A THERMODYNAMIC PARAMETER TO CHOOSE SECONDARY COOLANT FLUID

G. Grazzini, P. Ferraro
Dipartmento di Energetica, Via Santa Marta, 3,
50139 Firenze, Italy. e-mail: ggrazzini@ing.unifi.it

ABSTRACT

The heat exchange coefficient of ice slurry is higher than that of the mono-phase fluid. Conversely the ice crystals presence increases pressure losses that are growing with the ice concentration.
We defined two parameters considering entropy variation that provide the possibility to compare the ice slurries to the mono-phase solutions. The first is the ratio between ΔS and the heat exchanged. The second is the ratio between ΔS and the maximum entropy variation when the exchanged heat in the heat exchanger is transferred at the constant inlet temperature of the two streams. Those two parameters show the ice slurry is better than the liquid solution.

INTRODUCTION

Recently several different kinds of secondary fluids have been studied, as consequence of the indirect refrigeration systems development. In particular two-phase solutions, known as ice slurries, composed by water and an addictive (usually ethylene glycol or ethanol) and very small ice crystals, are very interesting.

The presence of ice in this solution allows transferring more cooling energy per unit of mass than a usual liquid solution. Then lower flow rate, and lower pumping power and pipe diameters are needed.

It is possible to design the plant keeping near constant temperature in the heat exchanger, obtaining better heat exchange conditions and smaller heat exchangers using ice slurries.

Many researchers demonstrate that the heat exchange coefficient of an ice slurry, because of the presence of ice crystals, is higher than that one of the mono-phase fluid and can be even higher than heat transfer coefficients of evaporation and/or condensation of some refrigerants (Paul, 1994).

Instead of this positive aspects, the presence of ice crystal implies an increase of pressure losses as showed by the correlations obtained from experimental data (Snoek et al., 1995, Liu et al., 1997, Bel and Lallemand, 1999)

The values obtained by those correlations clearly show that pressure losses of the ice slurry increase when growing the addictive concentration or the ice concentration.

1 INTRODUCTION OF A THERMODYNAMIC PARAMETER

Struggling effects, a better heat exchange and higher pressure losses, require evaluation criteria to choose which fluid have to be used. This work provides a parameter to consider both these phenomena and to compare the ice slurries and other mono-phase solutions.

Referring to an infinitesimal length of a heat exchanger, the entropy generation rate of the two streams is given by:

$$dS = \dot{m}_h ds_h + \dot{m}_c ds_c \tag{1}$$

where the heat transfer to the environment is disregarded and $\dot{m}_h$ and $\dot{m}_c$ are the mass flow rates.

Expressing the local entropy variation as:

$$ds = c_p \, dT/T - \left(\partial v/\partial T\right)_p dp \tag{2}$$

integral expression of each stream is:

$$\Delta S = \dot{m}\left(c_p \ln(T_o/T_{in}) - \int_{in}^{o}(\partial v/\partial T)_p\, dp\right) \tag{3}$$

Considering only one stream of the exchanger, the entropy variation per unit of exchanged heat, the proposed thermodynamic parameter, is:

$$\frac{\Delta S}{Q} = \frac{\dot{m}}{Q}\cdot\left(c_p \ln\left(\frac{T_o}{T_{in}}\right) + \frac{\beta\cdot\Delta p}{\rho}\right) \tag{4}$$

where β, the fluid volumetric expansion coefficient, and the density ρ are assumed constant along the considered length.

2 PARAMETER EVALUATION OF AN ICE SLURRY

The ice slurry entropy variation is given by two terms, eq.(3), the first function of temperatures (ΔS_t), the second of pressure losses (ΔS_p)

$$\Delta S_t = \dot{m}\cdot c_p^* \cdot \ln\left(\frac{T_o}{T_{in}}\right) \tag{5}$$

$$\Delta S_p = \dot{m}\cdot\frac{\beta}{\rho}\cdot\Delta p \tag{6}$$

Where c_p^* is evaluated as $Q/(\dot{m}(T_o - T_{in}))$. The ice slurry pressure losses Δp can be roughly calculated using the same relations of a liquid solution (Grazzini and Ferraro, 1999, Cavallini and Fornasieri, 2000).

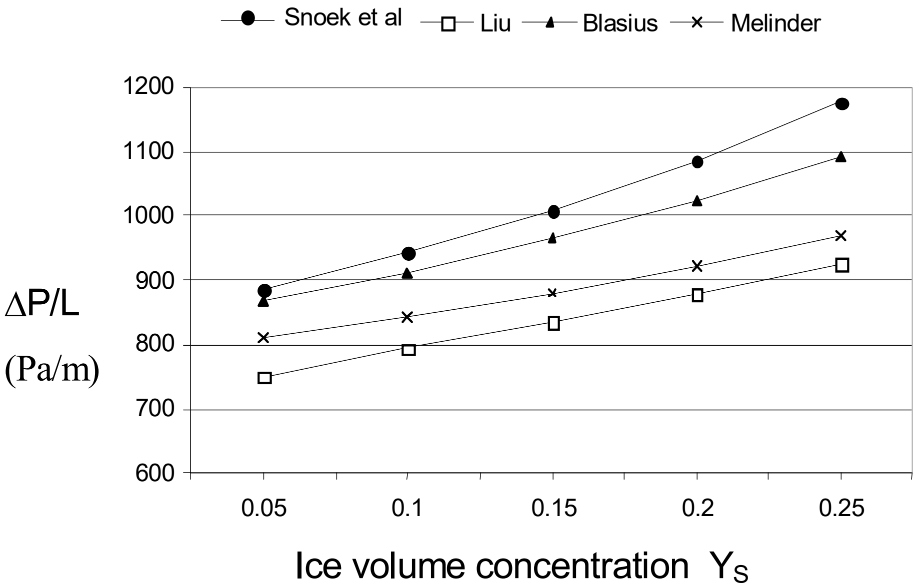

Figure 1 - Pressure losses given by different relations for ice slurries with 20 % ethylene glycol.

Figure 1 shows the pressure losses for ice slurry containing 20 % ethylene glycol, versus the ice concentration. The considered relations are the Blasius equation, one by Melinder (1997) for liquid solutions, and those experimental by Snoek et al. (1995) and by Liu et al. (1997).
When the flow rate is evaluated as:

$$\dot{m} = \frac{Q}{L_f \cdot \Delta X_S + c_p (T_o - T_{in})} \tag{7}$$

with c_p inlet value for multiphase fluid, then eq. (4) becomes:

$$\frac{\Delta S}{Q} = \frac{c_p^* \ln\left(\frac{T_o}{T_{in}}\right) + \frac{\beta}{\rho} \cdot \Delta p}{L_f \cdot \Delta X_S + c_p (T_o - T_{in})} \tag{8}$$

This equation shows that the ice slurry inlet temperature reduction increases the ΔS/Q quantity, for a fixed inlet X_S. Ice slurries with the same ice fraction, and exchanging the same thermal power, show smaller ΔS/Q when their inlet temperature is bigger.
The volumetric expansion coefficient β ($10^{-4} \div 10^{-5}$ order of magnitude) and Δp values imply that the contribution of ΔS_p to the total entropy variation is very small in comparison with ΔS_t. A good evaluation of ΔS for ice slurry, according to the variation of his characteristics, can be obtained considering only ΔS_t contribution. In particular we can evaluate, what happens decreasing the inlet temperature T_{in}, with constant average difference ΔT_m between temperatures of the two fluids inside the heat exchanger. As a consequence eq. (8) is simplified:

$$\frac{\Delta S}{Q} = \frac{c_p^* \ln\left(\frac{T_o}{T_{in}}\right)}{L_f \cdot \Delta X_S + c_p (T_o - T_{in})} \tag{9}$$

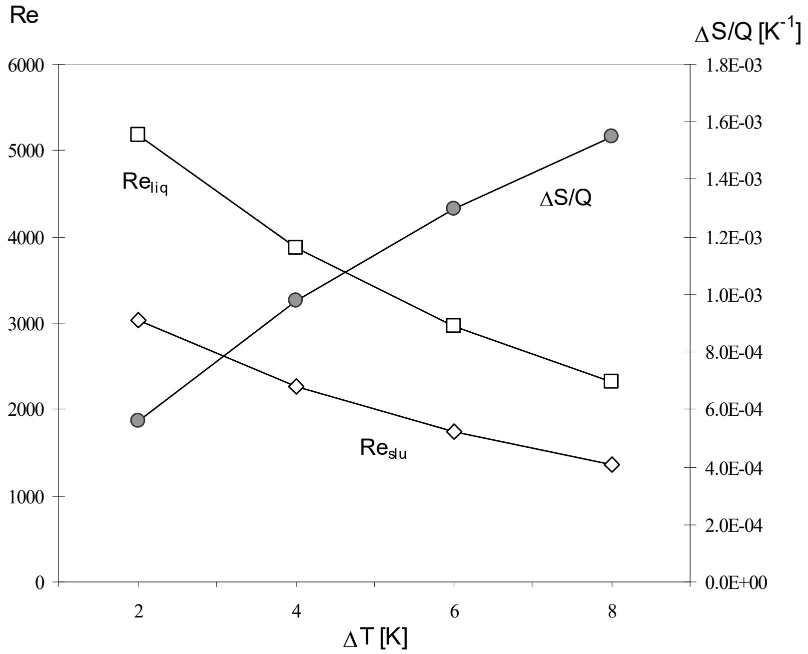

Figure 2 - ΔS/Q from eq.(9), and Re for the ice slurry (Re_{slu}) and for the liquid (Re_{liq}) versus ΔT for an ice slurry with inlet X_S = 0,15 (Q = 50 kW).

Figure 2 shows ΔS/Q, for a thermal power of 50 kW, as function of the difference ΔT between inlet and outlet temperatures in the heat exchanger, when the inlet ice fraction is $X_S=0.15$, function of T. At a fixed ethanol concentration C_{slu}, and considering eq. (7), the T_{in} decrease implies, not only a rise in ΔT, but also in the ice fraction X_S. Then the ΔS/Q function is different. Re_{slu} and Re_{liq} are evaluated changing kinematic viscosity.

Figures 3a and 3b show the presence of a minimum for ΔS/Q, with the solution in laminar or turbulent regime according with the increase of the exchanged thermal power Q.

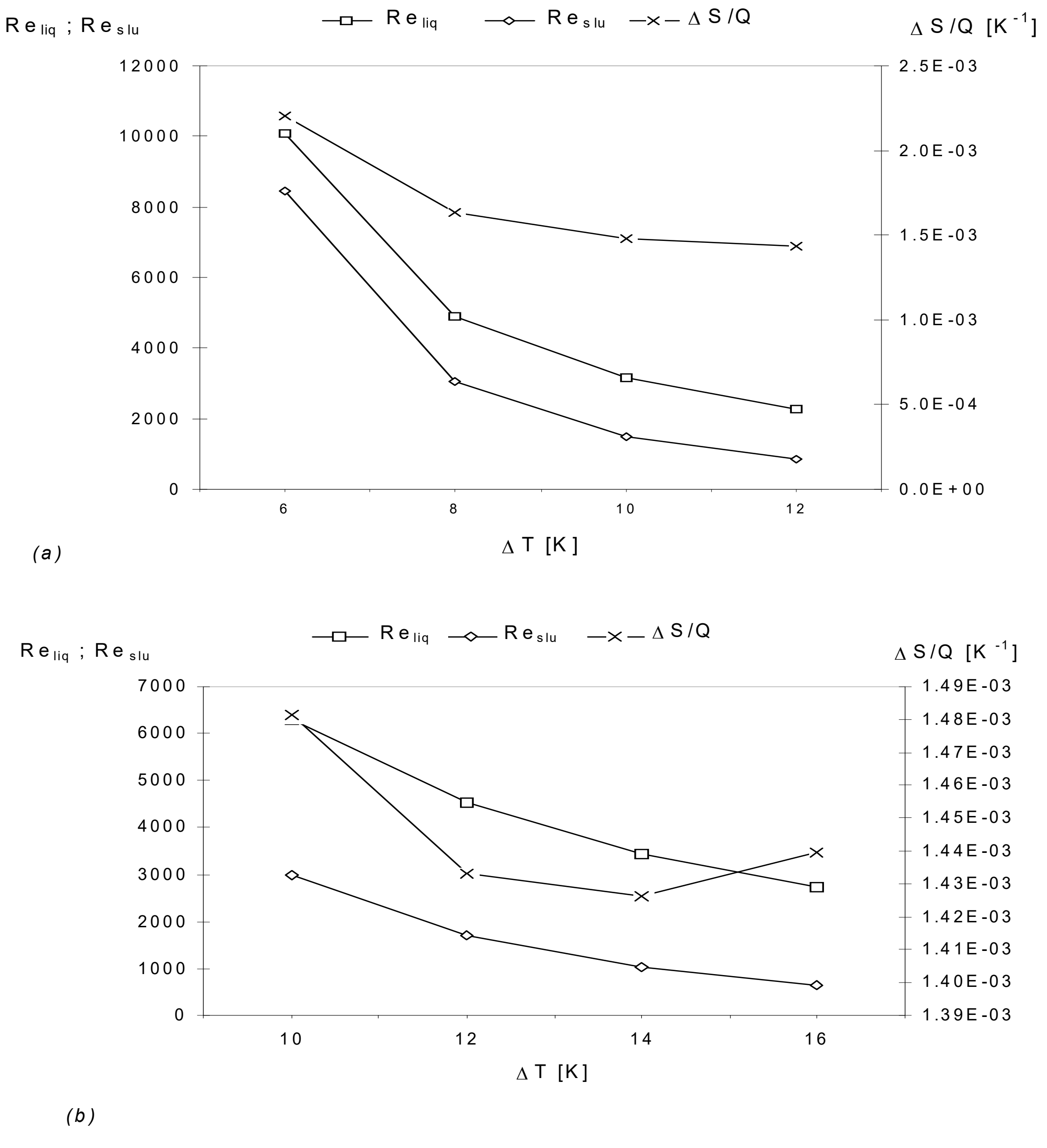

Figure 3 - ΔS/Q, Re for ice slurry (Re_{slu}) and liquid phase (Re_{liq}) versus ΔT for an ice slurry with C_{slu} =15 %; ((a): Q = 50 kW; (b): Q =100 kW).

The heat transfer coefficient of ice slurries can be calculated by the correlations given by Christensen and Kauffeld (1997):

$$\mathrm{Nu}_{slu} = \mathrm{Nu}_{fl} \cdot \left(1 + 0.103 \cdot X_s - 2.003 \cdot \mathrm{Re}_{slu}{}^{-0.192 \cdot (30-i)/30} \cdot X_s^{0.339 \cdot (\mathrm{Re}_{slu}/10000)}\right) X_S > 5\ \% \qquad (10)$$

$$\mathrm{Nu}_{slu} = \mathrm{Nu}_{fl} \qquad X_S < 5\ \% \qquad (11)$$

Using thermal conductivity of the ice slurry λ_{slu}, the heat transfer coefficient is:

$$\alpha_{slu} = \frac{Nu_{slu} \cdot \lambda_{slu}}{D_i} \tag{12}$$

The λ_{slu} is obtained considering the ice slurry a combination of a pure solid phase, the ice, and a liquid phase, the binary solution. Thermal conductivity λ_m of the solution liquid phase is obtained by the Filipov equation (Bel et al., 1995, Cavallini and Fornasieri, 2000):

$$\lambda_m = g_1 \lambda_1 + g_2 \lambda_2 - 0{,}72 \cdot g_1 g_2 \cdot (\lambda_2 - \lambda_1) \tag{13}$$

with $\lambda_2 > \lambda_1$, where respectively g_1, g_2, λ_1, λ_2 are the mass fraction and thermal conductivity the two solution components. The two-phase properties are considered by :

$$K = 1 + 3\,\beta\, Y_S + 3\,\beta^2\, Y_S{}^2\, \Phi \tag{14}$$

where:

$$\Phi = 1 + \frac{\beta}{4} + \frac{3\,\beta \cdot (\alpha + 2)}{16 \cdot (2\,\alpha + 3)}; \qquad \beta = \frac{\alpha - 1}{\alpha + 2} \quad ; \quad \alpha = \frac{\lambda_S}{\lambda_{fl}} \quad ; \quad K = \frac{\lambda_{slu}}{\lambda_{fl}} \tag{15}$$

λ_{fl}, calculated as λ_m from eq.(13), is used in eq.s (14-15) to obtain λ_{slu} value, that gives α_{slu} throughout eq. (12).

3 COMPARISON BETWEEN AN ICE SLURRY AND A LIQUID SOLUTION

Herein the comparison between ice slurry and a liquid solution considering a tubular heat exchanger having n pipes, with inside diameter D_i and thickness s is shown. The warmer fluid with constant temperature T_A and fixed heat transfer coefficient α_e (Table 1) are the conditions assumed.
At given ΔT_m , average temperature difference between warm and cool fluid, the exchanged heat is obtained by :

$$Q = UA \cdot \Delta T_m = UA \frac{T_A - T_{in} + T_A - T_o}{2} \tag{16}$$

$$Q = \dot{m} \cdot \left(c_p (T_o - T_{in}) + L_f \cdot \Delta X_S\right) \tag{17}$$

$$\frac{1}{UA} = \frac{1}{\alpha_i \cdot \pi \cdot n \cdot D_i \cdot L} + \frac{1}{\alpha_e \cdot \pi \cdot n \cdot (D_i + s) \cdot L} \tag{18}$$

neglecting thermal resistance of the pipes wall. A fourth equation can be obtained also searching minimum pressure losses or the increase of the entropy.
Figure 4 shows the comparison between an ice slurry with inlet mass ice fraction $X_S = 0.2$ and a liquid solution containing 20 % ethanol. This comparison considers an inlet-outlet ice slurry temperature difference of 0.5 °C and then the pipes length L and $\Delta S/Q$ for the two-phase solution can be obtained. The same heat exchanger, with defined dimensions, is used to evaluate a liquid solution substituting related thermophysic parameters in the equations (16-18).
Ice slurry has to be preferred to a monophase solution because figure 4 shows values of the ratio $(\Delta S/Q)_{liq} / (\Delta S/Q)_{slu}$ bigger than one.
The discontinuities in the graph are due to the boundary conditions change and in particular to the pipe diameter changes (table 1) at 150 and 230 kW .

Antifreeze	Ethanol
Antifreeze percentage in the liquid solution	20 %
Mass ice fraction (X_S)	0.2
Average temperature difference (ΔT_m)	15 K
Hot fluid temperature (T_A)	283 K
Inside pipe diameter (D_i)	0,020 m (50 kW ≤ Q ≤ 150 kW) 0,025 m (150 kW < Q ≤ 230 kW) 0,030 m (230 kW < Q ≤ 290 kW)
Pipe number (n)	3
Pipe thickness (s)	0,002 m
α_e	3000 W/(m^2 K)

Table 1 - Common values used in figures 4 and 5.

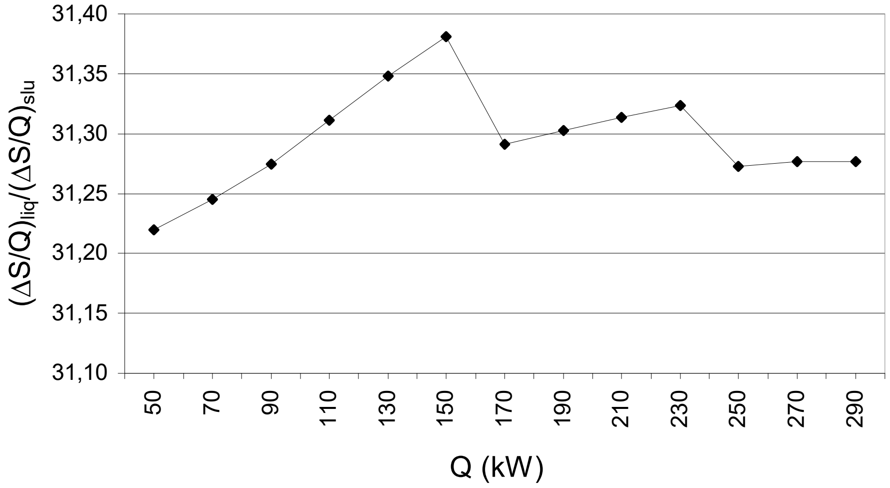

Figure 4 - $(\Delta S/Q)_{liq}/(\Delta S/Q)_{slu}$ versus Q for an ice slurry ($X_S = 0,2$) and a mono-phase solution with 20 %ethanol. Temperature difference of 0,5 °C is assumed for the ice slurry.

The ratio $\Delta S/Q$ have the dimension of a temperature. It is possible to consider a dimensionless ratio $\Delta S/\Delta S_Q$ introducing (Grazzini and Gori, 1988):

$$\Delta S_Q = Q \cdot \left(\frac{1}{T_{in}} - \frac{1}{T_A} \right) \tag{20}$$

This is the entropy variation that could be obtained by direct heat transfer between inlet streams at constant temperature.

Figure 5 shows the comparison between the fluids studied using this new parameter. The ice slurry is always to be preferred.

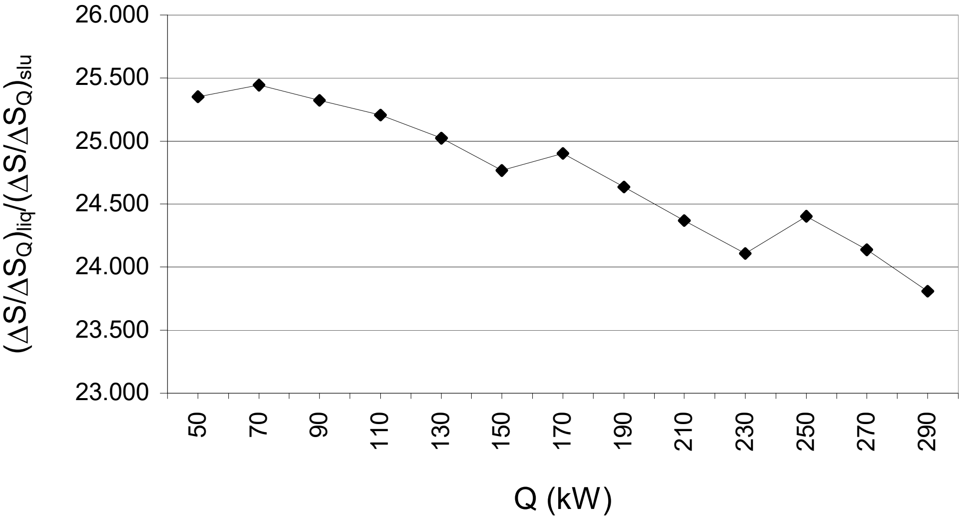

Figure 5 - $((\Delta S/\Delta S_{Q})_{liq}/(\Delta S/\Delta S_{Q})_{slu})$ versus Q for an ice slurry ($X_S = 0,2$) and a mono-phase solution with ethanol 20 %. Temperature difference of 0,5 °C is assumed for the ice slurry.

4 DISCUSSION

The proposed parameter can consider all the effects due to ice in the solution, the entropy production due to pressure losses and temperature differences. The above examples show the superiority of the ice slurries against the mono-phase solutions. The results are in agreement with those of Cavallini and Fornasieri (2000) that consider a parameter based mainly on pressure losses. As secondary fluid ice slurry is an heat carrier, so the influence of heat exchange can not be avoided when we have to choose between different fluid. Figures 4 and 5 could be obtained as ratio between the entropy generation of the two streams. The parameter we propose could be also useful to compare more than two fluids and to optimise heat exchangers (Grazzini and Gori, 1988) and related plants.

NOMENCLATURE

A	heat exchanger surface	(m^2)
C	antifreeze concentration	(%)
c_p	specific heat	$(J\ kg^{-1}\ K^{-1})$
D	pipe diameter	(m)
L	pipe length	(m)
L_f	heat of fusion	$(J\ kg^{-1})$
$\dot{m}$	mass flow rate	$(kg\ s^{-1})$
p	pressure	(Pa)
Q	heat power	(W)
Re	Reynolds number	
S	entropy	$(J\ K^{-1})$
T	temperature	(K)
U	global heat transfer coefficient $(WK^{-1}m^{-2})$	
v	specific volume	(m^3/kg)
X	mass fraction	
Y	volume fraction	

Greek symbols

α	heat transfer coefficient	$(WK^{-1}m^{-2})$
β	volumetric expansion coefficient	(K^{-1})
λ	heat conductivity	$(WK^{-1}m^{-1})$
ρ	density	(kg/m^3)

Subscripts

e	external
fl	liquid phase
i	internal
in	inlet
o	outlet
m	mean
S	ice
slu	ice slurry

REFERENCES

[1] Bel, O., Beron, R., Lallemand, A., 1995, Determination des proprietes thermophysiques d'un melange frigoporteur solide-liquide utilisé dans une boucle de refroidissement, *Proc. 19th Intern. Cong. of Refrig.*, vol. II, The Hague, The Netherlands, IIF/IIR, pp. 43-50.

[2] Bel, O., Lallemand, A., 1999, Etude d'un fluide frigoporteur diphasique - 2:Analyse expérimentale du comportement thermique et réologique, *Int. J. Refrig,* vol. 22, pp.175-187.

[3] Cavallini, A., Fornasieri, E., 2000, L'impiego del ghiaccio fluido (sospensione acqua-ghiaccio) nella refrigerazione, *Proc. 41° Conv. Ann. AICARR*, Milano, pp.475-508.

[4] Christensen, K. G., Kauffel, M., 1997, Heat transfer measurements with ice slurry, *Heat transfer issues in natural refrig.*, College Park, USA, IIF/IIR, pp. 161-175.

[5] Grazzini, G., Ferraro, P., 1999, Il calcolo delle perdite di carico di un fluido secondario, Zerosottozero, n. 4, pp.76-80.

[6] Grazzini, G., Gori, F., 1988, Entropy parameters for heat exchanger design, *Int. J. Mass Transfer.*, Vol. 31, n. 12, pp. 2547-2554

[7] Liu, D., Zang, E. Z., Zhao, J. M., Chen, P. L., 1997, Experiment study on friction loss characteristic of pipes with ice slurry, *Air condit. in high rise build. '97*, Shanghai, P. R. China, IIF/IIR, pp. 495-499.

[8] Melinder, A., 1997, *Thermophysical properties of liquid secondary refrigerants*, IIF/IIR, Paris.

[9] Paul, J., 1994, "Binary Ice", un metodo alternativo di refrigerazione, *Il Freddo*, n. 2, pp. 163-172.

[10] Snoek, C. W., Joanis, S. U., Gupta R. P., 1995, Pressure drop characteristics of ice-water flows, *Proc. Intern. Symp. on two-phase flow modelling and experim.*, Rome, pp. 655-662

UN PARAMETRE THERMODYNAMIQUE POUR CHOISIR UN FLUIDE REFRIGERATEUR SECONDAIRE

RESUME : Le coefficient d'échange thermique est plus grand pour un coulis de glace que pour un fluide monophasique. D'abord la présence de cristaux de glace donne des chutes de pression plus grandes quand la concentration de la glace augmente. Nous avons défini deux paramètres qui considèrent la variation d'entropie et qui donnent la possibilité de confronter les coulis de glace et les solutions monophasiques. Le premier est le rapport entre ΔS et la chaleur échangée; le second est le rapport entre ΔS et la variation maximum obtenue les deux courants de fluide restant à la même température. Les deux paramètres montrent que le coulis est préférable à la solution liquide.