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Arch. Min. Sci., Vol. 58 (2013), No 3, p. 901–912

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.2478/amsc-2013-0063

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MEASUREMENT OF SMALL VALUES OF HYDROSTATIC PRESSURE WITH THE COMPENSATION OF ATMOSPHERIC PRESSURE INFLUENCE

POMIAR MAŁYCH WARTOŚCI CIŚNIENIA HYDROSTATYCZNEGO Z KOMPENSACJĄ WPŁYWU CIŚNIENIA ATMOSFERYCZNEGO

Knowledge of pressure distribution (or differential pressure) determines the fluid flow description through the porous medium. In the case of big Reynolds numbers it is not difficult, but for laminar flows (i.e. for Re numbers Bear, 1988; Duckworth, 1983; Troskolański, 1957) from the scope 0.01 to 3) this description is virtually impossible on the basis of the tools available on the market. The previous study (Broda & Filipek, 2012) focused on the difficulty of measurement in the case of small differences of pressure and suggested a new original method for the measurement. A new unit for the measurement was constructed consisting of two separate measurement containers. Then the measurements were conducted, which necessitated temperature stabilization of the device and compensation of the atmospheric pressure influence on the measurement process.

This paper presents the results of the continuation of research concerning the methods and equipment for the measurement of very small pressure differences. The paper includes also the experience gained from the new measurement unit, which was presented in figures 1-5 subsequently presenting the concept of measurement of small values of hydrodynamic pressure with compensation of atmospheric pressure influence fig. 1; illustration presenting the state corresponding to the case of the lack of flow through the tested item fig 2; state corresponding to the fluid flow through the tested item fig. 3; then the description of the measurement of pressure drop on the tested item fig. 4 and the measurement methodology (relations (1) – (20)). Picture of the measurement unit and its components – fig. 5.

Furthermore, the authors present an exemplary measurement series and focus on the method of measurement and data processing – tables 1-8 and figures 6-8.

Table 4 presents the comparison of the measurement unit used in the previous research (Broda & Filipek, 2012) and the new one – presented in the paper. It should be noted that the structure has been simplified and the measurement accuracy has increased.

Keywords: small values of differential pressure, measurement, filtration, manometers

Znajomość rozkładu ciśnienia (lub różnicy ciśnień) determinuje opis przepływu płynu przez ośrodek porowaty. W przypadku dużych liczb Reynoldsa nie nastręcza to większych trudności, lecz dla przepływów laminarnych (tj. dla liczb Re (Bear, 1988; Duckworth, 1983; Troskolański, 1957) z zakresu 0.01 do 3)

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jest to praktycznie niemożliwe w oparciu o dostępne na rynku przyrządy. Przyczyny powodujące taką sytuację zostały omówione w poprzednim opracowaniu (Broda i Filipek, 2012), w którym zwrócono uwagę na trudności pomiarów związane z napięciem powierzchniowym czy włoskowatością (Adamson, 1997). Zaproponowano (Broda i Filipek, 2012) nową, autorską metodę pomiaru bardzo małych różnic ciśnień oraz skonstruowano odpowiednie stanowisko składające się z dwóch oddzielnych zbiorników pomiarowych oraz przeprowadzono pomiary. Z przeprowadzonych badań (Broda i Filipek, 2012) wynikała konieczność zastosowania stabilizacji temperatury urządzenia oraz kompensacji wpływu ciśnienia atmosferycznego na proces pomiarowy.

Niniejsza publikacja przedstawia wyniki kontynuacji badań nad metodami i aparaturą do pomiaru bardzo małych różnic ciśnień z uwzględnieniem zdobytych doświadczeń, w oparciu o nowe stanowisko pomiarowe, którego zasadę działania i budowę przedstawiono na rys. 1-5, kolejno przedstawiając koncepcję wykonania pomiaru małych wartości ciśnienia hydrodynamicznego z kompensacją wpływu ciśnienia atmosferycznego rys. 1; ilustrację obrazującą stan odpowiadający przypadkowi braku przepływu płynu przez badany obiekt rys. 2; omawiając stan odpowiadający przypadkowi przepływu płynu przez badany obiekt rys. 3. Kolejno omówiono stan odpowiadający pomiarowi spadku ciśnienia na badanym obiekcie rys. 4 oraz przedstawiono metodykę pomiaru (zależności (1) – (20)). Zdjęcie stanowiska badawczego oraz jego elementów ilustruje rys. 5.

W dalszej części artykułu autorzy przedstawiają przykładową serię pomiarową zwracając uwagę na sposób prowadzenia pomiarów oraz opracowywania wyników tabele 1-3 oraz rysunki 6-8.

W tabeli 4 przedstawiono porównanie stanowiska pomiarowego używanego w badaniach poprzednich (Broda i Filipek, 2012) oraz nowego – prezentowanego w artykule. Należy zwrócić uwagę na duże uproszczenie budowy stanowiska przy znacznym wzroście dokładności pomiarów.

Słowa kluczowe: małe wartości różnicy ciśnień, pomiary, filtracja, manometry

Knowledge of pressure distribution (or differential pressure) determines the fluid flow description through the porous medium. In the case of big Reynolds numbers it is not difficult, but for laminar flows (i.e. for Re numbers (Bear, 1988; Duckworth, 1983; Troskolański, 1957) from the scope 0.01 to 3) this description is virtually impossible on the basis of the tools available on the market. Therefore, a lot of research has concerned medium velocity distribution which penetrated the intended medium (Bear, 1988) or pressure distribution at high hydraulic gradients (Trzaska & Broda, 1991; Trzaska & Broda, 2000; Trzaska et al., 2005). This situation resulted from the lack of access to suitable measurement methods facilitating the measurement of very low pressure (Duckworth, 1983; Troskolański, 1957). It is possible technically to build such a sensor (Raymond 1997, 1998) but the solutions which have been used so far, are used for gas medium measurement, e.g. Askania (Filek et al., 1990). The causes of this situation were discussed in the previous paper (Broda & Filipek, 2012), where the difficulties of measurement, resulting from surface tension or capillarity, were pointed out (Adamson, 1997). A new original method (Broda & Filipek, 2012) was proposed to measure very small differences of pressure and a suitable unit consisting of two separate measurement containers was constructed. Then the measurement was conducted. This innovative method of small hydrostatic differential pressure measurement facilitates the measurement of hydrostatic differential pressure with accuracy up to 0.5 Pa. It was also possible to considerably limit the phenomenon of hysteresis (Broda & Filipek, 2012). It was also suggested that the accuracy of measurement should be extended by one order, which entails temperature stabilization of the tool and compensation of atmospheric pressure influence on the measurement process.

This paper presents the results of the research continuation concerning the methods and equipment for measurement of very small differential pressure with experience taken from the new measurement unit, the function and structure of which was presented below (Fig. 1-5).

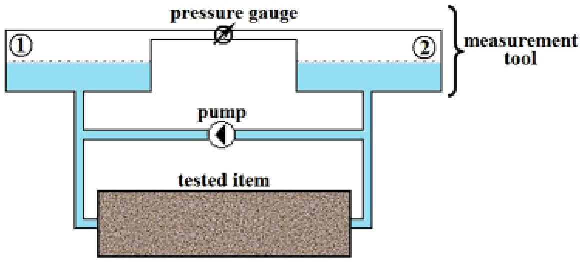

Fig. 1. Diagram of the unit for small value of hydrodynamic pressure measurement with compensation of atmospheric pressure influence

Figure 1 presents the idea of measurement of small values of hydrodynamic pressure with compensation of atmospheric pressure influence. In the diagram, three elements can be distinguished: the item being tested, the pump and the measurement tool. The pump generates differential pressure which facilitates the fluid flow through the tested item. The difference is measured with the measurement tool, which consists of two measuring containers marked 1 and 2 in the Fig. 1 and a pressure gauge.

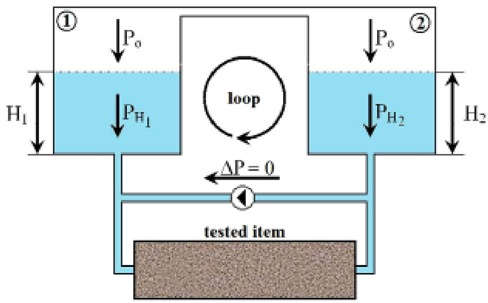

Fig. 2. Lack of fluid flow through a tested item

Let us consider the situation when there is lack of fluid flow through a tested item. When the pump is on, pressure ΔP is to be generated, flow intensity Q is to equal 0 ($v = 0$). If we apply the second Kirchhoff's law in hydrodynamic perspective (Cross method) (Gabryszewski, 1973), which says that algebraic sum of the pressure loss in every closed loop (network loop) is equal to 0, the situation (Fig. 2) can be described in the following way:

$$\sum P_{loop} = 0 \quad \Rightarrow \Delta P - P_{H_1} - P_o + P_o + P_{H_2} = 0 \quad \Rightarrow \Delta P = P_{H_1} - P_{H_2} \tag{1}$$

Taking into account the relation on hydrostatic pressure ($p = \rho gh$), (1) can be presented in the following way:

$$\Delta P = P_{H_1} - P_{H_2} = \rho g\, H_1 - \rho g\, H_2 = \rho g \left(H_1 - H_2 \right) \tag{2}$$

As a result, when $\Delta P = 0$, which is equivalent to $Q = 0$ ($v = 0$) for the pump out of operation, we get H_1 and H_2values being equal to each other and we can present it in the following way:

$$\Delta P = 0 \Rightarrow H = H_1 = H_2 \tag{3}$$

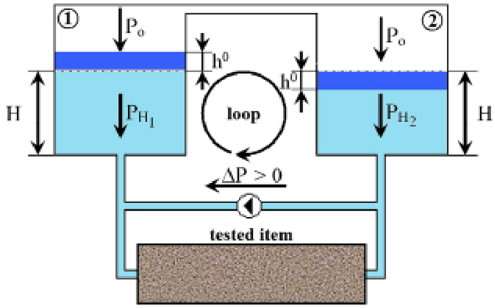

Fig. 3. Case of fluid flow through the tested item

If the pump is switched on ($\Delta P > 0$, $Q > 0$), it will cause, according to (1)-(3) – that H_1 fluid height value will increase above H value and H_2 will decrease. Assuming that these two containers are identical, we can present that difference as h^o parameter

$$\left.\begin{aligned} H_1 &= H + h^o \\ H_2 &= H - h^o \end{aligned}\right\} \Rightarrow h^o = H_1 - H = H - H_2 \tag{4}$$

Mass exchange between the containers will take as long as (2) condition obtains. The result will look as follows:

$$\Delta P = \rho g\left(H_1 - H_2\right) = \rho g\left(H + h^o - H + h^o\right) = 2\rho g h^o \tag{5}$$

ΔP depends on the difference of levels of free surface in both containers. In a steady state ΔP value will be equal to the equal value of pressure drop on the tested item.

Let us now install a tool for differential pressure measurement in the system presented in Fig. 3 as it was presented in Fig. 4. In a steady state, when there is no exchange of mass between the two containers, equation (1) looks as follows:

$$\sum P_{oczko} = 0 \Rightarrow \Delta P - P_{H_1} - P_o - P + P_o + P_{H_2} = 0 \tag{6}$$

After the transformation:

$$\Delta P = P_{H_1} - P_{H_2} + P \tag{7}$$

Fluid height value in the first container will increase and in the second container it will decrease above H value analogously as in the first case (Fig. 3). However, since measurement tool generating pressure drop P was applied, difference between H_1 and H_2 will not be as significant

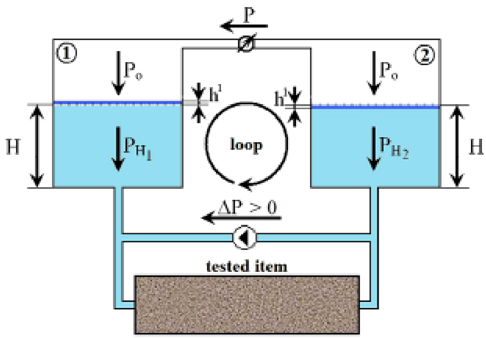

Fig. 4. State corresponding to the measurement of pressure drop on the tested item

as in the case discussed previously. Assuming that these two containers are identical, we can present this difference as h^1 parameter and then we can present the relation to determine ΔP:

$$\Delta P = \rho g\left(H_1 - H_2\right) + P = \rho g\left(H + h^1 - H + h^1\right) + P = 2\rho g h^1 + P \tag{8}$$

Let us compare equations (5) and (8)

$$\Delta P = 2\rho g h^o = 2\rho g h^1 + P \tag{9}$$

We should not forget that in steady state ΔP value will be equal to the pressure drop on the tested item and it is the value we try to determine by the applied measurement tool which measures P value. Unfortunately, as it can be concluded from relation (9), it is not possible to determine accurately of ΔP because of $2\rho g h^1$ segment.

By introducing proportion parameterb defined as:

$$\beta = \frac{h^1}{h^o} \tag{10}$$

we will obtain

$$2\rho g h^o = 2\rho g h^1 + P \Rightarrow P = 2\rho g h^o - 2\rho g h^1 \Rightarrow P = 2\rho g h^o(1-\beta) \tag{11}$$

where β parameter is always below 1. For $\beta = 1$ ($h^o = h^1$) the measured pressure $P = 0$, which corresponds to the lack of measurement tool (Fig. 3 and Fig. 4).

After the transformation

$$\Delta P = \frac{P}{(1-\beta)} \tag{12}$$

we achieve the relation that enables us to determine ΔP. However, this result is inconvenient from the engineer's point of view. In order to determine the assigned value, we have to know β parameter value, which is the function of the measured value. It would be more convenient to design the tool for small value measurement of hydrodynamic pressure in such a way that β parameter value would be small enough to be omitted.

$$\beta = \frac{\Delta P - P}{\Delta P} \tag{13}$$

The form of equation (13) suggests us the way of solving the problem. It expresses the definition of relative error in metrology and statistics (Szydłowski, 1978).

Every measurement tool has its so-called accuracy class which determines acceptable error of the measured value, which is marked as K. Therefore it may be assumed that real measurement error K_{acc} will amount to

$$K_{acc} = K + \beta \tag{14}$$

If we assume that β will be many times smaller than K, then the real influence of β parameter on real measurement error is to be neglected. The relation will be marked with n parameter:

$$n = \frac{\beta}{K} << 1 \tag{15}$$

Then the real error will amount to

$$n << 1 \Rightarrow K_{acc} = K\left(1 + n\right) \approx K \tag{16}$$

The relation given above (15), conditioning bon the class of the applied measurement tool, is crucial. If β value will be greater than the class of the tool, the measurement error will be greater than the class of measurement tool. In such a case, the application of this tool would not be economically viable.

In order to build a measurement tool for small values of hydrostatic differential pressure one should know the maximum volume that should be pumped into the tool (e.g. differential pressure transducer) and the volume should correspond to the maximum pressure measured $P_{\max}$. Let us assume that this parameter is marked as V_p and equal to:

$$V_p = Sh^1 \tag{17}$$

where S is the surface of one measurement containers (two identical containers) and h^1 is the height of elevation or drop of free surface of fluid in measurement containers (Fig. 4).

By substituting equation (17) to (10, 13) and implementing relation (15), we can determine the surface S of 1 and 2 containers,

$$S \geq \rho g \frac{1}{\beta} \frac{V_p}{\Delta P_{\max}} = \rho g \frac{1}{nK} \frac{V_p}{\Delta P_{\max}} \tag{18}$$

If we want to keep the measurement error resulting from the tool geometry below 0.001 $\Delta P_{\max}$, then S should be determined from the following relation:

$$S \geq 1000 \rho g \frac{V_p}{\Delta P_{\max}} \tag{19}$$

Assuming additionally that hydrostatic pressure for water is measured, S can be determined from the following relation:

$$S[\mathrm{m}^2] \geq 9{,}81 \frac{V_p[\mathrm{cm}^3]}{\Delta P_{\max}[\mathrm{Pa}]} \tag{20}$$

Air pressure change in a closed space in 1 and 2 measurement containers under the influence of atmosphere may occur only as a result of air temperature and pressure change (Górniak & Szymczyk 1999, Szargut 1997). However, in such a case cooling or heating and pressure influence occurs in both discussed environments. Regardless of the air volume change in 1 and 2, measurement vessels under the influence of atmosphere ΔP (Fig. 4) remains unchanged in accordance with (6) – similarly as β does. Therefore, we obtain a method of measurement for small values of hydrostatic pressure with compensation of atmospheric pressure influence.

Fig. 5 shows a laboratory unit for the measurement of small values of hydrostatic pressure with compensation of atmospheric pressure influence. Individual elements of the unit were marked with subsequent letters: A – tool for the measurement of small values of hydrostatic pressure; B – calibrated feeler gauges for standard values of hydrostatic pressure; C – registering gauges: value of hydrostatic pressure, atmospheric pressure, fluid temperature (manometric), air temperature over the free surface of the fluid; D – laptop for data storage; E – power supply.

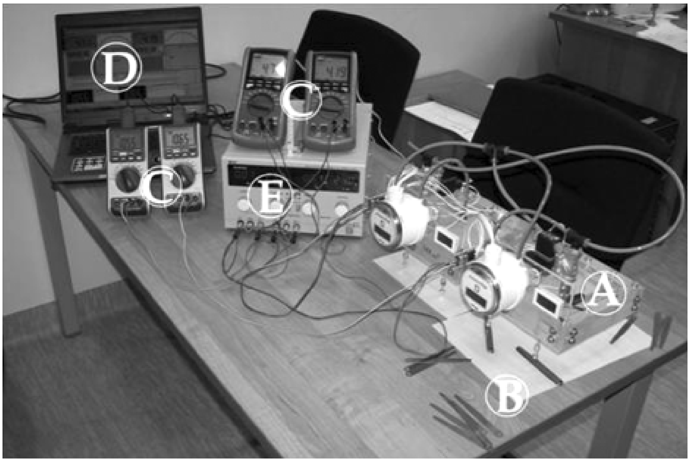

Fig. 5. Laboratory unit for measurement of small values of hydrostatic pressure with compensation of atmospheric pressure influence

Measurement process has been shown on the example of one completed measurement series. Table 1 presents assigned values of level difference of water and corresponding measured parameters of the medium for the series of 15 completed measurements. The symbols mean the following respectively:

H — difference of water levels assigned with feeler gauge in measurement containers, ΔH – feeler quality (error);

TABLE 1

Assigned values

Measurement No	H	ΔH	T_1	ΔT_1		T_2	ΔT_2		ρ	$\Delta\rho$	$P_{assgn.}$	$\Delta P_{assgn.}$
	mm	mm	°C	°C		°C	°C		kg/m^3	kg/m^3	Pa	Pa
00			23.23	0.05	0.5	23.33	0.05	0.5	997.50	0.00125		
01			23.07	0.04	0.5	23.16	0.04	0.5	997.54	0.00125		
02	1.00	0.01	22.90	0.05	0.5	22.99	0.05	0.5	997.58	0.00125	9.79	0.098
03	0.50	0.01	22.72	0.05	0.5	22.80	0.05	0.5	997.62	0.00125	4.89	0.098
04	1.50	0.02	22.71	0.05	0.5	22.76	0.03	0.5	997.63	0.00125	14.68	0.196
05	2.00	0.02	22.80	0.02	0.5	22.88	0.01	0.5	997.60	0.00125	19.57	0.196
06	2.50	0.03	22.82	0.00	0.5	22.91	0.01	0.5	997.60	0.00125	24.47	0.294
07	3.00	0.04	22.90	0.02	0.5	22.93	0.02	0.5	997.58	0.00125	29.36	0.392
08	3.50	0.04	22.98	0.03	0.5	23.02	0.03	0.5	997.56	0.00125	34.25	0.392
09	4.00	0.05	23.03	0.01	0.5	23.04	0.01	0.5	997.56	0.00125	39.15	0.490
10	4.50	0.05	23.03	0.01	0.5	23.04	0.05	0.5	997.56	0.00125	44.04	0.490
11	5.00	0.06	23.01	0.02	0.5	23.01	0.03	0.5	997.56	0.00125	48.93	0.588
12	0.25	0.01	22.91	0.03	0.5	22.90	0.03	0.5	997.59	0.00125	2.45	0.098
13	0.75	0.01	22.71	0.08	0.5	22.71	0.08	0.5	997.63	0.00125	7.34	0.098
14			22.16	2.54	0.5	22.47	0.04	0.5	997.72	0.00125		

T_1 — water temperature in measurement containers, ΔT_1 – standard deviation and measurement tool error;

T_2 — air temperature over water level in measurement containers, ΔT_2 – standard deviation and measurement tool error;

ρ — water density for assigned measurement temperature; $\Delta\rho$ – density error calculated with exact differential;

P_{assgn} — hydrostatic pressure corresponding to H (calculated in accordance with the relation $P_{assgn} = \rho g H$) relation; ΔP_{assgn} – pressure error calculated with exact differential method.

TABLE 2

Measured values

Measurement No	$P_{ref.}$	$\Delta P_{ref.}$	$P_{measured}$	$\Delta P_{measured}$	P_{hyd}	ΔP_{hyd}	ΔP
	Pa	Pa	Pa	Pa	Pa	Pa	Pa
1	2	3	4	5	6	7	8
00	2.488	0.037					
01	3.608	0.062					
02	3.677	0.086	13.581	0.055	9.904	0.140	0.500
03	3.704	0.081	8.809	0.034	5.106	0.114	0.500
04	3.679	0.085	18.302	0.059	14.624	0.144	0.500
05	3.773	0.074	23.121	0.095	19.348	0.169	0.500
06	3.815	0.069	27.878	0.066	24.063	0.135	0.500
07	3.822	0.087	32.788	0.066	28.965	0.153	0.500
08	3.857	0.095	37.431	0.052	33.574	0.147	0.500
09	3.861	0.109	42.283	0.087	38.422	0.196	0.500

TABLE 2. Continued

1	2	3	4	5	6	7	8
10	3.878	0.105	47.186	0.110	43.308	0.215	0.500
11	3.901	0.153	51.694	0.082	47.793	0.235	0.500
12	3.603	0.054	6.431	0.049	2.828	0.104	0.500
13	3.379	0.100	10.973	0.017	7.594	0.117	0.500
14	2.477	0.064					

The first step in measurement involved reference measurement P_{ref}, thenheight H was assigned and finally $P_{measured}$ was determined and finally $P_{hyd} = P_{measured} - P_{ref}$ was calculated – the most important value in our measurements. For the said values, standard deviation was calculated ΔP_{ref}, $\Delta P_{measured}$, ΔP_{hyd}. The last column in Table 2 shows the error of measurement increase ΔP. The manufacturer declares that within a year, with constant pressure measurement, the error should not exceed 0.5 Pa. However, since the measurement was made with relations to the assigned pressure value with a given accuracy, the error was determined with standard deviation (measurement tool calibration).

Fig. 6 shows itemized measurements and corresponding reference pressure values P_{ref} and measured pressure $P_{measured}$ during measurement process. What should be noted is that pressure value jump in A occurs when the system starts up, the measurement tool is switched on, and is equal to the pressure value at the moment when the system is stopped (B). Whereas, as it can be seen in Fig. 6, reference pressure of the whole measurement is constant.

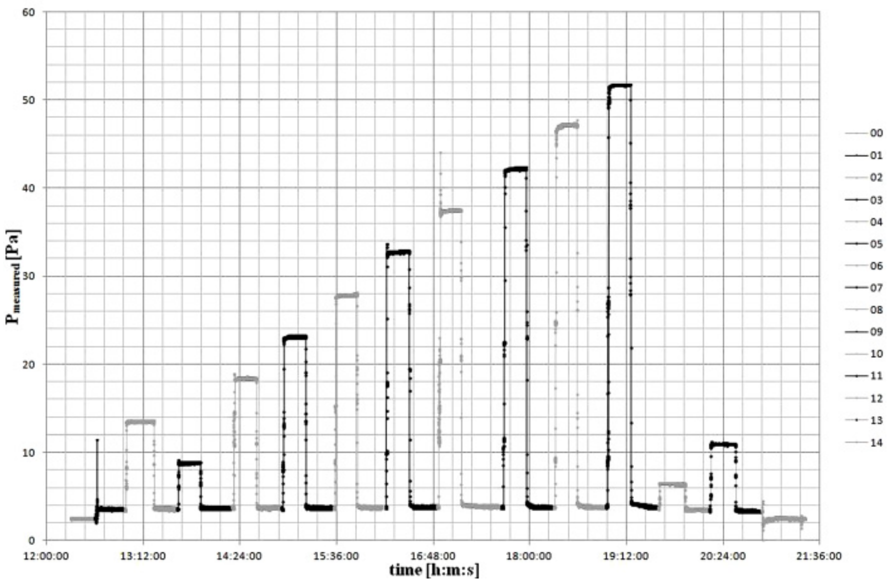

Fig. 6. Chart of the measured pressure value in time

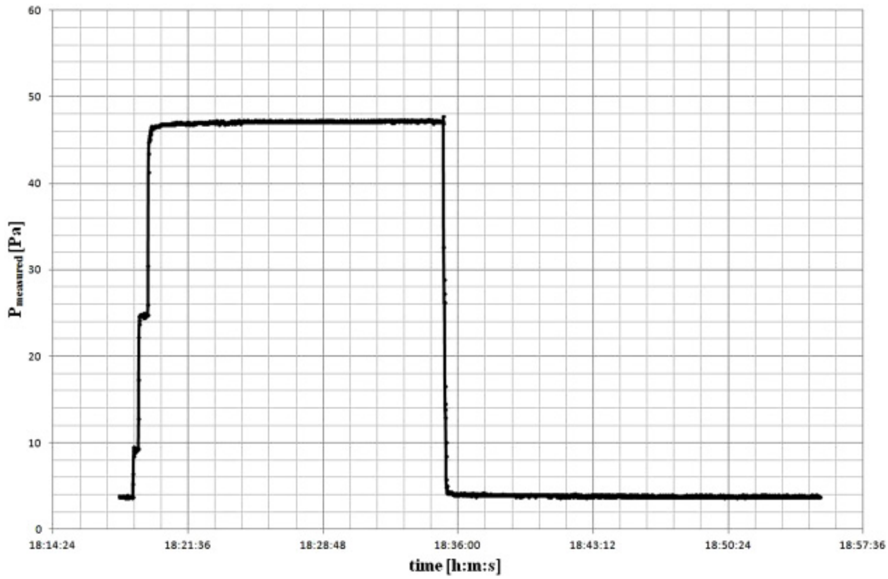

Fig. 7 Chart of the measured pressure value in time for selected pressure value

TABLE 3

Calibration of measured values

Item	Measurement No	P_{assgn}	P_{hyd}	Δ	P^{*}_{hyd}	Δ^{*}
		Pa	Pa	%	Pa	%
1	12	**2.45**	2.83	***15.59***	**2.51**	***2.52***
2	03	**4.89**	5.11	***4.34***	**4.85**	***0.82***
3	13	**7.34**	7.59	***3.45***	**7.41**	***1.01***
4	02	**9.79**	9.90	***1.19***	**9.79**	***0.06***
5	04	**14.68**	14.62	***0.39***	**14.65**	***0.2***
6	05	**19.57**	19.35	***1.16***	**19.52**	***0.3***
7	06	**24.47**	24.06	***1.65***	**24.37**	***0.4***
8	07	**29.36**	28.97	***1.35***	**29.42**	***0.19***
9	08	**34.25**	33.57	***1.98***	**34.16**	***0.27***
10	09	**39.15**	38.42	***1.85***	**39.15**	***0.02***
11	10	**44.04**	43.31	***1.66***	**44.18**	***0.33***
12	11	**48.93**	47.79	***2.33***	**48.80**	***0.27***

Table 3 shows the measurement results ordered in accordance with the assigned pressure value P_{assgn}, measurement results from Table 1 and a corresponding percentage difference:

$$\Delta = \frac{P_{as\,\mathrm{sgn}} - P_{hyd}}{P_{as\,\mathrm{sgn}}} 100\% \tag{21}$$

Then, the chart: $P_{assgn} - P_{hyd} = f(P_{assgn})$. For the marked points regression line was determined (Fig. 8).

P_{assgn} values (tab. 1, tab. 3) were substituted to the obtained regression equation and P^*_{hyd} and Δ^* (table 3) was achieved.

The obtained results are significantly more accurate estimates of the measured differential pressure. It can be concluded from the said measurements that if we assign differential pressure, we make the part of the fluid flow between the containers (Fig. 4), which entails that real differential pressure in 1 and 2 containers is smaller than the assigned one.

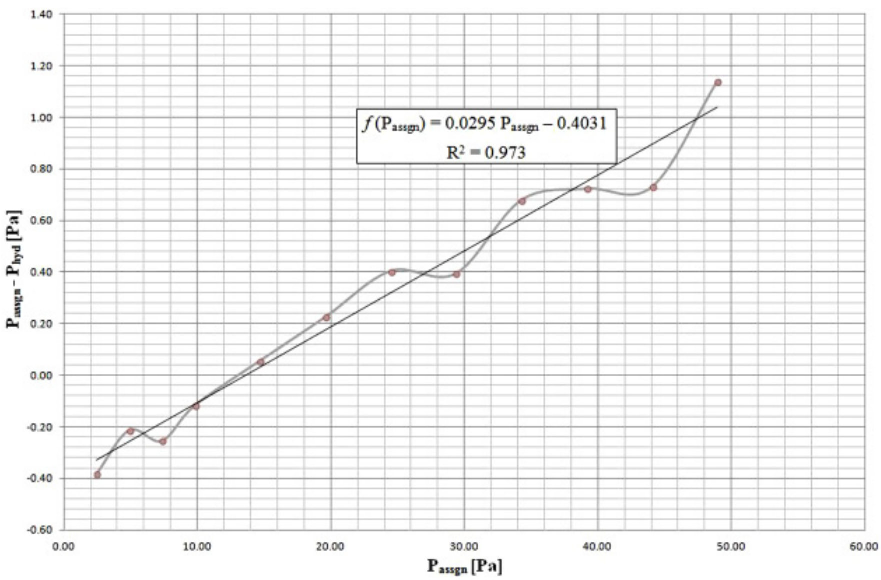

Fig. 8. Chart of $P_{assgn} - P_{hyd}$ relation to P_{assgn} value

For the small values of differential pressure, the obtained measurement error is the smallest since the measurement time was too short to determine the pressure value. In big jumps (Fig. 6) it may be omitted, but in small jumps a short measurement time significantly affects the occurrence of error (Fig. 7).

Concluding, the method devised on the basis of earlier tests and the measurement unit built on the basis of the method has a simpler structure: only one pressure transducer was applied without a very complicated operational system and without an additional module for reference pressure function. However, the implementation of atmospheric pressure compensation and of atmospheric temperature compensation in two identical measurement vessels significantly increased the accuracy and reliability of measurements.

Table 4 shows the comparison of the previous (Broda & Filipek, 2012) and the new method of measurement of small values of hydrostatic pressure.

The results of our research presented above are successful and outline next steps of the development of measurement method.

TABLE 4

Comparison of the old and new method of small values of hydrostatic pressure

	Old method (Broda & Filipek, 2012)	**New method**
Measurement method of hydrostatic pressure	Measurement of difference between free surfaces with reference to reference pressure.	Direct measurement of difference between two free surfaces
Number of pressure transducers	Two	One
Operation system	Very complicated	None
Additional module for reference pressure function	Present	None
Influence of atmospheric pressure on measurement accuracy	Vital	Compensation of atmospheric pressure influence with two measurement vessels
Influence of temperature on measurement accuracy	Vital	Compensation of atmospheric temperature influence with two measurement vessels

Acknowledgments

This article was written within Statutes Research AGH, No. 11.11.100.774

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Reveived: 13 December 2012