17th European Symposium on Computer Aided Process Engineering – ESCAPE17
V. Plesu and P.S. Agachi (Editors)

Modelling and numerical simulation of ice slurry storage tank

Denis Flick [a], Christophe Doursat [a], Mohamed Ben Lakhdar [b]

[a] *UMR Génie Industriel Alimentaire Cemagref,ENSIA,INRA,INAPG*
INAPG 16 rue Claude Bernard 75231 Paris Cedex 05, flick@inapg.fr
[b] *HEATCRAFT Worlwide Refrigeration, European Operations,*
42 rue Roger Salengro - BP 105 69741, Genas, France
mohamed.ben.lakhdar@heatcrafteurope.com

Abstract

Ice slurries, composed of an aqueous solution and water ice crystals, are used in new environmentally friendly refrigeration systems in order to reduce the amount of refrigerant. The slurry storage tank is an equipment which is important to correctly design. A numerical model was proposed to predict the evolution of the ice stock and the available cooling power in function of the tank geometry and the operating conditions. It takes into account ice settling, fluid circulation, ice formation (in generator) and ice melting (in utilisation loop and because of heat losses). It can be used to optimise the operating conditions and the geometrical parameters of the ice slurry storage tank.

Keywords: ice slurry, modelling, stratification

Introduction

Ice slurries, composed of an aqueous solution (of mono propylene glycol, Hycool..) and water ice crystals, are used in new environmentally friendly refrigeration systems in order to reduce the amount of refrigerant [1-4]. Ice slurry, produced with scraped or brushed surface heat exchangers for example, is first sent to a storage tank and then transported to all the devices needing refrigeration in the industrial plant. Many studies concerns ice slurry production, thermodynamical and rheological properties and heat transfers [5-7] but few studies concern ice storage. Between them some are focused on attrition, agglomeration and Ostwald ripening [8] and some analyse transient evolution of ice concentration inside the storage tank by 1D or 2D approaches [8-9]. The aim of this study was to develop a model in order to predict the evolution of the ice stock and the available cooling power in function of the tank geometry (and namely the inlet and outlet heights) and the operating conditions (generator and utilisation power and flow rate). This needs in fact to predict the evolution of the ice slurry state (ice fraction, temperature, residual solution mass fraction, mean diameter of the ice crystals) at each height in the tank. Indeed, ice crystals being lighter than the aqueous solution, stratification occurs inside the tank so that ice concentration depends on height. This explains the importance of inlet and outlet positions on the storage tank for ice slurry generation loop and utilisation loop. Moreover, refrigeration need varies and it is interesting to generate and store ice rather during the night (electricity cost) so that the storage tank management is an unsteady problem.

1. Modelling approach

The tank is a vertical cylinder with a stirring device at top level. This device rotates slowly; it does not induce a general fluid circulation in the tank but only avoid ice agglomeration at the top level where ice concentrates by settling. The tank is coupled to the ice generator and to the ice consuming devices (figure 1).

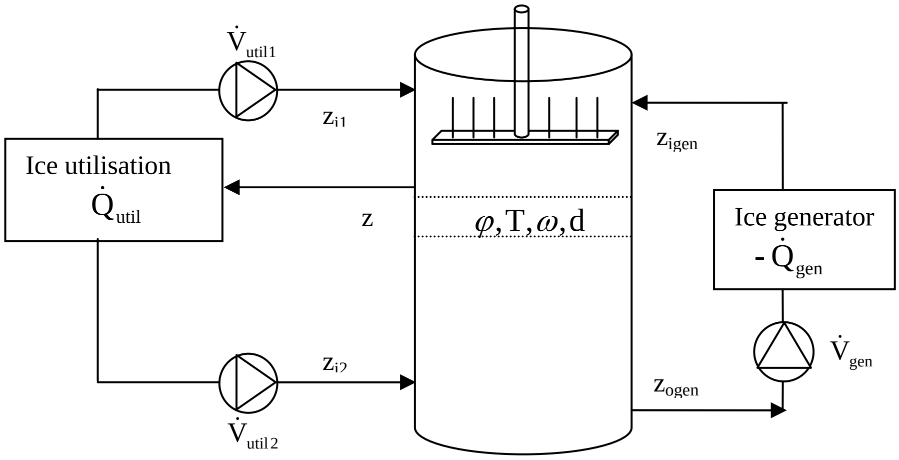

Figure 1: schema of the ice slurry storage tank

The aim of modelling is to predict the evolution of the ice slurry state (ice fraction:φ, temperature:T, residual solution mass fraction: ω, mean diameter of the ice crystals: d) at each height. The main hypotheses are the following. The solution flow and the ice settling are vertical. The slurry is homogeneous in a given horizontal section. The volume variation related to ice melting is not taken into account for the ice and solution velocity calculation and the total height of slurry in the tank is supposed constant. Nevertheless, the buoyancy forces, depending on density difference, are taken into account in the Stocke's law. The time constants for the generator and utilisation loops are neglected (in other words the volume of slurry in these loops is neglected in comparison with the volume of the tank). The constitutive equations are the following.

The mean velocity (v) at a given height can be calculated from the flow rates in the generation and utilisations loops and can be expressed in function of ice fraction (φ), solution and ice velocities (v_{sol} , v_{ice}).

$$(1-\varphi)v_{sol} + \varphi.v_{ice} = v$$

For low ice fraction, the settling follows Stocke's law for equivalent spherical particles (depending on the mean equivalent diameter d). But the settling is dumped (with a sigmoid penalization function f(φ)) when the volumetric ice fraction becomes near its maximal value (compact ice fraction: φ_{max}). The ice crystals do not agglomerate (forming clusters, which would settle more rapidly).

$$v_{ice} = v_{sol} + v_{set} \quad \text{with} \quad v_{set} = g(\rho_{sol} - \rho_{ice})d^2/(18\,\mu)\,f(\varphi)$$

All the ice crystals at a given height melt/grow simultaneously but they do not disappear/appear except in the utilisation/generation loops. The number of ice crystals per volume unit is noted: n. The effect of diameter distribution (around the mean value) on ice settling (settling velocity being smaller for smaller particles) is taken into account by an equivalent ice diffusivity ($D_{eq.ice}$).

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial z}\left(n v_{ice} - D_{eq.ice}\frac{\partial n}{\partial z}\right) = 0$$

For the enthalpy balance, only the latent heat of ice is taken into account, thus the volumetric enthalpy is: - $\varphi\ \rho_{ice}$ L. The ice crystals can melt inside the tank because of lateral heat losses or because they move toward warmer (less concentrated) region. The equation related to ice fraction calculation is:

$$\frac{\partial}{\partial t}\left(-S\rho_{ice}L\,\varphi\right) + \frac{\partial}{\partial z}\left(-S\rho_{ice}L\left(\varphi v_{ice} - D_{eq.ice}\frac{\partial\varphi}{\partial z}\right) - S\lambda_{eq}\frac{\partial T}{\partial z}\right) = h_g P\left(T_{ext} - T\right)$$

where S is the tank section, P its perimeter, λ_{eq} the equivalent thermal conductivity of ice slurry and h_g the global heat transfer coefficient (trough lateral isolation). The mean equivalent diameter is obtained by: $\varphi = n\,(\pi d^3/6)$

The mass concentration of solute per slurry volume unit is: (1- φ) $\rho_{sol}\ \omega$, where ω is the mass fraction of solute in the residual solution.

$$\frac{\partial}{\partial t}\left(S\rho_{sol}\,(1-\varphi)\omega\right) + \frac{\partial}{\partial z}\left(S\rho_{sol}\left((1-\varphi)\omega\, v_{sol} - (1-\varphi)D_{eq.sol}\frac{\partial\omega}{\partial z}\right)\right) = 0$$

The ice crystals are in local equilibrium with the surrounding solution, so that ω is related to T through the liquidus curve: $\omega = \omega_{sat}(T)$

The inlets and outlets of the tank correspond to source and sink terms for the ice crystals, enthalpy and solute balance equations, which are calculated from the ice generation and utilisation operating conditions.
These constitutive conservation equations (mass, solute, energy, number of ice crystals) were discretised by a semi-implicit finite volume method. Numerical resolution was performed with Matlab ®

2. Results and discussion

The model can be used to simulate steady state, ice storage (without ice utilisation, by night for example), ice utilisation (without generation, by day for example) or a more complex situation and for different inlet/outlet positions. Some results are now presented in a particular case: the tank is 3m high and its cross section is 2m², the generator is located inside the tank at the bottom ($z_{i.gen}=z_{o.gen}=0$), the ice slurry outlet is located at 2m and the partially melted ice slurry comes back at the top and at the bottom of the tank. The slurry is obtained from a water/ethanol mixture (ethanol mass fraction =0.2), the generated ice crystals have an equivalent initial mean diameter of 300 µm.
Figure 2 presents the evolution of ice fraction at the inlets and outlets of the tank during 3 operating stages: ice generation without utilisation (0-2h), ice generation and utilisation (2h-7h) and ice utilisation without generation (5h-7h).

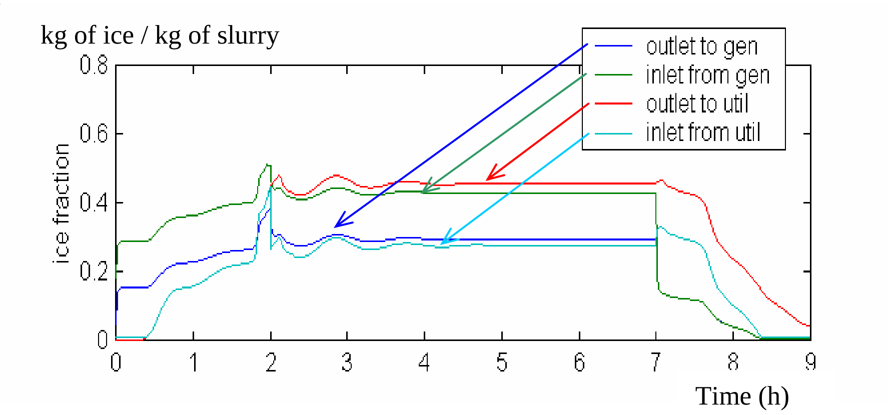

Figure 2: Evolution of the inlet and outlet ice fractions in unsteady operating conditions

Figure 3 details the results obtained in steady state with a generation power of 100 kW and a flow rate of 6 m^3/h in the utilisation loop (coming back to the tank half at bottom and half at the top).

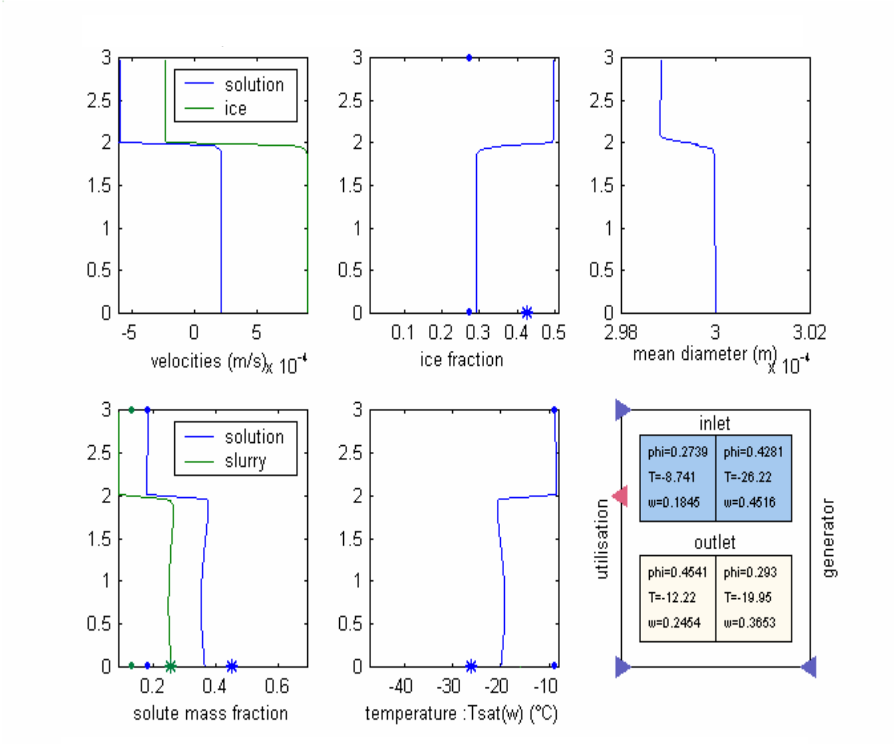

Figure 3: Velocity, ice fraction, mean diameter, solute masse fraction (relative to the slurry or to the residual solution) and temperature profiles at steady state (* outlet value , • inlet value)

In this case, 18% of ice is melted in utilisation loop, which corresponds to the difference between outlet (45%) and inlet (27%) ice fraction. Two distinct areas, quite homogeneous for all the variables, appear. In the upper part the mean velocity is negative (downward), but the solution flow rate is not sufficient to drag the crystals down. So, ice accumulates to finally get compact. Because of heat losses at the walls, the mean ice crystal diameter reduces slightly. In the lower part, the mean velocity is positive. The crystals are moving upwards faster than the solution because of the settling phenomenon.

Concerning the solute, in the upper part, the mass fraction related to the solution is lower than in the bottom part. Indeed, when the fluid returns to the tank from the utilisation loop, the solute is diluted because ice crystals were melted. Thus in the upper part, the solute mass fraction is near the value of return flow (0.18). But at the bottom, the generator being in this zone, the solution gets again more concentrated because of ice formation. Temperature also is different in the two parts of the tank because temperature is related to solute concentration (via the liquidus curve).

3. Conclusions

A general model of ice slurry storage tank has been proposed which takes into account ice settling, fluid circulation, ice formation (in the generator) and ice melting (in the utilisation loop and because of heat losses). It predicts the evolution of vertical profiles of ice fraction, mean equivalent crystal diameter, solute mass fraction, temperature, ice and solution velocities. This allows estimation of available utilisation power and total ice stock in function of the operating parameters. So, the model can be used to optimise the operating conditions and the geometrical parameters (notably input-output heights).

Acknowledgements

This paper was prepared with partial support from the project "ice cool", a European Community funded project in the 5th Framework program for research, sub-program for energy, environment and sustainable development. Contract n° NNE5-2001-00318

References

1. M. Kauffeld, M. Kawaji and P.W. Egolf, Handbook on Ice Slurries: Fundamentals and Engineering, International Institute of Refrigeration (IIR), Paris. 2005
2. P.W. Egolf, M. Kauffeld, From physical properties of ice slurries to industrial ice slurry application. Int. J. Refr. 28 (2005) 4-12
3. J.Guilpart, E. Stamatiou, L.Fournaison, The control of ice slurry systems: an overview. Int. J. Refr. 28 (2005) 98-107
4. M.A. Ben Lakhdar, A.Melinder, Facing the challenge to produce ice slurry for freezer applications. 5th Ice slurry workshop. May 2002 Stockholm (IIR Paris)
5. M.A. Ben Lakhdar, R. Cerecero, G. Alvarez, J. Guilpart, D. Flick, A. Lallemand, Heat transfer with freezing in a scraped surface heat exchanger. Applied thermal engineering. 25 (2005) 45-60
6. A. Melinder, E Granryd, Using property values of aqueous solutions and ice to estimate ice concentrations and enthalpies of ice slurries. Int. J. Refr. 28 (2005) 13-19
7. V.Ayel, O.Lottin, H Peerhossaini, Rheology, flow behaviour and heat transfer of ice slurries: a review of the state of the art. Int. J. Refr. 26 (2003) 95-107
8. M. Tanino and Y. Kozawa, Ice-water two-phase flow behavior in ice heat storage systems. Int. J. Refr .24 (2001) 639-651
9. P.W.Egolf, D.Vuarnoz, O.Sari, D.Ata-Caeser, A.Kitanovski,Front propagation of ice slurry stratification processes. 5th Ice slurry workshop. May 2002 Stockholm (IIR Paris)