MODIFICATIONS IN THE THERMOPHYSICAL PROPERTIES OF THE PROPYLENE GLYCOL-WATER SOLUTION BY ADDITION OF ICE CRYSTALS AS SECONDARY COOLANT

Pedro Samuel Gomes Medeiros, falecom-pedro@hotmail.com
Cleiton Rubens Formiga Barbosa, cleiton@ufrnet.br
Francisco de Assis Oliveira Fontes, franciscofontes@uol.com.br
Federal University of Rio Grande do Norte, Energy Laboratory, Thermal Systems Studies Group, Natal-RN, Brazil.

Abstract. *This paper makes an analysis of thermophysical properties of propylene glycol-water solution with the addition of ice crystals, consisting in a two-phase system as secondary coolant, called ice slurry. This new technology has shown great energy potential: beside transport energy as a heat transfer fluid, it has thermal storage property through the presence of ice storing cool by latent energy of fusion. The water-propylene glycol solution is the reference, which also function as carrier fluid in the ice slurry. The presence of ice changes the thermophysical properties of aqueous solution and some ones were determined: density, thermal conductivity and dynamic viscosity. Data were obtained by software simulation. The results indicate that presence of ice at a least concentration 1% by ice mass provides increased thermal conductivity and dynamic viscosity, without to express changes in density. With 20% ice mass, the thermal conductivity increases almost 45% compared to single-phase fluid, and the viscosity is increased 57%. The rheological behavior of ice slurry associated with its high viscosity requires a higher pumping power, which was not significant because, by having a higher thermal conductivity, allows a lower mass flow rate without the use of larger pumps. Thus, the ice slurry ensures its high potential as a two-phase secondary coolant in cool thermal storage systems, showing to be more efficient than single-phase fluids.*

Keywords*: Secondary Coolants, Thermophysical Properties, Propylene Glycol, Ice Slurry*

1. INTRODUCTION

The industrial refrigeration processes and air conditioning systems that operate by expansion-indirect with cool thermal storage use secondary coolants to transport the cool from tank storage to refreshed place. The selection of fluid is total importance for thermal efficiency in heat transfer process. The main thermophysical properties involved in the selection are melting point, density, specific heat, thermal conductivity and dynamic viscosity (Dinçer, 2003; Stoecker, 1998).

Water is known for its thermal and transport properties that satisfy its application as a heat transfer fluid, except for the fact that most industrial process refrigeration works in temperatures below melting point of water (Dossat, Horan, 2001). Thus, the addition of a soluble antifreeze additive generates a homogeneous solution able to solidify at temperatures below the melting point of pure water, composing a secondary coolant.

Currently, the secondary coolants most used are composed by water and antifreeze alcoholic. The brines were replaced by these solutions mainly ones make little or no corrosive activity, unlike the salts that are highly corrosive (Fink, 2003).

The antifreezes modify the thermophysical properties of water: there are changes in density, losses in the thermal conductivity and specific heat, and increase of dynamic viscosity (Ashrae, 2009; Melinder, 2007). These changes cause a lower thermal inertia, reducing the ability to heat transfer and thermal energy storage, and increased pumping power.

The thermal conductivity of a fluid could be improved if there is heat transfer in the form of latent energy of fusion, which is only possible after the introduction of phase change materials in the solution. The main emphasis is in the ice slurry that is a suspension of ice crystals dispersed in carrier fluid (Ashrae, 2008), which that carrier fluid is composed by water and antifreeze. Thus, the ice slurry is a two-phase system.

The mass concentration of ice depends on the technology used in slurry production, ranging between 2% to 10% or higher (Ashrae, 2008). Its thermophysical properties are geometry function and crystals size with a diameter smaller than 1 mm (Egolf, Kauffeld, 2005). In the Figure 1 is shown the microscopic photographic of ice particles.

The presence of ice microcrystals, in addition to improving the thermal conductivity, also changes the other thermophysical properties, which are proportional to the increased concentration of ice crystals.

The purpose of this research is to verify the behavior of water-antifreeze solution and its changes in the properties, function of the concentration of ice crystals added.

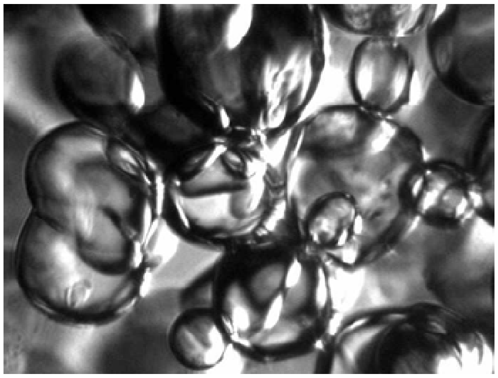

Figure 1. Microscopic photographic of ice crystals (Egolf, 2004).

2. METHODOLOGY

The data about thermophysical properties of secondary coolants and ice slurries were obtained by SecCool, a software developed by the Department of Mechanical Engineering at University of Denmark. This software contains a library with thermophysical properties of secondary fluids based mainly on the experimental parameters of ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers), and Ake Melinder, a researcher at the Department of Energy Technology at Royal Institute of Technology in Sweden.

For effect comparison, the solution without ice (single-phase system) was considered as the reference and related fluids containing ice crystals (two-phase system), quantifying the percentage difference among their properties. The single-phase secondary coolant analyzed is the water-propylene glycol solution, in mass solute concentration is 25%. Ice slurry studied is the aforementioned single-phase solution with ice added in the content of 1%, 10% and 20% by mass.

The thermophysical properties examined are density (thermodynamic property), thermal conductivity and dynamic viscosity (transport properties). These properties, respectively, refer to the amount of fluid occupied in the tank, its ability to transfer heat and its resistance to flow. The temperature analysis of the properties for all samples is -10 °C, temperature corresponding when the ice slurry tends to solidify for the value quoted depending on the concentration of the freezing point depressant additive. That temperature analysis is applied within the range of cool thermal storage systems.

The propylene glycol selection as an antifreeze is justified by the vast potential for commercial application of this product. Propylene glycol (1,2-propanediol) is a nontoxic glycol alcohol, with a melting point of -59 °C and low vapor pressure, which favors its use as antifreeze (Solomons, Fryhle, 2007), modifying the colligative properties of water. Ethylene glycol, for be toxic glycol alcohol, is being replaced by nontoxic products favoring the use of propylene glycol (Fink, 2003).

With these data, tables and graphs were developed to verify and to explore the influence of ice in single-phase coolant.

3. RESULTS AND DISCUSSION

From the data obtained in the software SecCool, is shown in Table 1 the numerical values of the thermophysical properties of fluids analyzed:

Table 1. Termophysical Properties of Single-phase Fluid and Ice Slurries

Sample	Thermophysical Properties (-10 °C)		
	Density (kg/m³)	Thermal Conductivity (W/m.K)	Dynamic Viscosity (cP)
Water/Propylene glycol-25%	1,027.7	0.4411	9.29
Ice Slurry-01%	1,026.5	0.4499	9.57
Ice Slurry-10%	1,015.3	0.5334	11.98
Ice Slurry-20%	1,003.1	0.6369	14.60

Based on these data, Table 2 presents the percentage difference of thermophysical properties of the ice slurry compared to the single-phase fluid:

Table 2. Relationship among Termophysical Properties of Single-phase Fluid and Ice Slurries

Relationship	Thermophysical Properties		
	Density (%)	Thermal Conductivity (%)	Dynamic Viscosity (%)
Ice Slurry-01% / Water-Propylene glycol	-0.12	2.00	3.01
Ice Slurry-10% / Water-Propylene glycol	-1.20	20.92	28.96
Ice Slurry-20% / Water-Propylene glycol	-2.38	44.39	57.16

By means of these tables, each property was analyzed separately:

3.1 Density

The density is defined as the amount of existing mass in unit volume. It is desirable that secondary fluid have density as high as possible, because, besides reducing the size water tank, presents properties of heat transfer more efficient when it comes to the of thermal diffusivity property.

Single-phase fluids have density greater than water because the solutes, that they are denser, make the fluid with higher density. The presence of ice in single-phase fluids, even in microscopic size and in small amounts, changes the density of the solution (figure 2).

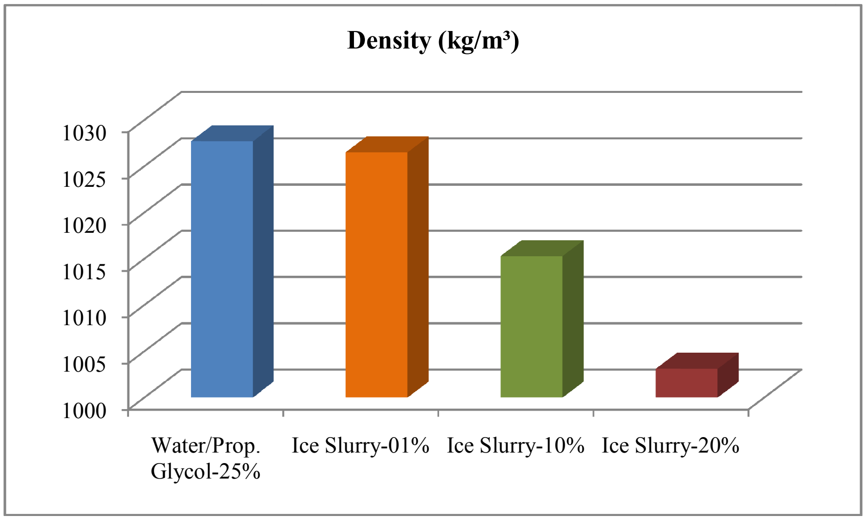

Figure 2. Density values of secondary coolants with and without ice crystals.

The ice has a density of 921 kg/m³ at 273 K (Çengel, Boles, 2006), i.e., less dense than pure water (1,000 kg/m³). As can be seen in tables 1 and 2, the density of ice slurry is lower than that of single-phase fluid. However, the addition of ice did not change in a significant way the values: the largest reduction is 2.38% for solution at 20% by ice mass.

Therefore, as there was no significant change in density with the addition of ice, there is no influence of density for the thermal diffusivity of the solution and water tanks do not suffer changes in their sizes for the same amount of fluid.

3.2 Thermal Conductivity

Thermal conductivity is a transport property characteristic of each substance, which indicates the rate at which a given material can transport energy under certain conditions of geometry and temperature. The mechanism of heat transfer in a solid is well defined and occurs through vibrations in its crystal structure, and in the case of metals, is complemented by the movement of free electrons present in the network, whereas the heat transfer mechanism in liquids is similar to those of gases, by molecular collisions and molecular diffusion (Çengel, 2007).

In this study is analyzed single-phase and two-phase secondary coolant, in which the mechanisms involved in heat transfer are different: for single-phase fluids, the transmission is through exchange of sensible heat until it reaches the melting point or boiling fluid; in ice slurry there is exchange of both sensible and latent heat in the fluid. The mechanism of ice slurry is characterized as a heat transfer in a multiphase system, i.e., with liquid phase (water-antifreeze) and solid phase (ice).

The latent heat absorbed by ice crystals is higher than the sensible heat absorbed by the single-phase solution, and this latent heat absorbed is proportional to the mass concentration of ice. The thermal conductivity of ice at 0 °C is 1.88 W/m.K, and -20 °C is 2.03 W/m.K (Cengel, 2007). Pure water at 0 °C has a thermal conductivity of 0.561 W/m.K and single-phase water-propylene glycol at 0 °C and -10 °C has a conductivity of 0.4503 W/m.K and 0.4411 W/m.K, respectively.

This proves why the addition of ice in single-phase fluid increased the thermal conductivity: to 10% by mass of ice, the increase is from 20.92%, and to 20% of ice conductivity increases 44.39%. The amount of 1% ice, considered insignificant 2% improvement in conductivity, showing that even small amounts beneficially affect the thermal conductivity of the solution (figure 3).

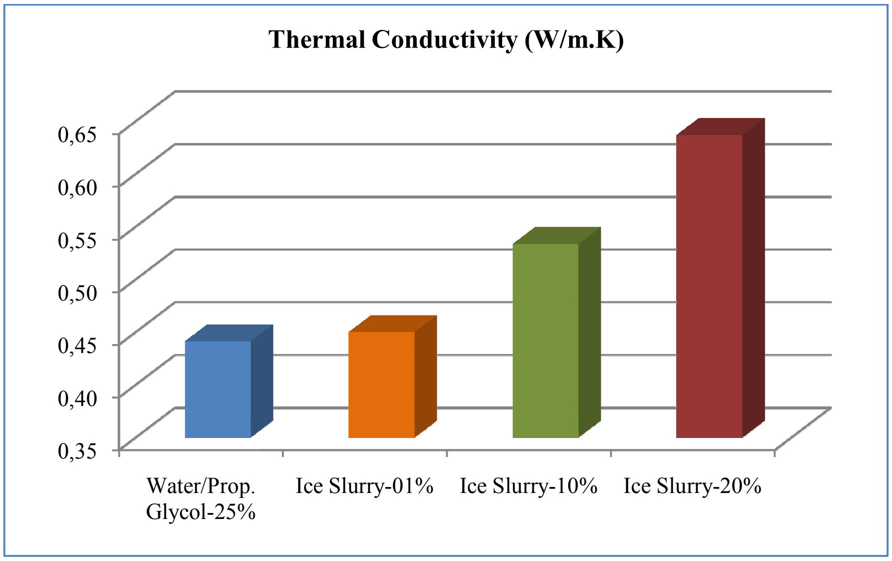

Figure 3. Thermal Conductivity values of secondary coolants analyzed

Another relevant factor for the increase of thermal conductivity in ice slurry is larger area of heat transfer by ice crystals. The thermal conductivity of two-phase solution is related to the fine ice particles dispersed in the fluid carrier and it is a function of their respective size (Ticona, 2007).

Therefore, the thermal conductivity property of the ice slurry is associated with ice crystals, because the latent heat of fusion and the greater area of heat exchange are crucial for greater efficiency in heat transfer compared to conventional single-phase fluids.

3.3 Viscosity

The dynamic viscosity is a transport property related to the internal resistance to fluid flow caused by cohesive forces among fluid molecules (Çengel, Cimbala, 2007). As was discussed in the topic thermal conductivity, the ice slurry is regarded like a multiphase system, with different behavior of the single-phase fluids when subjected to flow.

Unlike single-phase fluids, multiphase fluids require higher flow velocities mainly to support the solid particles in suspension. The single-phase fluid flow is homogeneous for all speeds imposed, unlike multiphase fluid behavior that have heterogeneous and can exhibit rheological properties of non-Newtonian fluids (Crowe, 2006).

The ice slurry is a non-Newtonian fluid and is treated as a viscoplastic fluid rheologically stable (Niezgoda-Zelasko, Zelasko, 2009). The most of single-phase systems behaves like a Newtonian fluid, with constant dynamic viscosity for a given pressure and temperature working. Multiphase systems do not have a constant dynamic viscosity, i.e., there is not a constant relationship between the shear stress and shear rate, and consider the temperature and pressure to determine the viscosity of the fluid multiphase (Chhabra, Richardson, 2008).

In this analysis, it is considered that the pressure conditions are the same for all fluids. The dynamic viscosity of the ice slurry is analyzed considering the slurries behave like a Newtonian fluid, showing a apparent viscosity (Chhabra, Richardson, 2008). Viewing the Tables 1 and 2, the viscosity of the ice slurry is greater that one of single-phase fluid, which the maximum increment is 57.16% for 20% by mass of ice. The addition of 1% of ice is enough to increase by

3% the viscosity of the solution and that this rate of viscosity is increased almost ten times when there is 10% by mass of ice (figure 4).

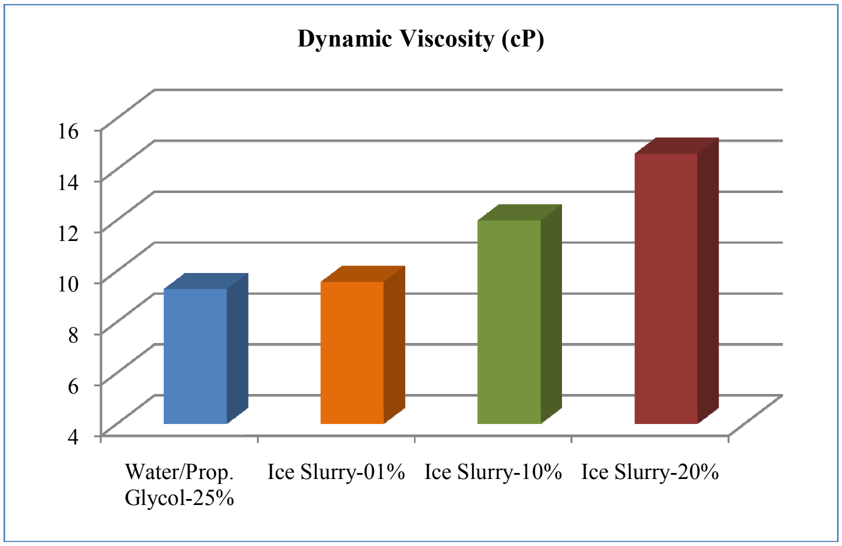

Figure 4. Data of dynamic viscosity for secondary fluids analyzed

These increases are substantial in viscosity, especially for the 20% solution of ice that it has a gain of almost 45% in thermal conductivity. The high viscosity increases the slurries are related to the size and geometry of ice crystals and their interactions with antifreeze additives. Although, they are microscopic crystals, they directly influence the viscosity and the difficulty of pumping.

Therefore, it can be stated that for the same conditions of fluid flow and single-phase and two-phase fluids, the ice slurry requires greater pumping power compared to single-phase fluids. This is justified by the high viscosity that the slurry has concomitant need for greater flow velocities.

4. CONCLUSIONS

After the comparative analysis of the ice slurry with the reference fluid (single-phase), can make several conclusions about the thermophysical properties of fluids, which they express several features for more efficient use in processes of heat transfer. The density of ice slurry is slightly lower than that of single-phase fluid, since ice is less dense than water. The reduction is not significant and there is no interference in the thermal efficiency and the constructive characteristics of the storage tanks of the refrigeration process.

The ice presence as a phase change material in two-phase fluids provides accumulation of cool thermal energy through latent heat of fusion, which also ensures a higher thermal conductivity compared to single-phase fluids. The microscopic ice crystals offer a larger heat exchange area, further increasing the power to energy transfer, primordial fact that justifies their applications.

Being a two-phase fluid, the ice slurry has unique characteristics in their flow, unlike the most of single-phase fluids that are Newtonian fluids, mainly to exhibit a much higher viscosity and variable, given the conditions of temperature and pressure. The rheological phenomena in the ice slurries are justified by the presence of ice changing all the flow conditions, requiring higher flows.

Overall, the ice slurries exhibit better properties and characteristics compared to conventional single-phase coolants that fully justify its use as a secondary fluid, despite being a new technology and little known. The main attraction is the lower costs with electric energy, installation and maintenance of refrigeration and air conditioning systems with cool thermal storage.

5. ACKNOWLEDGEMENTS

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