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HEAT EXCHANGE IN BOILING OF THERMOLABILE SUSPENSIONS

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Results are presented from an experimental study of boiling of a sugar crystal suspension in an intercrystalline solution under conditions of free motion and reduced pressure.

The intensity of heat transfer to boiling suspensions consisting of sugar crystals in an intercrystalline solution (massecuite) is described by more complex laws than the boiling of single-component systems. The amount of heat transfer to the massecuite is significantly lower than to the sugar solution or solute (water), and other conditions being equal, is dependent on the content of dry materials, thermal flux intensity, pressure, and thermophysical and boiling regime factors. The low value of α_2 is related to the fact that massecuites are thermolabile suspensions, and the heat-exchange process in vacuum crystallizers occurs at reduced pressures and low q values.

At the present time a significant number of studies have been published on heat transfer and the vapor formation mechanism for unary and binary liquids and solutions of organic and inorganic origin, but such data do not provide a complete physical picture of the boiling of suspensions, and do not allow calculation of α_2 in the design of vacuum crystallizers. For this purpose, the experimental equipment described in [1, 2] was used to obtain data under quasistationary conditions on the boiling of stable and metastable massecuites with concentrations $DM_m = 73.6-92.4\%$, $CR = 10-50\%$, $p = 5.2-68.4$ kPa, $q = 2-100$ kW/m². The pressure in each experiment was maintained constant, as were the parameters of the massecuite, while the thermal flux was varied, causing changes in α_2 . The dependence of α_2 on q obtained in this manner was not single-valued, indicating the existence of different heat exchange regimes — convective, and undeveloped and developed bubble boiling. Since in convective heat exchange and undeveloped bubble boiling α_2 is very unstable, the limits for commencement of developed bubble boiling were determined, these values indicating that with increase in the number of crystals in the massecuite the time for commencement of developed boiling is retarded, although the material in a layer adjacent to the wall is superheated by tens of degrees. This can be explained by an increase in effective viscosity, which leads to a decrease in the mobility of the massecuite mass. With increase in solid phase content the turbulization of the wall layer decreases, so that small vapor bubbles cannot overcome the increased hydrostatic pressure and their sphere of influence decreases in size.

The curves shown in Fig. 1 permit determination of the limits of thermal flux regulation during the massecuite cooking period for optimum use of energy resources at a given pressure over the material. The figure shows that the more stable heat and mass transfer region lies in the area above a line indicating a specific sugar crystal content in the massecuite.

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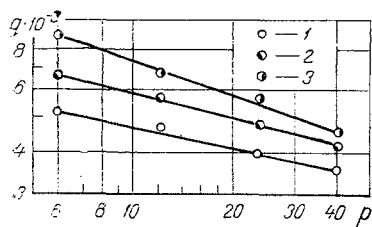


Fig. 1

Fig. 1. Limits of transition to developed bubble boiling of metastable massecuites $S = 1.1$ with sugar crystal content: 1) 10%; 2) 30%; 3) 50%. q , W/m^2 ; p , kPa .

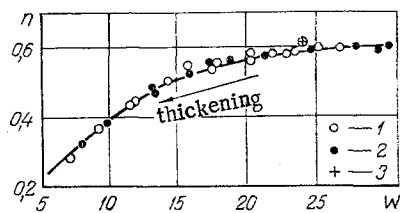


Fig. 2

Fig. 2. Degree to which thermal flux intensity affects heat liberation in boiling: 1) metastable; 2) stable massecuites; 3) sugar solutions with $DM = 80\%$. W , %.

Knowledge of the dependence of developed bubble boiling commencement permits selection of a vacuum crystallizer operating regime with constant heat-liberation coefficient.

This factor is of great significance, since the amount of water evaporated in the massecuite cooking process is decreased, and the effective viscosity and density coefficients increase, leading to a significant drop in α_2 . The value of α_2 is determined from the expression

$$\alpha_2 = \frac{q}{T_w + \Delta_{pc} + \Delta_{hd} - T_s}, \quad (1)$$

from which it is evident that when the massecuite concentration process is carried out in a vacuum crystallizer, α_2 must decrease, so that with constant increase in the dry material concentration DM , the physicochemical depression increases while the massecuite simultaneously thickens, increasing in density, which in turn leads to an increase in the hydrodynamic depression [3]. Thus, in order to ensure an increase in the wall temperature from T_w to $T_w + \Sigma\Delta$, the thermal flux must be greater than for unary liquids, i.e., in this case an increase in DM and the layer of cooked massecuite decreases α_2 .

Analysis of Eq. (1) permits us to seek paths for intensifying the heat and mass exchange processes. Thus, the effect of the term Δ_{hd} can be avoided if the process is performed in a thin layer of gravitationally adhering massecuite [4]. We must now consider the nature of physicochemical depression development. In boiling of massecuites, a boundary layer with increased DM content is formed about a vapor bubble, from which practically only solvent enters into the vapor phase, so there is then formed around the bubble a layer of solution with sugar crystals, depleted in solvent. Within the confines of this layer the dry material concentration DM varies from its maximum value DM_{max} at the phase boundary to the concentration value found in the main massecuite mass, DM_m . The chemical potential gradients which develop in the inhomogeneous concentration field [5] stimulate flows of solution components in the direction of the normal to the phase boundary surface. Since $DM_{max} > DM_m$, solvent particles move toward the phase boundary, while particles of the dissolved substance move into the volume of the solution. This mass transfer motion is intensified by the presence of a solid phase with higher density than the solution, which sinks downward, under the influence of gravity, toward the bottom of the apparatus, where the major portion of the heat-mass transfer process occurs. The presence of the solid phase hinders access of fresh (solvent-rich) portions of the solution to the massecuite-vapor phase boundary surface. Because of this, the saturation temperature increases in the layer by an amount approximately equal to the physicochemical depression.

An effect can be exerted on the interphase concentration surface in various ways: vapor draft into each individual boiling tube of the vacuum apparatus, mechanical intensification of the circulation, ultrasound or mechanical oscillations, or addition of surface-active substances (SAS) to the boiling massecuite. The hydrodynamic method of increasing circulation permits use of the kinetic energy of the injected vapor to destroy the interphase concentration layer, thus improving access of fresh (solvent-rich) portions of the solution to the growing bubble, which improves heat-mass transfer and increases α_2 [6]. The same result can be achieved by addition of surface-active materials. Studies have been performed [7, 8]

which show that crystallization of sugar solutions with surface-active material added causes increased transfer of material from the solution to the crystal surface, and decreases the massecuite cooking time for one crystallization by 18-20 min.

For massecuites with different DM and CR concentrations, a developed bubble boiling regime can be found in which the intensity of heat-mass exchange reaches its maximum value. For such a regime the relationship between heat liberation and thermal flux is given by the expression

$$\alpha_2 = Aq^n. \quad (2)$$

The proportionality coefficient and value of the exponent to which q is raised depend on the pressure over the massecuite and the thermophysical parameters of the massecuite itself.

In connection with the degradation of heat exchange with increase in content DM_m , it is useful to create an experimental curve of the dependence of the exponent n to which q is raised on the solvent content in the massecuite (Fig. 2). This curve shows clearly that in boiling down of a crystallizing suspension of organic origin it is necessary to select optimum process parameters to achieve correspondence between solvent evaporation intensity and phase conversion during crystallization.

Visual observations indicate that at pressures less than 30 kPa the qualitative changes in the boiling process noted in [9] are evident. Increase in critical vapor nucleus size due to decrease in vapor density, high adhesion capability of the intercrystalline solution, and high effective viscosity of the massecuite significantly hinder vapor-phase generation, and cause significant pauses in vapor formation and superheating of the heat-liberating surface. Bubble generation occurs only after an overall superheating of the massecuite mass [10]. All of the above factors lead to more significant irregularity in the heat-exchange process than that produced by decrease in α_2 . Vapor bubbles are formed at various points of the surface, with no clearly defined vapor formation centers. It is difficult to determine the breakaway dimensions of the bubbles at low q values, where isolated bubbles develop. At high q values the bubbles often lose their spherical form and at the moment of breakoff take on the form of an ellipsoid, elongated along the horizontal, while other bubbles break up into smaller ones, or combine with neighboring bubbles, creating shapeless vapor conglomerates. Such behavior can be found in massecuites with a crystalline content $CR = 10\%$ or more.

The heat-mass exchange process can be intensified under such conditions by all the techniques referred to above, as well as by performing the process on porous plates which permit partial penetration of the vapor into the porous body. This permits an increase in the number of active vapor-formation centers and avoids problems of sugar incrustation during crystallization.

NOTATION

A , numerical coefficient; CR , mass content of crystalline phase; S , supersaturation of intercrystalline solution; DM_m , mass concentration of dry material in suspension (massecuite); T_s , saturation temperature of suspension, determined by pressure above its surface, °K; T_w , temperature of heat-liberating wall, °K; q , thermal flux density, W/m^2 ; n , exponent; p , pressure, kPa; W , mass content of solvent in suspension; α_2 , heat-liberation coefficient, $W/(m \cdot ^\circ K)$; Δ_{hd} , hydrodynamic depression, °K; Δ_{pc} , physicochemical depression, °K.

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EQUATION OF STATE TAKING THE FEATURES OF THE INTERNAL ENERGY
INTO ACCOUNT AND BASED ON THE SATURATION LINE

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A method of constructing the equation of state, based on the use of thermodynamic relations between the internal energy of the material and its thermal parameters, is presented.

At present, the construction of a single (for liquid and gas) equation of state is subjected to the condition of describing not only the thermal parameters of the material, but also the caloric data with an accuracy close to that of experiment. However, in most works [1, 2] the question of the qualitative and quantitative account of the thermal and caloric properties in the near-critical regions has been left out of consideration. In [3], on the basis of an analysis of the possibility of using a virial equation of state to describe the thermodynamic properties of argon, it was shown that the structure of the virial equation does not allow the thermal data and the isochoric specific heat in the critical region to be generalized with sufficient accuracy. The boundaries of the region in which the virial equation of state cannot be used were established: $T = T_C \pm 0.1 T_C$, $\rho = \rho_C \pm 0.4 \rho_C$.

If the equation of state is to permit calculations of the thermal and caloric properties over a broad range of parameters of state, including the near-critical region, it is evidently necessary to assign the equation a form that takes account of the features of the material's behavior in the vicinity of the critical point. An attempt to solve this problem was made in [4]. But the equation of state constructed in [4] does not agree at all accurately with the conclusions of scale theory [5], requiring, in particular, divergence of c_v on approaching the critical point along the critical isotherm according to the law $(1-T/T_C)^{-\alpha}$, whereas the value of the critical index is, as shown by subsequent calculations [6], $\alpha \approx 0.108 \pm 0.010$.

In the present work a method of constructing the equation of state of liquid and gas is proposed, taking account of the features of the behavior of c_v in a broad range of parameters of state, including the near-critical region.

The well-known thermodynamic relation, in differential form, between the thermal parameters of the material and its internal energy u is used:

$$\left(\frac{\partial u}{\partial v}\right)_T = -\rho^2 \left(\frac{\partial u}{\partial \rho}\right)_T = -\frac{\partial \left(\frac{p}{T}\right)_v}{\partial \left(\frac{1}{T}\right)} \quad (1)$$

Choosing some reference curve $T_{re}(\rho)$ at the thermal surface, Eq. (1) is integrated:

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