Proceedings of the
International Conference on Mechanical Engineering 2011
(ICME2011) 18-20 December 2011, Dhaka, Bangladesh

ICME11-AM-050

THEORETICAL AND EXPERIMENTAL INVESTIGATION OF RESPONSE TIME IN PRESSURE MEASUREMENT WITH µ-TUBES

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ABSTRACT
This paper presents the theoretical and experimental analysis of response time of µ-tubes in pressure measurement. Theoretically, response time is calculated by using a mathematical formula. Experimentally, the response time of pressure measurement in µ-tubes was performed by using pressure chamber and pressure sensor. We also investigated the size effect, i.e., changing the diameter and length of µ-tubes to measure the pressure field and response time experimentally as well as theoretically. From the theoretical and experimental result, it is observed that response time is greatly influenced by the µ-tubes diameter and pressure differential rather than its length. For the convenience and wide application, we also used another parameter called Aspect Ratio (AR = Length/Diameter). The experimental and theoretical results served as a basis for the discussion of optimum dimensions of µ-tubes for the best response time.

Keywords: Response Time, µ-tubes, Aspect Ratio.

1. INTRODUCTION
Measurement of time varying static and dynamic pressures is applied in various fields, e.g. in the development of internal combustion engines, in automotive and airplane industry, acoustics, manufacturing processes, hydraulics, pneumatics, robotics, and medicine. Depending on the particular application, measurement of pressures is performed in the Pa to GPa amplitude range and in the Hz to kHz frequency range. These requirements should be considered in the selection of the pressure measurement sensor and the design of the measurement system. To best utilize the dynamic characteristics of the pressure measurement sensor, its ideal location is immediately on the measurement object, at the point where the measured pressure occurs. This is, however, not possible in all cases because of complex shape or geometry of the measurement object, and a micro tube, connecting the measured object and the pressure sensor, is often met as a component part of the pressure measurement system. In that case we have to check time response of the µ-tubes. If the time response of the µ-tubes is reasonable, we can use this kind of µ-tubes to measure pressure and the response time of the connecting µ-tubes on the magnitude of the measured pressure depends on the geometric, applied pressure and material characteristics of the connecting µ-tubes. A few articles have been published for the dynamic characteristics, i.e. response time of pressure measurement systems including connecting µ-tubes by different authors. Xie and Geldart [1] reports the influence of probe dimensions on the outcomes of different data analysis methods for fluidized bed pressure signals with a simple model but they did not give an experimental validation of the model. They suggested the use of probes with an internal diameter of 4 mm. Bajsic Ivan, Kutin Joze, and Zagar Tomaz [3] presents an experimental analysis of dynamic characteristics of connecting tubes of different lengths and diameters where inlet step pressure changes were generated by a system of two loudspeakers and pressure responses were measured by a piezoelectric measurement system to characterize the natural frequencies and damping of the system. Sinclair and Robbins [5] developed an analytical theory to estimate the time lag in a capillary-based pressure measurement system. The theory takes system volume, tubing length and diameter, fluid viscosity and pressure differential into account to estimate the time required for the pressure at the transducer to reach a prescribed percentage of the pressure at the measurement location. Here, in this paper we tried to calculate response time in pressure measurement with µ-tubes arrangement theoretically and experimentally. Size effect of µ-tubes on response time has also been calculated and discussed. The measurement system is described later in this paper. Later, there are also presented some results analysis of the connecting µ-tubes based on time response to a step change of pressure.

2. THEORETICAL ANALYSIS

2.1 Mathematical formulation of response time

Response time gives the concept that how fast a system can produce an output to a given input. pressure measured by a pressure transducer/manometer consist of two components: Acoustic lag (time interval for a pressure disturbance propagate at the speed of sound to be transmitted down the connecting microchannel tubing to the pressure sensor) and Pressure lag (time taken for the magnitude of pressure change to register due to viscosity in the tubes). To measure pressure using µ-tubes for pressure field measurement case we can consider the system with the following system to analyze the effect of µ-tubes in pressure measurement.

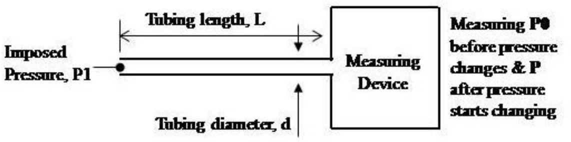

Fig 1: Schematic representation of a probe-transducer system with µ-tube

If we apply pressure at the open end of the µ-tubes, it will take some time to reach the pressure to the sensing device that is time lag or response time. Numerous studies have been conducted to determine the dependence of this lag on instrument and tubing parameters. Sinclair and Robbins [5] developed a theory to estimate the time lag in tubing systems. For a single tube, they suggest the following equation to describe the time lag or response time:

$$t = \frac{128\mu L}{\pi d^4}\left[\frac{V}{P1}\ln\frac{(P0-P1)(P+P1)}{(P-P1)(P0+P1)}\right] \quad (1)$$

Equation (1) is derived by using the following basic equation of fluid mechanics:

Poiseuille's equation: $$\Delta P = \frac{128\mu LQ}{\pi d^4} \quad (2)$$

Mass flow rate: $$\dot{m} = \rho \times A \times u \quad (3)$$

Ideal gas equation: $$PV = \frac{m}{M}RT \quad (4)$$

Research survey says that three factors affect the time lag in pressure measurement through µ-tubes. They are internal diameter of µ-tubes, applied pressure and length of µ-tubes. From the equation (1), it is clear that time lag is directly proportional to the length, inversely proportional to applied pressure, and inversely proportional to the fourth power of the diameter, i.e. diameter has tremendous effect in time lag compared to other factors.

2.2 Theoretical response time calculation

Theoretically we calculated the response time for different µ-tubes for constant applied pressure (10 kPa) by using Eq. (1) and the result is shown below in Table 1. Figures 2 and 3 represent the theoretical response time of µ-tubes for different aspect ratio and for different applied pressure, respectively. While calculating the response time we use viscosity (µ) property of air, measuring system volume (V), which is actually transducer volume and the value is approximately 7.853975 mm^3 , P_0 atmospheric pressure, P_1 applied pressure and P is 99% of P_1.

Table 1: Theoretical Response time of µ-tubes for different aspect ratio

µ-tubes Diameter, d (mm)	Response time, t (Sec)				
	AR = 100	AR = 200	AR = 300	AR = 400	AR = 500
0.10	0.3015	0.6030	0.9045	1.2060	1.5075
0.25	0.0192	0.0385	0.0578	0.0771	0.0964
0.50	0.0024	0.0048	0.0072	0.0096	0.0120
0.75	0.0007	0.0014	0.0021	0.0028	0.0035
1.0	0.0003	0.0006	0.0009	0.0012	0.0015

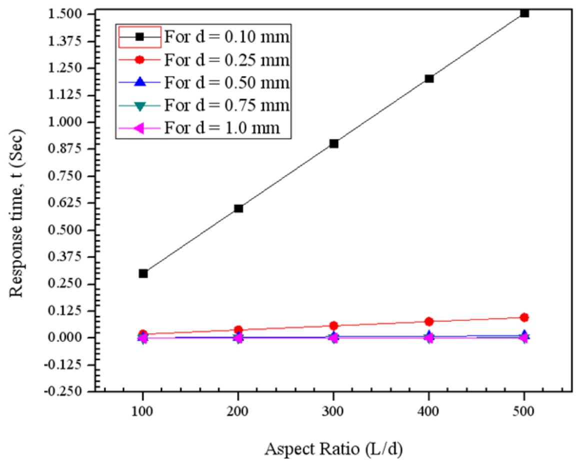

Fig 2: Response time of µ-tubes for different aspect ratio

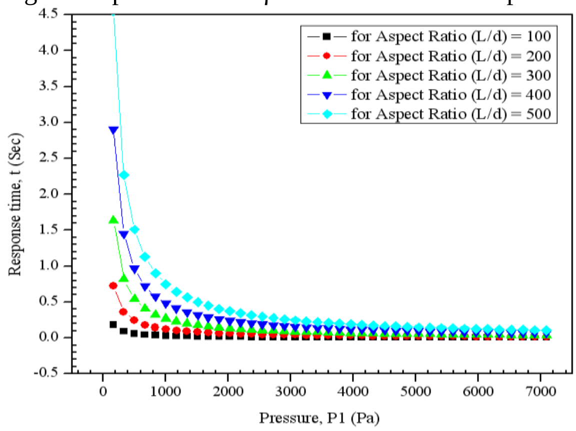

Fig 3: Response time of µ-tubes for different applied pressure

From the above theoretical response time calculation, we can see that the response time decreases as the diameter of µ-tubes increases and the response time increases as the aspect ratio of µ-tubes s increases for same diameter of µ-tubes.

3. EXPERIMENTAL ANALYSIS

Experimental Pressure measurement system with connecting µ-tubes was carried out with air, for a range of connecting µ-tube lengths and internal diameters. The experiments presented in this paper are carried out at ambient pressure and temperature. We performed the Static and Transient pressure measurement experiment to see the pressure response effect of µ-tubes in terms of response time and to compare the experimental values with the theoretical values. To perform the experiment we used a pressure chamber, pressure sensor, µ-tubes with different diameter and length, Syringe pump, oscilloscope, function generator and Power supply.

3.1 Pressure Chamber

In order to do the experiment, we have manufactured a Pressure chamber shown in Fig. 4 which consists a cylindrical volume. Pressure chamber is made from Aluminum. This pressure chamber consists of 4 ports (4 air passages on 4 walls), one port for applied pressure, two ports for pressure (one with micro tube and another one without micro tube) measurement and another one to release pressure through pressure release valve when needed for pressure measurement. The port without micro tube is used as reference pressure port.

Fig 4**:** Pressure chamber

3.2 Pressure Sensor

The following pressure sensors as shown in Figs. 5 and 6 were used in our static (Model: MS5536-60C) and transient (Model: MPXV10GC7U) pressure measurement experiment, respectively and the sensors were selected based on theoretical calculation which suits for our experiment. Because in our experiment, we need to measure small pressure change. So we selected this sensors which can measure small change in pressure and whose range is also small.

Fig 5**:** Pressure Sensor for static pressure measurement (Model: MS5536-60C)

Specifications:
- Pressure Range: 0 to 60 mbar (0 to 6000 Pa)
- Resolution: 0.05 mbar (5 pa)
- Provide digital pressure and Temperature information as 16-Bit data word each.

Fig 6**:** Pressure Sensor for transient pressure measurement (Model: MPXV10GC7U)

Specifications:
- Pressure Range: 0 to 10 kPa (0 to 10000 Pa)
- Sensitivity: 3.5 mV/kPa
- Provide uncompensated analog output voltage from the piezoresistive pressure sensor directly proportional to the applied pressure.

3.3 Pressure Measurement

Theoretically we calculated change in pressure inside the pressure chamber by using Boyle's formula (P1*V1=P2*V2) which is also used as the basis for the pressure measurement experiment. Here the total compressed volume of syringe is 1000 mm^3 and we divided 1000 mm^3 into 40 divisions and we took the reading of pressure change after each 25 mm^3 of volume change. While doing the experiment, flow rate of air was fixed to 250µl/min, i.e. we took the pressure measurement reading after 6 seconds consecutively. Table 2 represents the different dimensions of µ-tubes which are used in our experiment.

Table 2: μ-tubes of different aspect ratio for the experiment

No	AR (L/D)	Case-1		Case-2		Case-3		Case-4		Case-5	
		D (mm)	L (mm)	D (mm)	L (mm)	D (mm)	L (mm)	D (mm)	L (mm)	D (mm)	L (mm)
1	100	0.1	10	0.25	25	0.50	50	0.75	75	1	100
2	200	0.1	20	0.25	50	0.50	100	0.75	150	1	200
3	300	0.1	30	0.25	75	0.50	150	0.75	225	1	300
4	400	0.1	40	0.25	100	0.50	200	0.75	300	1	400
5	500	0.1	50	0.25	125	0.50	250	0.75	375	1	500

3.3.1 Static Pressure Measurement

In Fig. 7, we can see the experimental set-up for static pressure measurement. For the static pressure measurement, we applied pressure by syringe pump to the pressure chamber in which a pressure sensor (pressure sensor module: MS5536-60C interfaced with PC through comport) is connected through μ-tube and the pressure change is measured with compressed volume and time, respectively. Change in pressure inside the pressure chamber is calculated theoretically. As the sensor is digital, we will have digital value which is converted to pressure (Pa) value finally.

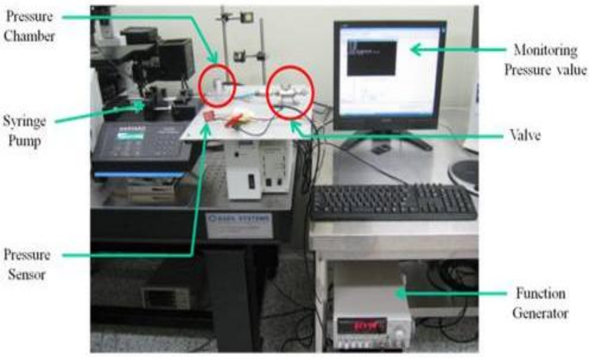

Fig 7**:** Experimental set-up for static pressure measurement experiment

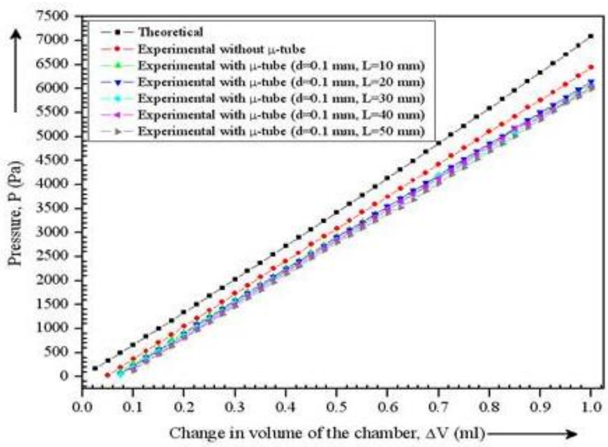

Fig 8**:** Experimental measured Pressure as a function of change in volume of the pressure chamber

Figure 8 represents the results obtained from static pressure measurement experiment for μ-tube of diameter 0.10 mm with different length. The upper most line in the graph represents the theoretical pressure value, then the line just below the upper most line represents the experimental value of pressure measurement without μ-tube and the rest represents the measured pressure value with μ-tubes. This trend is followed by μ-tubes with diameter 0.25 mm, 0.50 mm, 0.75 mm, and 1.0 mm. From the graph, we can see that pressure values with μ-tubes and pressure values without μ-tube are very similar and their values are very close to each other, i.e. negligible amount of pressure loss occurs.

3.3.2 Transient Pressure Measurement

In the Fig. 9, we can see the experimental set-up for transient pressure measurement experiment. Pressure change with time is known as transient response.

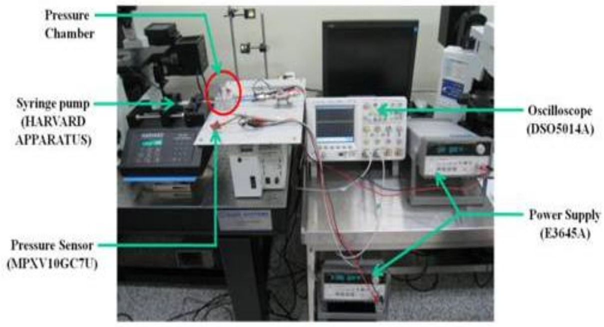

Fig 9: Experimental set-up for transient pressure measurement experiment

In case of transient pressure response measurement experiment, we used two pressure sensors (Model: MPXV10GC7U) at the same time connected to the pressure chamber. One sensor with μ-tube and another one without μ-tube. The sensor without μ-tube represents the reference sensor which is used to compare the result obtained by using μ-tube. We applied a certain pressure (approx 10 kPa) to the pressure chamber through syringe pump and the pressure release valve is suddenly released and then the response from the two pressure sensors are observed and saved as csv data form in oscilloscope for analysis. As the output of the pressure sensor is in mV we need to convert the mV output into pressure (pa) value. So the saved csv data is reduced by using Microsoft excel program and by using the sensitivity (3.5 mV/kPa) of the pressure sensor, we transformed the mV into pressure (Pa) value, i.e. the data obtained from oscilloscope is reduced and analyzed to get the pressure value. The results obtained from the transient pressure measurement experiment are shown in the Figs. 10 and 11.

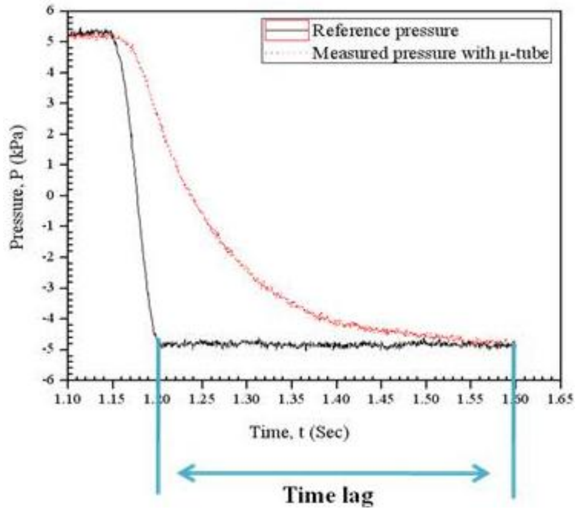

Fig 10**:** Transient response of μ-tube for d = 0.1 mm & L = 10 mm

In the Figs. 10 and 11, solid line represents the reference sensor's pressure signal and the dotted line represents the sensor's (connected with μ-tube) pressure signal. And the difference of the time between the two pressure signal line, where they meet with each other, (point of convergence) is the time lag by which we can determine the fastness of μ-tubes.

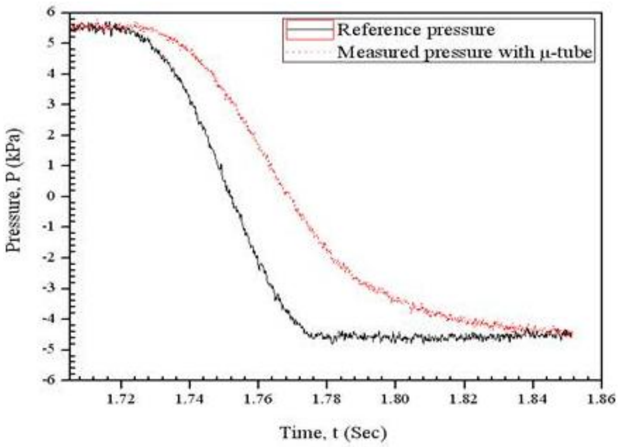

Fig 11**:** Transient response of μ-tube for d = 0.25 mm & L = 125 mm

3.4 Response Time Measurement

In the transient pressure measurement experiment, the time difference between two pressure sensors signal is the time lag or response time and the experimental response time of μ-tubes for different aspect ratio are shown in the Table 3.

Table 3**:** Experimental Response time of μ-tube for different aspect ratio

μ-tube Diameter, d (mm)	Response time, t (Sec)				
	AR = 100	AR = 200	AR = 300	AR = 400	AR = 500
0.10	0.397	0.82775	1.13907	1.35554	1.42978
0.25	0.010 8	0.03252	0.05813	0.0710	0.07436
0.50	-	0.0023	0.0029	0.0037	0.006

4. RESULT ANALYSIS

4.1 Theoretical Response Time

Theoretically, we calculated the response time for different μ-tubes for constant applied pressure (10 kPa) by using Eq. (1) and the result is shown in the Table 1. We have seen from the calculated response time that three factors affecting the time lag in pressure measurement through μ-tubes are internal diameter of micro tube, applied pressure, and length of μ-tubes which represents the reflection of Eq. (1). However, increasing the tubing diameter beyond approximately 3mm has little impact, and may violate the applicability of Eq. (1) for analysis. From the calculated theoretical response time, we can see that the response time decreases as the diameter of μ-tubes increases and the response time increases as the aspect ratio of μ-tubes increases for same diameter of μ-tubes.

4.2 Experimental Response Time

Experimentally we performed both static and transient pressure measurement to measure the response time of μ-tubes.

4.2.1 Static pressure measurement

We performed static pressure measurement experiment with the μ-tubes. Theoretical and experimental measured pressure (static) is graphically plotted in Fig. 8. In static pressure measurement, measured pressure without μ-tube and using μ-tube are increasing linearly with compressed volume of syringe pump and the values are very close to each other. From the graph, we can see that both pressures are very similar. The difference between theoretical and measured experimental (static) pressure is the pressure loss which is very small and the pressure loss occurred mainly due to the viscous resistance of the μ-tube.

4.2.2 Transient pressure measurement

We also performed the transient pressure measurement experiment with the μ-tubes. In transient pressure measurement we have seen that response time of µ-tube is drastically changes when there is small change in diameter as shown in the Figs 10 and 11. On the other hand, response time of micro channel pitot tube is not so drastically changes when there is small change in length of micro tube, i.e. the dependency of time lag on tubing length is not as sensitive as it is to applied pressure or tubing diameter.

4. 3 Comparison between theoretical and experimental result

Theoretical and experimental calculated response time is shown in Table 4. From Table 4, we can see the calculated and experimental data are in reasonable agreement for micro tube with diameter 0.10 mm and 0.25 mm, and for other cases their values differ much from each other. But from Figs 10 and 11 (transient pressure measurement), we can see the time lag effect of micro tube in pressure measurement and the time lag value is very small in case of larger diameter µ-tubes, i.e. both the signal lines are identical.

Table 4**:** Comparison between theoretical & experimental response time

µ-tube diameter, d (mm)		Response time, t (Sec)				
		AR=100	AR=200	AR=300	AR=400	AR=500
0.10	Theoretical	0.301507	0.603013	0.90452	1.206027	1.507533
	Experimental	0.397	0.82775	1.13907	1.35554	1.42978
0.25	Theoretical	0.019296	0.038593	0.057889	0.077186	0.096482
	Experimental	0.0108	0.03252	0.05813	0.0710	0.07436
0.50	Theoretical	0.002412	0.004824	0.007236	0.009648	0.01206
	Experimental	-	0.0023	0.0029	0.0037	0.006

There is always some error between theoretical and experimental result. The reason is that theoretically formulas are developed neglecting some factors which can affect the result while in case of experiment we cannot make sure about the accuracy of the result due to some experimental constraints.

5. CONCLUSIONS

This paper reports the influence of µ-tubes dimensions (diameter, length) and applied pressure on the response time in pressure measurement theoretically and experimentally. In this research, we performed the theoretical and experimental analyses to see the response effect (fastness) of µ-tubes with different dimensions in pressure measurement to justify whether it can be used to measure pressure. From theoretical and experimental results we observed that the following can be pointed out from this research:

(1) Larger diameter with smaller length of µ-tubes shows the good pressure response in terms of response time for a specific applied pressure.

(2) On the other hand, if the applied pressure increases, the response time is also decreases, i.e. fastness increases.

6. REFERENCES

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7. NOMENCLATURE

Symbol	Meaning	Unit
d	Internal diameter of tubing	m
h	Height of Cylinder (Pressure chamber)	M
L	Length of tubing	m
P	Pressure at any time t	Pa
P0	Initial pressure at time t0	Pa
P1	Final applied pressure at orifice or open end of tubing	Pa
P_1	Pressure at initial condition	Pa
P_2	Pressure at final condition	Pa
ΔP	Change in pressure ($P_2 – P_1$)	Pa
r	Radius of cylinder (Pressure chamber)	m
R	Radius of syringe chamber	m
t	Time lag or Response Time	s
V	Total measuring system volume	m^3
V1	Volume at initial condition	m^3
V2	Volume at final condition	m^3

Greek Symbol	Meaning	Unit
µ	Viscosity of fluid (air)	Pa-s
ρ	Density of fluid (air)	Kg/m^3

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