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Short communication

Heat transfer at solid melting in solutions

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Abstract

The paper presents a method for the experimental determination of the individual heat transfer coefficient during the melting of a solid body in a solution. Using this method the melting rate and the individual heat transfer coefficient were determined for a spherical ice particle (with the temperature 258 K) melting in a water–urea solution (with the mass concentration of 20, 30, and 40%, respectively, and with the temperature 293, 311 and 314 K). The experiments were conducted for several solution flow rates (0–0.1375 $m^3 s^{-1}$). Using the results obtained experimentally, the influence of temperature, concentration and solution velocity on the melting rate and on the individual heat transfer coefficient was studied. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Melting mass transfer; Melting heat transfer; Ice melting; Heat transfer coefficient

1. Introduction

Technical literature comprises a large number of articles dealing with melting produced by electric, dielectric or induction heating as well as by other heating agents.

There are many papers [1–4] that deal with the melting process of materials in contact with a heated surface.

Some articles deal with the melting process produced by direct contact with liquid heating agents containing component of the same kind with the one in the solid phase. The melting process is studied at particle level [5,6] or in a fixed bed of particles [7]. In the latter case, the heat transfer is analyzed using ice particles and water as a heating agent.

Other articles [8–14] study the heat transfer during the melting of ice blocks or ice cylinders [15,16] in saline solutions. The local heat transfer coefficient is determined for a 3.5% saline solution and for a temperature between 274.8 and 292.8 K.

Paper [17] analyses theoretically the heat and mass transfer at ice melting in solutions of NaCl and glycerin. The differential equations that describe the melting process are solved through an iterative method based on the Newton algorithm.

This paper presents a method for the experimental determination of individual heat transfer coefficient during the melting of a spherical particle formed of a pure substance in a solution containing a component of the same kind as the melting particle. The method is applied for the study of ice melting in urea solutions of different concentrations.

A study concerning the influence of temperature, concentration and of the liquid phase velocity over the melting rate and over the individual heat transfer coefficient, as well as one concerning the influence of Reynolds and Prandtl numbers on the Nusselt number is conducted.

2. Method for the determination of the individual heat transfer coefficient

Three elementary processes occur when a particle formed of a single component, A, melts in a solution containing the components A and B namely, heat transfer from the solution to the particle, melting and mass transfer of component A through the liquid phase from the surface of the particle to the bulk of the solution. A small amount of the heat is transferred by conductivity towards the particle at its surface.

The melting rate of the particle may be determined with the relation

$$v_m = -\frac{dm}{S\,dt} \tag{1}$$

For a spherical particle relation (1) becomes

$$v_m = -\frac{\rho_s}{2}\frac{dD}{dt} \tag{2}$$

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Nomenclature

C_∞	concentration of component A in the bulk solution ($\mathrm{kg\,m^{-3}}$)
C_p	specific thermal heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
D	particle diameter at a given time (m)
m	mass of the particle at a given time (kg)
q	specific thermal flux ($\mathrm{W\,m^{-2}}$)
S	area of the particle exterior surface ($\mathrm{m^2}$)
t	time (s)
T_m	melting temperature (K)
T_∞	liquid phase temperature in the bulk solution (K)
v	fictitious velocity of the melting agent (equal to the ratio between the flow rate and the column cross-section) ($\mathrm{m\,s^{-1}}$)
v_m	melting rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
ΔH_m	latent melting heat ($\mathrm{J\,kg^{-1}}$)
$Nu = \alpha D/\lambda$	
$Pr = C_p\eta/\lambda$	
$Re = \rho v D/\eta$	
α	individual heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
η	liquid viscosity ($\mathrm{N\,s\,m^{-2}}$)
λ	liquid thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
ρ	liquid density ($\mathrm{kg\,m^{-3}}$)
ρ_s	particle density ($\mathrm{kg\,m^{-3}}$)

Experimental determination of the melting rate is done by monitoring the mass of the particle in time and then by using relation (1) or (2).

In order to determine the individual heat transfer coefficient the following equation is used:

$$q = \alpha(T_\infty - T_\mathrm{m}) \tag{3}$$

The melting temperature when the liquid phase is a solution is different from the melting temperature of the pure component A and is read from the equilibrium diagram of the system.

Relation (4) gives the specific thermal flux q, in the case of a negligible heat transfer towards the particle,

$$q = v_\mathrm{m}\,\Delta H_\mathrm{m} \tag{4}$$

3. Experimental

The experiments were conducted in the laboratory with the installation presented in Fig. 1. The installation consists of a stainless steel vertical column (1) with the diameter 0.1 m that represents the melting chamber. On the top of the column there is a lid (2) with slits for the rod (3) and thermometer fixation (4). The rod is attached to the support (5). The ice particle is fixed at the bottom of the rod (immersed in the melting chamber). The liquid phase is evacuated from the melting chamber through a tube (6). A centrifugal pump insures the liquid phase transportation, sucking up the liquid from the tank (8). Temperature is maintained at a prescribed

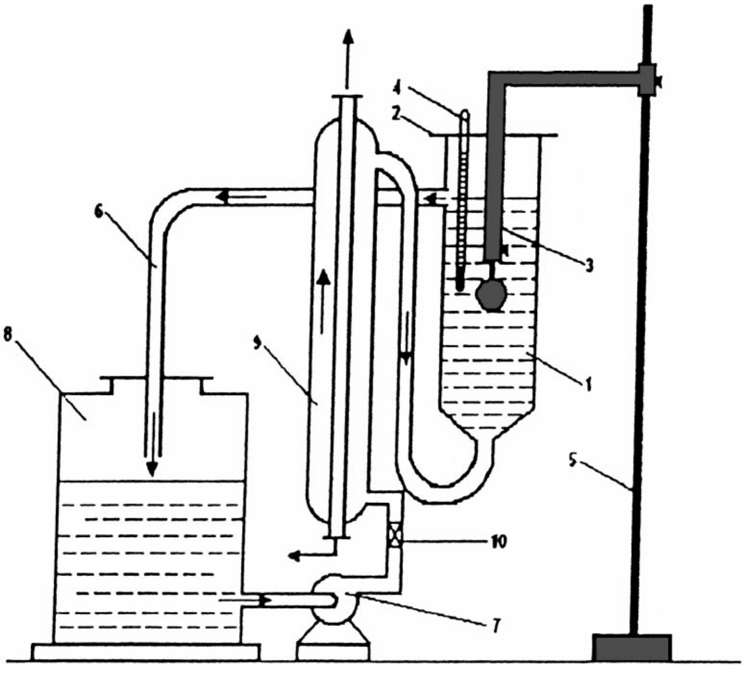

Fig. 1. Experimental installation: (1) column (melting chamber), (2) lid, (3) rod, (4) thermometer, (5) support, (6) tube, (7) pump, (8) tank, (9) heat exchanger, (10) valve.

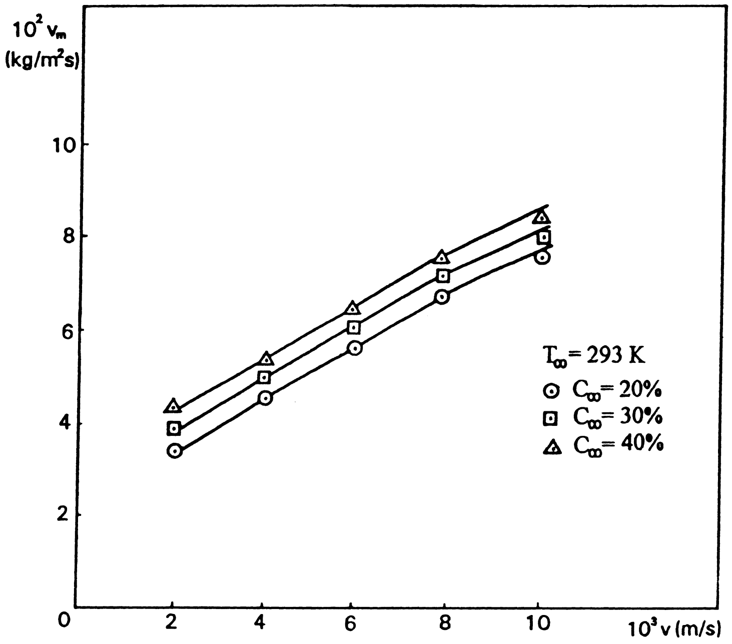

Fig. 2. Variation of the melting rate with the urea solution concentration and velocity, $T_\infty = 293\,\text{K}$.

value with the heat exchanger (9). The liquid flow rate is adjusted manually with the valve (10).

Ice spherical particles were used in the experiments; the melting agent was water–urea solutions, having in turn the mass concentrations 20, 30 and 40%. The experiments were conducted at atmospheric pressure for three temperatures (293, 307 and 314 K) and for several flow rates of the cooling agent.

As for ice particles, they were obtained with special devices using gradual freezing at the temperature 258 K. The device may produce particles having the diameter 0.045 m.

4. Results and discussion

In order to determine the melting rate of the ice particles in urea solutions, the change of the particle mass in a given time was firstly determined. For this purpose the particle mass was determined with a technical balance before and after immersion in the melting agent.

Using the experimental data and relation (2) the melting rate of the ice particles was calculated. The results obtained are illustrated in Figs. 2 and 3 and in Table 1 and represent the dependencies of the melting rate on the urea solution

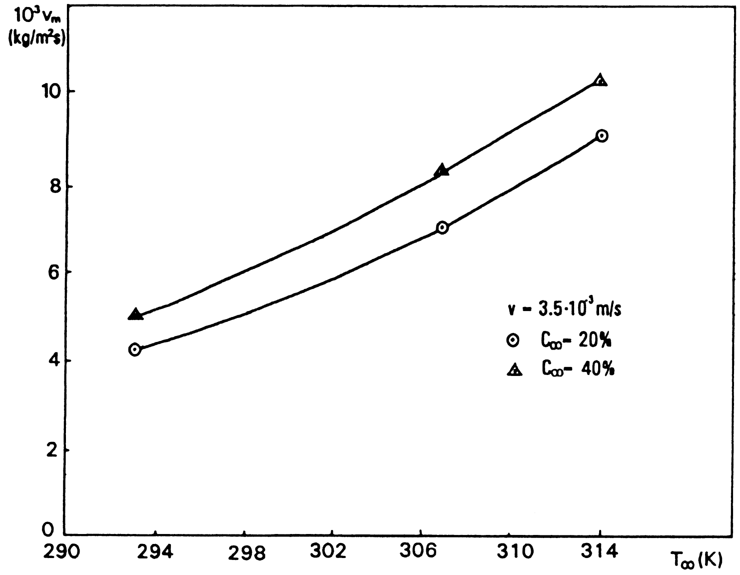

Fig. 3. Variation of the melting rate with the urea solution temperature and concentration and velocity $v = 3.5 \times 10^{-3}\,\text{m}\,\text{s}^{-1}$.

Table 1
Experimental data

T_∞ (K)	C_∞ (%)	v_m (kg m^{-2} s^{-1})	α (W m^{-2} K^{-1})	*Nu*	*Re*	*Pr*
311	20	0.07060	695.4	61.86	187.4	6.37
	40	0.08236	811.2	83.76	142.0	8.77
314	20	0.0919	750.6	67.03	210.8	5.67
	40	0.1040	849.5	88.14	165.9	7.52

Table 2
Physical properties

Property	Value	References
Ice density (258 K)	919.2	[18]
Ice melting heat (kJ kg^{-1})	334.9	[18]
Solid–liquid equilibrium data for the water–urea system (*T* (K), *C* (%))	273, 0; 267, 20.0; 263, 33.5	[19]

velocity, concentration and temperature. Obviously, in these conditions, the heat and mass transfer are realized mainly through forced convection. Therefore, the melting rate is very much influenced by the melting agent velocity. The melting rate is influenced to a greater extent by the solution concentration for large values of the melting agent than it is for small values. Consequently the mass transfer in this case has a larger influence on the melting rate than it has for zero velocity of the melting agent. Temperature has a positive influence on the melting rate.

Using the data from Table 2 and relations (3) and (4) the melting temperature (T_m) and the individual heat transfer coefficient were calculated. The dependence of the individual heat transfer coefficient on the melting agent velocity is represented in Figs. 4 and 5. The coefficient α increases for larger values of the velocity and of the temperature of the melting agent.

The diagrams in Figs. 4 and 5 show that for both zero and non-zero velocity of the melting agent the urea solution concentration has a positive influence on the individual heat transfer coefficient. This influence is more pronounced so as the melting agent velocity is large.

The increase in the individual heat transfer coefficient with the increase in the urea solution concentration may be explained by the mass transfer that takes place at the surface of the particle during melting, enhancing the melting process. Water resulting from melting is transferred in the solution. The water mass transfer is determined by the difference in water concentration at the surface of the ice particle and in the bulk of the urea solution. This leads to the conclusion that the values of the individual heat transfer coefficient are apparent values since they include the contribution of the mass transfer.

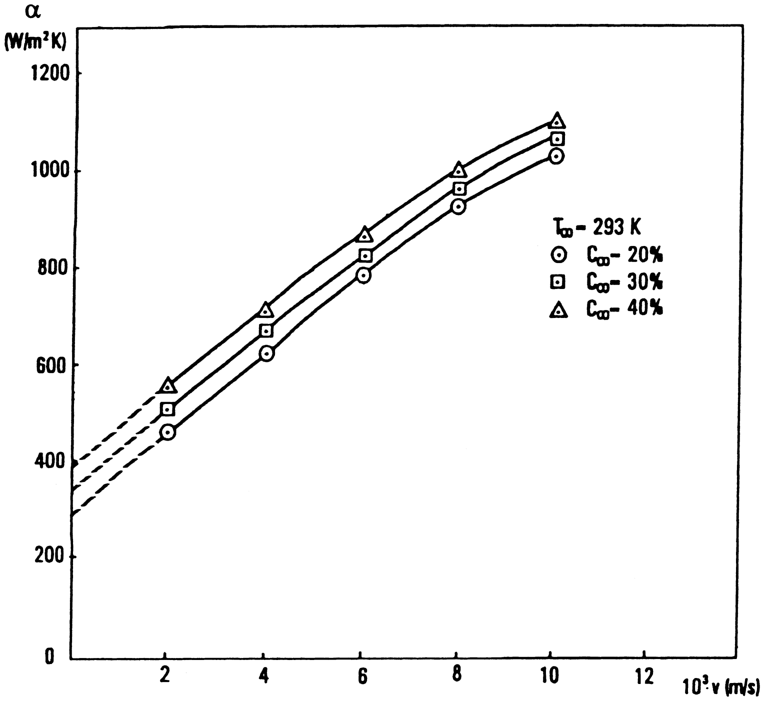

Fig. 4. Variation of the coefficient α with the solution velocity and concentration (temperature of the solution is 293 K).

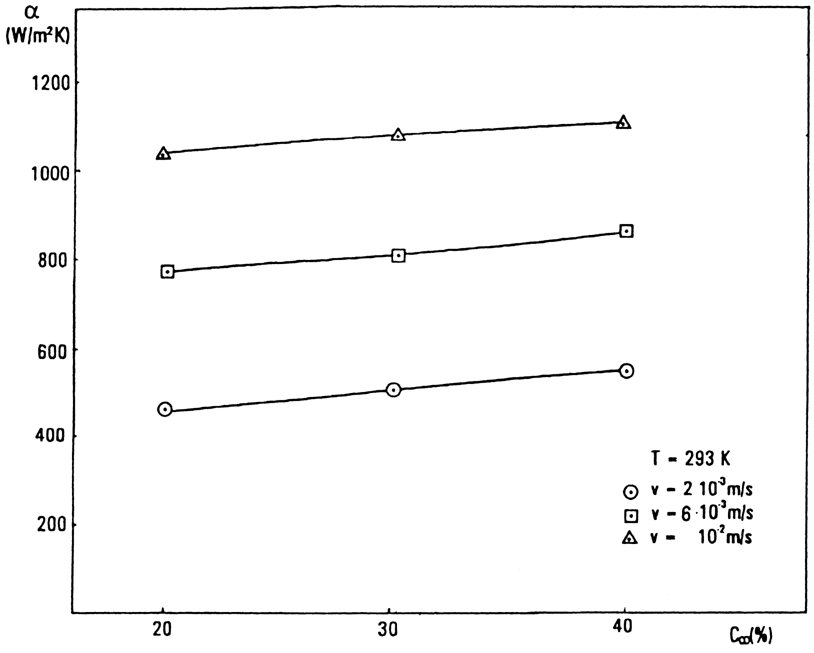

Fig. 5. Dependence of the coefficient α upon the solution concentration (temperature of the solution is 293 K).

As for temperature, we may note its positive influence upon the individual heat transfer coefficient (Table 1). An increase in the urea solution temperature leads to an increase in the individual heat transfer coefficient.

The diagram in Fig. 6 shows the way that the Reynolds and Prandtl numbers influence the Nusselt number. As may be seen an increase in the Reynolds number leads to an increase in the Nusselt number. For increasing Prandtl numbers, i.e. for increasing solution concentration, the Nusselt number increases.

At the same time the data in Fig. 6 indicate that the experimental values obtained for the Nusselt number are larger than those corresponding to Ranz and Marshall equation,

$$Nu = 2 + 0.6\,Re^{0.5}\,Pr^{0.33} \tag{5}$$

This may be explained by the substantial contribution of the mass transfer in the melting process.

In order to verify the accuracy of the method for the determination of the individual heat transfer coefficient, the experimental results obtained in the laboratory were compared

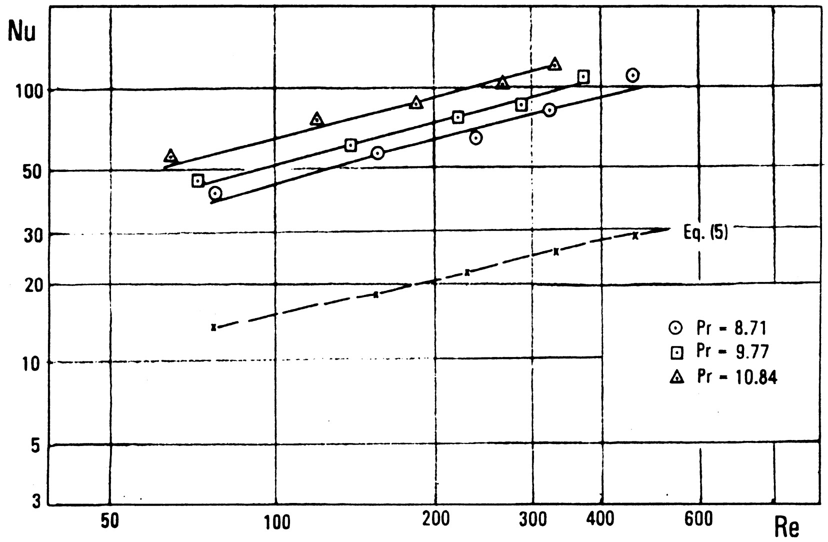

Fig. 6. The dependence Nu versus Re, $T = 293$ K.

Table 3
Comparison between the experimental data obtained in this paper and those obtained by other authors

	System		
	Ice sphere–urea solution	Ice cylinder–saline solution	Ice disk–water
T_∞ (K)	295	279.1	293
C_∞ (%)	3.5	3.5	0
α ($\mathrm{W\,m^{-2}\,K^{-1}}$)	280 (experimental)	221 [15]	336 [5]

to those given by other authors. Since the hydrodynamic conditions in this experiment are different from those used by other authors, the comparison was made for the case of zero solution velocity. The results are presented in Table 3. As may be seen from the table, the experimental results we obtained are close to those obtained by other authors, which proves that the method used in this paper for the determination of the coefficient α is correct.

5. Conclusions

In this paper, the authors present a method for the experimental determination of the individual heat transfer coefficient during the melting of a particle formed of a single component in a solution that contains that component.

Using spherical ice particles and water–urea solutions the melting rate and the heat transfer coefficient were determined for several temperatures and concentrations of the solution and for several velocities of the melting agent.

The results obtained show a positive influence of the solution velocity and concentration and also of the melting agent temperature upon the melting rate, the individual heat transfer coefficient and the Nusselt number. The Prandtl number is also positively influenced by concentration.

The experimental results agree with those obtained by other authors, which proves the validity of the method proposed for the determination of the individual heat transfer coefficient.

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