ON MEASURING DYNAMIC PRESSURE IN MULTIPHASE FLOWS

Cesar Augusto de Gaspari, c023377@dac.unicamp.br

Emerson dos Reis, emersonr@fem.unicamp.br
College of Mechanical Engineering of State University of Campinas, FEM / DETF / UNICAMP
Campus Zeferino Vaz, Barão Geraldo - Campinas, S. P., Brazil - Zip Code 13.083-970

Abstract. *In the present days, dynamic pressure data is largely used for monitoring the Fluidynamics of multiphase flows, which is frequently done by using common discrete in time signal analysis techniques. However, there is a discrepancy between the relative easy in which dynamic pressure data can be obtained, for example, via modern electronic transducers coupled to PC based data acquisition systems, and the difficulty in evaluate its quality, since it depends on a large group of parameters, which are mainly related to the transducer and pressure connections characteristics. Therefore, this work is aimed in contribute to reduce such discrepancy. A compiled set of information from literature is present: amplitude and frequency band of pressure dynamic signals from gas-solid and gas-liquid two-phase flows, types of electronic transducers used, such as resistive, capacitive, piezoresistive, optic, etc, and installation tips considering the fluids properties, geometry of the pressure taps and hose use. In an abridged way, it was found the frequency band from 0 to 400Hz and pressure amplitude of the dynamic component up to 40kPa. Additionally, among the several types of pressure transducers studied, the piezoresistive was evaluated as the most adequate for this application due to a number of discussed reasons, however, transducer compatibility with multiphase media should be considered.*

Keywords: *Dynamic Pressure Measurement, Two-phase Flows, and Electronic Transducer.*

1. INTRODUCTION

The term “dynamic pressure” commonly refers to pressure signals that vary in both amplitude and frequency along a short time interval. Several areas are related with the technology that makes use of the information acquired from dynamic pressures: multiphase flow, combustion engines, turbo machinery, aerodynamics, acoustics, robotics, medicine, ballistics, etc. Conversely, in the present days, there is a discrepancy between the relative easy in which dynamic pressure data can be obtained, for example, via modern electronic transducers coupled to a data acquisition system based in a PC, and the difficulty in evaluate its quality, since it depends on several parameters mainly related to the characteristics of the transducer and pressure connections.

Procedures for static calibration of pressure sensors are well known and standardized (Davis and Welch, 1988, Ehrlich, 1993, Bean, 1994), however, they are still being elaborated and implemented for the dynamic pressure calibration (de Gaspari, 2006). They usually are related only with the determination of some representative parameters of electronic pressure transducers such as sensitivity, amplitude response, phase response, resonant frequency, ringing frequency, damping ratio, rising time, and overshoot. Therefore, this information is not sufficient for complete characterization of dynamic performance of such transducers in different ranges of frequency and amplitude.

Dynamic pressure calibration is difficult because of the limitation of dynamic pressure calibration sources available. Dynamic calibrators are simply not commercially available. However, substantial improvement has been made in the state-of-the-art of both dynamic pressure calibrators and high-frequency pressure transducers to meet many current measurement requirements for amplitude, frequency, and accuracy (Diniz *et al*., 2003).

In addition, some manufacturers inform little or any data on the dynamic response of their pressure transducers, while other ones declare their products as capable of providing measures with high precision in frequencies extending up to hundreds of kilohertz. Between those two limits, several doubts appear since a metrological method well established that assures the quality of the data still doesn't exist as discussed, and a gap of information about uncertainties and tracebility is present. Consequently, this research field is still opened to new investments.

In the literature, the American Society of Mechanical Engineers - ASME published in 1972 a first version of a Guide for Dynamic Calibration of Pressure Transducers (ANSI B88.1-1972), ASME (1995), which indicates the dynamic properties of the sensor that should be considered, but it doesn't indicate how to make the complete characterization of the sensor. Consequently, in spite of the importance of this document, it doesn't represent any standard for testing and estimating the measurement uncertainties in dynamic pressure measurements.

More recently, the Instrument Society of America – ISA published another document about dynamic pressure sensor calibration (ISA-37.16.01-2002). Also this document is not a step-by-step procedure that can be followed without fail to the absolute truth in pressure measurements. Neither it discuss in detail all factors that can affect the accuracy of pressure measurements, e.g., environmental effects, signal transmission, or recording techniques. It concentrates on the factors that directly affect dynamic response, such as adapters and mechanical attachments physically a part of, or relatively inseparable from the transducer, and electronic equipment that, in practical use, is required for the operation of the transducer. The description of equipment and techniques appearing in this document was limited to their use as directly related to dynamic pressure calibration. Consequently, it represents only an up-to-date of the ASME document.

Therefore, due to the exposed above, this work is aimed in contribute to the study of dynamic pressures measurement with focus on multiphase flows, when the principal aspect is the presence of two or more different components flowing together, which can cause data degradation due to several factors mainly associated to the distinct components properties.

2. MEASURING SYSTEMS OF DYNAMIC PRESSURES

A dynamic pressure measurement system for fluid flowing in a pipeline is schematized in Fig. 1. It is composed basically of five elements: (1) a hole through the pipe wall called of pressure tap; (2) the hoses and connections whose transmit the mechanical pressure signal to the transducer sensor element; (3) the electronic transducer that can be of several types; (4) the data acquisition system where the analogical data from the transducer is converted to digital; and (5) the PC where it can be later analyzed for collecting indirect results by using discrete in time signal analysis techniques.

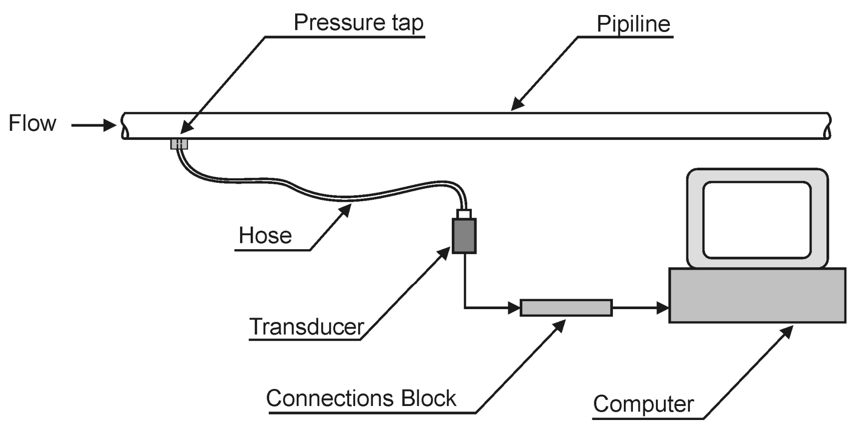

Figure 1. A generic dynamic pressure measurement system in a pipeline fluid flow

The outline shown in Fig. 1 represents a typical case of multiphase flow in a straight horizontal pipeline. In spite of this, the following considerations should be made if the multiphase flow is gas-liquid:

- The transducer is located below the pipeline, maintaining the connections and hose filled with liquid and avoiding the presence of small gas bubbles, which can degraded the data quality due to the their low density relative to the liquid and high compressibility;
- A static pressure component is added to the measured data, since there is a level difference between the pressure tap and the transducer sensor element;
- The hose length, material and diameter have influence over the data quality;
- The pressure tap geometry has influence over the data quality. These last two considerations are discussed ahead.

If the pipeline of Fig. 1 is transporting a gas-solid mixture (particulate like sand, ash, any flour), different considerations can be made:

- It is preferable the transducer to be installed above the pipeline in order to minimize the particulate to enter in the hose;
- A simple gas filter can be provided close to pressure tap in order to reduce the particulate entrance, which can also contaminate the sensing element of the transducer, and obstruct the connecting hose. However, the filter can affect the dynamic pressure data since it causes an obstruction to the dynamic pressure signal;
- If the hose stays without particulate, the effect of the pressure due to the level difference between the tap and the transducer should be disregarded due the low gas density.

Usually, in piping flow analysis, differences among the flow pressure points around the same cross sectional area are disregarded when the diameter is small, but it depends on the actual parameters under study. Furthermore, the pressure tap allows accessing the pressure information by a hole though the pipe wall, therefore, it can interfere the fluidynamic around the hole by making the measured pressures quite different from those when the tap is not present. Ideally, the interference should be null by establishing the same conditions before the presence of the hole. Figure 2 shows an outline of a pressure tap with the fluid flowing tangentially to the tap hole of diameter designed by *d*, and concordance radius *r*.

According to Ismail *et al.* (1998), it is not enough simply to make a hole and to attach a tube and/or hose length to transport the pressure signal to a transducer. Firstly, it is recommended the axis of the hole to be as near as possible of 90° in relation to the axial pipe axis. Secondly, it is recommended a tap hole of diameter, *d*, as small as possible. However, the surface tension and flow presence into the measurement system should be considered. For example, in air-water two-phase flow, the diameter of the hole shouldn't be less than 3 mm (Reis, 2003). Thirdly, the concordance radius, *r*, between the tap hole and the internal surface of the pipe should be as small as possible, otherwise, some interference would appear in the fluid flow caused by an accentuate chamfer or presence of burrs due to the drilling operation.

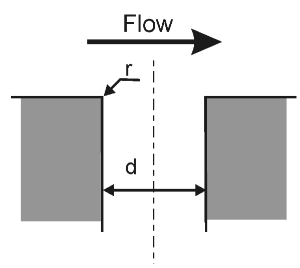

Figure 2. Recommended geometry for the pressure tap hole

The hose is also important on the performance of the dynamic pressure measurement system. For use in dynamic pressure measurements, it should be the as short as possible due: (i) the pressure variation related to the fluid viscosity and density into the hose, which depends on the viscous and inertial forces acting on the fluid along it, therefore, the diameter of the hose, when the smallest as recommended before, should have a strongest influence due to the viscous force, but a minimal influence due to the inertial one (Hjelmgren, 2002), this effect is important mainly when the fluid into the hose has high viscosity and density like water or oil; (ii) deformations due to the internal pulsating pressure should also have influence on the system performance when hose of elastic material is used, therefore, hoses of a rigid material are recommended; (iii) hoses should not be used instead when absolutely necessary, otherwise the pressure transducer should be installed directly in the pressure tap.

The effect (i) only will be present if some fluid displacement exist into the measurement system, which should occur due to the following: (a) internal volume variation into the hose by deformation, i. e., (iii) discussed above; (b) internal volume variation into the pressure transducer due to its measurement sensor, such as a diaphragm movement; (c) gas compressibility into the hoses or transducer, which is important when the peak to peak amplitude is greater than about 1% of the absolute mean pressure. The last data can be estimated from the p-v-T relation for ideal gas, which $\Delta\rho/\rho_0 = \Delta p/p_0$ and, for $\Delta\rho/\rho_0 \leq 1\%$ also $\Delta p/p_0 \leq 1\%$, assuming isothermal condition (de Gaspari, 2006).

Another element presented in Fig.1 is the pressure transducer (or gauge). A large group of electronic pressure transducers is available in the market, and some of them can be applied to the dynamic pressure measurement, while others are suitable only for static (or mean) pressure measurements. Therefore, by understanding the characteristics of each one, besides their sensing principle, it is important for a suitable choice of the electronic transducer that should contribute to accurate dynamic pressure measurements.

The transducers can be represented by a mass-spring-damper system as schematized in Fig. 3, in which the mass, the spring rigidity constant and the damping factor of a diaphragm, for example, is represented by *m*, *k* and *c*, respectively. The parameter *F* designs the force due to the pressure generated by the flow, and *x* is the effective linear displacement of the sensor. By extending this idea, the whole dynamic pressure measurement system has its resonant frequency as combination result of the whole components operating together, i. e, the dynamic performance of the whole system is under influence of all mechanical components: pressure tap, hose and transducer, as shown in Fig. 1.

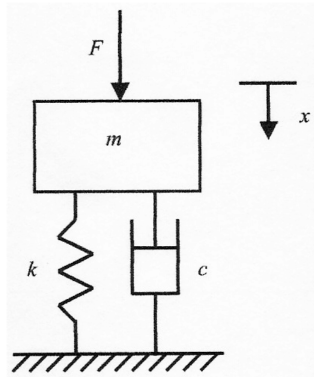

Figure 3. Representation of the transducer sensing element with mass + spring + damper

Following is presented the main characteristics of each sensing principle of main electronic pressure transducers available in the market, which can be used in dynamic pressure measurements (Webster, 1999, and Hjelmgren, 2002).

Resistive pressure sensors are based on strain gauges fixed on the surface of a diaphragm. When pressures are applied, the sensor (diaphragm) deforms and changes the electrical resistance of the strain gauges. Generally a Wheatstone electronic bridge is used being the output voltage proportional to the electrical resistance, which is amplified by an electronic circuit to the DC voltage level of 0-5 or 0-10 V, or converted to DC current of 0-20 or 4-20 mA instead. Therefore, due to the diaphragm as the sensing element, this type of transducer has generally high m and low k, and is limited to measuring frequencies range up to 20 Hz. For static measurements the carrier frequency system have some definite advantages, such as higher immunity to thermoelectrical noise. For dynamical measurements, however, the transducer may be disadvantageous due to inferior high-frequency properties. Manufacturers: Omega, Gefran, Honeywell, Transtec, etc.

Piezoelectric sensors are quite different from resistive ones. The piezoelectric effect is related to the property of some crystalline materials, e.g. quartz, tourmaline and some ferroelectric ceramics, that can deposit an electrical charge on metal plates attached to its surface when change occurs in the applied force. Very small deformations are needed which means that the sensors can be made very rigid resulting in high natural frequencies (high k). This characteristic makes them as being very suitable for dynamic measurements. The sensor element consists of a bar-shaped transverse-effect quartz element. The sensor element is preloaded with a preloading sleeve. The front part of the sleeve is designed as the pressure transmission component. Pressure applied to the diaphragm is converted to a force that is transmitted to the sensor element. Charges appearing on the lateral surfaces of the quartz bar are collected on vacuum-deposited electrodes. A helical spring connects the charge to the connector. Since the charge inevitable leaks out due to finite resistance and capacitance, the sensor is not suited for truly static measurements. The measuring system is characterized by a so-called discharge time that describes the time-rate of charge leakage. Discharge time depends not only on the transducer itself but also on cables and charge amplifiers used. The induced charge is not easily measured. Generally, a charge amplifier converts the high-impedance charge signal in a low-impedance voltage signal that can be measured (and displayed) with standard instruments. Charge amplification can be performed either by electronics internal to the transducer or by external electronics. Manufacturer: Kistler.

An alternative sensing principle that has the same advantages about the piezoelectric is the piezoresistive one. In this case, the piezoresistive effect over semiconductor materials such as silicon is used as the sensing principle, and it is suitable for measuring both static and dynamic pressure components. However, internally compensated transducers are already available due to the high sensitivity of semiconductor properties as a function of temperature. Piezoresistive and piezoelectric sensor also have high resonant frequency of up to 500 kHz, and they can be found in market with reduced size to be the sensing element flush mounted at the internal surface of the measurement section. Manufacturers: Kulite, Endevco, Omega, Druck, Keller, etc.

In general, fiber optic sensors have the advantages of small size, low weight, immunity to electromagnetic interference, high sensitivity, very large bandwidth, capability of combining remote sensing and data transferring, and allow ground loops elimination. Interferometric sensors and intensity-based sensors are two important sensor categories. Interferometric sensors measure differential phase changes that are somehow related to pressure. Very high resolution can be achieved with fiber interferometers but the cost of the associated signal processing has been prohibitive to high-volume use. Intensity-based devices measure changes in received optical power. Intensity-based fiber sensors require simple processing techniques but are generally less accurate than interferometric sensors due to sensitivity to the source power drift and fiber attenuation variations. A low-cost solution utilizes an optical fiber in front of a flexing diaphragm for optical reflection measurement of pressure-induced deflections. This type of sensor was used to detect misfire or knocking in an automotive engine. As a next step a low-cost (not high accuracy) sensor was developed for dynamic (up to 15 kHz) automotive applications. It consists of an optoelectronic transceiver (fiber optic coupler, a near infrared LED and a PIN photodiode, external power supply, and a minimum of analogue circuitry) coupled to a fiber-optic sensor head. Therefore, interferometric sensors and intensity sensors are both important categories of transducers for dynamic pressures measurements. Manufacturer: Paroscientific.

Capacitive pressure sensors typically use a thin diaphragm as one plate of a capacitor. Applied pressure causes the diaphragm to deflect and the capacitance to change. This change may, or may not, be linear and is typically on the order of several pF out of a total capacitance of 50-100 pF. The change in capacitance may be used to control the frequency of an oscillator or to vary the coupling of an AC signal through a network. The electronics for signal conditioning should be located close to the sensing element to prevent errors due to stray capacitance. Silicon micro-machining and large-scale integration technologies are being used to produce capacitive sensors that are small, rugged, lightweight and require low power. The size of the sensor may be only a few square millimeters with a thickness of some tens of micrometers yielding a mass of below 0.1 g (low m). Additionally, this type of transducer commonly has low volume variation (high k), and it is another important type of transducer for dynamic pressure measurements. Manufacturers: Rosemount, EG&G, Smar, Honeywell, Foxboro, etc.

Several configurations based on varying inductance or inductive coupling are used in pressure sensors. They all require AC excitation of the coil(s) and, if a DC output is desired, subsequent demodulation and filtering. The linear variable differential transformer (LVDT) types have a fairly low frequency response due to the necessity of driving the moving core of the differential transformer. The LVDT uses the moving core to vary the inductive coupling between the transformer primary and secondary. Another type of sensor is it of variable reluctance. In this case, the sensor is composed of a sensor diaphragm of pressure and a bridge with two reels, one on each side of the diaphragm. The reels are linked in series and mounted such that its axes are perpendicular to the plan of the diaphragm. The excitement signal is applied simultaneously to the two reels by the connection point among them, like this, when a differential pressure is applied, the diaphragm is inflected and approaches to a reel while it goes away of the other. In that way, considering that the material of the diaphragm is magnetically permeable, the close presence to one of the reels increases the magnetic flow through the same, which increases the impedance of the reel, while the opposite happens in the opposite reel. Again, the sensibility of the sensor depends on flexibility of the diaphragm. Manufacturers: Shinkawa, Kearfott, Validyne, etc.

Among the seven types of pressure sensors discussed, the piezoresistive one was evaluated by de Gaspari (2006) as the most suitable for dynamic pressure measurement. However, the engineer should consider the sensor compatibility with the measurement medium. While resistive, capacitive and inductance ones can be manufactured for a number of different media, the piezoresistive type isn't recommended for conductive or corrosive liquid and gases, instead when informed by the manufacturer.

3. DYMANIC PRESSURE IN MULTIPHASE FLOWS

When two of more immiscible components in different phases or not are flowing together, for example air-water, air-sand, water-oil, called as gas-liquid, gas-solid, and liquid-liquid respectively, one of the most interesting phenomena is the special arrangement of each component into the system, called of flow regime or flow pattern. In horizontal pipelines like that showed in Fig. 1, when the two-phase flow is gas-liquid, the flow patterns can be bubbly, plug, slug, stratified smooth, wavy or annular (Chisholm, 1986). Otherwise, when the flow is gas-solid, which is very common in solids pneumatic conveying, the flow patterns can be from dispersed (or light) type flows to dense phase flows (Marcus *et al*., 1990). Other multiphase flow systems, instead of pipelines, are common in industrial applications like in bubble columns, fluidized beds, evaporators and condensers, orifice plates or other differential pressure device, etc.

Due to their intrinsically natural instability, multiphase flows are complex and always generate pressure oscillations, in which the frequency and amplitude is dependent of their fluidynamic. Therefore, pressure variations represent useful information to study multiphase flows, since several flow characteristics can be determined by applying a number of signal analysis techniques on the dynamic pressure data.

From the information available in literature, items 3.1 and 3.2 ahead present a compiled set of information about dynamic pressure study of gas-liquid and gas-solid two-phase flows, respectively, with special attention for frequency and amplitudes of pressure signals reported by the authors, which was compiled in two tables that correlate the transducer type, manufacturer and model, subject of the study, frequency range and amplitude reported in each work.

3.1 Gas-liquid two-phase flows

Table 1 presents recent information of dynamic pressure signals from gas-liquid flows. One can observe a gap of information about Manufacturer/Model, which wasn't presented by the authors in some cases. Consequently, it represents a limitation of information available in the literature (de Gaspari, 2006).

Table 1. Information reported about gas-liquid two-phase flows and dynamic pressure signals

Reference	Transducer Type	Manufacturer/Model	Study	Frequency Range [Hz]	Amplitude [Pa]
Groen *et al.* (1995)	Piezoresistive	Druck/ Not informed	Bubble column	0 to 7	Not informed
Letzel *et al.* (1996)	Piezoelectric	Kistler/7261	Bubble column	0 to 170	0 to 60
			Fluidized bed	0 to 10	2,000 to 3,000
Ferreira (1997)	Capacitive	Transmitel/4Ez2B3	Pipeline and orifice plate	0 to 9	-1,200 to 1,200
Keska *et al.* (1998)	Resistive, capacitive and optical	Not informed	Bubble column	0 to 30	0 to 4,000 Pa.
Elperin *et al.* (2002)	Piezoresistive	Omega/PX236	Pipeline and venturi	0 to 100	-20,000 to 20,000
Wang *et al.* (2003)	Variable Reluctance	Validyne/DP15	Pipeline and tee junction	0 to 15	196 to 490

In a general way, several types of transducers have been used for studying gas-liquid two-phase flows from dynamic pressure signals. Additionally, a little attention was paid to the dynamic characteristics of the measurement system used as observed by de Gaspari, (2006).

Frequency range from 0 up to 170 Hz was reported (Letzel *et al*., 1996) using a Kistler mod. 7261 piezoelectric sensor, and amplitude ranges from –20 up to 20 kPa, including the negative gauge pressures range of in a venturi nozzle (Elperin *et al*., 1998), and –1.2 kPa to 1.2 kPa in an orifice plate device (Ferreira, 1997). However, only positive amplitudes of gauge pressure were reported in bubble columns and pipelines with a tee junction (Groen *et al*., 1995, Letzel *et al*., 1996, and Keska *et. al*., 1998).

3.2 Gas-solid two-phase flows

Table 2 presents recent information about dynamic pressure signals from gas-solid flows. As occurred for gas-liquid two-phase flows, a gap of information exists about in Manufacturer/Model columns, which wasn't presented by the authors in several cases. Consequently, it also represents a limitation of information available in literature (de Gaspari, 2006).

Table 2. Information reported about gas-solid two-phase flows and dynamic pressure signals

Reference	Transducer Type	Manufacturer/Model	Study	Frequency Range [Hz]	Amplitude [Pa]
Bai *et al.* (1999)	Not informed	No informed	Fluidized bed	0 - 25	0 - 350
Li (2002)	Not informed	Not informed	Horizontal conveying pipeline	0.78 - 400	0 – 1,000
Miccio *et al.* (2003)	Piezoresistive	Druck/PTX510	Combustion fluidized bed	0 - 50	-1,500 to 1,500
Alberto *et al.* (2004)	Not informed	Not informed	Fluidized bed	0 - 7	200 to 1,400
					1,690 to 1,870
					1,140 to 1,380
					1,680 to 1,850
Sasic *et al.* (2005)	Capacitive	Honeywell/143PC03D	Fluidized bed	0 - 10	Not informed

In a general way, capacitive and piezoresistive pressure sensor were used. As before, a little attention was also paid about the dynamic characteristics of the used measurement systems as observed by de Gaspari (2006).

Frequency range from 0 up to 400 Hz was reported (Li, 2002) for pneumatic particulate conveying in a horizontal pipeline, and amplitude ranges from –1.5 to 1.5 kPa, including the range of negative gauge pressures in a combustion-fluidized bed (Miccio *et al*., 2003). However, only positive amplitudes of gauge pressure were reported still in fluidized beds, however, at near to the ambient temperature (Bai *et al*., 1999, Alberto *et al*., 2004, and Sasic *et. al.*, 2005).

Therefore, among the gas-liquid and gas-solids studies discussed above, the frequency range was from 0 Hz (static component) to 400 Hz, and the amplitudes of gauge pressure from a larger range from –20 kPa to 20 kPa, or 40 kPa. These data has been used by the authors to develop a metrological method, including procedures and calibration device, for operation of electronic pressure transducers in two-phase flows at Department of Thermal and Fluids Engineering at FEM/UNICAMP.

4. CONCLUSIONS

This work presented a contribution in dynamic pressure measurement area for studying multiphase flows. It was presented several information about this subject: composition of the measurement system for this application, characteristics of each component, types of electronic pressure transducers available in the market, and recent works published in literature.

It was discussed about the influence of several factors on the performance of the measurement system: tips on pressure tap and hoses installation and characteristics to be considered when choosing pressure transducers. Therefore, in this work, the piezoresistive one evaluated as the most suitable for this application, but compatibility with the medium should be considered.

Information from recent gas-liquid and gas-solid works in the literature were provided. Frequency range was reported from 0 Hz (static component) to 400 Hz, and the amplitudes of pressure from –20 kPa to 20 kPa among all those studies. Being this information useful to develop a metrological method, including procedures and calibration device, for operation of electronic pressure transducers in two-phase flows.

Finally, it is recommended to the engineer always evaluate the performance of whole dynamic pressure measurement system, which can be made by dynamic calibration (Diniz *et al*., 2003). Otherwise, the data can be influenced by many systems limitations into the frequency and amplitude ranges of pressure signals from multiphase flows, and they couldn't reflect the truthfully of the flows fluidynamic.

5. AKNOWLEDGEMENTS

The support of PIBIC/CNPq and SAE/UNICAMP is deeply appreciated.

6. REFERENCES

Alberto, C., Felipe, S. and Rocha, S. C. S., 2004, "Time series analysis of pressure fluctuation in gas-solid fluidized beds", Brazilian Journal of Chemical Engineering, Vol.21, pp. 497-507.

American Society of Mechanical Engineers, 1995, "A Guide for Dynamic Calibration of Pressure Transducers", ANSI B88.1-1972 (R1995), ASME, USA.

Bai, D., Grace, J. R. and Zhu J., 1999, "Characterization of gas fluidized beds of group C, A and B particles based on pressure fluctuations", The Canadian Journal of Chemical Engineering, Vol.77, pp. 319-324.

Bean, V. E., 1994, "NIST Measurement Service: NIST Pressure Calibration Service", National Bureau of Standards and Technology, Special Publication 250-39.

Chisholm, D. "Two-phase Flow in Pipelines and Heat Exchangers", Pitman Press Ltd., 1983.

Clark, C., 1990, "The Practice of Dynamic Pressure Measurement", Measurement and Control, Vol. 22, pp. 298-301.

Davis, R. S. and Welch, B. E., 1988, "Practical uncertainty limits to the mass determination of a piston-gage weight", Journal of Research of the National Bureau of Standards, Vol.23, n.5.

de Gaspari, C. A., 2006, "Calibração Dinâmica de Transdutores de Pressão para o Estudo de Escoamentos Multifásicos", Annual Report of PIBIC/CNPq, College of Mechanical Engineering, State University of Campinas. Report in portuguese.

Diniz, A. C. G. C., Vianna, J. N. and Neves, F. J. R., 2003, "Calibração dinâmica de sensores de pressão: métodos e meios", Metrologia – 2003 Anais, Recife, Pernambuco, Brazil.

Ellis, N., Briens, L. A., Grace, J. R., Bi, H. T. and Lim, C. J., 2003, “Characterization of dynamic behavior in gas-solid turbulent fluidized bed using chaos and wavelet analyses”, Chemical Engineering Journal, Vol.96, pp. 105-116.

Elperin, T. and Klochko, M., 2002, “Flow regime identification in a two-phase flow using wavelet transform”, Experiments in Fluids, Vol.32, pp. 674-682.

Elrlish, C., 1993/94, “A Review of Gas-operated Piston Gauges”, Metrologia, Vol.30.

Ferreira, V. C. S., 1997, “Differential pressure spectral analysis for two-phase flow through an orifice plate”, International Journal of Pressure Vessels and Piping, Vol.73, pp. 19-23.

Groen, J. S., Mudde, R. F. and Van den Akker, H. E. A, 1995, “Time dependent behavior of the flow in a bubble column”, Int. of Chemical Engineers, Vol.73, pp. 615-621.

Hjelmgren, J., 2002, “Dynamic Measurement of Pressure – a Literature Survey”, Sp Swedish National Testing and Research Institute, SP Report 2002:34.

Ismail, K. A. R., Gonçalves, M. M. and Benevenuto, F. J., 1998, “Instrumentação para Engenharia”, Campinas, São Paulo, Brazil.

Keska, J. K., Smith, M. D. and Williams, B. E., 1999, “Comparison study of a cluster of four dynamic flow pattern discrimination techniques for multi-phase flow”, Flow Measurement and Instrumentation, Vol.10, pp. 65-77.

Letzel, H. M., Schouten, J. C., Krishna, R. and Van den Bleek, C. M., 1997, “Characterization of regimes and regime transitions in bubble columns by chaos analysis of pressure signals”, Chemical Engineering Science, Vol.52, pp. 4447-4459.

Li, H., 2002, “Application of wavelet multi-resolution analysis to pressure fluctuations of gas-liquid two-phase flow in horizontal pipe”, Powder Technology, Vol. 125, pp. 61-73.

Marcus, R. D., Leung, L.S., Klinzing, G.E and Rizk, F., 1990, “Pneumatic Conveying of Solids"”. Chapman and Hall, New York, 596p.

Mcdougall, S., Saberian, m., et al., 2005, “Using dynamic pressure signals to assess the effects of injected liquid on fluidized bed properties”, Chemical Engineering and Processing, Vol. 44.

Miccio, F, Miccio, M, Olivieri, G. and Silvestre, A., 2003, “On the mechanism of bubbling fluidized-bed combustion of gas oil”, Ind. Eng. Chem. Res., Vol.42, pp. 3973-3981.

Persico, G., Gaetani, P. and Guardone, A., 2005, “Dynamic calibration of fast-response probes in low-pressure shock tubes”, Measurement Science and Technology. Vol.16, pp. 1751-1759.

Reis, E. dos. 2003, “Estudo do escoamento pistonado horizontal ar-água em tubulações com ramificação T”, College of Mechanical Engineering, State University of Campinas, 2003. PhD Thesis in portuguese.

Sacic, S., Leckner, B. and Johnsson, F., 2005, “Fluctuations and waves in fluidized bed systems: the influence of the air-supply system”, Powder Technology, Vol. 153, pp. 176-195.

Schutte, P. C., Cate, K. H., Young, S. D., 1985, “Dynamic pressure calibration standard”, Proceedings of the 31st ISA International Instrumentation Symposium, USA.

Sun, T., Zhang, H. and Hu, C, 2002, “Identification of gas-liquid two-phase flow regime and quality”, IEEE Instrumentation and Measurement Technology Conference, Anchorage, ak, USA.

Tsuji, Y. and Morikawa, Y., 1982, “Flow pattern and pressure fluctuation in air-solid two-phase flow in a pipe at low air velocities”, International Journal of Multiphase Flow, Vol.8.

Tutu, N. K., 1982, “Pressure fluctuations and flow pattern recognition in vertical two-phase gas-liquid flows”, International Journal of Multiphase Flow, Vol.8.

Validyne Engineering, 2006. “Estimating the Frequency Response of Variable Reluctance Pressure Sensors in Gas”. 21 Apr 2006, < http://www.validyne.com/tecnotes/resp.htm>.

Van ommen, J. R., Schouten, J. C., et al, 1999, “Monitoring fluidization by dynamic pressure analysis”, Chemical Engineering Technology, Vol.22.

Van Ommen, J. R., Van der Schaaf, et al., 2004, “Optimal placement of probes for dynamic pressure measurement in large-scale fluidized beds”, Powder Technology, Vol.139.

Wang, S. F., Mosdorf, R., Shoji, M., 2003, “Nonlinear analysis on fluctuation feature of two-phase flow through a T-junction”, International Journal of Heat and Mass Transfer, Vol.46, pp. 1519-1528.

Webster, J. G. (editor-in-chief), 1999, “Measurement, Instrumentation, and Sensors Handbook”, CRC press.

Zhong, W., Zhang, M., 2005, “Pressure fluctuation frequency characteristics in a spout-fluid bed by modern arm power spectrum analysis”, Powder Technology, Vol.152, pp. 52-61.