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EXPERIMENTS WITH FLUIDS IN MAGNETOHYDRODYNAMIC CHANNEL

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ABSTRACT

In 1999 the new method for generation of modulated or pulsing jets was proposed based on magnetohydrodynamic phenomenon. The basic theoretical analyses were presented and the next steps of the idea elaboration were outlined. The experimental channel simulating the "Hartmann" problem was then designed and some preliminary tests were performed. Simultaneously, the numerical experiments based on more precise theory then that presented in 1999 were processed in last years. Finally, the set of experiments was realized aimed at determination of the magnetohydrodynamic effects in various liquids under several conditions in testing "Hartmann-like" channel. The conductivity, liquid velocity and magnetic field were changed and resulting electric voltage was measured. The results are discussed with regard to their application for liquid jet modulation.

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1. INTRODUCTION

Few years ago we have suggested a new method for generation of modulated jets based on an application of the inverse magnetohydrodynamic phenomenon. Up to now this method has been studied theoretically. Both the analytical and the numerical approach were applied and the results were analyzed with regard to the potential for use of the magnetohydrodynamic effects to water flow modulation and pulsing jet generation. The next step of our research was a verification of our theory in practice. By virtue of the theoretical results an experimental chamber has been designed and after some preliminary tests and few modifications of materials used for a chamber output the set of tests was performed. These tests were aimed at verification of the magnetohydrodynamic influence of the flow even for so low-conducting liquids as water.

2. THEORETICAL BACKGROUND

The mathematical description of the magnetohydrodynamic phenomenon was prepared and the solution of the set of equations has been found in the form of the Fourier series by Hlaváčová & Mádr (2001).

$$u_P\left(y,t\right)=\frac{4}{\pi\rho}\sum_{k=1}^{\infty}\frac{\left(-1\right)^{k-1}}{2k-1}\cdot\cos\frac{\left(2k-1\right)\pi y}{2\,y_0}\cdot\left(\frac{\sigma E_0 B_0\cos\left(\omega t-\varphi_k\right)}{\sqrt{\omega^2+\lambda_k^2}}+\frac{1}{\lambda_k}\frac{\partial p}{\partial x}-\mathrm{e}^{-\lambda_k t}\left(\frac{\lambda_k\sigma E_0 B_0}{\omega^2+\lambda_k^2}+\frac{1}{\lambda_k}\frac{\partial p}{\partial x}\right)\right) \quad (1)$$

The theoretical study shows that it is possible to influence the flow rate of the liquid by an application of a strong harmonic electric field (provided that liquid is flowing perpendicularly to it and to the strong magnetic field). To be able to study this problem a simplification known as Hartmann problem was made.

Steady Hartmann problem analyzed by Hlaváčová & Hlaváč (1999) led to the equation

$$u=\left(\frac{1}{\sigma B_0^{\,2}}\frac{\partial p}{\partial x}+\frac{E_z}{B_0}\right)\left(\frac{1}{\cosh H_a}-1\right) \quad (2)$$

This equation defines the flow profile in terms of pressure gradient $\partial p/\partial x$, magnetic induction B_0 and electric field intensity E_z. This equation, on the other hand, should make possible to calculate the pressure gradient from the measured transversal voltage on the fluid flowing with known velocity across the known magnetic field.

3. EXPERIMENTAL PROCEDURE

Realization of the experiment proving the conclusions resulting from the mentioned theory, however, appeared to be rather difficult. The direct measurement of the immediate flow rate in the chamber was impossible. Methods of a mechanic anemometry could neither prove nor exclude the theory. Laser anemometry would require usage of additives that may influence the observed process. Furthermore, an unknown pressure gradient $\partial p/\partial x$, necessary for calculation of the modulation ratio m, makes an additional mischief in verification of the theory. Therefore our own method for experimental approach has been suggested.

We decided that, at the same time, the fact itself that it is possible to measure magnetohydrodynamic effect on flowing water or similar liquids in simple laboratory conditions should be considered to be a sort of affirmation of the presented theory. Therefore, a testing measurement on the flowing low-pressure water and low-concentration water solutions of blue and green vitriol was performed.

Two different types of experiments were realized – measurement of the transversal voltage risen on the electrodes of the chamber as a consequence of the flowing of the liquid through the transversal magnetic field (single chamber measurement) and measurement of the effect of the harmonic electric field on the flow rate of the liquid (double chamber measurement).

The first aim of the measurement was to find out whether magnetohydrodynamic effect on the tested liquids is strong enough to be measured, i.e. whether the liquid flowing through a strong magnetic field creates on the lateral walls of the chamber voltage high enough to be registered by a common apparatus. The next task was to find out whether and how this voltage depends on the variable parameters of the experiment, i.e. the magnetic induction, the flow rate and the liquid conductivity. Moreover, the experimental data should enable to determine the pressure gradient in the chamber that is necessary for a further processing of the theoretical conclusions.

The magnetic field was generated by an electromagnet Phylatex (see Fig. 1.). Electromagnet consisted of two great coils with variable gap between them. It was fed from the external source by streams up to 12 A, the change of the feeding voltage enabled to preset several values of the magnetic field induction. This configuration provided relatively homogenous (deviation not exceeding 1 per cent) magnetic field large enough to cover the whole volume of the measuring chamber. The gap between the cores of the electromagnet was set to be as small as possible, i.e. the measuring chamber was fixed by the cores and simultaneously they also fixed the measuring probe of the Gauss-meter used for measuring of the magnetic field induction. This configuration remained stable during all the experiments.

Two different chambers were used for the measurement. They were made of plastic plates with thickness 4, 6 and 10 mm. Their inner dimensions were 15x52x120 mm and 15x56x120 mm. Their endings were provided with the cylindrical inlets with the diameter 9 mm enabling the connection of hosepipes for an input and an output of the liquid. There were two electrodes placed at the smaller sidewalls of the chambers. One of the chambers has got the electrodes at the inner side of the walls, so that there was not necessary to include the influence of another material into the calculations. As far as the electrodes are hence in the direct contact with the measured liquid the originally designed copper was replaced by titanium, in order to prevent rising of the electrochemical potentials and transient effects. It came out, however, that neither this arrangement solved the problem. Therefore, the second chamber was provided with the electrodes on its outer walls and voltage transformer was connected to them on account of the planned realization of the inverse magnetohydrodynamic phenomenon.

Because of better agreement with the conditions applied during the theoretical analysis as well as better handling the first chamber (with inner electrodes) was chosen for the initial experiments. The outer dimensions enabled to change the magnetic field induction from 0.20 to 0.98 T. The experimental set up did not enable to reach exactly the chosen value of the magnetic field induction. This disadvantage makes the evaluation more difficult and it also partially distorts the measured data. The measured data appeared to be not fully reliable as there happened to occur some unexplainable changes during the measurement. In the case of prolonged experiments the measured value of the magnetic field induction usually slightly dropped down. This effect should be explained by the stream instability as a result of conductor heating in coils. This explanation, however, cannot cover singular unexpected drop downs or growths. Therefore, some results had to be considered gross errors and excluded from further treatment.

Starting point of the measurement was zero voltage, after switching on the movement of the liquid, however a voltage of about 20 till 40 mV appeared on the electrodes. This value usually varied throughout the measurement (most often gradually increased). It was also different in various experimental days. Unfortunately, no obvious dependence on other measurement parameters (room temperature, prolongation of the measurement, time delay from the previous measuring series, flow rate, short-circuit on the electrodes etc.) was observed. The deviations appeared to be greater when dealing with salt solutions. Several times it was even necessary to finish the experiment because the voltage became completely un-expectable. This fact leads to the presumption that the instability of the initial voltage is connected with the rising of the electrochemical potentials on the electrodes. This negative effect should be excluded when placing the electrodes outside the chamber.

The liquid was driven either by the sludge pump Royal Einhell SP760, which in fact drained it from the vessel or by the pressure of the water main. Using the closed looping (sludge pump measurement) the results may be rather distorted by the fact that the temperature of the liquid gradually grew up. The volume of the liquid in the looping is too small to be cooled down when running through the looping. The growth of temperature should be accompanied by the change of conductivity as well as viscosity. There was no direct influence of these changes observed in our measurement, however. When the water was taken from the water main and then driven away to the drainage the hole system appeared to be more stable.

The flow rate of the sludge pump was unchangeable whilst the flow rate from the water main was controllable by the tap. The experiments were realized with five different flow rates set by the tap (namely 0.03 $l.s^{-1}$, 0.10 $l.s^{-1}$, 0.15 $l.s^{-1}$, 0.24 $l.s^{-1}$ and 0.40 $l.s^{-1}$), the flow rate of the sludge pump was 0.42 $l.s^{-1}$. Velocity of the flow inside the chamber was calculated from the cross-section of the chamber and measured flow rate; it varied from 0.04 $m.s^{-1}$ to 0.53 $m.s^{-1}$. Gauss-meter Tesla was used for determination and measurement of the magnetic field induction. The voltage induced in chamber was measured with laboratory digital multimeter M3850 Voltcraft. The more exact measuring apparatus with much higher resolution did not prove to be effective as its results were so inconsistent that it was impossible to evaluate them.

As a whole several series of measurement were realized being focused on various parameters of the magnetohydrodynamic phenomenon. First of all the water driven by the sludge pump was measured. Then the same configuration with sodium chloride water solution with mass concentration of about 0.28 % was investigated. Conductivity of the liquid measured by Behrotest LF86 was approximately 0.41 $S.m^{-1}$.

The solutions of the blue and the green vitriol were also measured, their mass concentration being about 2.5 % and 5.2 % respectively. The estimated mass concentration was calculated from the measured conductivity of solutions that were 0.62 $S.m^{-1}$and 1.18 $S.m^{-1}$ respectively. Although conductivity of the used liquid was rather big, there was nearly no change in the obtained data compared with the previous measurement. Nevertheless, the whole system was significantly less stable. Therefore, the vitriol measurements were realized only for the maximum magnetic field induction.

The results of all measurements are summarized in Tab. 1. Application of the measured data in the equation (2) made possible to calculate the pressure gradient $\partial p/\partial x$. The calculated values of the Harmann number H_a and the pressure gradient are also enclosed in Tab. 1. The results are consistent enough to consider the suggested method for pressure gradient determination as verified.

The final part of our experiments was aimed at enforcing the flow modulation by electric and magnetic fields. We have used both chambers. The one with outer electrodes was the first in the flow direction. The alternating voltage from the frequency generator was transformed to a higher level and connected to the electrodes producing so inside the chamber an alternating electric field. The magnetic field was almost constant (the waviness caused by imperfection of the source was less 0.1 % at the most important frequency – 50 Hz). Nevertheless, we have got only one available measurement device for proving the modulation – the second chamber with inner electrodes. Therefore, we connected it downstream just after the first one as close as possible. The experimental configuration, however, required installing of both chambers into one gap between poles of magnet. So there was necessary to use a connecting house about 200 mm long and reflected between the chambers. In spite of this arrangement inducing huge attenuation of the estimated enforced modulation the measurable response was observed. The modulating voltage was about 100 V (measured at the electrodes), the frequency was ranging from 200 Hz up to 500 Hz. The pure water driven by sludge pump was used for these experiments.

5. RESULTS AND DISCUSSION

The evaluation of the results of measurement of the single magnetohydrodynamic chamber can be summarized into the following relationships. The first is the one correlating the voltage induced in the chamber with the flow rate. The experimental results show that the voltage change on the side electrodes in the chamber is in due proportion with the flow rate (and therefore with the velocity of the flow) when the liquid is moving with a steady velocity through a strong homogenous magnetic field with constant induction $\boldsymbol{B_0}$. This relationship is evident from the graph in Fig. 2. Similarly, the voltage change on the side electrodes in the chamber is also in due proportion with the induction of the applied magnetic field (see Fig. 3.).

Rather non-expectably, the value of the conductivity of the applied liquid plays no important role in the steady flow (see Fig. 3.). Moreover, all trials aimed at improving of the phenomenon effect through the increase of conductivity (introducing CO_2 gas into the water, applying ionization radiation just at the chamber inlet, changing of pH factor through adding of acids or alkalis) failed. Furthermore, it should be estimated that the presence of Fe-ions in the liquid might influence in the negative way the course of the magnetohydrodynamic effect. The extent of measurement is insufficient neither to prove nor to disprove this hypothesis.

Nevertheless, the experimental results and their evaluation enabled to utilize measurement of voltage on the sidewalls of the magnetohydrodynamic chamber as a method for determination of the pressure gradient $\partial p/\partial x$. Within the measured range the pressure gradient appeared to be in due proportion with the flow rate the linear coefficient being –45.6 for the applied chamber (see Fig. 4.). This result can be considered as very significant because it enables us to improve the numerical model predicting effects of the inverse magnetohydrodynamic phenomenon.

In spite of the fact that arrangement of the experimental equipment used for tests of enforced modulation was rather unprofessional some values were measured there. The switch on of both the electric and the magnetic fields caused a jump in a voltage measured through the second (measuring) chamber. The jump was only about 1 mV but it was evidently bound to the magnetohydrodynamic phenomenon as it disappeared when either the electric or the magnetic fields were switched off or the water flow was turned off. Nevertheless, we had no possibility at the time to continue in experiments, to measure frequencies of the voltage induced in the measuring chamber or prepare more powerful source for the enforcing voltage generation. However, we prepare some new devices that should eliminate the problems of the up-to-date elements and configuration.

6. CONCLUSIONS

The most important results can be summarized as follows:

- the effects of the magnetohydrodynamic phenomenon are measurable even for liquids with low conductivities;
- the amount of the magnetohydrodynamic effect is directly proportional to the flow rate of the liquid (i.e. to the flow velocity);
- the amount of the magnetohydrodynamic effect is directly proportional to the magnetic induction applied perpendicularly to the liquid flow velocity;
- measurement of the voltage induced by the magnetohydrodynamic phenomenon can be used for evaluation of the pressure gradient along the liquid flow inside measuring chamber.

7. ACKNOWLEDGEMENTS

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9. NOMENCLATURE

B_0	magnetic field induction …[T]
E_0	electric field intensity (amplitude of the field)…[V.m^{-1}]
p	pressure …[Pa]
t	time …[s]
y_0	half-width of the channel …[m]
ρ	density of the liquid …[kg.m^{-3}]
σ	conductivity of the liquid …[S.m^{-1}]
φ_k	phase of the *k*-th term of the Fourier series …[-]
λ_k	eigenvalue of the *k*-th term of the Fourier series …[s^{-1}]
ω	circular frequency of external electric field…[s^{-1}]

10. TABLES

Tab.1. The results of pressure gradient ∂p/∂x measurement.

liquid	conductivity σ	flow rate q	magnetic induction B_0	average voltage change ΔU	velocity of the liquid u_0	Hartmann number H_a	pressure gradient $\frac{\partial p}{\partial x}$
	$S.m^{-1}$	$l.s^{-1}$	T	mV	$m.s^{-1}$		$Pa.m^{-1}$
pure water	0.0204	**0.030**	0.81	1.20	0.0386	0.0273	**-1.4**
			0.65	1.00		0.0220	**-1.4**
			0.47	0.75		0.0160	**-1.4**
			0.20	0.37		0.0068	**-1.4**
	0.0204	**0.095**	0.79	4.10	0.1220	0.0267	**-4.3**
			0.66	3.43		0.0222	**-4.3**
			0.48	2.45		0.0163	**-4.3**
			0.21	1.07		0.0072	**-4.3**
	0.0201	**0.150**	0.76	6.75	0.1977	0.0257	**-7.0**
			0.64	5.50		0.0216	**-7.0**
			0.46	3.96		0.0155	**-7.0**
			0.21	1.71		0.0069	**-7.0**
	0.0203	**0.240**	0.77	10.55	0.3082	0.0260	**-11.0**
			0.63	8.68		0.0213	**-11.0**
			0.46	6.23		0.0155	**-11.0**
			0.20	2.75		0.0068	**-11.0**
	0.0202	**0.400**	0.73	17.36	0.5128	0.0246	**-18.2**
			0.60	14.35		0.0201	**-18.2**
			0.45	10.23		0.0150	**-18.2**
			0.21	4.53		0.0069	**-18.2**
	0.0209	**0.417**	0.96	22.64	0.5344	0.0330	**-19.0**
			0.90	24.20		0.0309	**-19.0**
			0.90	22.00		0.0309	**-19.0**
			0.90	22.05		0.0309	**-19.0**
salt water	0.411	**0.417**	0.84	17.80	0.5344	0.1269	**-19.1**
			0.83	17.86		0.1258	**-19.1**
			0.78	18.20		0.1185	**-19.1**
			0.68	15.01		0.1037	**-19.1**
			0.49	10.61		0.0747	**-19.0**
			0.22	4.59		0.0333	**-19.0**
rusty water	0.0235	**0.417**	0.98	21.78	0.5344	0.0343	**-19.0**
	0.0235		0.98	22.91		0.0341	**-19.0**
	0.0215		0.96	22.83		0.0349	**-19.0**
	0.0219		0.76	18.00		0.0277	**-19.0**
blue vitriol	0.6393	**0.417**	0.91	23.91	0.5344	0.0318	**-19.0**
			0.90	23.48		0.0315	**-19.0**
green vitriol	1.1770	**0.417**	0.97	22.95	0.5344	0.2496	**-19.5**

11. GRAPHICS

Fig. 1. Measurement of the magnetohydrodynamic effects in liquids: left side - the configuration; right side - the detail of measuring apparatus.

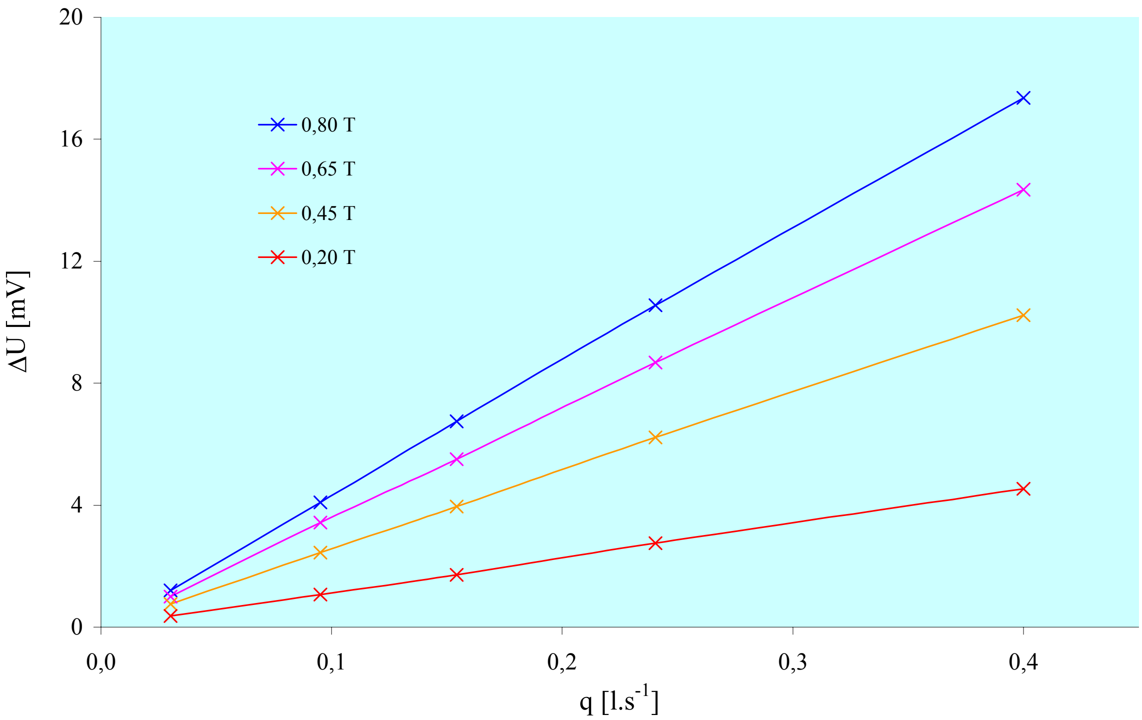

Fig. 2. The growth of the voltage change ΔU on the side electrodes with growing flow rate *q*.

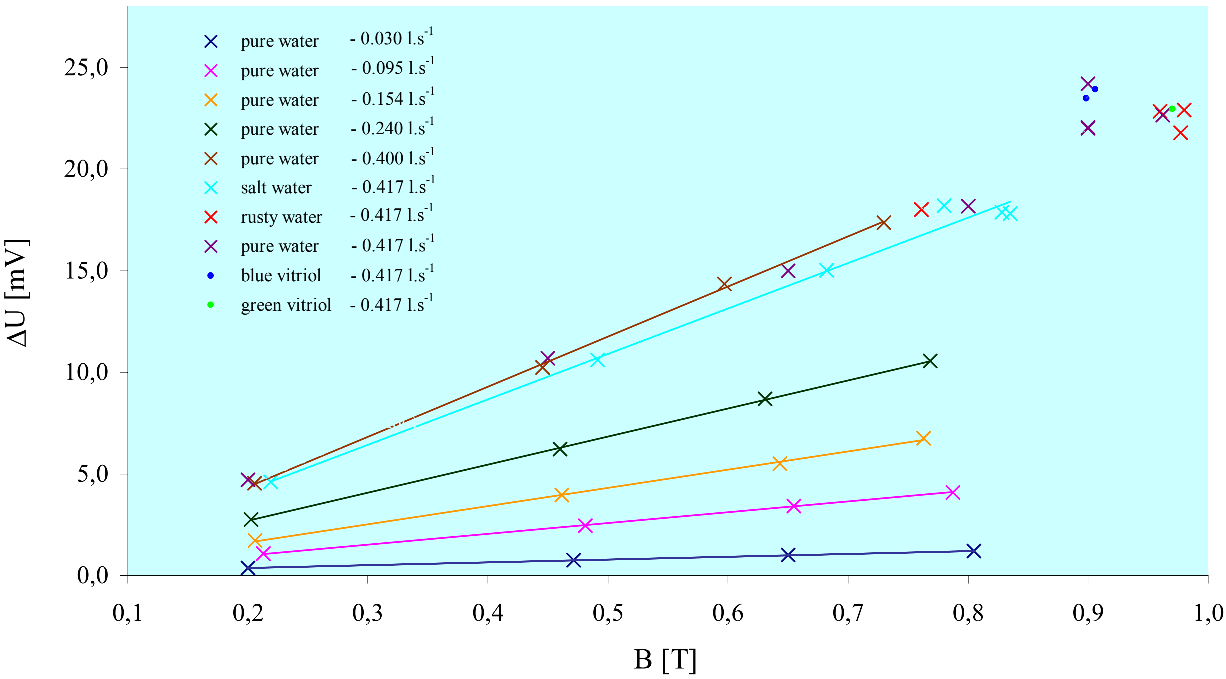

Fig. 3. The growth of the voltage on the electrodes ΔU with growing magnetic field induction B.

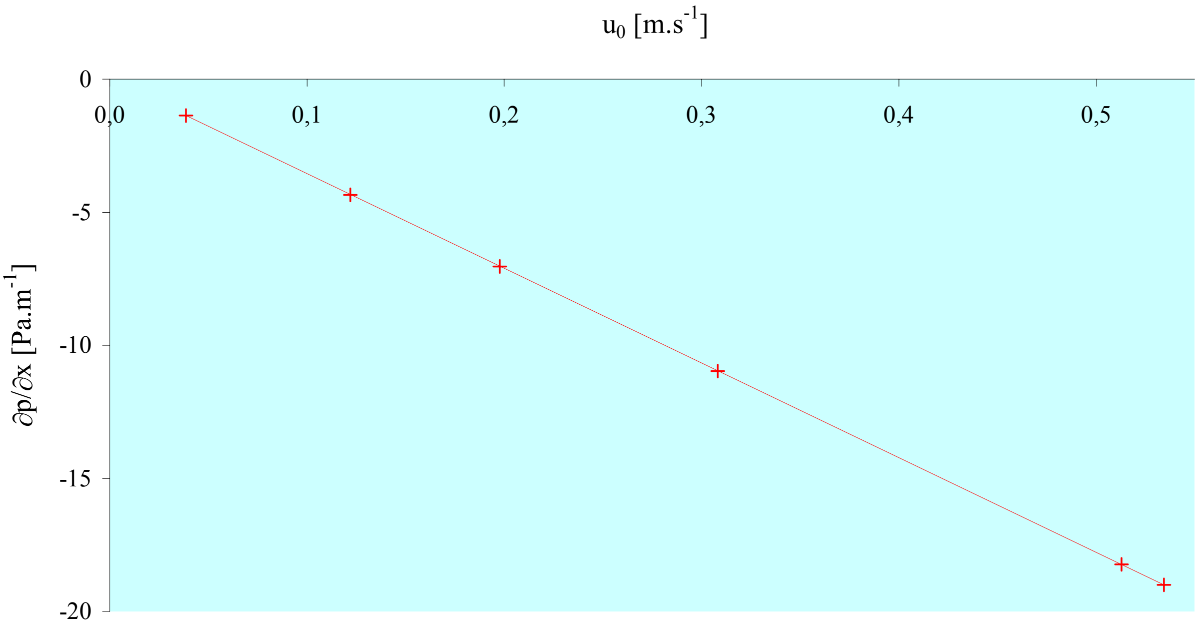

Fig. 4. Pressure gradient $\partial p/\partial x$ versus velocity of the liquid flow u_0.