PHYSICAL PROPERTIES OF STABILIZED ICE SLURRY FOR TRANSPORT OF COLD THERMAL ENERGY

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A dispersion of phase-change materials is proposed as an experimental biphasic refrigerant. The phase change material is water stabilized by a tri-dimensional network of polymer, obtained by using a polymerizing process. The particle contains 90 per cent of water and has the consistency of a viscoelastic solid above the phase-change temperature. The measured values of the physical properties of the biphasic refrigerant, that is, specific heat, latent heat, density are presented for the considered temperature range. Pressure drop measurements are investigated and results show that the pressure drops of the slurry increased over the whole range of measured flow rate, while remaining in suitable values for a practical use. A supercooling phenomena is observed if the size of the particles becomes lower than 1mm, but the degree of supercooling however does not exceed 3 °C. The various advantages of this slurry show that this fluid appears well adapted for a wide variety of schemes where the production involves low temperature intervals, such as the refrigeration industry.

Keywords: cold storage and application of ice energy in homes and industry

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Introduction

Restrictions on the use of greenhouse gases e.g. carbon dioxyde (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HCFs) etc, harmful on the layer of ozone, constraint the refrigeration and air-conditioning industry to develop practical solutions for the production and distribution of cold energy. One of them is the use of indirect cooling system which allow a significant reduction of primary refrigerant charge. Nevertheless, these systems currently have a limited efficiency because of the low heat capacity of the secondary fluid. In order to overcome these deficiencies, a promising technique is the application of biphasic fluids in which the dispersed component can undergo a solid-liquid phase transition. Such secondary fluids offer indeed many advantages as high cooling capacity, the possibility of using the same medium for both energy transport and storage (thereby reducing losses during the heat exchange process), a constant temperature during heat exchange, high heat transfer rates to the phase change component due to large surface area to weight ratio, a lower pumping rate, a higher heat transfer coefficient than conventional single-phase working fluid [1-3].

Among different slurries, ice-water slurry is one of the first PCMs suspension used in industrial applications. The fluid consists of mixtures of water (or ethanol/water) and fine ice particles which the size distribution (0.1 to 3 mm) depend on different production methods and the storage method. Several studies have been shown that heat capacity will be increased 2-4 times more than a traditional monophasic fluid and the size of the district cooling machinery can be reduced accordingly [4-6]. The major economical and technical drawback appears though the high cost of icemaking equipment and its maintenance. Actually, new research is focused on fluidized bed heat exchangers as an alternative solution to produce low-cost ice slurry [7].

An alternative form of ice slurry is presented in this paper. The idea is based on the stabilization of water (or ice) by a polymeric matrix. Water or ice is thus kept inside a tri-dimensional network. This form of coating gives the opportunity to use this slurry like a conventional secondary fluid.

The aim of this work is to present some experimental studies on the physical properties of this original slurry. The first part of this paper is devoted to a presentation of this double-phase working fluid and quantitative results concerning its thermophysical properties are presented in the second part in order to point out the potentialities of the material to accumulate and transport a great quantity of thermal energy.

Presentation of the stabilized ice slurry

The making of the particles of the slurry, which was the subject of a patent Anvar (Flaud et al. [8]), is based on a process of mass polymerization. The obtained particle contains a water concentration close to 90 per cent and has the consistency of a viscoelastic gel for a temperature above 0 °C. The phase-change element is thus retained in the network both because of interfacial stress and chemical bonds and no exudation of water occurs during the phase change cycle (Fig. 1). A very small quantity of antifreeze protein (AFP) is introduced in the water mother solution in order, for the final particle, to inhibit agglomeration of particle containing ice. Same additives are used for ice slurry [9, 10].

***Fig. 1**. Schematic representation of a spherical PCM particle*

The final material remains a well shape-defined sample, requiring no coating. It appears white and hard when frozen as opposed to transparent and elastic when unfrozen. Particles are then dispersed in a carrier fluid, which must be selected very carefully because it constitutes the greater fraction of the circulating material and serves as intermediary for heat transfer between the dispersed phase and the heat exchanger surfaces. Syltherm HF manufactured by Dow Chemical Company is chosen as suspending phase. A solid fraction of 25 % is taken for this study.

Physical characteristics of the slurry

The thermal characteristics and the flowability of the slurry, and their variation with weight fraction are reviewed in this section.

Thermal characteristics

Table 1 shows the specific heat capacity and the latent heat of the slurry as a function of the weight fraction of particles. This data are established taking into account that the measured specific heat capacity of a particle is 3.9 kJ·kg^{-1} °C^{-1} (for $T > 0$ °C) and the latent heat is 292 kJ·kg^{-1} and that the measured specific heat capacity of the suspended phase is 1.549 kJ·kg^{-1} °C^{-1}.

Table 1

Latent heat and specific heat capacity of the slurry

Weight fraction (%)	Latent heat (kJ·kg^{-1})	Specific heat capacity (kJ·kg^{-1} °C^{-1})
10	29.2	1.78
20	58.4	2.02
30	87.6	2.25
40	116.8	2.49

The density of the continuous phase oscillates between 906 kg·m^{-3} (at 20 °C) and 912 kg·m^{-3} (at -20 °C). The density of the particle is respectively 1047 kg·m^{-3} for $T > 0$ °C and 920 kg·m^{-3} for $T < 0$ °C. According to the temperature and the weight fraction considered, the slurry is thus presented in the form of a quasi-homogeneous fluid when $T < 0$ °C. For $T > 0$ °C, the slurry is non-homogeneous because of phenomenon of sedimentation. A separation between the phases can be observed when the flow is stopped.

Pressure drop

A small-scale loop circuit is built for studying the fluid with in steady isothermal conditions. Flow tests were conducted with the carrier fluid and 25 % particle slurry at flow rate Q between 1 and 5 m^3/h. Temperature in the test section is maintained constant at 23 °C and then at -7 °C respectively. In order to validate the reliability of the loop and the results, experimental runs was performed using at first the suspending phase. Experimental runs were then performed with slurry at different flow rates.
Fig. 2 and Fig. 3 show the variation of the pressure loss with the velocity along the test section for two temperatures, 23 °C and -7 °C respectively. For the single phase and the two-phase mixture, one can observed that the pressure drop increases with velocity and decreases with temperature. This measured pressure-drop represents the results of a single quasi-steady test.

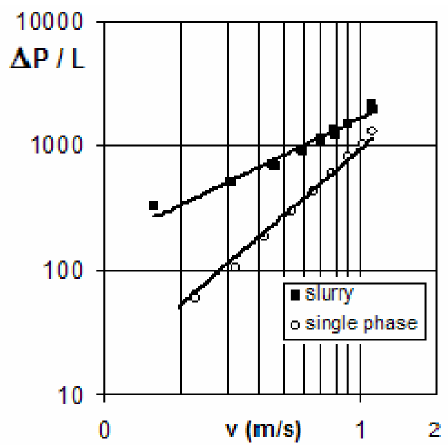


***Fig. 2.** Pressure drops versus velocity at T = -23 °C*

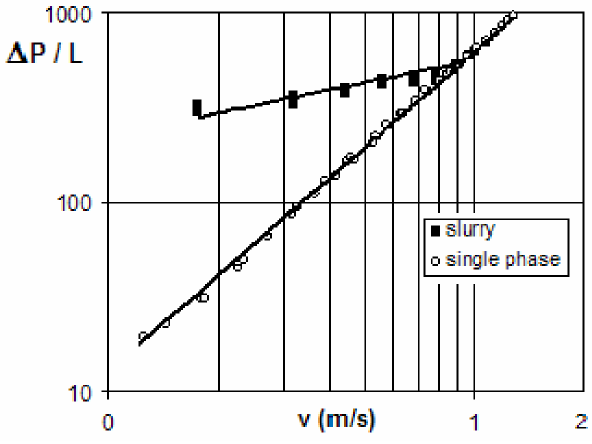


Fig. 3. *Pressure drops versus velocity at T = -7 °C*

Experimental data, presented in logarithmic coordinates, show that, for the carrier fluid, the pressure drop increases as $V^{1,75}$. This result is found in accordance with classical formula of Blasius form for turbulent flow. The maximum deviation of the measured pressure drop from the predicted values of the Blasius equation was 2 %. Therefore, the experimental system can be considered reliable.

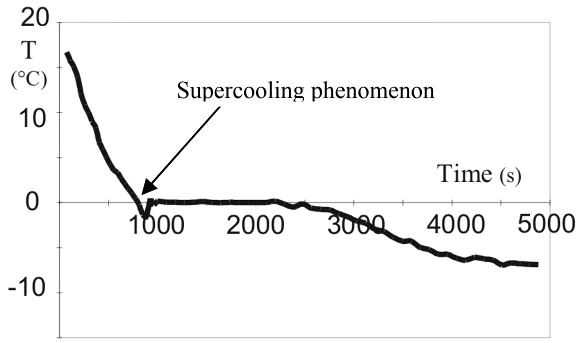
For the slurry, on note that i) pressure drops are, for low velocity, always higher than pressure drops of the carrier fluid and ii) pressure loss of the particles flow at solid state (-7 °C) is greater than pressure loss at liquid state (+23 °C). At high velocity (> 1 m/s), pressure drop of the slurry tends to data of the single phase, which is characteristic of a symmetric suspension flow pattern. One note that this effect is very well observed for T = = 23 °C comparatively for T = -7 °C, although particle density is closer to carrier fluid density for T = -7 °C. This result can be interpreted with volume expansion of particles and particle aggregates. At intermediate velocity (< 1 m/s), the divergence of the slurry curves from the suspending fluid increases with decreasing flow rate, which reflects an asymmetric suspension flow pattern.

Aggregation phenomena

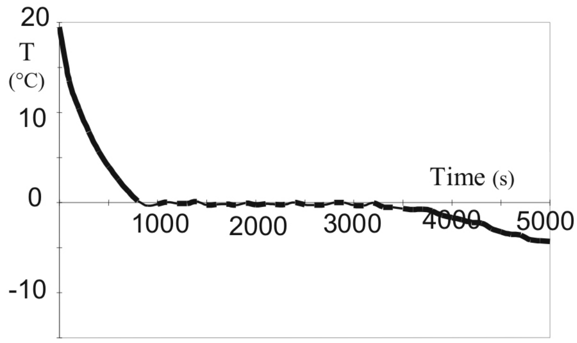
Cooling tests, carried out in a thermostated bath, showed that no aggregation appears when the slurry was placed under mixing (even weak). No difficulties are observed if a stagnant slurry is mixed again (for periods up to 60 min). On the other hand, an aggregation of the particles appears when the phase change liquid-solid is carried out without mixing. The phenomenon of aggregation is related to the dendritic form of the ice. Dendrites have the possibility of developing out of the polymeric matrix. Links between particles can thus be established if the slurry is placed without agitation. These links will be all the more easy to break that the size of particles is important.

Supercooling phenomena

Fig. 4 presents examples of recording of the temperature of slurry subjected to a cooling in a very slightly agitated tank. The slurry is characterized by the size from their particle respectively 0.6 mm (Fig. 4, *a)* and 2 mm (Fig. 4, *b*). It can clearly seen that supercooling occurs during the freezing process for slurry which average size of particle is 0.6 mm. The degree of supercooling is about 2 °C for this example.



a



b

Fig. 4. *Cooling of the slurry in an agitated tank*

This delay with solidification is related mainly to the size of the particles [11, 12]. For an average mean size higher than 1mm, the fluid does not present practically any supercooling when the fluid is mixing.

Principal advantages of the slurry

For the purpose of air-conditioning applications, the use of the slurry instead of conventional chilled water presents several advantages. The principal ones of them are those of ice slurry. One can quote in particular:

1) the quasi-constancy of the temperature in the whole of the circulating pipe;
2) a circulation under a range of pressure close to the atmospheric pressure;
3) high heat transfer coefficient because of the presence of the liquid phase;
4) the possibility of making energy storage.

The other advantages which are specific to this slurry are:

a) a constant weight fraction in the circulating pipe;
b) more significant weight fraction (> 35 per cent) by the polydispersity of the PCM particles;
c) the absence of a generator of ice. A passage though a heat exchanger surface (evaporator) is enough to reload the slurry in "ice".
In addition, these advantages create considerable interest in this slurry-based air conditioning.

Concluding remarks

A prototype of slurry is presented as a potential working fluid for district cooling and air conditioning process. This double-phase fluid consists of particles of a gel containing a water concentration close to 90 per cent, dispersed in a carrier fluid with adjusted density and viscosity. This mixture is presented as a suspension of aqueous gel in oil for the temperature $T > 0$ °C, and as a suspension of gel of ice in oil for the temperature $T < 0$ °C.
The thermal parameters of this slurry are very near of those ice slurry, described in literature (for example [4, 13]). Its originality and its principal advantage is becoming from the classic heat exchanger surface used to store the latent cold heat.
Research is continuing on this slurry in order to determine other properties as heat transfer coefficient, pressure drop and flowability for different configurations.

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