

IMPURITY TRANSFER RATES DURING THE CRYSTALLISATION OF SUCROSE

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Abstract

The crystallisation rate of sucrose is well documented in the literature, but this is not the case when the rate at which impurities are incorporated into the sucrose crystal is concerned. A simple procedure to calculate a rate of impurity transfer, based on the mass of the impurity incorporated into the crystal per unit time and per unit crystal surface area, is proposed and its derivation is described. Experimental work, involving the pilot plant crystallisation of refinery liquors, was carried out to investigate the usefulness of the concept. Both physical factors such as temperature, viscosity and the sucrose crystallisation rate, and chemical factors such as the type and concentration of the impurity are expected to influence the impurity transfer. It is shown that the rate concept can be used to measure these effects. Some practical conclusions are included.

Introduction

The presence of impurities in sugar crystals has been the subject of much work in the sugar industry. In 1985 Mantovani *et al.* carried out extensive work on inclusions in sugar crystals. Mullin (1993) reviewed work on inclusion and related it to the sucrose crystallisation rate. Boistelle (1975) reported on the effects of the concentration of impurities, of supersaturation and of pH on the habit of sucrose crystals. In South Africa, Lionnet and Moodley (1996) have discussed the effects of the concentration of the impurities, of the type of the impurities and of the crystal size on impurity transfer into the crystal. Finally, Vaccari (1996) reviewed the work done to date and noted that there is a degree of confusion concerning mechanisms for impurity transfer. The general conclusions are that the more important impurities for cane sugar are colour, potassium, calcium and polysaccharides. The factors that have an effect on the impurity transfer are the rate of crystallisation, the concentration and type of the impurity and the crystal size.

Many workers (VanHook, 1981; Mantovani *et al.*, 1985, 1986; Lionnet, 1987, 1988; Donovan and Williams, 1992; Lionnet and Moodley, 1996; Vaccari, 1996) confirmed that colour transfer increases as the rate of crystallisation of sucrose increases. Saska (1991) showed that the uptake of dextrans is similarly affected.

In view of the importance of the sucrose crystallisation rate, it is useful to look at how this is measured. Nyvlt *et al.* (1985) showed that there are many ways in which the sucrose crystallisation rate can be measured. Generally, for well defined

conditions, crystal growth can be expressed as a mass dependent rate G , in $\text{kg/m}^2/\text{s}$ or as a mean linear velocity, V , in m/s . These two basic rates are related, need some characteristic crystal dimension and depend on volume and shape factors being calculated.

Both the above rates and shape factors are widely used in the sugar industry. Vaccari *et al.* (1996), Guimaraes *et al.* (1995), Grimsey and Herrington (1994), Bennett and Fentiman (1969) and Day (1971) have used them for sucrose. Finally, they have been reviewed in detail by Bubnick and Kadlec in 1992, for sucrose. These authors showed that it is possible to calculate G and V using the measurement of one or two of the crystal dimensions.

It will be shown that a simple rate of impurity transfer can be derived following an approach similar to that used for G . It is therefore instructive to look at a method for obtaining G .

The rate of crystallisation of sucrose

An approach described by Bubnick and Kadlec (1992) will be followed, but crystal dimensions will be based on an image analysis system. This system yields two crystal dimensions, the first, L , along the b -axis, and the second, W , along the c -axis. Most other workers have used sieving which yields only one dimension.

Equations 1 to 4 are used to define the following quantities: a crystal characteristic dimension, D_c , where

$$D_c = (L^2 W)^{1/3}$$

a volume shape factor, α , where

$$\alpha = \frac{m}{\rho L^2 W}$$

the surface area of one crystal, A , where

$$A = \beta D_c^2$$

and a crystal shape factor, F , where

$$F = \frac{A}{m^{2/3}}$$

In Equations 1 to 4, m is the mass (kg) of one sucrose crystal, ρ is the density of sucrose (kg/m^3), A is the surface area (m^2) of one crystal, α is the volume shape factor, β the surface area shape factor and F the crystal shape factor ($\text{m}^2/\text{kg}^{2/3}$).

F is a function of the type of crystal. Bubnick and Kadlec (1992) reported that F varies between 0,0392 and 0,0490 $m^2/kg^{2/3}$, averaging 0,0447 for sucrose. Bennett and Fentiman (1967) gave values of 0,0412 and 0,0455 $m^2/kg^{2/3}$. In this work the average value of 0,0447 $m^2/kg^{2/3}$ is taken.

The value of α was obtained as follows: one hundred crystals, produced from different runs in the pilot crystalliser, were divided into eight groups, based on visual inspection of size. The average values of L and of W for each group were determined using an image analysis system. The average mass was then obtained by weighing each group of crystals and dividing the total mass by the number of crystals in the group. Linear regression of m versus L^2W yielded

$$m = 539,2 \times L^2W$$

for eight sets of observations with a correlation coefficient of 0,98. Since the density of sucrose is 1 587 kg/m^3 , the value of α is calculated to be 0,34. Bubnick and Kadlec (1992) have reviewed the work on sucrose shape factors and give a value of 0,31 for sucrose crystals from beet and a sizing technique similar to the one used here. When sizing was by sieving, these authors report a value of 0,75 for α .

By suitable manipulations of Equations 1 to 4, β can now be calculated from

$$\beta = F(\alpha\rho)^{2/3}$$

and is found to equal 2,94.

Two growth rates are now defined by Equations 5 and 6, for the sucrose crystal

$$V = \frac{dD_c}{dt}$$

$$G = \frac{dm}{dt} \cdot \frac{1}{A}$$

where V is in m/s while G is in $kg/m^2/s$, and t is the crystallisation time in s.

By using Equations 1 to 6, it can be shown (see Appendix 1) that G is given by Equation 7:

$$G = \frac{3\alpha\rho}{\beta} \cdot V$$

This approach assumes that the seed or nuclei are negligibly small.

Rate of impurity transfer

There is no clear information in the literature about the rate at which impurities are incorporated into the sucrose crystal. A simple rate of impurity transfer, based on the mass of impurity incorporated into the sucrose crystal, per unit time and per unit crystal surface area, is proposed.

This impurity transfer rate, R_i , is defined by Equation 8:

$$R_i = \frac{\text{Mass of impurity in crystals}}{\text{Time} \times \text{Surface area of crystals}}$$

The mass of the impurity in the crystals is the product of the mass of crystals (M_c , kg) and the concentration of the impurity in the crystal (X_i , kg/kg crystal), and the time is again the crystallisation time in seconds. Equation 8 deals with the total number of crystals and the surface area is therefore that of N crystals. Then

$$R_i = \frac{M_c X_i}{t \frac{M_c \beta}{\alpha \rho D_c}} = \frac{\alpha \rho D_c X_i}{t \beta}$$

where $\frac{M_c \beta}{\alpha \rho D_c}$ is the surface area of a mass M_c of crystals.

Both G and R_i are based on the measurement of L and W by an image analysis system. They do not require the mass of the crystals, a quantity which is often difficult to obtain under industrial conditions.

Experimental

Pilot plant pan

This is shown in Figure 1 and has been described previously (Lionnet, 1987, 1988; Lionnet and Moodley, 1996).

All liquors used for the work originated from local refineries and thus represented actual industrial streams. When necessary the feed liquors were spiked with colour (refinery jet 4), potassium and calcium (as AR salts, chloride form), starch (soluble), other polysaccharides (carboxymethyl cellulose; carrageenan, food grade), silica (sodium silicate) and phosphate (sodium hydrogen phosphate).

Feed liquors and affinated crystals were analysed for the relevant impurities. Both the feed to the pan and the condensate were weighed. These masses together with pol, brix and colour analyses allowed material balances to be done yielding masses of masecuite, of sugar and of run-off. Temperatures and crystallisation times were noted. The average values of L and W of the crystals were obtained.

Results

The sucrose crystallisation rate

The rate at which sucrose is crystallised, G, as defined here, is well documented in the literature. Values measured in this work are compared with published ones in Table 1. The values found here compare well with those published, and agree with those obtained from South African refineries.

The rate of impurity transfer

Ranges and average values for the rates of impurity transfer, R_i , are shown in Table 2. The values in this table show that the ranges are wide and that there can be large differences between the different species. Colour and the polysaccharides show the highest rates.

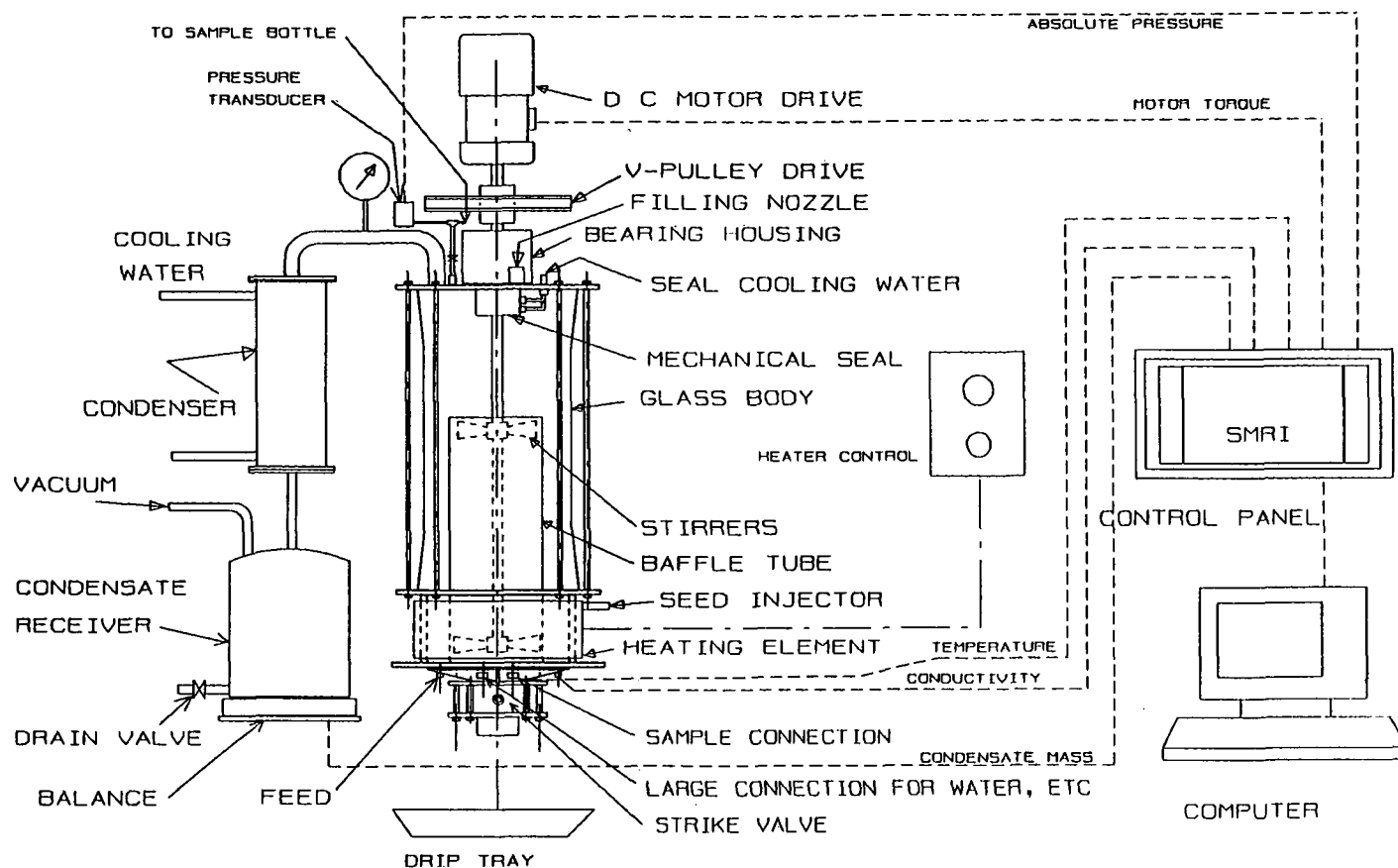


Figure 1. The pilot pan.

Table 1. G (kg/m²/s) from this work and from the literature.

Author(s)	G (kg/m ² /s)		
	Minimum	Maximum	Average
This work	6,0 x 10 ⁻⁶	5 x 10 ⁻⁵	2 x 10 ⁻⁵
Guimaraes <i>et al.</i> (1995)	0,1 x 10 ⁻⁵	2 x 10 ⁻⁵	-
Grimsey and Herrington (1994)	2,0 x 10 ⁻⁶	13 x 10 ⁻⁵	-
Kraus and Nyvlt (1994)	0,2 x 10 ⁻⁶	4 x 10 ⁻⁶	-
Lionnet (1989) for SA Refineries	1,0 x 10 ⁻⁵	6 x 10 ⁻⁵	3 x 10 ⁻⁵
Maurandi <i>et al.</i> (1984)	0,2 x 10 ⁻⁵	2 x 10 ⁻⁵	1 x 10 ⁻⁵
Bennett and Fentiman (1969)	2,0 x 10 ⁻⁵	20 x 10 ⁻⁵	-

Table 2. Ranges and averages for rates of impurity transfer, R_i.

Species	R _i (kg/m ² /s)		
	Minimum	Maximum	Average
Colour	2 x 10 ⁻⁵	2 x 10 ⁻³	4 x 10 ⁻⁴
Starch	5 x 10 ⁻¹¹	3 x 10 ⁻⁸	5 x 10 ⁻⁹
Carrageenan	6 x 10 ⁻¹⁰	2 x 10 ⁻⁸	1 x 10 ⁻⁸
Carboxymethyl cellulose	1 x 10 ⁻⁹	1 x 10 ⁻⁸	5 x 10 ⁻⁸
Potassium	5 x 10 ⁻¹²	1 x 10 ⁻¹⁰	3 x 10 ⁻¹¹
Calcium	5 x 10 ⁻¹²	8 x 10 ⁻¹¹	4 x 10 ⁻¹¹
Silica	2 x 10 ⁻¹¹	2 x 10 ⁻¹⁰	5 x 10 ⁻¹¹
Phosphate	1 x 10 ⁻¹¹	5 x 10 ⁻¹⁰	2 x 10 ⁻¹⁰

Effect of G on R_i

The experimental work shows that the rate at which sucrose is crystallised has a strong positive effect on the rate at which impurities are transferred into the crystal. This relationship takes the form

$$R_i = a \times G^b$$

where a and b are constants.

Specific sets of experiments were carried out for colour and for potassium, the results being given in Table 3. Typical results for colour are plotted in Figure 2.

Effect of the concentration of the impurity on R_i

The effect of the concentration of the impurity (F_i) on the rate of transfer was also investigated, again using relationships of the form

$$R_i = a \times F_i^b$$

where a and b are constants, and some results are given in Table 4. Again the relationships are well established. Generally, concentrations are raised to powers between 0,7 and 0,8 for colour, inorganic ions and phosphate, while the polysaccharides show somewhat higher values.

Multiple regressions

The combined effects of G and of the concentration of the impurity in the feed are best measured by using all the relevant results in multiple regressions.

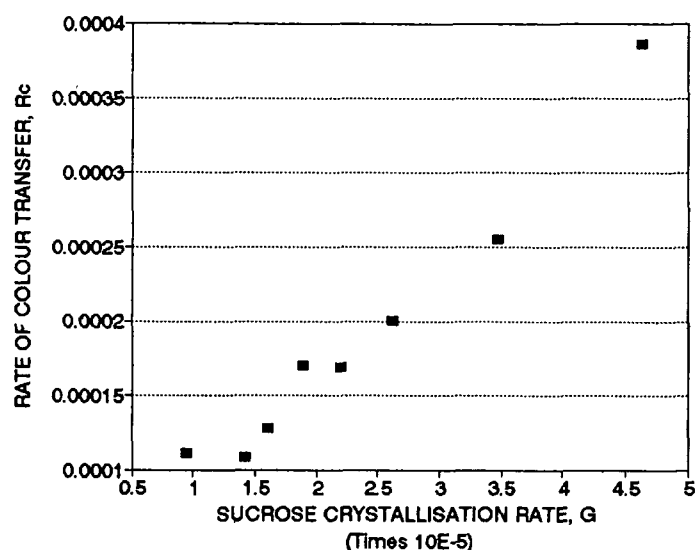


Figure 2. Relationship between rate of colour transfer and sucrose crystallisation rate.

Table 3. The effect of G on the transfer of colour and of potassium.

Specie	Set number	$R_i = aG^b$		n	Correlation coefficient
		Value of a	Value of b		
Colour	1	4 161	1,5	6	0,95
	2	1,6	0,85	9	0,96
	3	15	1,0	9	0,99
	4	123	1,1	9	0,96
	5	171	1,2	6	0,97
Potassium	6	$1,2 \times 10^{-7}$	0,80	9	0,89
	7	$1,6 \times 10^{-6}$	1,0	9	0,96
	8	$7,5 \times 10^{-6}$	1,1	9	0,98
	9	$1,0 \times 10^{-4}$	1,3	6	0,95

This has the advantage that all the relevant data are used thus giving overall findings. The results are shown by Equations 10 to 13.

$$R_{ic} = 0,074 F_c^{0,81} G^{1,1} \quad (n = 83; r = 0,98) \quad (10)$$

$$R_{ik} = 2,10 \times 10^{-8} F_k^{0,62} G^{1,1} \quad (n = 58; r = 0,95) \quad (11)$$

$$R_{ica} = 1,7 \times 10^{-7} F_{ca}^{0,43} G^{1,1} \quad (n = 37; r = 0,80) \quad (12)$$

$$R_{ist} = F_{st}^{1,0} G^{2,5} \quad (n = 29; r = 0,99) \quad (13)$$

where F_i is the concentration of the impurity in the crystallisation feed liquor, in mg impurity per kg water in feed.

Correlation coefficients are not always good indicators of fit for logarithmic regressions. It is often useful to plot the results. This has been done for colour and potassium in Figure 3, where the calculated values of R_i (equations 10 and 11) have been plotted against the measured values. The fits are good. These results show that the rate of impurity transfer depends nearly entirely on the concentration and type of the impurity in the feed liquor and on the sucrose crystallisation rate. The effect of the crystallisation rate is similar for colour

and for the ionic impurities, with G being raised to a power close to unity.

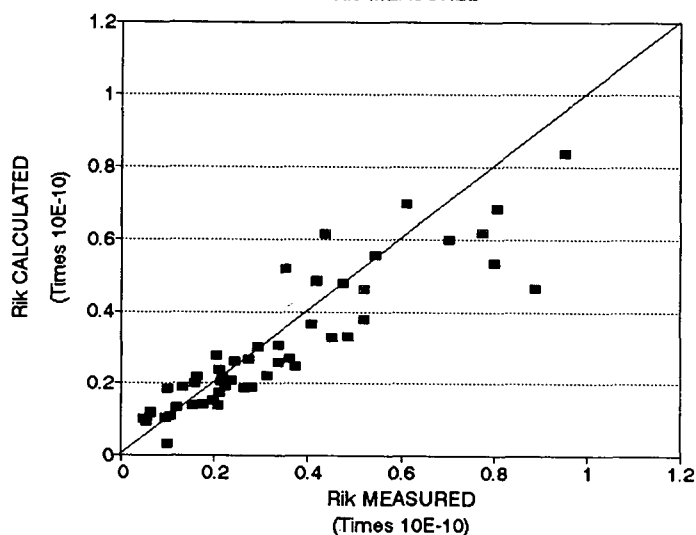
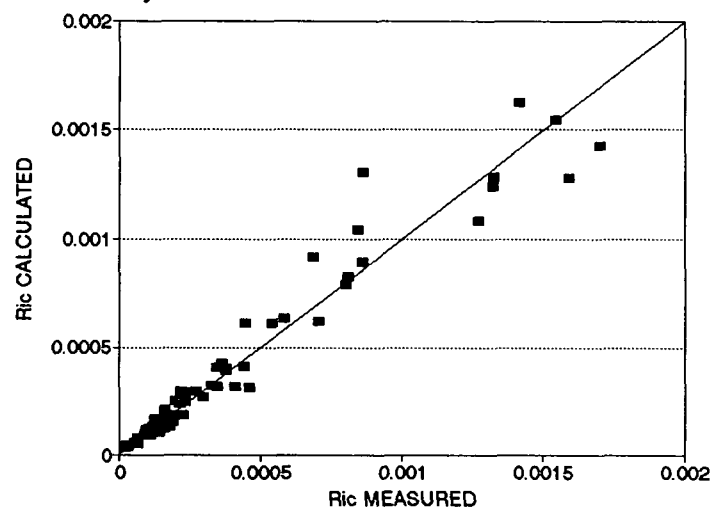


Figure 3. Rates of impurity transfer measured and calculated, (a) colour and (b) potassium.

Effect of the crystal size on R_i

Multiple regressions have also been used to investigate the effects of crystal size, expressed here through the crystal characteristic dimension, D_c , on impurity transfer rates. Equation 14 was obtained, for colour as the impurity

$$R_{ic} = 2,3 \times 10^{-4} F_c^{0,77} D_c^{0,69}$$

for 83 sets of observations and with a correlation coefficient of 0,95, both independents being statistically significant at least at 5%.

This result confirms the trend found (Lionnet, 1987; Mann 1987) in industry, namely that the rate of impurity transfer increases as the crystal becomes larger. As a first approximation the rate of colour transfer increases by about 70% for a doubling of D_c . The effect of D_c on R_{ic} is shown graphically in Figure 4. The trend found with colour probably applies to all the impurities, but could not be detected in all cases because of the relatively small range for D_c .

Table 4. The effect of concentration on the impurity transfer rate.

Species	Set number	$R_i = a F^b$		n	Correlation coefficient
		Value of a	Value of b		
Colour	1	$1,9 \times 10^{-6}$	0,68	8	0,98
	2	$1,0 \times 10^{-6}$	0,74	6	0,99
	3	$0,5 \times 10^{-6}$	0,79	5	0,99
	4	$0,8 \times 10^{-6}$	0,66	7	0,92
Potassium	6	$1,8 \times 10^{-13}$	0,66	5	0,99
	7	$1,1 \times 10^{-13}$	0,68	8	0,89
	8	$0,6 \times 10^{-13}$	0,74	6	0,89
	9	$0,2 \times 10^{-13}$	0,90	5	0,96
Starch	10	$3,9 \times 10^{-13}$	1,10	5	0,94
	11	$8,5 \times 10^{-13}$	1,10	5	0,99
	12	$6,0 \times 10^{-15}$	1,60	5	0,98
Carrageenan	13	$1,4 \times 10^{-16}$	2,20	5	0,93
Carboxymethyl cellulose	14	$1,4 \times 10^{-16}$	0,94	9	0,92
Silica	15	$1,8 \times 10^{-11}$	0,37	4	0,97
Phosphate	16	$3,1 \times 10^{-12}$	0,78	4	0,98

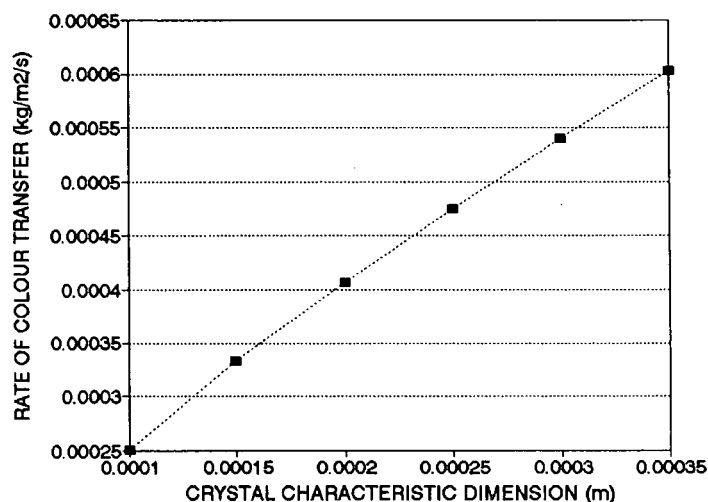


Figure 4. The relationship between R_{ic} and D_c .

Effect of temperature on R_i

The effect of temperature was investigated by setting the absolute pressure in the pan, to obtain crystallisation temperatures between 60 and 80°C. All the other parameters were kept as constant as possible. The Arrhenius model was used:

$$\ln k = \ln A - \frac{E_a}{RT}$$

where k is the rate of the process, A the pre-exponential factor, E_a the activation energy, R the gas constant and T the temperature.

In each case, the logarithm of G or of R_i was related to $1/T$ through linear regressions. A good fit, indicated by a high correlation coefficient and normal residuals, showed that the

process follows the Arrhenius model. The slope of the line is then equal to $-E_a/R$.

The model was found to fit the data for G and for all the inorganic species. In the case of starch, four sets of experiments were performed; with there being much scatter, with E_a ranging from 6 to -34 kJ/mol. Statistically, the activation energy for the transfer of starch was found not to be different from zero. The other polysaccharides were not investigated here. Complete results are given in Table 5.

Table 5. Activation energies for G and for R_i , over a temperature range of 60 to 80°C.

Species	E_A (kJ/mol) ±5% confidence interval
G	18 ± 6
Colour (R_{ic})	19 ± 7
Potassium (R_{ik})	28 ± 11
Calcium (R_{ica})	30 ± 19
Starch (R_{ist})	0

The activation energy of the crystallisation rate of sucrose has been well documented in the literature. Honig (1959) reviewed the early work and, at constant supersaturation, found values of 19-29 kJ/mol over the temperature range 60 to 80°C. VanHook (1981) quoted 30 kJ/mol at 60-80°C. More recently, Maurandi *et al.* (1984) quoted values of 21-38 kJ/mol over a temperature range of 40-70°C. The value obtained here (18 kJ/mol) is not out of line and compares with the lower ranges given in the literature. There are no values in the literature for the activation energies of rates of impurity transfer and the results given in Table 5 can be taken as a first approximation for the activation energies for the transfer of colour, of the ionic species and of starch in the sucrose crystal. The value for colour is similar to that for G , while those for the ionic species are somewhat higher but the precision is lower. Starch shows a different result in that its activation energy is not statistically different from zero indicating that temperature has no clear effect on the rates at which this impurity is incorporated in the sucrose crystal. The rate of incorporation of starch is however much higher than those of the ionic impurities, as shown in Table 2.

The effect of viscosity

Viscosity was investigated by adding the polysaccharides carrageenan or carboxymethyl cellulose (CMC) to the feed liquors, the liquors being then crystallised as usual. The objective here was to change the viscosity only. This is of course difficult, if not impossible, and it will be shown later that the results are more complex than could be expected from the viscosity alone.

The effect of polysaccharides on viscosity

The addition of carrageenan and of carboxymethyl cellulose (CMC) to the feed liquors did increase the viscosity, as measured on the run-off from the masseccite produced. The

effects of the two polysaccharides were however not the same, as shown in Table 6. The viscosity increased slightly with carrageenan but more than doubled with carboxymethyl cellulose.

The effect of viscosity on the rate of crystallisation of sucrose

Only the results with carboxymethyl cellulose will be used here. These are summarised in Table 7, where the sucrose crystallisation rate has been expressed in mass of crystals produced per unit time. Doubling the viscosity, in the range used here, reduced the crystallisation rate by 2 to 5%. The effect is thus not very marked.

Table 6. Increase in viscosity of run-offs with the addition of selected polysaccharides to feed liquors.

Polysaccharide added (% m/m)	Viscosity (Pa.s)	
	Carrageenan	Carboxymethyl cellulose
0,1	0,33	0,47
0,2	0,35	0,97
0,4	0,37	1,96

Table 7. The effect of viscosity on the sucrose crystallisation rate.

Run-off viscosity (Pa.s)	Sucrose crystallisation rate (kg crystal/sec)
0,1	0,00109
0,2	0,00107
0,4	0,00101

The effect of viscosity on the rate of impurity transfer (R_i)

In most cases the impurity transfer rate increased as the viscosity increased, which is unexpected in terms of the relation between R_i and G. Furthermore, the rate of change with viscosity depended on whether the viscosity had been caused by the addition of carrageenan or by that of carboxymethyl cellulose. This is illustrated in Table 8 for colour and potassium. It is evident that the effects depend more on the type of the polysaccharide than on the viscosity itself.

Table 8. Change in transfer rates as viscosity increases.

Run-off viscosity (Pa.s)	R _{ic}		R _{ik}	
	Carrageenan	CMC	Carrageenan	CMC
0,10	100	100	100	100
0,15	161	189	100	367
0,20	222	478	100	635

A further test was done, with the additions of large amounts of carrageenan, to yield the results in Table 9. Thus, for constant levels of calcium, potassium and colour in the feeds, but increasing carrageenan contents, all the impurities increased in the crystal, as the polysaccharide level increased. A similar result was found with phosphate as impurity, during another test run, but the trends were less obvious. Much more work is obviously required here.

Conclusions

The simple rate of impurity transfer proposed in this work has been found to be a useful parameter, capable of quantifying the rate at which different impurities enter the sucrose crystal. Ranges for individual impurities were wide and there were large differences between the various species. This indicates that the parameter is sensitive to crystallisation conditions and to species.

Table 9. The effect of carrageenan on the level of impurity in the crystal. Ca²⁺, K⁺ and colour in feed unchanged.

Impurities in feed (mg/kg)				Impurities in crystal (mg/kg)			
Carrageenan	Ca ²⁺	K ⁺	Colour	Carrageenan	Ca ²⁺	K ⁺	Colour
3 400				805	15	8	55
3 800	1 975	2 195	1 885	1 653	18	14	49
5 600				1 908	55	21	55
7 900				2 995	85	57	70

The calculation of R_i does not require the mass of crystals, but is based on the characteristic dimension of the crystals, from an image analysis system.

Under specified crystallisation conditions, R_i was nearly totally dependent on the rate of sucrose crystallisation, G, and on the concentration of impurity in the feed liquor, F_i. This relationship took the form

$$R_i = \text{constant } G^a F_i^b$$

with the value of 'a' close to unity for colour and ionic impurities, but higher (>2) for starch and some other polysaccharides. The value of 'b' varied from 0,4 to 1, depending on the type of the impurity.

Under industrial conditions G cannot be reduced because of throughput and plant utilisation considerations. Thus, impurity transfer rates can only be reduced by decreasing the concentration of the impurities in the feed liquors.

The work has also confirmed the effect of crystal size on impurity transfer. Again, industrial considerations limit reductions in crystal size, which reinforces the need to reduce the concentrations of impurities in the liquors.

The effect of temperature on R_i has been investigated. Activation energies for the various species ranged from 19-30 kJ/mol, which indicates that, for a 10°C drop in temperature, R_i would decrease by about 20-40%. Starch (soluble) was an important exception, showing an activation energy not statistically different from zero. More work is required, firstly to confirm this finding and secondly to investigate other organic impurities such as gums.

Finally, the effect of viscosity has been found to be complex. As expected, higher viscosities reduced the rate at which sucrose can be crystallised. The use of commercially available polysaccharides to increase viscosity has shown that the presence of this type of material can result in higher impurity transfer rates. This does not seem to be due to viscosity effects alone. The polysaccharides themselves showed high

transfer rates and could react with the impurities thus causing their incorporation into the crystal. Practical observation has been that the presence of carrageenan and of carboxymethyl cellulose results in the formation of many conglomerates. Whether this is the case with other 'gums' has not been established. More work remains to be done here.

Acknowledgements

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Nomenclature

A	crystal surface area	m ²
a,b	constants	
D _c	crystal characteristic dimension	m
F	crystal shape factor	m ² /kg ^{2/3}
F _i	concentration of impurity in feed liquors	mass/mass
G	crystallisation rate of sucrose	kg/m ² /s
L	crystal dimension along b-axis	m
M	mass of one crystal	kg
M _c	mass of all crystals	kg
N	total number of crystals	
R _i	rate of impurity transfer	kg/m ² /s
t,τ	time of crystallisation	s
V	crystallisation velocity	m/s
W	crystal dimension along c-axis	m
X _i	concentration of impurity in crystal	mass/mass

Greek

α	volume shape factor
β	surface area shape factor
ρ	density of sucrose kg/m ³

Subscript

k	potassium
ca	calcium
st	starch.

APPENDIX 1

For a single crystal:

$$G = \left(\frac{dm}{dt}\right) \cdot \left(\frac{1}{A}\right) \text{ and } F = \frac{A}{m^{\frac{2}{3}}}$$

Thus $\frac{dm}{dt} = G \cdot A$ and $A = F \cdot m^{\frac{2}{3}} \therefore \frac{dm}{dt} = G \cdot F \cdot m^{\frac{2}{3}}$

Separating variable $m^{-\frac{2}{3}} dm = G \cdot F dt$

Assume a boiling cycle from t=0 to t=τ and a crystal that grows from m=0 to m=mc

Integrating $\int_0^{mc} m^{-\frac{2}{3}} dm = \int_0^{\tau} G \cdot F dt$ and assuming

G and F are constant over the boiling cycle

$$\left(\frac{1}{1-\frac{2}{3}} \cdot m^{(1-\frac{2}{3})}\right)_0^{mc} = (G \cdot F \cdot t)_0^{\tau}$$

$$3 mc^{\frac{1}{3}} = G \cdot F \cdot \tau$$

But the surface area of the crystal ac is given by $ac = F \cdot mc^{\frac{2}{3}} \therefore F = \frac{ac}{mc^{\frac{2}{3}}}$

Substituting: $3mc^{\frac{1}{3}} = G \cdot \frac{ac}{mc^{\frac{2}{3}}} \cdot \tau$ then $3mc = G \cdot ac \cdot \tau$

Multiply both sides by n the number of crystals: $3mc \cdot n = G \cdot ac \cdot n \cdot \tau$

Now the $mc \cdot n = M_c$ the total mass of crystals at the cycle end and

$ac \cdot n = A_c$ the total surface area

of the crystals at the cycle end.

$$\therefore 3 \cdot M_c = G \cdot A_c \cdot \tau$$

But $A_c = \frac{M_c \beta}{\alpha \cdot \rho \cdot D_c}$

$$\therefore 3 \cdot M_c = G \cdot \frac{M_c \beta}{\alpha \cdot \rho \cdot D_c} \cdot \tau$$

$$\therefore G = 3 \cdot \frac{\alpha \rho}{\beta} \cdot \frac{D_c}{\tau}$$