

# MASSECUITE BOILING

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## Abstract

Experiments conducted in a pilot vacuum pan have shown that the evaporation rates obtained when boiling massecuite decrease with increasing brix, tube length and hydrostatic head and increase with higher vacuum, steam pressure and purity.

## Introduction

Since the invention of the vacuum pan by Howard in 1813, the principal objective of pan design has been to improve circulation so as to produce better quality sugar and increase the evaporation rate. Natural circulation is caused by the difference in hydrostatic head between the two phase mixture of massecuite and vapour in the tubes and single phase massecuite in the downtake. It is affected by the hydraulic resistance of the channel through which flow takes place, by the physical properties of the fluid and the amount of vapour formed.

Although research on the factors affecting circulation has been in progress for many years, to date no satisfactory method has been proposed for optimizing pan design and operation, and the improvements achieved so far have largely been the result of trial and error.

Experiments that have been done to obtain a better understanding of the mechanism of circulation and how to determine the factors that affect it, are described in this paper.

## The Boiling Process

The decrease in hydrostatic head in the tube which produces circulation results from the formation of vapour as ebullition takes place. The changes in temperature and void fraction that occur when a fluid boils in a vertical tube are indicated in Figure 1.

As the liquid enters the tube it is subcooled, that is, its temperature is below the boiling temperature corresponding to the pressure at that point. In region AB, heat transfer is entirely by single phase forced convection. As heat is transferred to the liquid, the temperature adjacent to the heating surface increases until point B at which it reaches the boiling temperature and ebullition starts, but the bulk of the liquid is still subcooled. Between B and C, the vapour bubbles grow because of the additional heat input and as a result of decompression as the liquid rises up the tube. At the same time, heat penetrates towards the centre of the tube so that the bulk liquid temperature increases. The heat transfer in region BC is known as

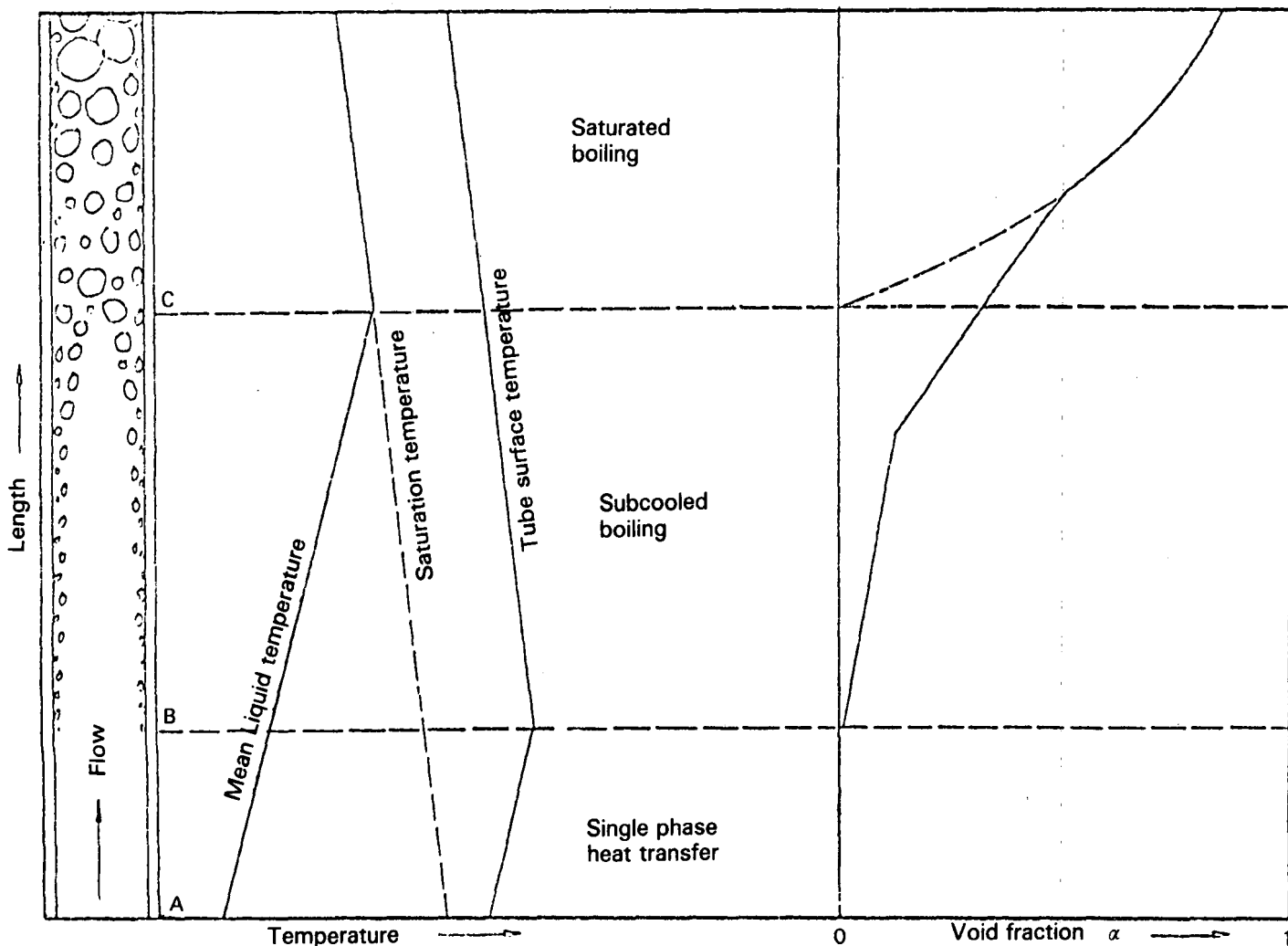


FIGURE 1 Diagram of temperatures and void fractions when boiling in a vertical tube

subcooled boiling. Transition to saturated boiling occurs when the average combined enthalpy of the liquid and vapour equal the saturation enthalpy of the liquid. This happens a short distance upstream of point C. Boiling then extends across the entire sectional area of the tube, and is known as saturated boiling. From this point there is a gradual decrease of the fluid temperature because of the decompression effect. However, under certain conditions transition to saturated boiling does not occur and subcooled boiling extends to the tube outlet.

The increase in void fraction is gradual in the subcooled region, but very pronounced when saturated boiling starts.

**Experimental Details**

Two different series of experiments were conducted. The first was of a more fundamental nature aimed at defining the variables that influence heat transfer, vapour holdup and hydraulic losses during boiling, producing equations for these processes and combining them to form a mathematical model of pan circulation. The apparatus used is shown in Figure 2. It comprised of a single, steam jacketed tube 0,1 m in diameter and 1,3 m long. The velocity at the inlet was controlled by a positive displacement circulation pump. Pressures were measured at ten points along the tube. Axial temperatures were obtained by doing a traverse with a resistance thermometer, and the void fraction along the tube was determined by gamma ray absorption. The fluids used in the experiments were syrup, molasses and C-massecuite seed.

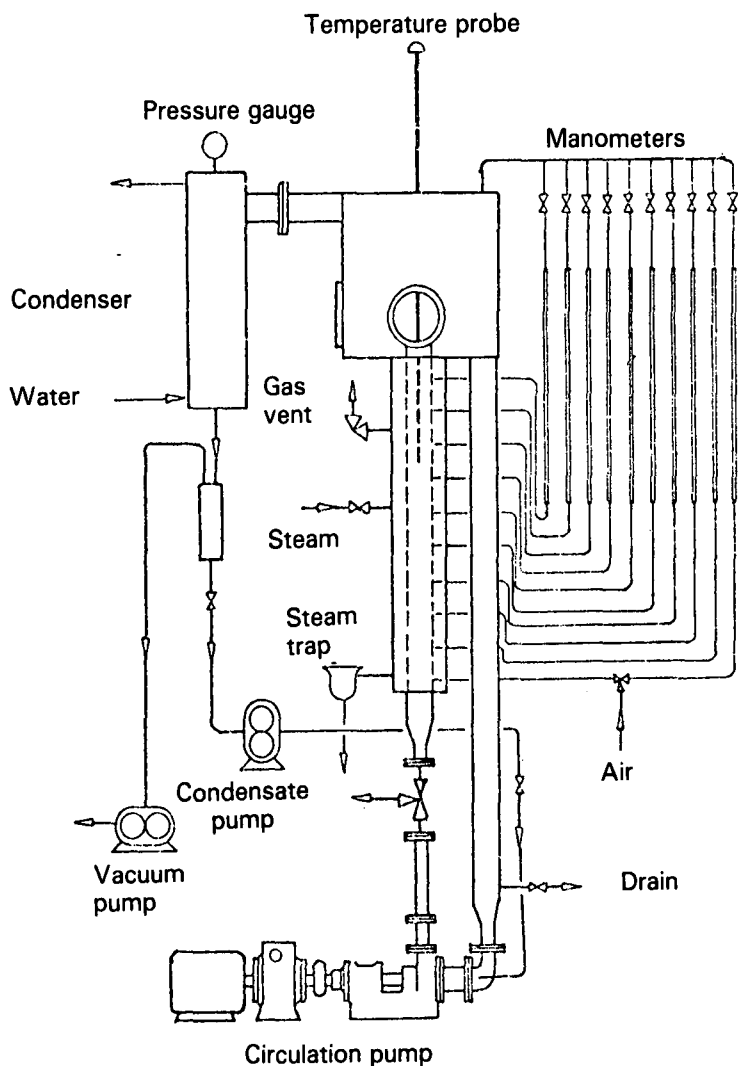


FIGURE 2 Diagram of experimental pan

The second set of experiments was more empirical. Its objectives were to assess the effect of tube length, head above the tubes, steam pressure, vacuum and brix on the evaporation rate. The experimental pan used is shown in Figure 3. It consisted of four 0,1 m diameter tubes 0,6; 1,0; 1,4 and 1,8 m long, connected to a common downtake and vapour space. Each tube had an individual steam jacket with its own steam inlet, in-condensable gas vent and condensate drain. The tests were done with A-, B- and C-massecuites. No correction was applied for steam quality. The influence of the different variables was assessed by factorial experiments and by means of a regression analysis. The high and low levels used in the factorials are given in Table 1.

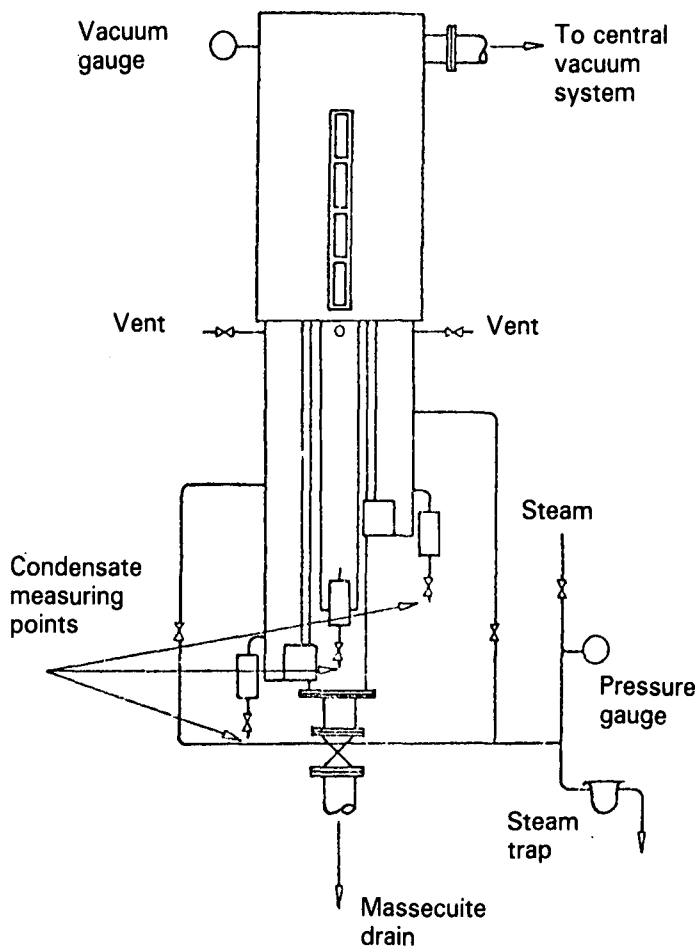


FIGURE 3 Layout of pilot vacuum pan

TABLE 1

Range of variables in factorial experiments

Massecuite	Pressure (kPa abs)	Vacuum (kPa abs)	Head (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

**Results**

The change in temperature, pressure and void fraction observed when boiling C-massecuite seed is shown in Figure 4. Initially there is a gradual increase in void fraction characteristic of subcooled boiling with a sudden increase when the change to saturated boiling occurs. This point also coincides with the maximum axial temperature.

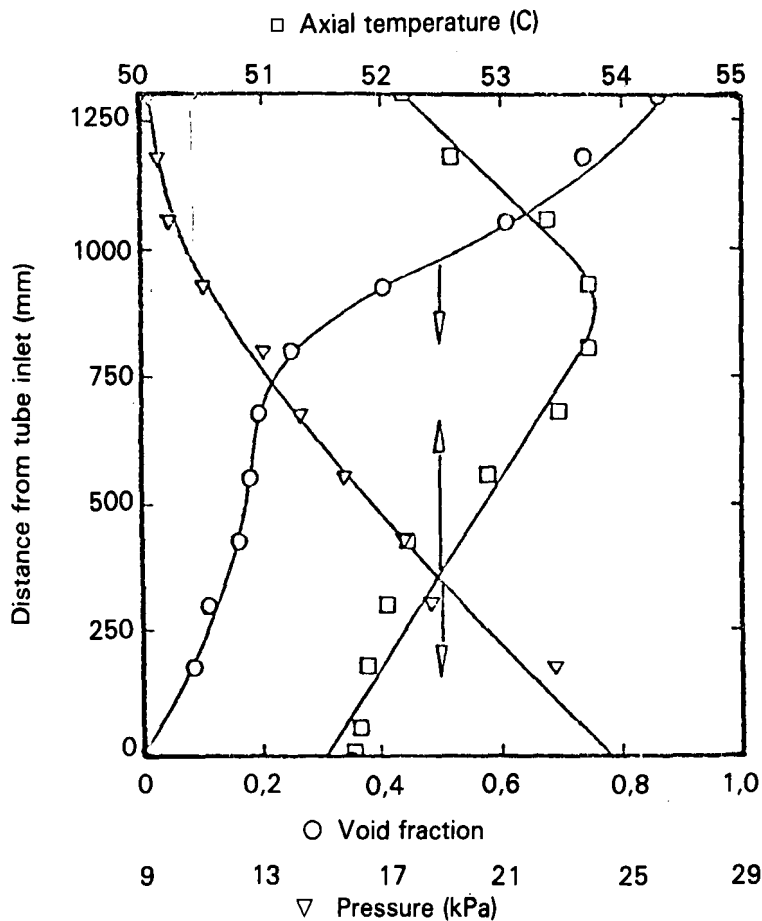


FIGURE 4 Pressure, temperatures and void fraction observed when boiling C-masseccite seed. (Steam pressure 145 kPa abs. Vacuum 9 kPa abs. Brix 87,2. Purity 55,80.)

The length of the subcooled region was found to be a function of the heat flux and of the velocity up the tube. This study showed that when boiling under certain conditions, the subcooled region extended to the tube outlet. Subcooled boiling of C-masseccites had been observed previously by Webre<sup>1</sup> as far back as 1934 when he did temperature traverses across the tube outlet, but he had failed to recognize it as such.

A regression analysis gave the following equation for the boiling heat transfer coefficient.

$$h = 3,72 \frac{k}{D} (Re_{TP})^{0,387} (\rho_f/\rho_g)^{0,22} \dots \dots \dots (1)$$

- where h = local boiling film heat transfer coefficient (W/m<sup>2</sup> · °C)
- k = thermal conductivity (W/m · °C)
- D = tube diameter (m)
- Re<sub>TP</sub> = two phase non-Newtonian Reynold number
- ρ<sub>f</sub> = density of masseccite (kg/m<sup>3</sup>)
- ρ<sub>g</sub> = density of vapour (kg/m<sup>3</sup>)

Thus the heat transfer coefficient is improved by an increase in velocity and void fraction, and a decrease in viscosity and vapour density.

The main difficulty in using this equation is the estimation of the void fraction in the subcooled region, since thermal equilibrium between vapour and masseccite does not exist there. The fraction of the heat transferred in this region which produces vapour was found to be a function of the pressure, with proportionally more vapour formed at higher pressures.

The equations obtained were combined to produce a mathematical model of the boiling process, with which it is possible to calculate by a stepwise and iterative method, the void fraction and evaporation rate along the tube and the resulting circulation. To verify the accuracy of the model it has been used to calculate the evaporation measured in the second set of experiments.

The relation between the measured and calculated values is shown in Figure 5.

The results of the factorial experiments are given in Tables 2, 3 and 4.

**TABLE 2**  
Evaporation rates (kg/m<sup>2</sup>-h) for A-masseccite (Bx = 90,7; Pty = 81,6)

Steam pressure	Vacuum	Head	No. of repeats	Tube length (m)			
				0,6	1,0	1,4	1,8
H	H	L	3	45	39	37	32
H	H	H	4	47	36	37	32
H	L	L	2	23	25	26	22
H	L	H	3	28	20	19	16
L	H	L	3	29	22	23	21
L	H	H	3	31	28	26	23
L	L	L	2	16	13	12	14
L	L	H	2	12	13	11	11

**TABLE 3**  
Evaporation rates (kg/m<sup>2</sup>-h) for B-masseccite (Bx = 91,5; Pty = 66,4)

Steam pressure	Vacuum	Head	No. of repeats	Tube length (m)			
				0,6	1,0	1,4	1,8
H	H	L	3	23	21	24	21
H	H	H	2	19	13	15	14
H	L	L	2	18	16	15	13
H	L	H	2	15	12	10	9
L	H	L	2	17	15	13	14
L	H	H	2	16	11	11	10
L	L	L	3	11	9	7	7
L	L	H	3	11	9	6	6

**TABLE 4**  
Evaporation rates (kg/m<sup>2</sup>-h) for C-masseccites (Bx = 93,9; Pty = 59,4)

Pressure	Head	No. of repeats	Tube length (m)			
			0,6	0,1	1,4	1,8
H	L	3	9,0	7,8	6,2	5,5
H	H	1	8,2	7,0	6,4	5,5
L	L	3	7,5	5,6	5,0	4,9
L	H	3	6,7	6,1	4,3	4,8

The factorial experiment showed that the shorter the tubes, the higher is the evaporation rate per unit heating surface area. The percentage increase as a function of tube length and masseccite type is shown in Table 5.

**TABLE 5**  
Effect of tube length on evaporation rate

Masseccite type	Tube length (m)			
	0,6	1,0	1,4	1,8
	% increase			
A	35	14	12	-
B	38	18	7	-
C	52	28	6	-

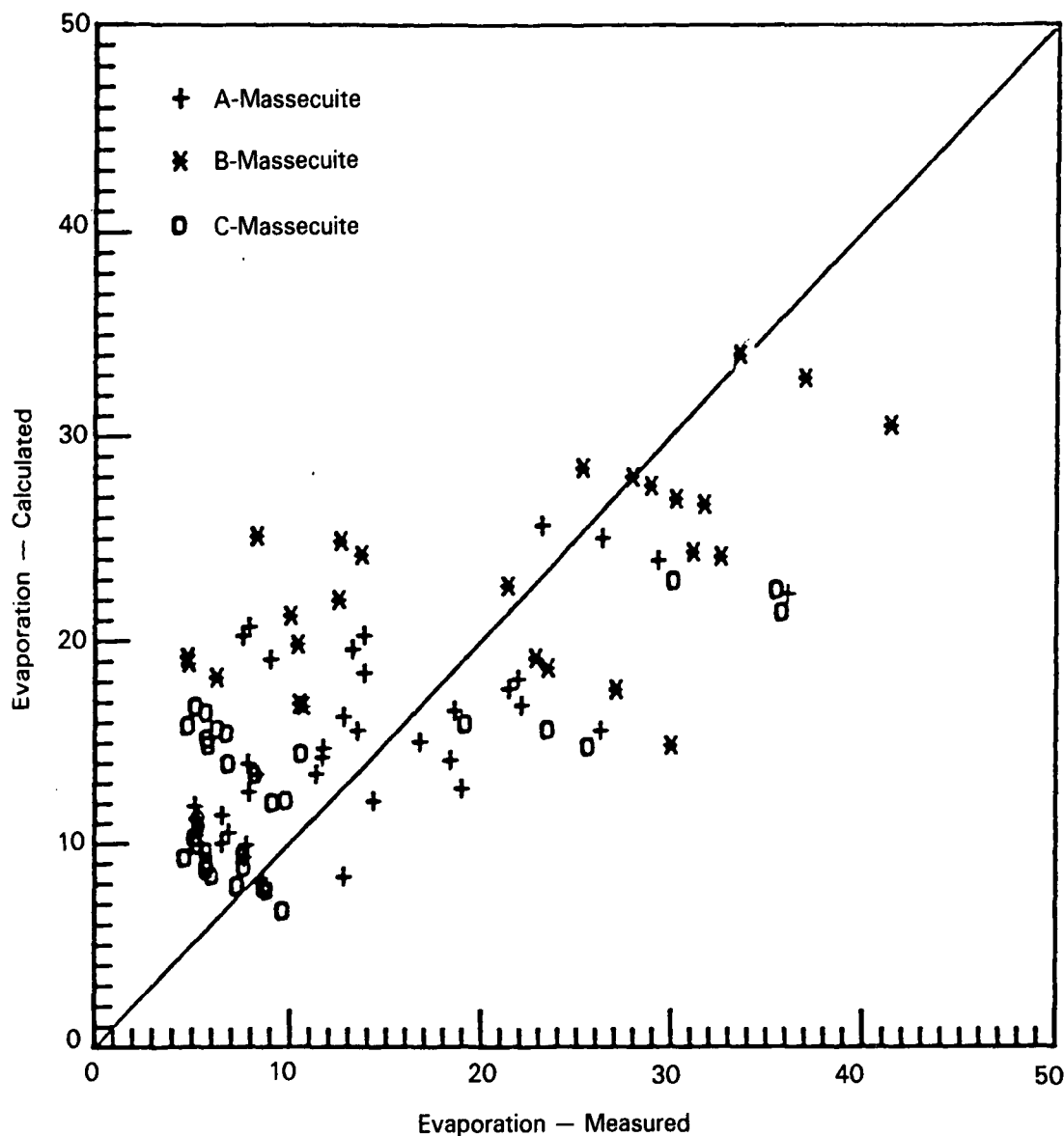


FIGURE 5 Evaporation rates calculated using mathematical model compared to rates observed in second set of experiments

The increase in evaporation rate between high and low hydrostatic heads was 23, 27 and 5% respectively for A-, B- and C-massecuites.

The effect of increased vacuum on the evaporation rates of A- and B-massecuites was a gain of 81 and 51%, while the effect of increased steam pressure improved the evaporation rate of A-, B- and C-massecuites by 59, 52 and 24% respectively.

A regression analysis gave the following equation with the variables in decreasing order of significance.

$$\log n(\text{Evaporation}) = 15,92 - 0,165 (\text{Bx}) - 0,0601 (\text{Vac.}) + 0,0311 (\text{Pty}) + 0,00639 (\text{Pres.}) - 0,321 (\text{Length}) - 0,298 (\text{Head}) (2)$$

The correlation coefficient was 0,81 for 254 sets of data. In this equation the vacuum and steam pressure are in kPa absolute and the tube length and hydrostatic head are in metres. Evaporation rates calculated using equation (2) versus measured values is shown in Figure 6.

#### Application to pan design

Over the years, the main improvements to batch pan design have been a decrease (from about 4 to about 2,5) in the circulation ratio — the ratio of the sectional area of the tubes to that of the downtake. The tube length has also been decreased from more than 1 m to 0,6 m. The effect of both these changes has been to increase the pan diameter and lower the hydrostatic

head for the same heating surface to volume ratio. The results of the experiments described in this paper show that these changes were in the right direction because a lower hydrostatic head and shorter tubes produce an improved exaporation rate.

A tube diameter of 0,0974 m is almost universally used for batch pans in the South African sugar industry. French manufacturers<sup>2</sup> have however, supplied pans with tubes of 0,0889 m while in Australia<sup>3,4</sup>, tubes of 0,114 and 0,123 m have been used. The mathematical model derived from this study was used to assess the effect of tube diameter on the evaporation rate for batch pans. The results are shown in Table 6.

TABLE 6

Calculated evaporation rates resulting from changes in tube diameter

#### Specifications:

Pan capacity	50 m <sup>3</sup>	Purity	58,6
Heating surface/volume	5,5 m <sup>2</sup> /m <sup>3</sup>	Steam pressure	135 kPa abs.
Circulation ratio	2,5	Vacuum	10 kPa abs.
Brix	94,65		

Pan	Diameter (m)		Tube length (m)	Head (m)	Graining volume %	Evaporation (kg/m <sup>2</sup> -h)
	Downtake	Tube				
5,12	2,22	0,0889	0,6	1,55	31,1	5,6
5,49	2,38	0,0974	0,6	1,33	36,7	5,8
6,17	2,68	0,123	0,6	0,86	48,3	6,2

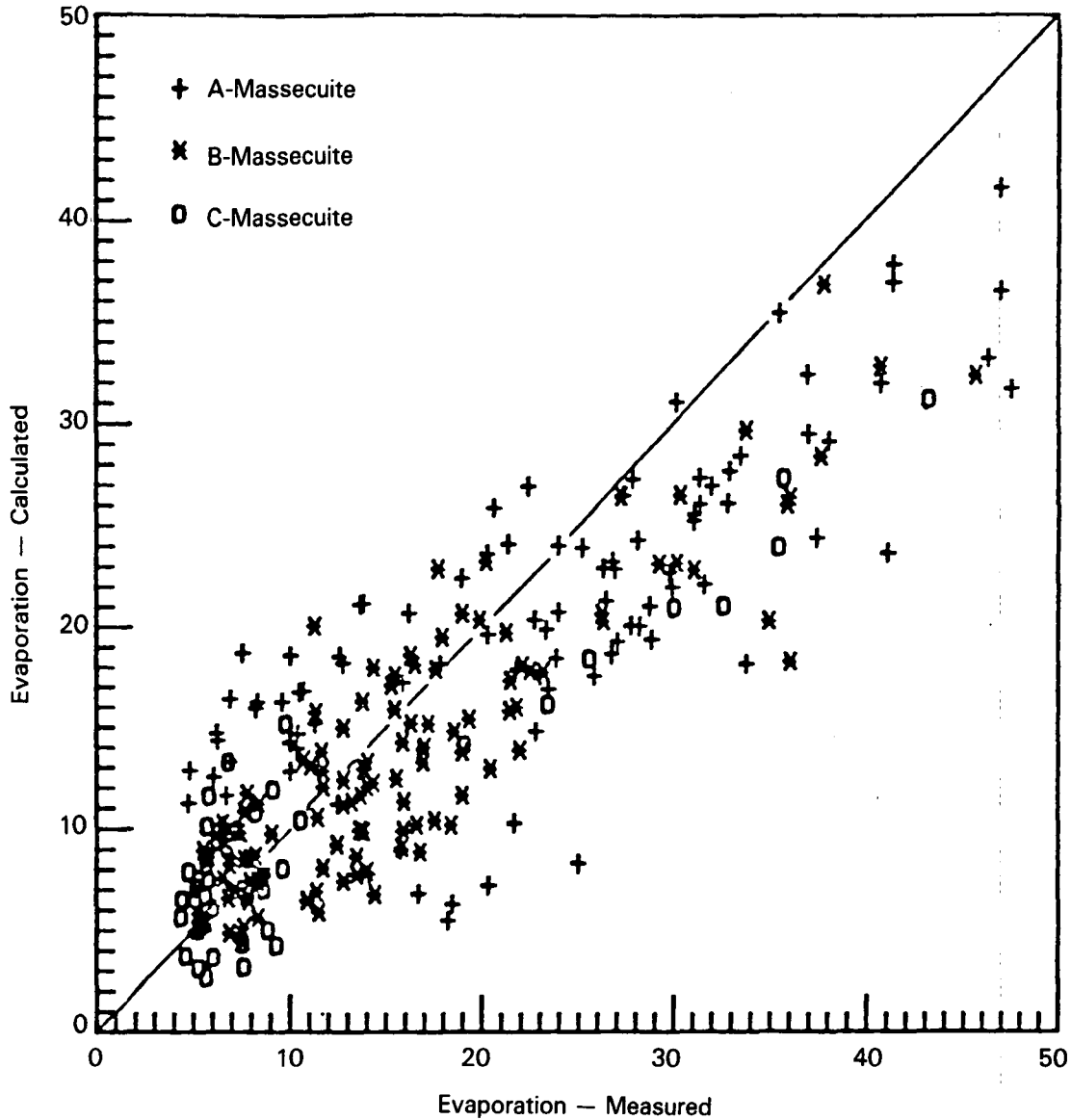


FIGURE 6 Evaporation rates calculated using Equation 2 versus measured rates

A slightly better evaporation rate is obtained with the larger tube because of the decrease in hydrostatic head. On the other hand, there is an appreciable increase in the graining volume.

Continuous pans have been designed with longer tubes than those in use in batch pans. The evaporation rate on C-massecuite obtained with typical lengths used in these pans has been calculated using Equation (2) and are shown in Table 7. The evaporation rate of a batch pan (with short tubes) has been included for comparison.

TABLE 7  
Evaporation rates as a function of head and tube length

Tube length (m)	Head (m)	Evaporation (kg/m <sup>2</sup> -h)	Type of pan
0,6	1,33	7,56	Batch
1,2	0,40	8,73	Continuous
1,5	0,40	7,47	Continuous
2,0	0,40	6,36	Continuous

**Conclusions**

These experiments show that the evaporation rates obtained during massecuite boiling decrease with increasing brix, tube length and hydrostatic head, and increase with higher vacuum, steam pressure and purity.

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