STORAGE AND MIXING OF ICE SLURRIES IN TANKS

F. MEILI, O. SARI, D. VUARNOZ, P. W. EGOLF
University of Applied Sciences of Western Switzerland
CH-1401 Yverdon-les-Bains, Switzerland
(E-mail : francois.meili@eivd.ch)

Experimental results on storage and mixing of ten-percent-talin/water ice slurries are presented. For this purpose a system with a storage tank, with a volume of 1000 liters and a mixing device containing three slightly inclined cones, was investigated. In first experiments the angular velocity of the mixing device was varied. The variance of numerous temperatures (measured at different locations with different heights in the tank) yields a suitable measure to quantify the stratification. Above a critical rotation frequency f_{cr} - which is a function of the ice fraction - the entire fluid gets into motion and a very good mixing is obtained. In practice it is important to have knowledge of f_{cr} . A system should be operated at f_{op} slightly above f_{cr} . Lowering the frequency to values below the criticality, the variance remains small. The temperature field is still homogeneous, but by buoyancy the ice particles develop a non-homogeneous distribution. In further experiments intermittent operation was investigated. Such running conditions are very advantageous (especially at night), because electrical energy is safed.

1. INTRODUCTION

To run an ice slurry system conveniently a storage tank with one or several efficient mixing elements is essential. This guarantees a homogenous ice particle field. The calculation of the size of a storage tank is well-known. An example how to proceed is given in Chapter 3. A very complex procedure is mixing. Stretching and folding processes occur as known from the theory of nonlinear dynamics (see e.g. [1]). Because of the lack of a consistent theory, practically for every single new case a particular study is performed. Therefore, a tremendous amount of literature is available (e.g. [2]-[5]). A theoretical approach based on dimensional analysis for Bingham fluids is outlined in Ref. [6], which leads to very good results to describe the mixing behaviour of ice slurries including the estimations of the power consumptions of impellers.

2. EXPERIMENTAL SET-UP

The measurements to determine the performances of the storage tanks and mixing elements are performed with the device that has been used for heat transfer investigations and visualization experiments. A detailed description is found in [7]. In order to calculate energy demands additional power meters were inserted into the primary and secondary circuit. Furthermore, in the primary circuit a mass flow meter and numerous temperature probes were mounted. To measure the stratification in the tank two rows of five temperature sensors at different heights were installed (see Figure 1).

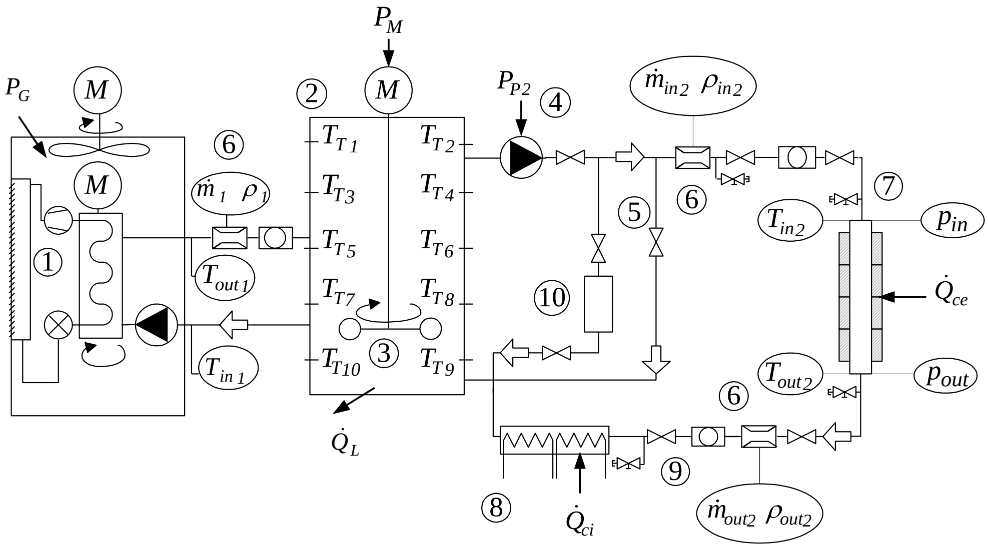

Figure 1: The device "Coulis de glace" adapted to investigate the behaviour of a storage tank (Figure 2) with a mixing impeller (Figure 3).

The main elements of the device are listed in Table 1. The numbers relate to Figure 1. System parameters are described in Table 2 underneath.

1	*Refrigerating machine and ice generator: Unelco 2.5 TR*	*6*	*Mass flow meter: Endress & Hauser Promass 63F*
2	*Storage tank: 1000 liter*	*7*	*Heat exchanger*
3	*Mixing element: Visco Jet*	*8*	*Electric heaters: Mösch, 9 kW*
4	*Pump: Grundfos CRE/CRNE, 3 stages, motor: 0.75 kW, 0 – 1 kg/s*	*9*	*Experiments with ultra sonic device*
5	*Bypass*	*10*	*Microscopic visualization of ice particles*

Table 1: Brief description of the main elements in the experimental system “Coulis de glace”.

Measurements	***Nomenclature***	***Range***
Solution Water/Talin, (mass percent talin)	x_T	*10 %*
Frequency of the scraper	f_{scr}	*0 – 17.2 Hz*
Frequency of the mixing device in the storage tank	f_{mix}	*0 – 4.1 Hz*
Evaporating temperature in the ice generator	T_{evap}	*- 13 °C*

Table 2: Parameters related to the presented experiments.

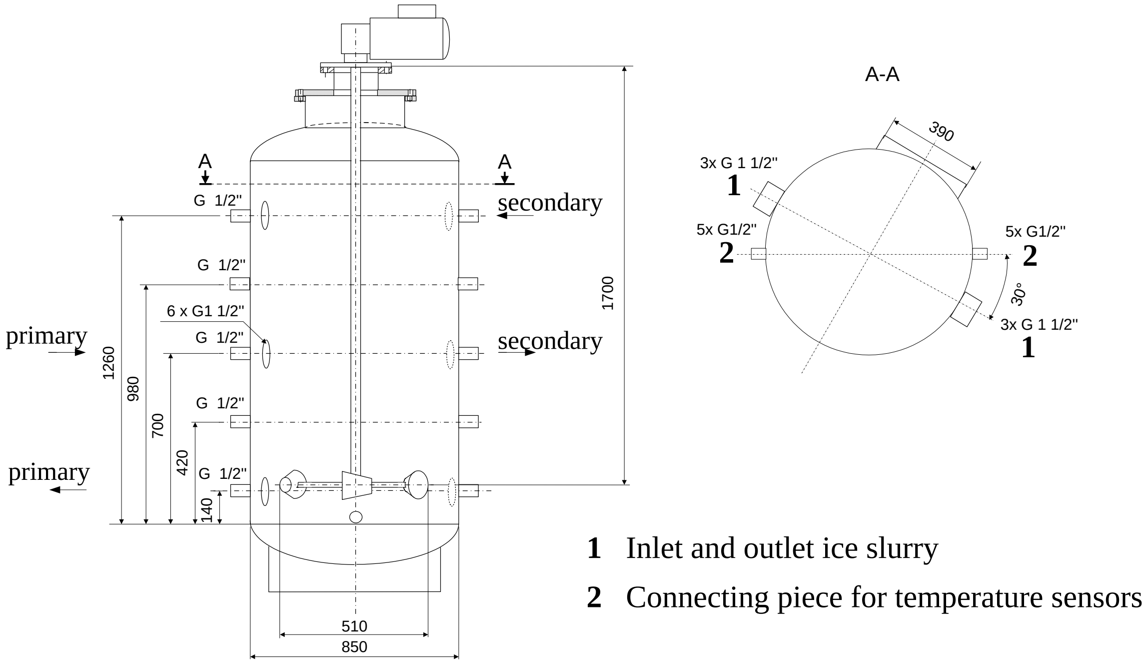

Figure 2 : Schematic presentation of the storage tank with mixing device mounted on a slab, which is rotated by the motor on the top of the storage tank.

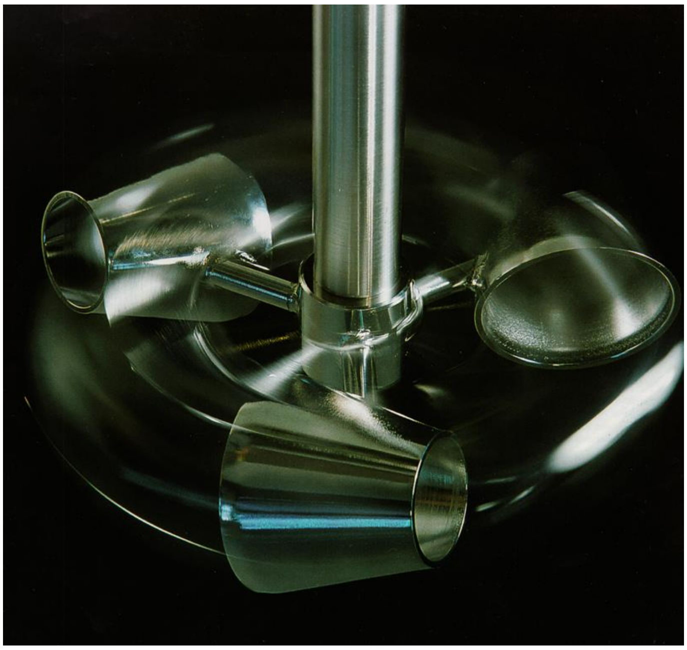

Figure 3: The mixing element with three cones as already used in previous experiments on fluiddynamics, thermodynamics, and visualization (photography by Visco Jet AG).

Very good results were obtained with a VISCO JET impeller. Therefore, in a first phase, only experiments with this device were performed. Comparisons with other mixers are under consideration.

3. CALCULATION OF STORAGE TANK SIZE

To design a storage tank knowledge of the daily energy consumption of the consumers must be available. An example of a cooling profile is given in Ref. [8] and is shown in Figure 4. In this example the energy consumption begins at noon.

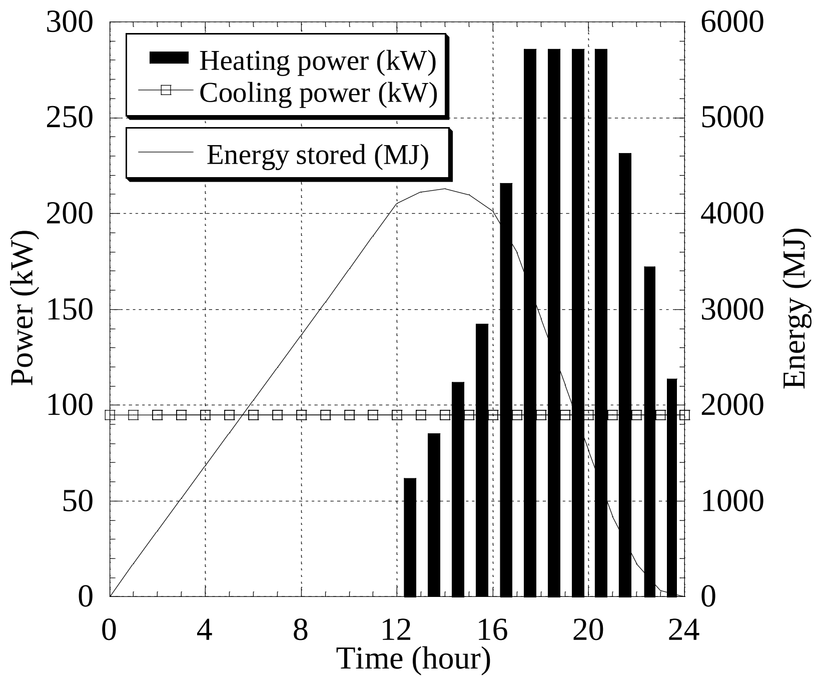

Figure 4 : Cooling profile during one day. The ice generator is continuously running. The energy stored in the tank is shown by the solid curve with a maximum at approximately 2 pm.

The maximum heat removal in the consumers is

$$E_C(T) = \left(\sum_{k=1}^{24} \dot{Q}_k \right) \cdot \Delta t = (12 \cdot 0 + 62 + 86 + 112 + 142 + 216 + 4 \cdot 286 + 232 + 172 + 114) kW \cdot$$
$$3600 s = 8.2 \cdot 10^9 J, \qquad (1)$$

where Δt denotes a equidistant time interval and T the period of one day: T=24h·3600s= 86400 s. The energy $E_c(T)$ is assumed to be equal to the cooling energy released by the ice generator during twenty four hours $E_G(T)$. The cooling power of the ice generator is then calculated by

$$E_G(t) = \dot{Q}_G \cdot t \;\Rightarrow\; E_G(T) = \dot{Q}_G \cdot T \;\Rightarrow\; \dot{Q}_G = \frac{E_G(T)}{T} = \frac{8.2 \cdot 10^9 J}{86400 s} = 95 kW \;. \qquad (2a\text{-}e)$$

The maximal storage of energy required in the storage tank is then

$$E_{\text{stor max}} = \max_{0 \le t \le T} \{E_G(t) - E_C(t)\} = 4620 \ \ MJ - 365 \ \ MJ = 4255 \ \ MJ \ , \tag{3a-c}$$

which in this example is obtained between the thirteenth and the fourteenth hour of the day.

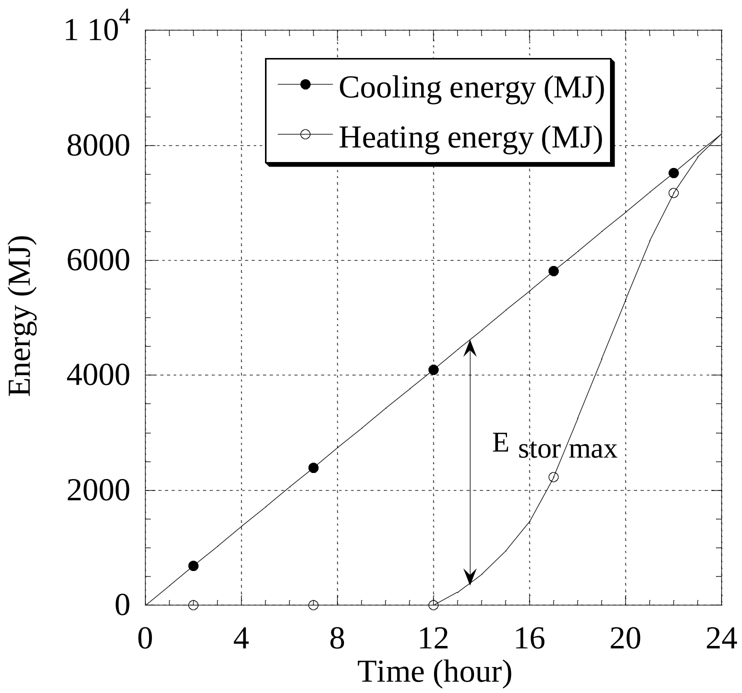

Figure 5 : The linear production of cold over twenty four hours, and the nonlinear consumption beginning at noon. At half past one in the afternoon the maximal storage capacity must be available. This defines the storage volume (see in the remainder).

The maximum volume is then calculated by using the density and enthalpy density of the ice slurry

$$V_{\text{stor max}} = f_{stor} \frac{E_{\text{stor max}}}{\rho_{\min} \left| h_{\max} - h_{\min} \right|} . \tag{4}$$

The volume of the tank is chosen a factor $f_{stor} \approx 1.2$ higher than the calculated value. This safety factor assumes some losses in volume, e.g. by a bad circulation, or a freezing of ice slurry in edges of the storage tank, etc.

3. STRATIFICATION

Without mixing in the storage tank, ice particle accumulations in the center and the top of the tank are observed. Then ice particles freeze together yielding ice clusters, which when swept out into the piping system may block the flow. A mixing of the ice slurry in the tank leads to a homogeneous ice particle field. Our intention was to quantify the stratification. For this purpose the variance (or the standard deviation) of the temperature measurements distributed regularly over the whole space in the tank (see Figure 1) is the most suitable quantity

$$V = \frac{1}{N}\sum_{i=1}^{N}(T_i - \bar{T})^2, \qquad \bar{T} = \frac{1}{N}\sum_{i=1}^{N}T_i, \qquad \sigma = \sqrt{V}, \qquad N = 10. \tag{5a-d}$$

A homogeneous temperature distribution is represented by equal temperatures at every location in the tank: $T_i = \bar{T}, \forall i$, leading to V=0. On the other hand a stratification always is presented by V>0.

To perform an experiment, initially a large stratification was produced (0.1<V<1). In order to study only the influence of the mixer, the valves of the tank were closed. Then the mixer was accelerated to a certain frequency and - after obtaining a steady state - the variance was determined. Results are shown in Figure 6.

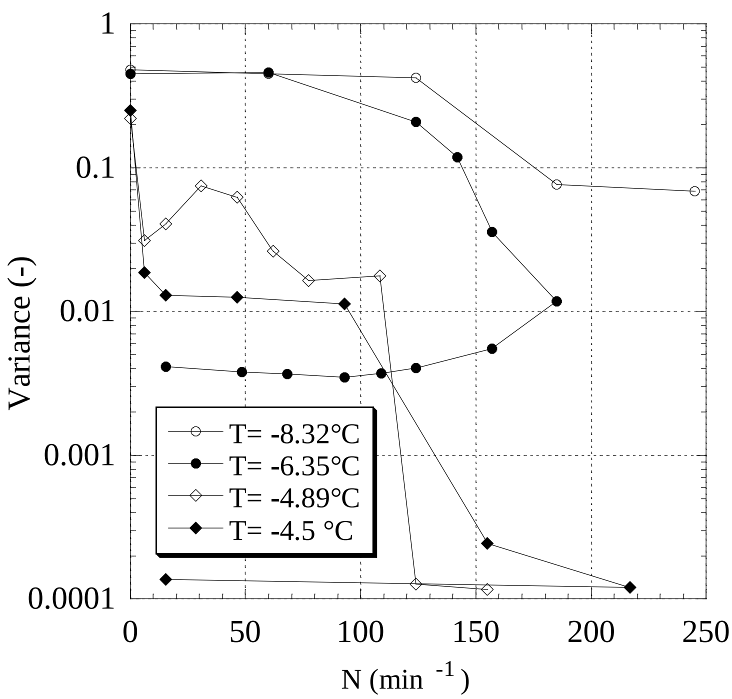

Figure 6: The variance of the temperature in a single-logarithmic scale for numerous rotation frequencies.

The results are very informative. For all the ice fractions the variance shows a steep decay. The mean frequency of this narrow domain of sudden decrease is defined and denoted by the critical frequency f_{cr} . Above this critical frequency the temperature field is homogeneous. Therefore, an operation of the mixer should always be performed at approximately f_{op}=1.2 f_{cr}. In the case where the ice fraction is at the highest value, the mixer was designed to be too small (see Figure 6, experimental serie characterized by T=-8.32 °C). Even a further increase of frequency (to infinity) causes no improvement in homogeneity. Larger cones or a larger number of mixing elements are the solution. If the temperature and the ice particle field are very homogenous ($\sigma \approx 0.0001$) and the mixer frequency is reduced below the criticality, dependant on the quality of the insulation of the tank, the temperature field remains homogenous for some time. But this certainly is not the case for the ice particle field. This was checked by removing small samples of ice slurry from the bottom and the top of the tank. Therefore, a hysteresis behavior was observed. This phenomenon shows that one has to be very careful in interpreting features of the ice particle field by means of temperature measurements.

4. INTERMITTENT MIXING

In refrigeration applications the demand for cold at night is very often negligible. Therefore high savings could be achieved, if the mixing elements could be stopped over the night time. If

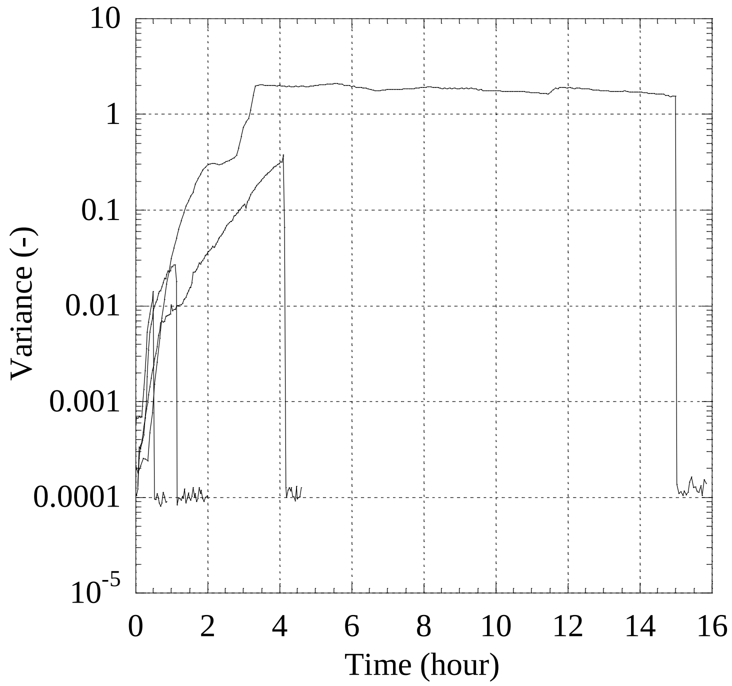

Figure 7: The variances during the experiments are shown. The (initial/final) mean ice slurry temperatures in the four experiments characterized by their time interval of standstill were: 30 min: (-5.09 °C/-4.98 °C), 1h: (-4.95 °C/-4.76 °C), 4 h: (-4.71 °C/-4.22 °C), 15 h: (-6.82 °C/-4.53°C). The mixer frequencies were: 30 min: (2.3 Hz/2.1 Hz), 1h: (2.1 Hz/1.9 Hz), 4 h: (1.9 Hz/1.6 Hz), 15 h: (3.5 Hz/3.2 Hz).

no freezing - leading to percolation - occurs in the tank, the mixer could be started again in the morning. Some time later, when the ice particle field returns to a homogeneous state, the pumps could start to transport homogenous ice slurry towards the consumers. The investigations presented in this Chapter had the objective to yield results on intermittent mixing. Especially important was the question, if a mixing element, which was brought to rest during the entire night time, in the following morning can resolve the clustering ice particles.

Four experiments were performed. After obtaining homogeneous fields, in each case the mixing impeller was turned off and the pumps were further running. After the time interval (30 min, 1 hour, 4 hours and 15 hours) the impeller was switched on again. The times to obtain homogeneity a second time were measured. They can be seen in Figure 7: Experiment with a standstill of the mixing device of 30 min: 2 min, 1 h: 4 min, 4 h: 6 min, and 15 h: 6 min. Finally the main result of these investigations is that in a closed system with a covering lid on the top of the tank - if there is no demand of cold during the night - the mixing devices may be turned off. The advantage is a large saving of electrical energy. No disadvantages have been observed by an application of this procedure.

5. CONCLUSIONS AND OUTLOOK

Numerous power consumption measurements of mixing elements were performed. As predicted by theory, the results confirm a power-law dependence with an exponent three on the rotation frequency of the mixing element. Such results shall be presented elsewhere, e.g. on one of the following IIF/IIR workshops on "Ice Slurries".

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