ULTRASONIC VELOCITY PROFILER UVP-XW FOR ICE-SLURRY FLOW CHARACTERISATION

D. Vuarnoz, O. Sari , P.W. Egolf, H. Liardon

University of Applied Sciences of Western Switzerland
CH-1401 Yverdon-les-Bains, Switzerland

ABSTRACT

To analyse flows and to determine the flow patterns the investigation of velocity profiles can lead to valuable informations. For example, they can be on the rheological nature of the fluid or on the type of flow (laminar, transitional or turbulent flow). Ice slurries consist of suspensions containing a large number of small ice particles. They yield a pumpable ice for environmentally friendly cooling purposes in research and industrial applications. From their velocity profiles, which show a plug, the rheogram can be constructed. The results compare well with the measured data, obtained by applying an Ostwald rheometer. Two UVP sensors were placed on a rectangular horizontal channel to measure the downstream velocity component in the horizontal and the vertical direction and to investigate deviations, caused by a variation of the mass flow and the buoyancy force acting on the ice crystals. Furthermore, the influence of an additional heat transfer (with a constant heat flux) in a horizontal heat exchanger on the horizontal temperature and velocity profiles was investigated. When the heat transfer rates are increased, higher degrees of asymmetry of the velocity and temperature profiles are observed.

1. INTRODUCTION

At present multifunctional fluids are developed, which show very high energy densities. They are applied for storage and transportation of thermal energy. At high solid particle fractions of 25 to 40 mass % their energy density and viscosity is high. The first is advantageous and the second a drawback. If both effects are taken into consideration - compared to conventional brines - approximately five to thirty times improved transport fluids are obtained. Usually they are mixtures of a heat transfer fluid (e.g. glycol, water, etc.) with a storage material (e.g. paraffin wax, salt hydrates, or ice (in the case of ice-slurries), etc., which is finely dispersed in the carrier fluid. These new fluids define multi-component and multi-phase suspensions, which are named *Phase Change Slurries (PCS)* [1]. An important subgroup of this class of fluids are the *Ice Slurries.* Usually they are generated by a mechanical-scraper type ice generator. A commercially available type (also used in our laboratory) creates particles of ellipsoidal shape, the largest diameter is approximately 300 μm and the width to length ratio 0.7 [2].

In the flow at least two forces act on the ice particles. Viscous forces are transferring kinetic energy from the ice particles motion to the carrier fluid by friction and the density difference between the ice and the fluid leads to buoyancy forces, described by Archimede's law. The buoyancy force may separate the components of the fluid and, therefore, lead to additional complexities of the flow and thermodynamic behaviour. This implies the occurrence of different flow patterns. Flow pattern diagrams are constructed, which show in which domain of a parameter space, what kind of flow pattern occurs. These are mainly homogeneous, heterogenous, moving-bed, and stationary-bed flow (see e.g. [3]).

Numerous of these multiphase fluids are opaque in respect to an optical observation. Measurements of velocity profiles with Pitot tube sondes are extremely difficult to apply and even completely fail in the case of moving and stationary bed flows (see Kitanovski et al. [3]), and Kawaji et al [4]). Numerous other techniques also have their disadvantages or even failings, but such cannot be discussed here. The ultrasonic Doppler Echography method permits to measure velocity profiles without any perturbation of the flow. The velocity profiles are influenced by numerous physical quantities, e.g. the composition of the fluid, the ice fraction, the ice particle size distributions, cluster creation and Ostwald ripening, etc. The non-intrusive UVP method must be applied carefully, and an open question is how the measured particle velocity is related to the bulk velocity. It is assumed that in most cases the difference is small.

2. METHODS

2.1 Experiments

The goal of all our experiments was to characterize ice-slurry (two-phase) flow by an ultra sound visualization and a following analysis of the averaged ice particle velocity profiles.

Measurement	Objective	Main parameter
A	Determination of rheogram	-
B	Influence of mean velocity	Mass flow
C	Disturbance by heat transfer	Heat flux

Table. 1 : Experiments performed with UVP, which are presented in this article.

2.2 Device

As in the experiment by Mori [5] (FIG. 1), the material of the pipe is plexiglass. The positions of the sensors for each class of experiments is shown in Table 2. All the measurements, presented in this article, were performed in a horizontal pipe or channel (see Sari et al. [2]).

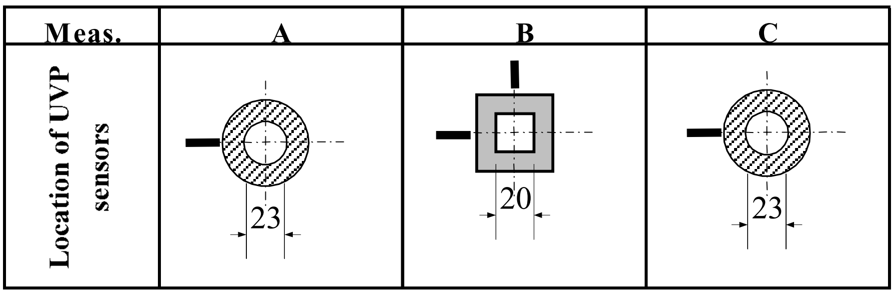

Figure 1 : Positioning of measuring probes shown in cross sections.

2.3 Parameters of the measurements

In case A and C each measurement of a velocity profile is determined by averaging over 1028 profiles and in case B over 500 profiles. Only the projections of the velocity vectors to the main direction of the flow is taken into account. Unfortunately, up to present, no data on ultra sound speed in ice slurries are available. During the measurements the applied instrument UVP XW-3-Psi records data with a sound speed assumed to be 1480 m/s. The frequency of the ultra sound beam is 2 MHz. Comparison between (relative) profiles are meaningful even by directly evaluating the output data of the instrument (see measurements B and C). Absolute velocity profiles - as shown in case A - need an additional scaling, which only leads to correct results, if the flow is homogeneous. The scaling factor is determined by the mass conservation law. An integration of the product “density times velocity” over the tube cross flow area must be in agreement with the mass flow measured by a coriolis mass flow meter.

3. RESULTS

3.1 A – Construction of ice slurry rheograms

In a horizontal pipe with laminar ice slurry flow the downstream velocity component is measured at different locations in the radial direction. The obtained profiles show a cylindrical plug, which is in correspondance with the theory of laminar Bingham flow. The obtained profiles are symmetric to the axis of the pipe. The mass flow was 0.5 kg/s.

From an average velocity profile - if additionally the pressure drop is measured (see Ref [2] - it is possible to construct a complete rheogram [6]. Taking the laminar flow theory of a Bingham fluid into consideration (see Ref. [7]), one finds for the critical shear stress (eq. 7) and for the viscosity (eq. 8):

$$\tau_0 = -\frac{1}{2} r_1 \frac{dp}{dz} \qquad (7) \qquad\qquad \mu = -\frac{1}{4} \frac{1}{u(r_1)} \frac{dp}{dz} \left(r_2 - r_1 \right)^2 \qquad (8)$$

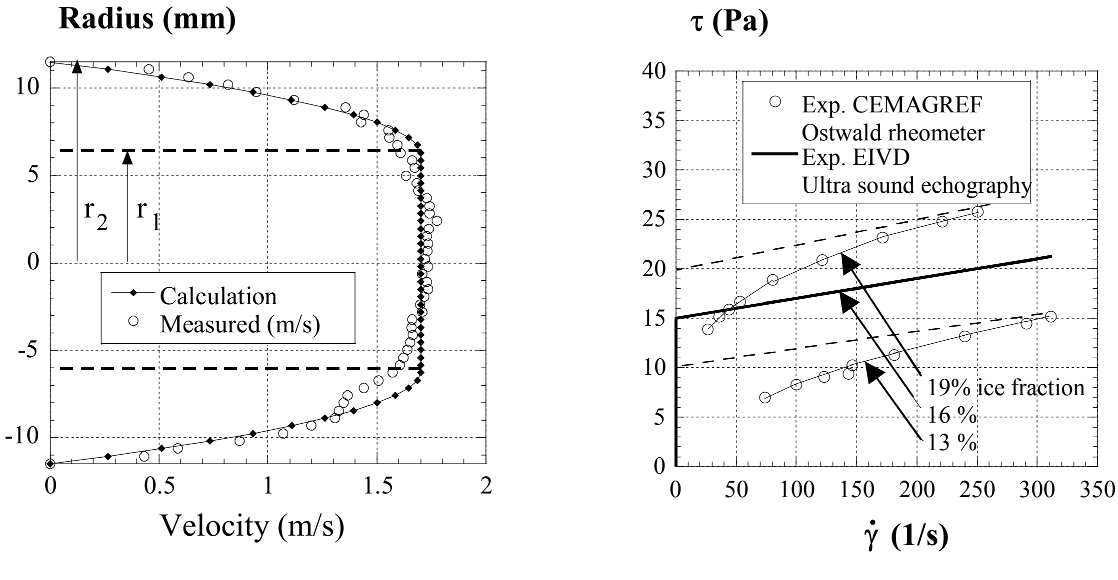

Figure 2 : On the left hand side the measured and calculated velocity profiles are compared. On the right rheograms measured with 13% and 19 % ice fractions at CEMAGREF, in Paris, France [8] and the idealized rheogram, constructed with the viscosity and critical shear stress determined with the UVP method (data obtained from the figure on the left) are shown.

Velocity profiles were thoroughly investigated with the UVP method, but without taking data on the pressure drops. Ben Lakhdar shows experimentally determined rheograms with the same concentration of talin in water [8]. That gives us the possibility to calculate the pressure drop of a pipe of 1 m length, 23 mm diameter, with a mass flow of 0.5 kg/s as adjusted in our experiments. The density was determined to be 967.7 kg/m^3. The result is dp/dz =-4850 Pa/m. With these data the velocity profiles were calculated (see FIG. 2).

Because of small disturbances in the measurement of the velocity profile, the radius of the rectangular plug r_1 may be difficult to determine. The result can be improved by fitting parabolic curves into the two flanks of the measured profile and afterwards estimating the positions of the maxima of these two parabolas, which define direct measures of r_1.

3.2 B – Dependence of the ice particle velocity profile on mass flow

Optimal conditions for optical observation are given with a diascopic neon light, a translucent glass, which leads to a homogeneous light difussion, and a colour filter. After the experimental imaging, some treatments of the pictures are performed, whereby a specially adapted software was applied. Particle velocity profiles, measured with UVP, are obtained with two transducers located as shown in FIG. 1. The first sensor produces a picture of the profile from the top to the bottom. The second UVP measurement is performed in a horizontal plane from the right to the left. We plot the two resulting velocity profiles in the same diagram, with the aim to visualize some differences between them. It is expected that the horizontal profile is perturbed by buoyancy, especially at low velocities. To control the stability of the flow, during experimentation the time evolutions of the velocity profiles were observed. The alterations were negligible.

Meas.	C_I (%)	ρ (kg/m^3)	T (°C)	$\dot{m}$ (kg/s)	u (m/s)	Δp (Pa)	Re	He
1	7.6	979	-4.32	0.21	0.54	189	500	9334
2	7.5	976	-4.31	0.09	0.23	72	122	9305
3	7.5	980	-4.31	0.06	0.15	38	0.7	9344

Table 2 : Experimental parameters and measured values of three experiments.

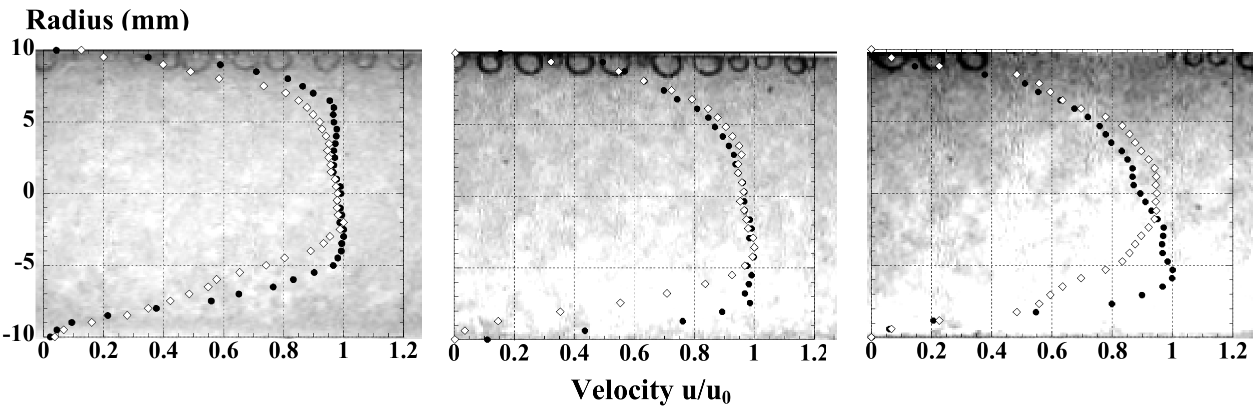

Fig. 3 : Variation of the particle velocity profiles depending on the mass flow. From the left to the right: 0,21 kg/s, 0,09 kg/s, 0,06 kg/s. Black pointers show vertical profiles and white ones belong to horizontal profiles. In the background ice slurry particles flowing through the tube can be recognized.

The results show that the vertical profiles are more sensitive to a reduction of the mass-flow than the horizontal profiles. The horizontal profiles show a reduction of the plug diameter with decreasing mass flow, but the symmetry is conserved. In the vertical profiles it is seen that the dynamic axis of the flow (see in Ref. [3]) is decreasing toward smaller mass flows. Some problems of US beam reflexion at the wall opposite to the transducer must be solved.

3.2 C – Influence of heat transfer

The experimental device is described in Ref. [2]. Because horizontal profiles are less dependent on buoyancy, they were chosen for a study of the influence of heat transfer on the flow patterns. Table 4 presents the conditions of the experiments with heat transfer. The velocity profiles with three different heat transfer rates are shown in FIG. 4.

Mesures	$\dot{Q}$ (W)	ρ_{in} (kg/m^3)	ρ_{out} (kg/m^3)	$\dot{m}$ (kg/s)	u (m/s)	Δp (bar)	Re out	He out
1	0	967.49	967.74	0.50091	1.246	0.0131	847.48	1228
2	621	967.43	967.94	0.50061	1.246	0.0134	878.62	1306
3	2409	967.56	968.81	0.51681	1.246	0.0118	1058	1393

Tab 4 : Experimental parameters and measured values of three experiments.

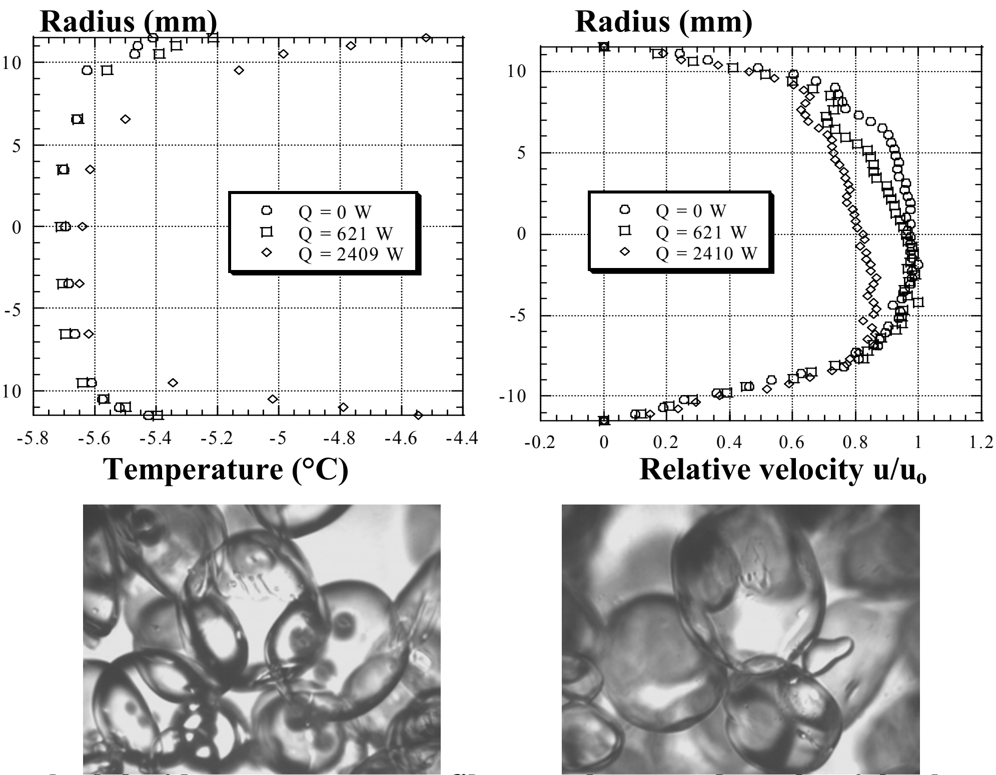

Fig. 4 : On the left side temperature profiles are shown and on the right the particle velocity profiles corresponding to the parameters presented in Table 4. Photographs (1061*762 μm) show ice slurry particles at the inlet of the heat exchanger.

According to the measurements, the plug region (seen in the velocity profiles) is largest when the highest heat transfer rate is applied. It is difficult to exactly determine the central plug region of the flow. But it can be seen that with an increasing heat transfer rate an asymmetry develops. This is also observable in the temperature profile.

4. CONCLUSIONS

In a horizontal channel averaged horizontal and vertical velocity profiles have been determined. The influence of the mean velocity or mass flow and a perturbation by a heat transfer rate has been experimentally studied. Data on ultra sound velocity measurements in ice slurries are still missing and would lead to a further substantial improvement to interpret and evaluate such measurements.

ACKNOWLEDGMENTS

We are grateful to the HES-SO for funding our work. Furthermore, we thank Met-Flow SA for supporting us with high-tech material. M. Takeda we are thankful for very useful remarks.

REFERENCES

[1] **Inaba, H.,** "New challenge in advanced thermal energy transportation using functionally thermal fluids." Int. J. Therm. Sci, **39**, 991-1003, 2000.

[2] **Sari, O., Vuarnoz, D., Meili, F., Egolf, P. W., 2000.** "Visualization of Ice Slurries and Ice Slurry Flows." Proceedings of the Second Workshop on Ice Slurries of the International Institute of Refrigeration, Paris, France, 25-26 May.

[3] **A. Kitanovski, A. Poredoš, P. Reghem, B. Stutz, J.P. Dumas, D. Vuarnoz, O. Sari, P.W. Egolf, T.M. Hansen, 2002.** "Flow patterns of ice-slurries flows." Proceedings of the Fifth Workshop on Ice Slurries of the International Institute of Refrigeration, KTH, Stockholm, Sweden, 30-31 May.

[4] **Kawaji. M., Stamatiou, E., Hong, R., Goldstein, V., 2001.** "Ice-slurry flow and heat transfer characteristics in vertical rectangular channels and simulation of mixing in a storage tank." Proceeding of the Fourth Workshop on Ice Slurries of the International Institute of Refrigeration, Osaka, Japan, 12-13 November.

[5] **M. Mori, Y. Takeda, N. Furuichi, M. Aritomi, H. Kikura, 1999.** "Development of a new type flow metering system using UVP." Proceeding of the Second International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, Paul Scherrer Institute, Villigen, Switzerland, 20-22 September.

[6] **Windhab, E., Ouriev, B., Wagner, T., Drost, M., 1996.** "Rheological Study of Non-Newtonian Fluids." Proceeding of the First International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, Paul Scherrer Institute, Villigen, Switzerland, 9-11 September.

[7] **P. W. Egolf, J. Brühlmeier, F. Özvegyi, F. Abächerli, P. Renold, 1996.** "Kältespeicherungseigenschaften und Strömungsverhalten von binärem Eis." Forschungsbericht zuhanden der Stiftung zur Förderung des Zentralschweizerischen Technikums, June.

[8] **M. A. B. Lakhdar, 1998.** "Comportement thermohydraulique d'un fluide frigoporteur diphasique : le coulis de glace ." Ph D thesis, Institut National des Sciences Appliquées de Lyon, Paris, April.

NOTATION

p	Pressure	Pa	r	Radius	mm
z	Axial distance	mm	u	Velocity	m/s
C_I	Concentration	%	f	Frequency	Hz
T	Temperature	°C	w	Water	-
$\dot{m}$	Mass flow	kg/s	a	Additive	-
Δp	Pressure drop	Pa	$\dot{\gamma}$	Shear velocity	s^{-1}
Re	Reynolds number	-	μ	Dynamic viscosity	Pa·s
He	Hedström number	-	ρ	Density	kg/m^3
$\dot{Q}$	Thermal heat flow	W	τ	Shear stress	Pa