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Rheological Characteristics of Ice Slurries Based on Propylene- and Ethylene-Glycol at High Ice Fractions

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***Abstract*—**Ice slurries are considered as a promising phase-changing secondary fluids for air-conditioning, packaging or cooling industrial processes. An experimental study has been here carried out to measure the rheological characteristics of ice slurries. Ice slurries consist in a solid phase (flake ice crystals) and a liquid phase. The later is composed of a mixture of liquid water and an additive being here either (1) Propylene-Glycol (PG) or (2) Ethylene-Glycol (EG) used to lower the freezing point of water. Concentrations of 5%, 14% and 24% of both additives are investigated with ice mass fractions ranging from 5% to 85%. The rheological measurements are carried out using a Discovery HR-2 vane-concentric cylinder with four full-length blades. The experimental results show that the behavior of ice slurries is generally non-Newtonian with shear-thinning or shear-thickening behaviors depending on the experimental conditions. In order to determine the consistency and the flow index, the Herschel-Bulkley model is used to describe the behavior of ice slurries. The present results are finally validated against an experimental database found in the literature and the predictions of an Artificial Neural Network model.

***Keywords*—**Ice slurry, propylene-glycol, ethylene-glycol, rheology, artificial neural network.

I. Introduction

TODAY to produce cold, the choice of the appropriate refrigerant is limited. Especially since most remaining fluids, even if they do not destroy the ozone layer, are greenhouse gases. The solution is to use other fluids to transport cold. Researches have shown that ice slurry transports the cold well, is energy efficient and avoids breaks in the cold chain [1].

In recent years, there is a growing interest for two-phase refrigerants and in particular for ice slurries. They represent an alternative secondary fluid in conventional refrigeration systems. Several definitions of ice slurry have been proposed among others [2]-[4]:

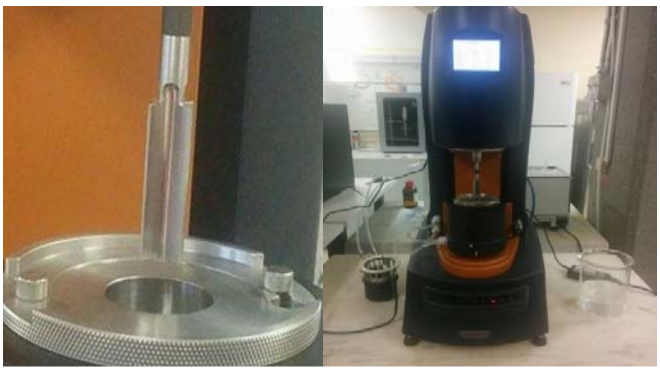
- Definition 1. Ice slurry consists of a number of ice particles in an aqueous solution.
- Definition 2. Fine-crystalline ice slurry is an ice slurry with ice particles with an average characteristic diameter, which is equal or smaller than 1 mm.

Attention needs to be given to the concentration of additives, which are commonly used in secondary refrigerants, and which affect all thermo-physical properties of the slurries like its freezing temperature. Many authors [5]-[7] have discussed the behavior of ice slurries and explained when it behaves as Newtonian or non-Newtonian fluids. Several experiments show that ice slurry behaves as Newtonian fluid at low ice concentrations, and as a non-Newtonian fluid at high ice concentrations generally up to 25% [7]. With the appearance of new ice slurry generators are able to produce more concentrated ice slurries (up to 70%); for the fishery industry especially, there is a clear need to develop new correlations for the ice slurry properties. This paper is an attempt to fill this gap for the dynamic viscosity. The objective is then to develop new correlations valid for a wider range of ice concentration, to be used in future numerical modelings.

The paper is organized as follows. First, the experimental method is described in Section II. The dynamic viscosity will be described by the Herschel-Bulkley model for steady state conditions in Section III from different rheograms for PG or EG additives and different ice fractions. Finally, the present results are validated by an experimental database available in the literature and the predictions of an Artificial Neural Network model in Section IV.

II. Experimental Apparatus

The experimental apparatus illustrated in Fig. 1 represents a Discovery Hybrid Rheometer HR-2 manufactured by TA Instrument using a vane-concentric cylinder geometry with four full-length blades.



(a) (b)

Fig. 1 (a) Discovery Hybrid Rheometer HR-2 (b) Vane-concentric cylinder geometry

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The vane geometry with a large gap is commonly used to characterize the rheology of complex fluids [8], [9]. Many studies used the vane to study concentrated aggregated dispersions [10]-[12]. According to Barnes et al. [8], [9], the vane in-cup geometry has several advantages: Shear sensitive samples can be measured without damaging their structure before testing and the gap can be sufficiently wide compared to the size of the particles.

The ice slurry generator is the 341 model developed by Taylor Bazinet. The ice concentration is controlled mainly by controlling the time to produce the slurry and by the viscous resistance during the solidification process.

III. Rheological Measurements

All measurements are performed under steady state conditions to enable to deduce the most appropriate rheological law describing the viscous behavior of ice slurries. Note that the elastic component of ice slurries is negligible.

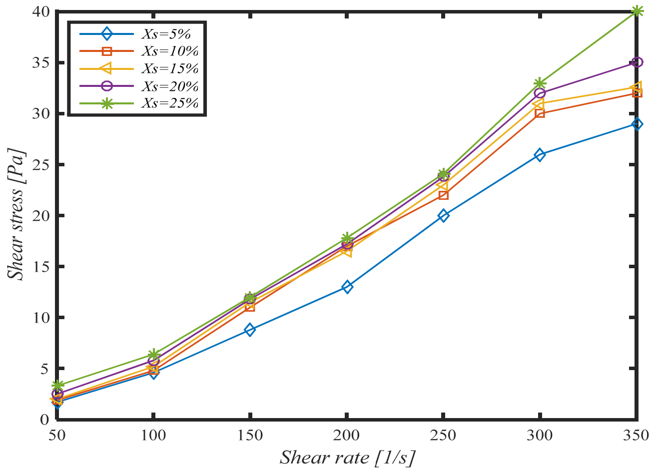

Fig. 2 Variation of the shear stress vs. shear rate for Xi=24% PG at low ice fractions *Xs*.

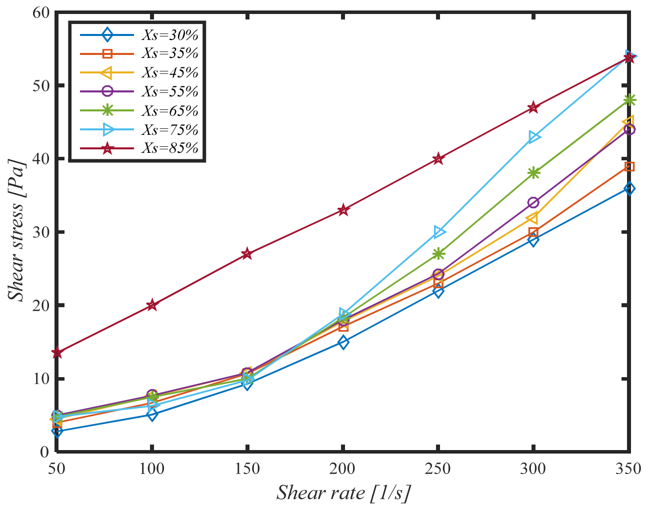

Fig. 3 Variation of the shear stress vs. shear rate for Xi=24% PG at high ice fractions *Xs*.

Figs. 2-5 show the evolution of the shear stress against the shear rate for a fixed initial concentration of EG and PG Xi=24% and for ice fractions ranging from 5% to 85%. It is observed that the shear stress increased with the shear rate for each case. As expected, the experimental rheograms obtained show that the ice slurry exhibits a non-Newtonian behavior, the flow changes from thickening to shear thinning as the ice fraction increases confirming previous results of [13]-[15]. It is also noticed that when the additive concentration is equal to 24%, the ice slurry behaves similarly to a Newtonian fluid at low ice concentrations.

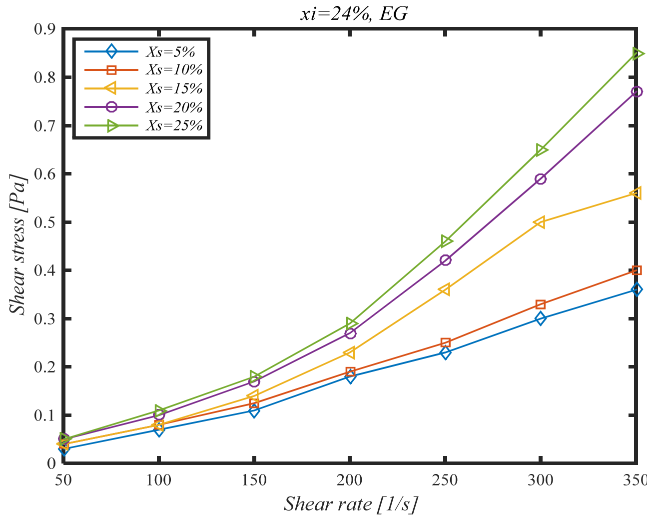

Fig. 4 Variation of the shear stress vs. shear rate for Xi=24% EG at low ice fractions *Xs*.

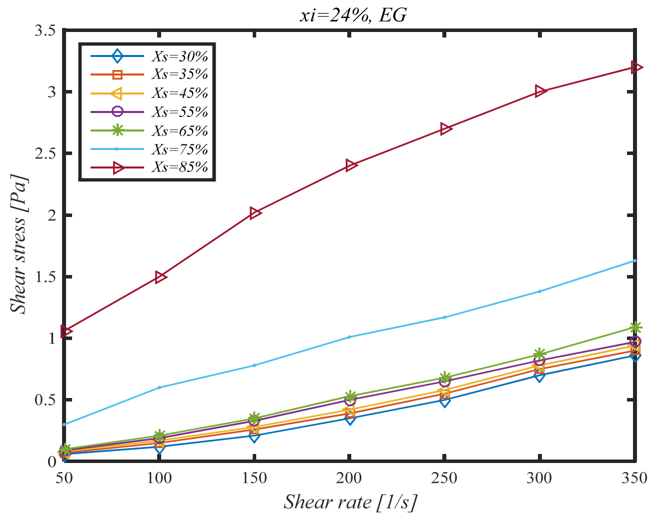

Fig. 5 Variation of the shear stress vs. shear rate for Xi=24% EG at high ice fractions *Xs*.

For the viscous behavior, choosing the appropriate rheological model is an important step before describing the ice slurry behavior. Niezgoda-Żelasko and Zalewski [4] proposed to focus on the Herschel-Bulkley fluid model to describe the ice slurry behavior. This three-parameter models links the shear rate ($\dot{\gamma}$, s^{-1}) to the shear stress (τ, Pa) as:

$$\tau = \tau_0 + k\dot{\gamma}^n \quad (1)$$

where τ_0 is the yield stress (Pa), k is the consistency index ($Pa.s^{-n}$) and n is the flow index.

In order to determine the coefficients k and n, experimental results were post-processed using the least squared method. The method has been applied for both additives PG and EG and three additive concentrations, namely 5%, 14% and 24% even if measurements with the 24% additive concentration are represented in the next section. Ice mass fraction varies from 5% to 85%.

The present results provide a correlation for the flow index, n (Xs,Xi), as a function of the initial PG and EG concentrations for Xi=24% and ice mass fractions, Xs, ranging from 5 to 85%.

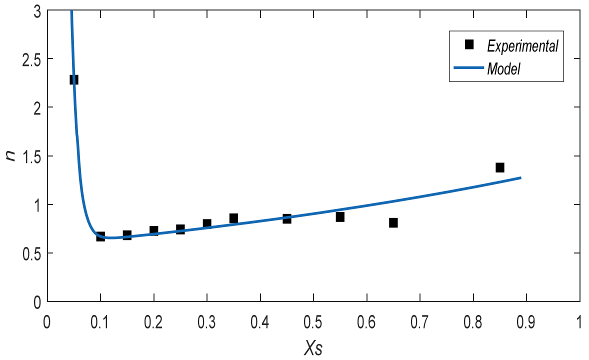

Fig. 6 Variation of the flow index n as a function of ice fraction for Xi=24% PG

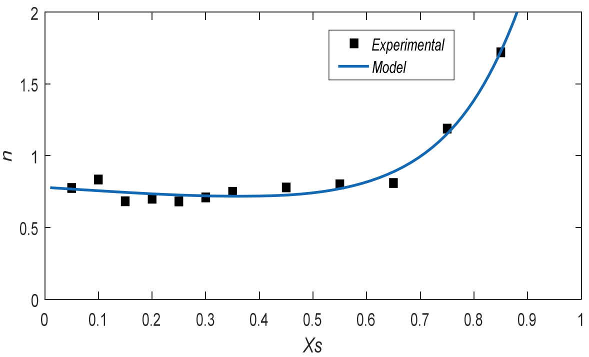

Fig. 7 Variation of the flow index n as a function of ice fractions for Xi=24% EG

Fig. 6 shows the variation of the flow index n as a function of ice fraction for Xi=24% of PG. The HB model and the least square approach provides the correlation (R^2=0.96):

$$n(Xs, Xi = 24\%) = 82.48e^{-77.94Xs} + 0.5819e^{0.877Xs} \quad (2)$$

Fig. 7 shows the variation of the flow index n as a function of ice fraction for Xi=24% of EG. The HB model and the least square approach provides the correlation (R^2=0.97):

$$n(Xs, Xi = 24\%) = 0.7783e^{-0.357Xs} + 0.002465e^{7.231Xs} \quad (3)$$

For both additives at Xi=24%, the ice slurry exhibits mainly a shear thinning behavior up to Xs=70% and then a shear-thickening behavior is observed at higher ice fractions.

Fig. 8 shows the variation of the consistency k as a function of ice fraction for Xi=24% of PG. The HB model and the least square approach provides the correlation (R^2=0.99):

$$k(Xs, Xi = 24\%) = 5.945 \times 10^{-15} e^{41.06Xs} + 1.202e^{0.3532Xs} \quad (4)$$

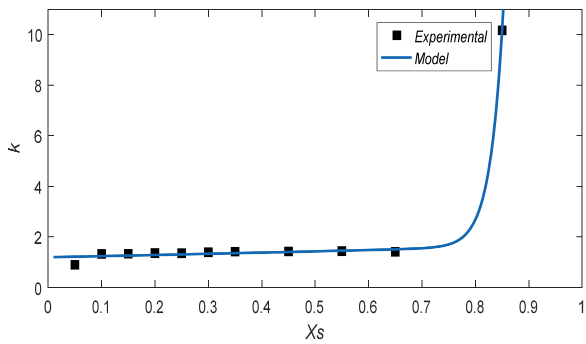

Fig. 8 Variation of the consistency k as a function of ice fraction for Xi=24% PG

Fig. 9 shows the variation of the consistency k as a function of ice fraction for Xi=24% of EG. The HB model and the least square approach provides the correlation (R^2=0.98):

$$k(Xs, Xi = 24\%) = 8.067 \times 10^{-10} e^{21.92Xs} + 1.165e^{0.0344Xs} \quad (5)$$

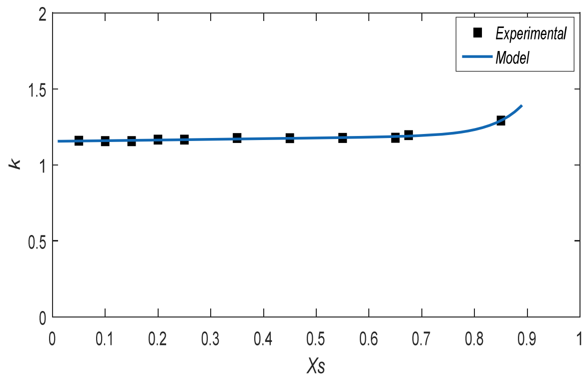

Fig. 9 Variation of the consistency k of ice slurry as a function of ice fraction for Xi=24% EG

The yield stress is calculated using the experimental rheograms shown by extrapolating the rheograms at very low shear rates. The results are not shown here but will be used in the ANN model.

IV. Artificial Neural Network Model

This section presents an Artificial Neural Networks model (ANN model) used to predict the rheological characteristics of ice slurries. In order to construct this model, an experimental database is established from the present results and also from experimental data reported in the literature [15], [16] and our experimental results are used to train and test the ANN model for a total number of 460 different experimental data. Five input parameters are employed: Type of additive (EG or PG), additive concentration, ice fraction, ice slurry temperature and shear rate. The shear stress was selected as the output parameter and so is predicted by the ANN model [17]-[18].

Table I summarizes the range of values for input and output variables implemented in the ANN model.

TABLE I
INPUT AND OUTPUT VARIABLES

	Parameters	*Min*	*Max*	*Average*	*Unit*
Input variables	Type of Additive	PG or EG		/	/
	Additive concentration	5	24	14.76	%
	Ice fraction	3	85	37.16	%
	Ice slurries temperature	-18	-1.9	-7.8	^0C
	Shear rate	50	350	196.34	*1/s*
Output variables	Shear stress	0.02	58	9.06	*Pa*

TABLE II
THE PARAMETERS OF THE ANN MODEL [18]

Parameters	*Value*
Number of input layer neurons	5
Number of hidden layer	1
Number of first hidden layer neurons	10
Number of output layer neuron	1
Maximum number of epochs	1000
Learning rate	0.5
Learning cycle	11

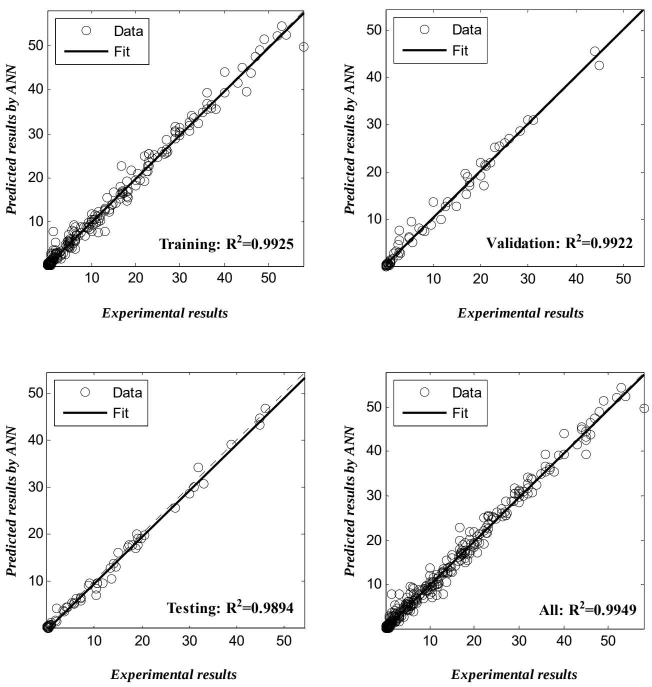

Fig. 10 The correlation between the experimental values and the predicted ANN output

The ANN network is trained using the multi-layer feed-forward network algorithm [19], [20] and the Levenberg-Marquardt method [21]. The parameters of the ANN model are reported in Table II.

Fig. 10 shows the correlation between the experimental values and the predicted ANN output for shear rate for training, testing, validation and all data set. This figure illustrates a suitable correlation between the predicted output and experimental data.

Finally, in order to validate the ANN model and improve its performance and precision, additional experimental studies are performed and compared to the ANN model predictions (Figs. 11-13) for Xi=14% PG or EG and two ice fractions Xs=25% or 55%. It is seen that the predictions of ANN model (the output from the ANN model) are generally in very good agreement with the experimental results, showing that ANN model may be a suitable tool to predict the shear stress under different conditions without requiring time consuming experiments.

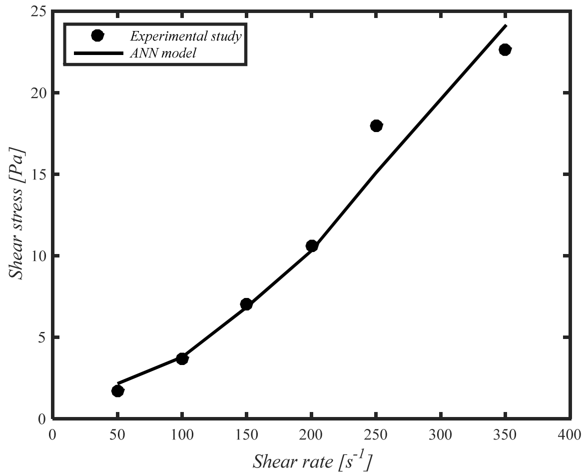

Fig. 11 Shear stress vs. shear rate for Xi=14% PG and 25% ice fraction

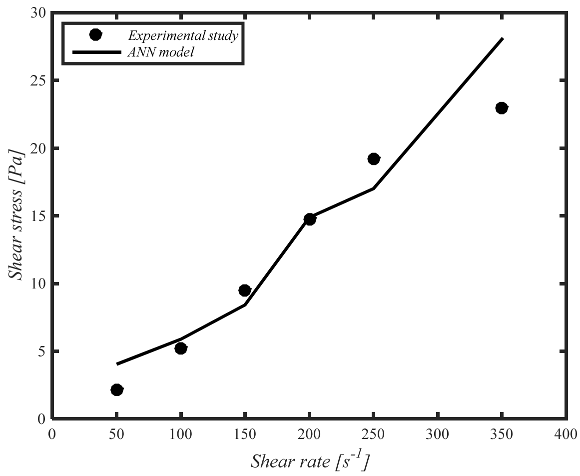

Fig. 12 Shear stress vs. shear rate for Xi=14% PG and 55% ice fraction

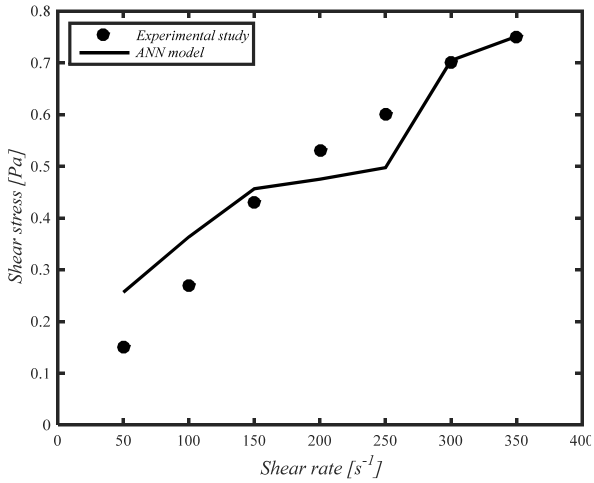

Fig. 13 Shear stress vs. shear rate for Xi=14% EG and 55% ice fraction

V. Conclusion

This paper focused on the influence of the ice concentration at fixed solute concentration (Xi=5, 14 and 24%) on ice slurry behavior. First, we have presented the rheological behavior of ice slurries under steady state conditions. The experimental results are given for fixed initial concentrations of PG and EG and ice mass fractions ranging from 5 to 85%. The rheograms showed that the shear stress increased with the mass fraction of ice. A non-Newtonian character of ice slurry was confirmed and its rheological parameters (consistency and flow index) were determined using experimental data. The ice slurry flows is shear thinning ($n < 1$) or shear thickening ($n > 1$) depending on the initial additive and ice concentrations. Furthermore, it is seen that the predictions of ANN model are in good agreement with the experimental results.

Acknowledgments

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References

[1] Bédécarrats, J. P. (2010). Utilisation rationnelle de l'énergie par les techniques de stockage et de transport du froid par chaleur latente, Habilitation dissertation, Université de Pau et des Pays de l'Adour.

[2] Kauffeld, M., Wang, M. J., Goldstein, V., & Kasza, K. E. (2010). Ice slurry applications. International Journal of Refrigeration, 33(8), 1491-1505.

[3] Egolf, P. W., & Kauffeld, M. (2005). From physical properties of ice slurries to industrial ice slurry applications. International Journal of Refrigeration, 28(1), 4-12.

[4] Niezgoda-Żelasko, B., & Zalewski, W. (2006). Momentum transfer of ice slurry flows in tubes, experimental investigations. International Journal of Refrigeration, 29(3), 418-428.

[5] Boumaza, M. (2009). Experimental Investigation of Rheological Characteristics of Ice Slurry. In ICF12, Ottawa.

[6] Metzner, A. B. (1985). Rheology of suspensions in polymeric liquids. Journal of Rheology, 29(6), 739-775.

[7] Mellari, S., Boumaza, M., & Egolf, P. W. (2012). Physical modeling, numerical simulations and experimental investigations of Non-Newtonian ice slurry flows. International Journal of Refrigeration, 35(5), 1284-1291.

[8] Barnes H. A. and Carnali J. O. (1990) The vane-in-cup as a novel rheometer geometry for shear thinning and thixotropic materials Journal of Rheology. 34, 841-866.

[9] Barnes A. B., Nguyen Q. D. (2001) Rotating Vane Rheometry - A Review, J. Non-Newtonian Fluid Mech. 98 1-14

[10] Liddell P. V. and Boger D. V. (1996) Yield stress measurement with the vane, J. Non-Newtonian Fluid Mech. 63, 235-261

[11] Turian R. M., Ma T. W., Hsu F. L. G., Sung D. J. (1997) Characterization, settling, and rheology of concentrated fine particulate mineral slurries Powder Tech. 93, 219-233

[12] Zhang X. D., Giles D. W., Barocas V. H., Yasunaga K., and Macosko C.W. (1998) Measurement of foam modulus via a vane rheometer, Journal of Rheology. 42(4), 871-889.

[13] Ben Lakhdar, M.A., (1998). Comportement thermohydraulique d'un fluide frigoporteur diphasique: le coulis de glace, Etude théorique et expérimentale, Ph.D. thesis. INSA, Lyon, France.

[14] Guilpart, J., Fournaison, L., Lakhdar, M. B., Flick, D., & Lallemand, A. (1999). Experimental study and calculation method of transport characteristics of ice slurries, Proceedings of the First Workshop on Ice Slurries of the International Institute of Refrigeration, Yverdon-les-Bains, Switzerland; 27–28 May 1999. p. 74–82.

[15] Mellari, S. (2016). Experimental investigations of ice slurry flows in horizontal pipe based on monopropylene glycol. International Journal of Refrigeration, 65, 27-41.

[16] Kitanovski, A., Vuarnoz, D., Ata-Caesar, D., Egolf, P. W., Hansen, T. M., & Doetsch, C. (2005). The fluid dynamics of ice slurry. International Journal of Refrigeration, 28(1), 37-50.

[17] Lippmann RP (1987) An introduction to computing with neural nets. ASSP Mag IEEE 4(2), 4–22

[18] Demuth H, Beale M, Hagan M (2007) Neural network toolbox 5,user's guide. The MathWorks Inc, Natick.

[19] Erkaymaz, O., Özer, M., & Yumuşak, N. (2012). Performance Analysis of a Feed-Forward Artifical Neural Network with Small-World Topology. Procedia Technology, 1, 291-296.

[20] Laïdi, M., & Hanini, S. (2012). Approche neuronale pour l'estimation des transferts thermiques dans un fluide frigoporteur diphasique. Revue des Energies Renouvelables, 15(3), 513-520.

[21] Goudarzi, K., Moosaei, A., & Gharaati, M. (2015). Applying artificial neural networks (ANN) to the estimation of thermal contact conductance in the exhaust valve of internal combustion engine. Applied Thermal Engineering, 87, 688-697.