means of which the expansion losses at the tube outlet can be obtained. This sub-routine also calculates the void fraction in the tubes and thus the hydrostatic head.

The basis of the sub-routine is to divide the tube into a number of subdivisions. The change in the values of the pertinent variables and parameters is assumed to be linear within each subdivision. The calculation is done stepwise for each subdivision. The values assumed for the calculations are corrected by iteration until congruence is obtained.

The friction loss is calculated by the method of Metzner and Reed[12] to account for the non-Newtonian properties of massecuite and by the method of Griffith and Wallis[6] to account for the two-phase conditions. (Eq. 2)

The gravitational loss for each section is obtained assuming a normal two-phase pressure balance and the acceleration loss using the momentum equation of Butterworth and Hewitt.[16]

This procedure establishes the pressure gradient along the tube, and allows calculation of the saturation temperature by the method of Genotelle[17] and of the boiling point elevation by the method of Batterham and Norgate.[18] This establishes the boiling temperature profile along the tube.

The local massecuite film heat transfer coefficient is calculated using Eq. 1, and the overall heat transfer obtained by calculating the condensate and tube wall resistance.

Calculation of the local void fraction entails three distinct regions: the high subcooling, low subcooling and saturated boiling regions. For the high subcooling region which covers the boiling conditions for massecuite considered in this paper, the void fraction is calculated using Eq. 3.

A test for convergence of the subroutine is done by comparing the void fraction calculated with the void fraction that prevailed at the start of the iteration. If convergences is not achieved, the new values for the local void fraction are used in the equations to calculate the gravitational, acceleration and friction losses. New pressure and saturation profiles are established, and the procedure for calculation of the heat transfer and local void fraction is repeated until convergence is obtained.

The resistance to flow then consists of the contraction, friction and expansion losses for the tubes and downtake plus the acceleration losses in the tubes, and friction losses under the tube plate. The driving force is the difference in hydrostatic head between the tubes and downtake. If the resistance and driving force do not agree, the circulation velocity is corrected and a new iteration is done until convergence is obtained.