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Isothermal and non-isothermal crystallization in amorphous sucrose and lactose at low moisture contents

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Abstract

Differential scanning calorimetry has been used in isothermal and non-isothermal modes to provide information on the crystallization of sucrose and lactose at low water contents. Using approaches previously applied to polymer crystallization an attempt has been made to combine the isothermal and non-isothermal data into a single curve. This is achieved by the use of appropriate shift factors in the time and temperature domains. This was successful for sucrose but not for lactose. It was suggested that this was because lactose crystallizes into multiple forms whereas sucrose crystallizes in a single form. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Sucrose; Lactose; Crystallization; DSC; Master curve

1. Introduction

Sugar crystallization at low moisture contents is of considerable practical importance in both the food and pharmaceutical industries. The major variables which can affect crystallization rates under these conditions are moisture content [1], temperature [2] and the presence of other materials [3]. This contribution concentrates on the effect of temperature on crystallization. Data from non-isothermal (conventional) differential scanning calorimetry (DSC) and isothermal differential scanning calorimetry are combined. Results are compared for sucrose, which if we disregard the hydrates formed at high moisture contents [4], exists in only one form and lactose which shows a complicated phase behavior, crystallizing in multiple forms [5].

If the rate of crystallization in an amorphous polymer or sugar glass is comparable with the rate of scanning in a calorimeter then crystallization will be observed when the glass is heated beyond the glass transition temperature T_g. The position of the crystallization peak changes significantly as the scanning rate changes. This is in contrast with T_g, which changes only slightly and the melting temperature T_m, which does not change over the range of rates normally used in these experiments.

The crystallization, which occurs in these materials as the temperature is raised, is known as cold crystallization and is conventionally analyzed using isothermal DSC methods. A sample is heated, as rapidly as the particular machine in use will permit, to a temperature in the region of the crystallization exotherm. The subsequent evolution of heat with time can then be followed at a constant

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temperature. Cold crystallization peaks are of great interest to the food industry as evidenced by the work carried out by Roos and Karel [6,7]. However, in the past they have not been used extensively in quantitative work. In this paper, we have attempted to apply the approach of Chan et al. [8,9] to sucrose and lactose. This approach allows isothermal data obtained at different temperatures and non-isothermal data obtained at different heating rates to be combined on a single master curve.

Isothermal crystallization of biopolymers, sugars and conventional polymers appears to be well described by the Avrami equation [10]:

$$\theta(t) = 1 - \exp(-kt^n) \tag{1}$$

where $\theta(t)$ is the extent of crystallization at time t normalized to a value of unity for the maximum crystallinity obtained, and k and n are constants Analysis normally proceeds by using a transformed version of this equation:

$$\mathrm{Log}[-\ln(1-\theta)] = n\ \ln(t) + \ln(k) \tag{2}$$

and plotting $\log[-\ln(1-\theta)]$ against $\ln(t)$. The slope gives the value of n, a clue to the mechanism of crystallization, while the intercept gives the value of k, the rate at which the reaction proceeds.

The Avrami equation is only directly applicable to isothermal data there are, however, good reasons for wanting to analyze the non-isothermal data. Firstly, most industrial processes involve the cooling and heating of products and seldom approximate to the isothermal condition. Secondly, the non-isothermal procedure would appear to be more rapid, in that all temperatures are accessible in one run, and experimentally less demanding, in that step jumps in temperature followed by a very short period of temperature equilibration are not required. Thirdly, a greater temperature range is reliably accessed using non-isothermal methods compared with isothermal methods.

Following the discussions of Chan et al. [8,9] the equivalence of isothermal and non-isothermal or dynamic measurements is the subject of considerable controversy and confusion. Almost all models of crystallization can be expressed in the following form:

$$(\partial\theta/\partial t)_T = k(T)f(\theta) \tag{3}$$

For example the Avrami equation can be expressed in the differential form as follows:

$$(\partial\theta/\partial t)_T = k^{1/n}(T)n(1-\theta)[-\ln(1-\theta)]^{n-1} \tag{4}$$

If θ is a function of both time and temperature then

$$\mathrm{d}\theta = (\partial\theta/\partial t)_T \mathrm{d}t + (\partial\theta/\partial T)_t\ \mathrm{d}T \tag{5}$$

and the dynamic rate is

$$\mathrm{d}\theta/\mathrm{d}t = (\partial\theta/\partial t)_T + (\partial\theta/\partial T)_t(\mathrm{d}T/\mathrm{d}t) \tag{6}$$

The isothermal rate then differs from the non-isothermal rate by the second term in Eq. (6). However, it has been reported [8] that θ is not a state function of t and T and the total differential in Eq. (5) cannot be taken. In fact it appears that the non-isothermal is equivalent to the isothermal rate and the results of non-isothermal experiments can be viewed in terms of many infinitesimal isothermal steps. In addition, the manipulation of Eq. (3) suggests that with the introduction of a reduced time (ε), both isothermal and non-isothermal data can be placed on the same master curve according to the following conditions:

$$\varepsilon = a(T)t \qquad \text{isothermal} \tag{7}$$

$$\varepsilon = \int_0^t a(T)\,\mathrm{d}t \qquad \text{non-isothermal} \tag{8}$$

where the shift factor $a(T) = k(T)/k_r$ is the ratio of the rate at temperature T to the rate at a reference temperature.

2. Materials and methods

Freeze-dried sucrose and lactose were prepared by crash cooling 10% sugar solutions contained in aluminium foil trays in liquid nitrogen. The amount of liquid in the tray was just sufficient to cover the bottom giving a depth of several millimeters. The freeze drying was carried out at a pressure of less than 0.03 mbar with a condenser temperature of -51 °C and was normally complete in less than 2 days. The freeze drying procedure was not carried out in separate steps in the manner of Saleki-Gerhardt and Zografi [11], as this

type of refrigerated shelf control was not available. After freeze drying, the material was stored in vacuum over phosphorous pentoxide. Residual moisture was in the region of about 1% for sucrose and 5% for lactose, giving a T_g for both in the region of 330 K. Perkin–Elmer DSC2 and DSC7 calorimeters with intracooler accessories were used for all calorimetric measurements. Temperature and enthalpy calibrations were carried out using indium and cyclohexane standards.

Isothermal runs were carried out using Perkin–Elmer software with an initial rise in temperature of approximately 320 K/min. Non-isothermal runs were carried out in a conventional manner at five rates of temperature increase namely 40, 20, 10, 5 and 2.5 K/min. For both types of experiments, between 4 and 8 mg of sample were sealed hermetically in aluminium pans.

3. Results and discussion

Non-isothermal data for sucrose obtained at four heating rates can be seen in Fig. 1.

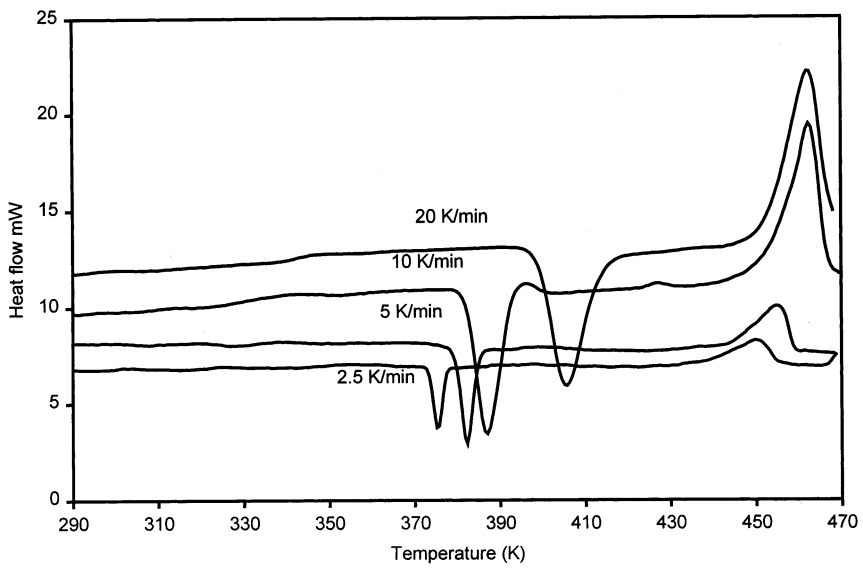

Fig. 1. Thermograms for sucrose obtained in the scanning mode. Heating rates are indicated.

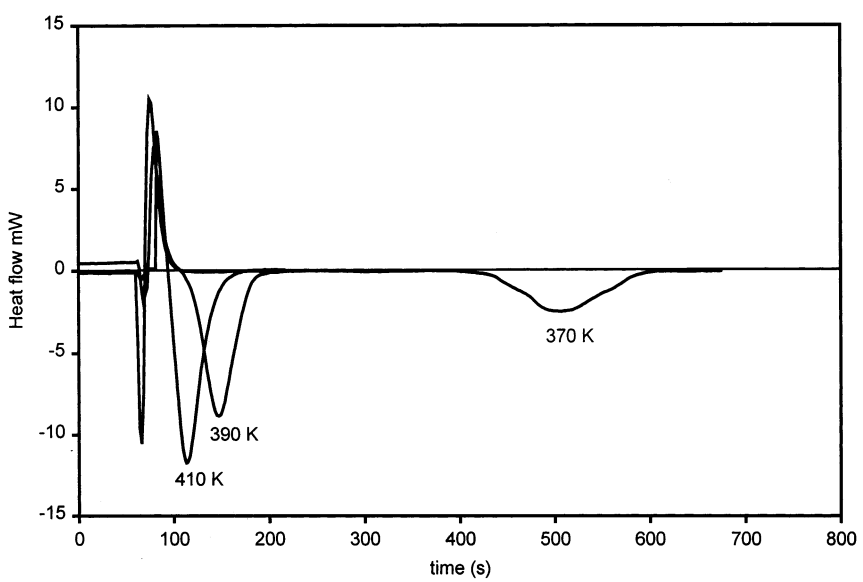

Fig. 2. Power/time plots for sucrose. A reference temperature of 390 K was chosen.

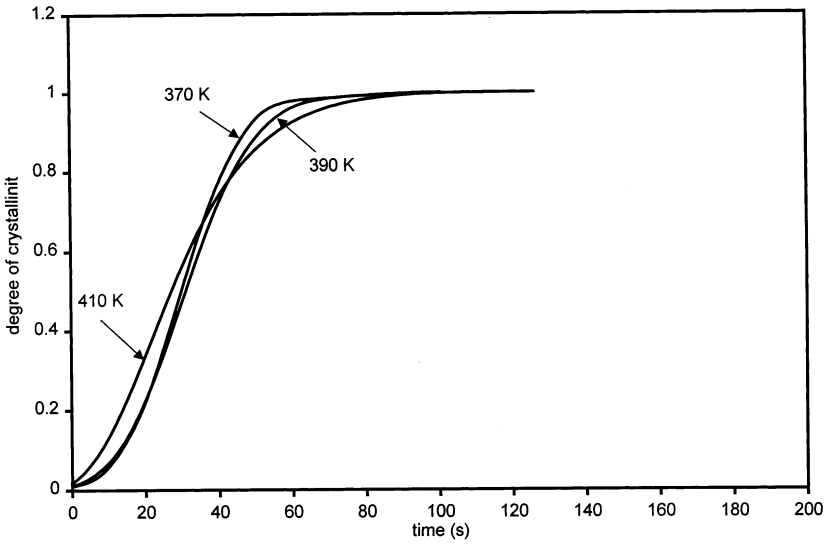

Fig. 3. The application of shift factors to isothermal sucrose data. This places all data on the reference curve at 390 K.

Similarly some of the data used for the isothermal plots can be seen on Fig. 2. To analyze the latter it is necessary to first reset the time axis to

$$t' = t - t_i \quad (9)$$

where t_i is the induction time functionally defined as the time at which the crystallization reaches 1%, or the minimum detectable level. This can vary depending on the sensitivity of the technique but unless taken into account, absurd values for n, the Avrami index, are generated. Whether an induction time as such exists at all, is the subject of some controversy [12]. It can be defined as the most probable time from the beginning of isothermal crystallization to the point at which a stable crystal nucleus starts to grow.

The shift factor obtained for the isothermal data, is simply that factor which when multiplied by the time, places the original $\theta(t)$ curve, after subtraction of the induction time on some arbitrarily chosen reference $\theta(t)$ curve. Fig. 3 displays the consequence of this shift where the reference temperature is 390 K. There was a poor fit for temperatures much greater than about 420 K. This was probably due to the inability of the DSC to achieve the desired temperature in a sufficiently rapid time or to the mechanism of crystallization, the $f(\theta)$, changing at the higher temperatures. If the latter is the case then the non-isothermal approach provides no improvement over isothermal measurements.

For the non-isothermal data, consideration of Eq. (3) at two different heating rates and a constant degree of crystallinity j, leads to the following equation for the shift factor [9]:

$$(\mathrm{d}\theta/\mathrm{d}t)_T/(\mathrm{d}\theta/\mathrm{d}t)_r = [k(T)/k_r][f(\theta)_j/f(\theta)_j] = a(T) \quad (10)$$

The curves in Fig. 4 make this clearer. Shift factors are calculated according to Eq. (10) and Fig. 4.

The DSC data were firstly corrected for lag temperature based on the melting shape of an indium peak. It was assumed that the samples behave in the same way, i.e., had the same thermal contact as the indium. The data were also normalized to the final crystallinity. Curves similar to Fig. 4 were generated. The $\mathrm{d}\theta/\mathrm{d}T$ curves were transformed to $\mathrm{d}\theta/\mathrm{d}t$ by multiplying by the heating rate $\mathrm{d}T/\mathrm{d}t$. The shift factors were then calculated.

Fig. 5 combines the shifted isothermal and non-isothermal data, with the exception of the 2.5 K/min points on a single crystallinity time plot at a reference temperature of 390 K. This type of procedure has been used extensively to treat rheological data [13] but is less commonly met in work using DSC. For sucrose, in agreement with work on polymers such as PET, the isothermal and non-isothermal data, with the exception of the lowest rate, fall on the same curve. Isothermal measurements appear therefore to have wider applicability than

the simple isothermal condition and can describe more realistic situations where the temperature varies. In addition, the advantages of non-isothermal treatment of data are that a wide range is reliably accessed and that the demands on instrumentation are not so severe. For example in the normal scanning mode there is no requirement, as there is in isothermal DSC, that the machine should jump instantaneously to a single temperature with the minimum of transients and thereafter record small heat flows.

Fig. 6 shows the shift factors for both isothermal and non-isothermal data plotted against temperature. Since the shift factor can be regarded as a measure of crystallization

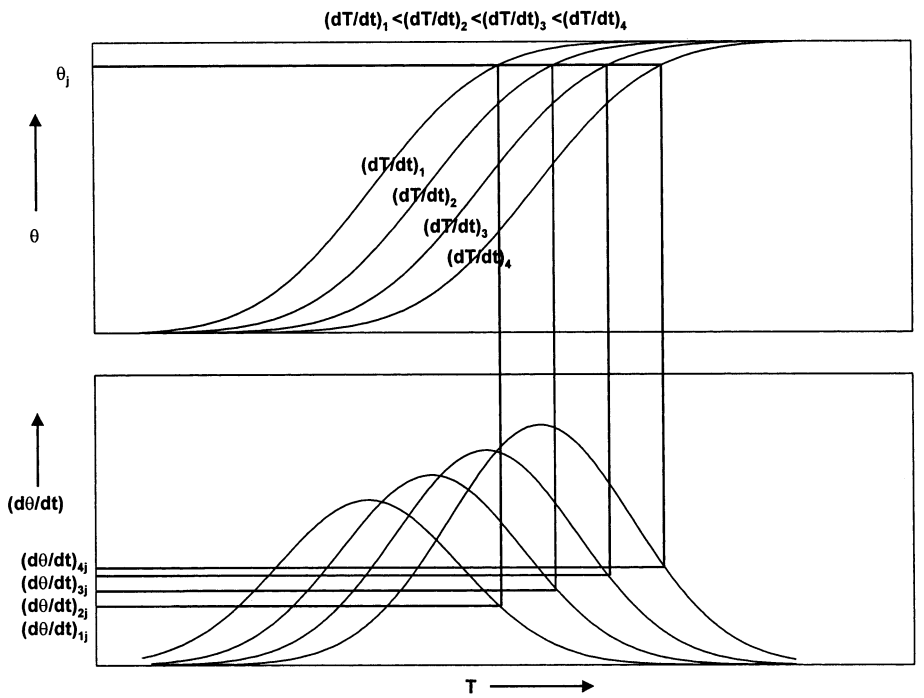

Fig. 4. The method for obtaining the shift factors from non-isothermal data (adapted from Ref. [8]). These traces are for cold crystallization or crystallization upon heating.

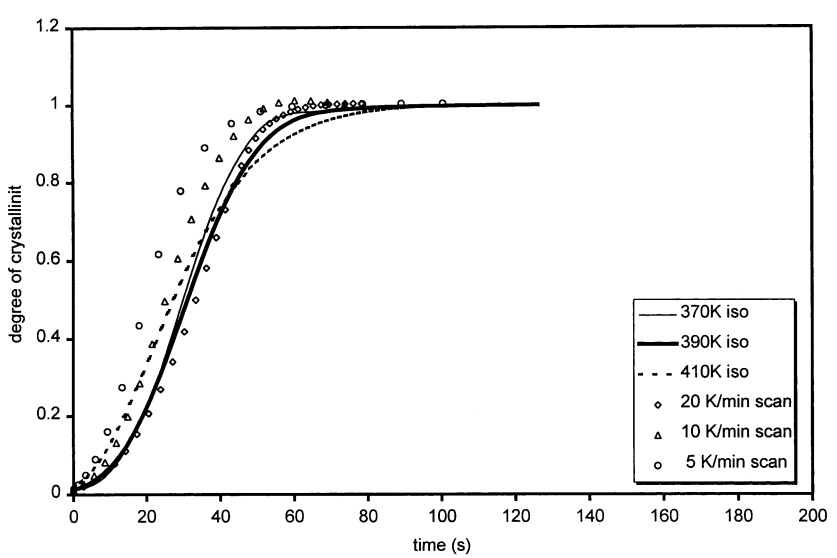

Fig. 5. Master curve plot for sucrose crystallinity against reduced time which contains both isothermal and non-isothermal data (reference temperature 390 K).

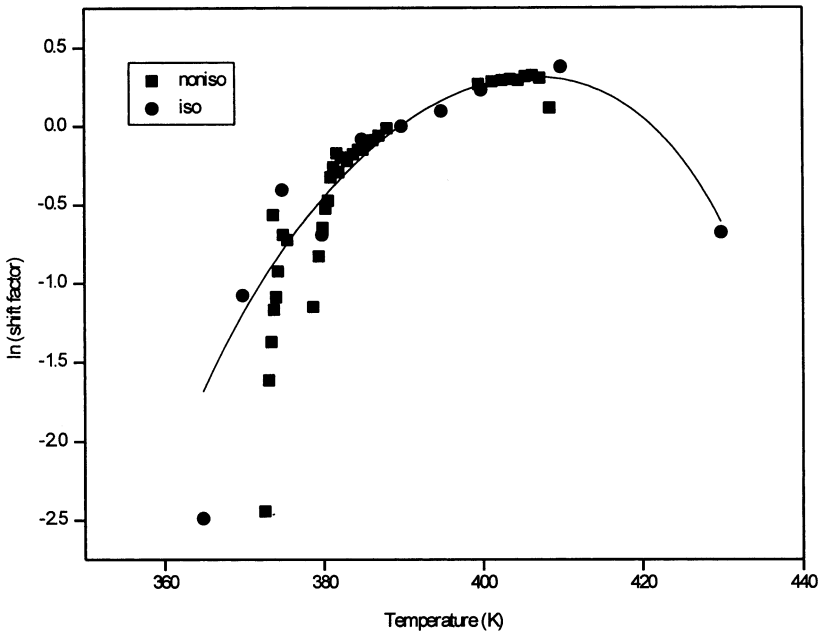

Fig. 6. Shift factors plotted against temperature for sucrose. The solid line is the fit of Eq. (11) to the data using parameters $A_0 =$ 2.65E4/s, $U = 2000$ J/mol, $T_g = 330$ K, $K_g = 2.3$E5 K^2, and $T_m = 500$ K.

rate the curve shows the interplay between factors promoting the growth of crystals which decreases towards the glass transition of the material, i.e., at low temperature, and the nucleation of crystals which decreases towards the crystalline melting point, i.e., at high temperature. Its shape can be predicted by a Lauritzen and Hoffman like equation:

$$\text{Rate of crystallization} = A_0 \exp\{-[U/R(T-T_g)]\}\exp\{-K_g/T\Delta Tf\} \quad (11)$$

where $\Delta T = T_m - T$, $f = 2T/(T + T_m)$ and A_0 is a pre-exponential factor, U is an activation energy of transport, K_g is a nucleation exponent, T_g is here a transition temperature normally 30 K below the true T_g and T_m is the melting temperature. In principle any type of crystallization model [14] having the properties of decreasing mobility at lower, and decreasing nucleation at higher temperatures will produce this type of plot. Lauritzen and Hoffman [15] theory, derived as it is from the polymer area, contains many other predictions, such as the thickness of lamellae, however most of these are not considered and are probably not applicable to the present work on small carbohydrate molecules.

Crystallization of lactose.—The same analysis was applied to isothermal and non-isothermal lactose data. The shift factor temperature plot is shown in Fig. 7. The most obvious feature of the curves obtained for lactose lies in the poor agreement of the non-isothermal with the isothermal data when compared with the sucrose results (Fig. 6). The cause of this becomes obvious on observing the raw data for lactose (Fig. 8). Almost certainly, transitions to and between different forms of lactose are occurring as evidenced by the irregular shapes of the crystallization peaks. This is particularly dramatic at the lowest rate of 2.5 K/min, but is also probably present, albeit in a more gradual form, at higher rates where the existence of asymmetric peaks implies complex behavior.

We believe that during a scan one form of lactose crystallizes out, depending on moisture content and temperature range and is then transformed to a more stable form for the new temperature and moisture content. It should be borne in mind that lactose can crystallize in the α monohydrate as well as multiple anhydrous forms [16], so the possibility exists of substantial changes in moisture content, particularly at these low levels which can further affect the crystallization kinetics. The whole

picture is given additional complication by the fact that the induction times for the initiation of the crystallization of each form may be different.

The small peaks observed above the main crystallization peak at the lower rates probably indicate the loss of water of crystallization, i.e., the presence of at least some α-lactose monohydrate.

General discussion.—The Lauritzen–Hoffman type plot for sucrose shows reasonable agreement between isothermal and non-isothermal data suggesting that they are both measuring the same underlying events. Only the 2.5 K/min data shows substantial disagreement with the isothermal values. This is also the case for the master curve plot (Fig. 5) where the integrals generate some anoma-

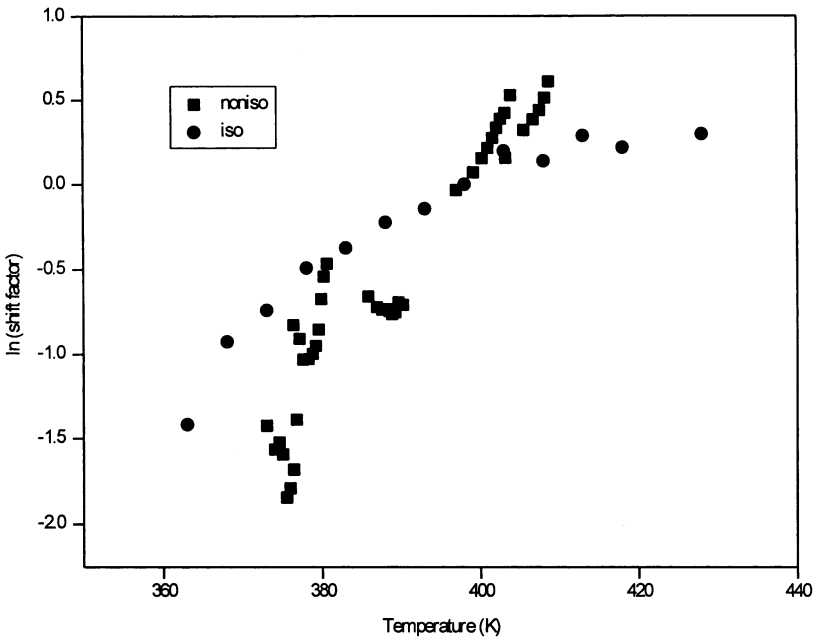

Fig. 7. Shift factors plotted against temperature for lactose.

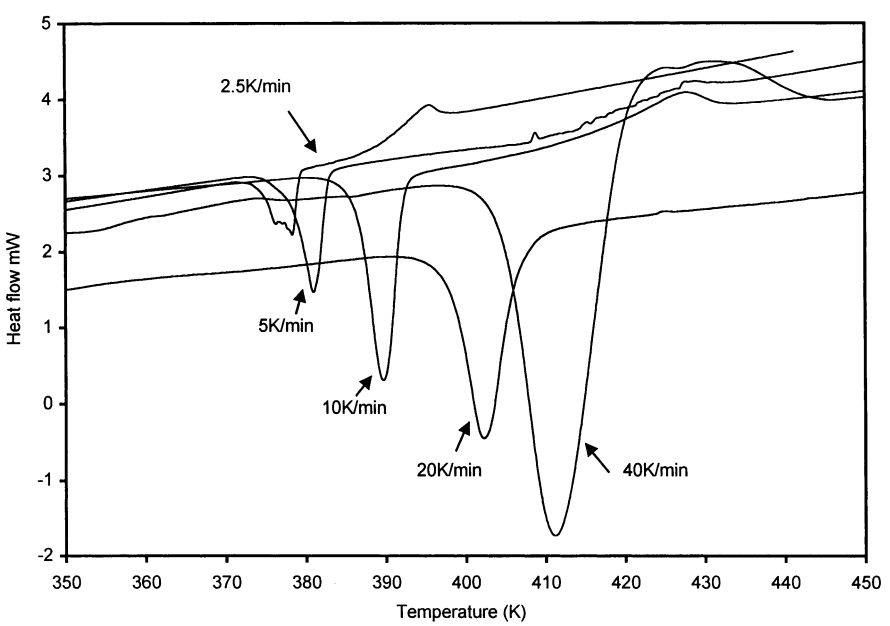

Fig. 8. Thermograms for lactose at different heating rates. The difference in overall areas reflects the difference in scanning rate. Note the existence of multiple and asymmetrical peaks.

lous negative time values (not shown) at 2.5 K/min. The reason for the latter is probably that these experiments were carried out on the DSC2, with an insufficient number of points at the lower rates, spanning the relatively sharp peaks. This leads to substantial interpolation in the calculation of $d\theta/dt$ for different values of θ.

For lactose the approach does not result in such a good description of the results. In an effort to disentangle what is occurring in these experiments, it is necessary to use a method, which enables the identification of the different species and any transitions between forms. Clearly cross polarization-magic angle spinning nuclear magnetic resonance spectroscopy (CP-MAS NMR) experiments are the way forward. A high temperature CPMAS probe capable of reaching up to ~ 420 K and giving snapshot results with a time resolution of less than a few minutes would be required.

Perhaps the most important point to be made is why there is a difference between lactose isothermal and non-isothermal data, after all, if different forms appear at different temperatures, then this should be present in both isothermal and non-isothermal plots. Isothermal data is obtained either by Avrami fits to crystallization data or by a shift factor, which forces the data at one temperature to lie as closely as possible on the reference temperature. In both cases there is an averaging of the data. This is not the case for the non-isothermal treatment where, as can be seen in Fig. 4, the slope at a single point is taken so discrepancies between the two methods of treating the data are exposed. We feel, however, that this is probably only part of the explanation and there is a real possibility that different forms are produced in the two types of experiment due to the different conditions. There is also the possibility of small differences in water content [17] leading to large variability in the results.

We believe these data offer an interesting and novel view of the crystallization of sugars relevant to the food and pharmaceutical industry.

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