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Experimental Investigation of the Time Effect of Pressure Fluctuations in Steady Turbulent Pipe Flows

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Abstract: In the study, which performed experimentally, the behavior of time variation of the static pressure in pipe water flows has been investigated in terms of pipe diameter, flow rate and pipe roughness. In the experiments, five pipe types in different materials and in different roughness were used. In the steady and horizontal pipe water flows, which performed at low Reynolds numbers, the static pressure at different tap locations which is longitudinally placed have been measured. The water heights in the piezometer hoses, which is inserted on pressure taps, has been recorded with a camera for three minutes for each flow rates. A total of 21 snapshots were obtained from each camera recordings at equal time intervals and the pressures were determined from that snapshot images through water height readings. The sanpshots of any flow rate has shown that all pressures at the tap locations fluctuate together over the time in the same phase, frequency and amplitude. When RMS values, which shows the pressure fluctuation in mean intensity over the time, was examined, it was observed that the fluctuation amplitudes is independent of pipe roughness but has a relation with velocity of the pipe flow.

Keywords: Pipe flows, Pressure fluctuations

Introduction

Osborne Reynolds (1842-1912) has discovered laminar and turbulent flow behavior by injecting ink into glass-tubular flow in his experiments. At low flow velocities the ink followed a uniform flow path and not mixed to the flow along, while at high flow velocities the ink mixed to the flow over the entire cross section of the pipe flow as the ink moving downstream. In the laminar flows, due to the low flow velocity, fluid particles follows a smooth flow path, for this reason the laminer flows is smooth. Whereas in the turbulent flow, the instabilities in the flow cause the flow to get mixed in so that the fluid particles do not follow a uniform flow path. In general, all flows must be laminar, however some factors that degrade the flow stability, such as surface roughness, upstream turbulence, and heat transfer in the flow, force the flow to be turbulent. For this reason, if precise flow conditions are provided, all flows will remain laminar (Özışık, 1985). Turbulent flows include fluid clusters that are formed continuously and moved along the flow while spinning its around. These moving fluid clusters are called turbulent structures or swirl motions. These vortex structures form continuously, move, divide and disperse in the flow and eventually turn into sensible heat in the flow then disappears. They are responsible of the conversion of some of the mechanical energy into sensible heat energy. This describe why the energy loss is greater in turbulent flows. For example, especially for flows over a solid surface (flow through aircraft, turbine, and compressor blades) the flow being turbulent not only increases energy loss but also gain the vibration and noise to the flow. As a result, in addition to the viscous forces in the turbulent flow, there are also additional drag forces, so that the energy losses in turbulent flows are much higher than laminar flows which viscous forces are dominated.

The flow over a flat surface first becomes laminar and after a certain flow distance, the flow stability is degraded then it becomes turbulent flow. Fig. 1 shows the steps of a flow as being laminar, transition and

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turbulence, over the pipe inner surface. The distance from inlet to where the flow first undergo a turbulent state is called transition length, L_t. After the transition length a transitional flow establishs, which is an intermittent flow between laminar and turbulent states. After the transitional flow the flow becomes full turbulent. Some detailed experimental and theoretical progresses for the laminer to turbulent transition in pipe flows have been reported by Kerswell (2005) and recently by Willis a.e (2008). Factors such as inlet smoothness, inlet geometry type, surface roughness, upstream turbulence, mixing the flow at inlet and heating-cooling applications are highly influential on triggering the flow to a turbulent state (Ghajar & Tam, 1995). The smooth velocity profile at pipe inlet starts to change along the downstream and after a certain critical flow distance the velocity profile no longer change. The pipe flow region where the velocity profile changes is called developing flow and where the velocity profile is constant is called fully developed flow. In the fully developed pipe flow region, pressure drop is linear and due to has a relation with it, the wall shear stress is constant also. The measured pipe distance from inlet to where the flow start to fully devloped is called entrance length L_e. In general, the flow are assumed to be fully developed when time-averaged flow quantities (velocity and pressure field) and turbulence quantities (turbulence velocities u'' v) no longer changes, (Zagarola & Smits, 1998).

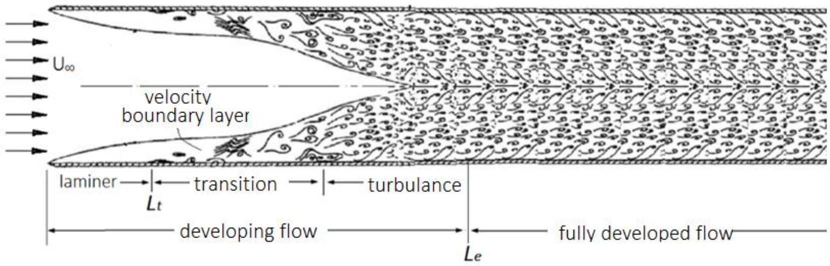


Figure 1. Developing and fully developed flow at pipe entrance

Osborne Reynolds has discovered the dimensionless Reynolds numbers so to specify the flow state. Through his experiments, he has observed that the pipe flow remained as laminer until a Reynolds number of 13000 when the sensitive flow conditions was provided by him and a turbulent state also has reached after a Reynolds number of 2300 when disturb the flow at pipe inlet. For that reason it is hard to mention about a definitely Reynolds number where turbulent pipe flow is established. In general, pipe flows are acccepted as laminer for Re<2300 and otherwise are accepted as turbulent (White F.M., 2003).

The flow properties measured at any point in a turbulent flow field shows fluctuating values over the time. As shown in Fig 2, the turbulence flow exhibits non-periodic statistical wavy flow characteristics.

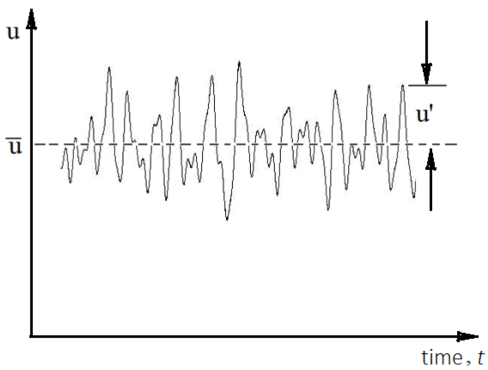


Figure 2. Variation of the instant velocity over the time
at at any point in the turbulent flow field

Because the turbulent flows changes with time and position, it requires analytically time dependent and three dimensional flow solution. Therefore it is so difficult to solve the turbulent flows theoretically. One simplification to the solution is to evaluate the turbulent flow over the time average effects. The flow properties can be separated into two parts as the time average value and the fluctuation value, which is the amount of deviation from the mean value, as shown in the instantaneous velocity graph.

$$u = \bar{u} + u' \qquad\qquad P = \bar{P} + P'$$

u' : velocity fluctuation or amplitude value *u:* instantaneous velocity $\bar{u}$: time mean velocity value
P' : pressure fluctuate or amplitude value *P:* instantaneous pressure $\bar{P}$: time mean value

Time mean value can be found by integrating the instantaneous value over the time as shown in Equ.1

$$\bar{u} = \frac{1}{\Delta t}\int_{t}^{t+\Delta t} u\,dt \qquad (1)$$

In turbulent flows, Reynolds average Navier Stokes equations (RANS), which include mean flow effects, are formed by substituting the flow properties into the basic flow equations, separated as mean and fluctuate values. RANS equations consits of continuity and momentum conservation equations which are called also time-mean basic flow equations. A RANS equation, that define a Newtonian and an incompressible turbulent flow field is given below which shows a momentum equation in x direction also.

$$\rho\left(\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} + \bar{w}\frac{\partial \bar{u}}{\partial z}\right) = -\frac{\partial \bar{P}}{\partial x} + \rho g_x + \mu \nabla^2 \bar{u} - \rho\left(\frac{\partial \overline{u'^2}}{\partial x} + \frac{\partial \overline{u'v'}}{\partial y} + \frac{\partial \overline{u'w'}}{\partial z}\right)$$
(2)

While the time mean flow characteristics can be known in a turbulent flow, the time mean effects of the turbulence fluctuation quantities shown in Equ.1 ($-\rho\overline{u'v'}$, $-\rho\overline{u'w'}$ and $\rho\overline{v'^2}$) are not known. The terms formed in the differential flow equation represent the time mean effects of the turbulence in the flow field. These terms are called turbulent stresses or Reynolds stresses. For the solution of Reynolds stresses, many empirical turbulent models are developed. Through this way, turbulent flows are solved in a simple way using RANS equations.

Due to turbulent flows are complex type flows, even though many studies performed it is still exactly not solved with all mystery so it is still of interest in many researchers. In this study, which was aimed to gain a contribution to the solution of turbulent flows, an experimental study of turbulent pipe flows was carried out. In the experimental work, steady and circular pipe water flows were carried out to cover laminar, transition and turbulence flow regimes. In the experiments, time-dependent static pressure measurements were made at different downstream locations of flow field. The pressures measured in each flow rate are analyzed by time-dependent graphs. As a result, in a given flow rate, the static pressures values at all pressure tap locations is fluctuated in the same phase, frequency and amplitude.

If the following sections are summarized, in section 2 the experimental set up, flow conditions and properties are presented. In section 3, the whole study are concluded by analysing the time-dependent variations and the time averages of the experimental results with graphics.

Experiment Set Up and Flow Properties

In order to carry out the experiments, the experimental setup shown in Fig. 3 is prepared. The test setup consists of a pump, a flow rate measurement tank, a rectangular board which the piezometer tubes are attached, a flow control valve, test tubes and a camera for recordings. Water were used in pipe flow experiments. Pressure tappings were welded on the test pipes at regular intervals to measure the static pressures of the flow. The plastic piezometer hoses inserted on pressure taps are glued on the rectangular board and a tape meter is glued next to it to indicate the water height. As can be seen in Fig. 3, different flow rates were carried out by regulating the flow control valve. However the flow rates was measured through weighting tank shown in the test setup.

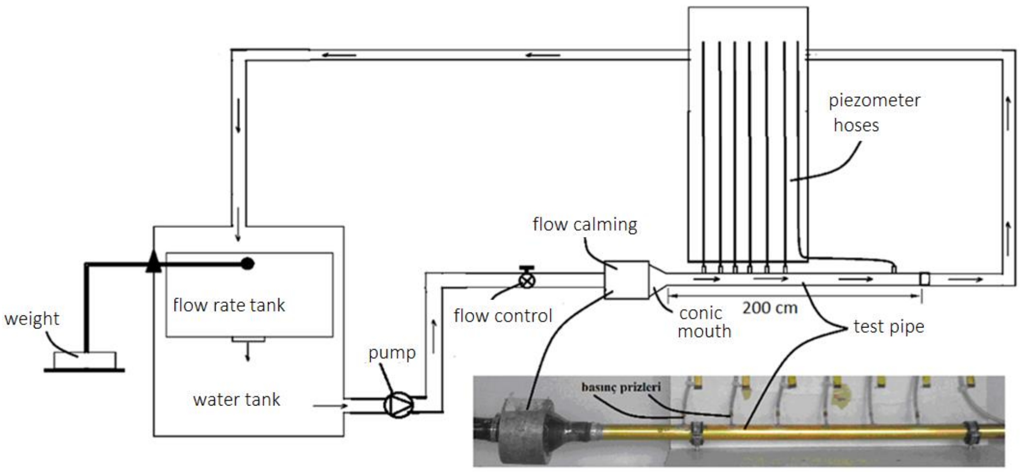


Figure 3. Two dimensional scheme of the experimental set up and test pipe details

To measure the static pressures over the time, the rectangular board which the piezometer hoses were attached was recorded with a camera for three minutes for each flow rate. Snapshots were taken at five second intervals from the camera recording. A total of 21 instantaneous pictures were captured from each flow recordings. The water heights in the piezometer hoses were read from these images and the values were tabulated.

The test tube is connected to a flow calming conic element. In this way it was desired that the fluid enter to the test tube with a low turbulence and a uniform velocity profile. Several studies have reported that the upstream turbulence flow to the test tube is effective on triggering the flow to turbulence (Özışık 1985, Nikuradse, 1932). The test pipe and the presure taps sequenced on the pipe has shown in Fig. 4. A pipe length of 4 m were used in experiments which correspond to a flow distance of 72D. In most experimental studies reported in the literature, it has been reported that fully developed flow generally occurs at flow distances between 30D and 50D (Laufer (1953), Sarpkaya (1975), Haung ve Chen (1974), Patel ve Head (1974)). These reported entrance lengths were found at locations by observing the mean cross sectional velocity profiles where no longer change observed along the flow. Barbin and Jones (1963) has reported that fully developed flow was observed at distances between 10D and 20D when the pressure gradient reaching the constant values along the flow. According to that information supplied, the length of the test pipe is long enough to cover some of the fully developed flow. Pressure taps are welded on pipe at seven diferent stations. The distances between taps are shown on Fig. 4. According to Fig. 4, the 7th tap is placed on the pipe with a distance of 1.7 m away from the pipe inlet and 1 m away from 6th tap. As depicted on Fig. 4, the first six taps were placed on the pipe with equal intervals. The five pipe types used in the experiment are not the new manufactured ones, they are pipes that were dismantled from the old piping systems. Therefore the suface roughness of these pipes were found through the pipe flow measurements. Since the last two taps are in the fully developed flow section, the pressure differences between them were measured and the relative roughness of each tube was found through. In this method, the relative roughnesses were found by comparing the variation of the fully developed Darcy friction factors with Reynolds numbers, which were calculated from that pressure differences, to the Colebrooke equation. The pipe types, diameters and relative roughness found in the experiment are given in Table 1.

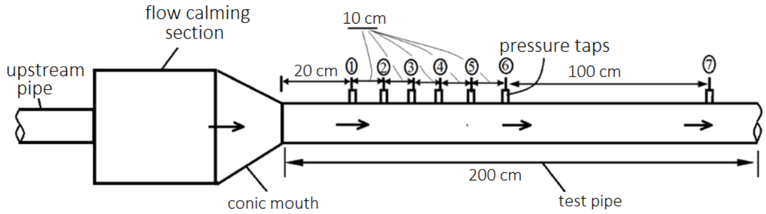


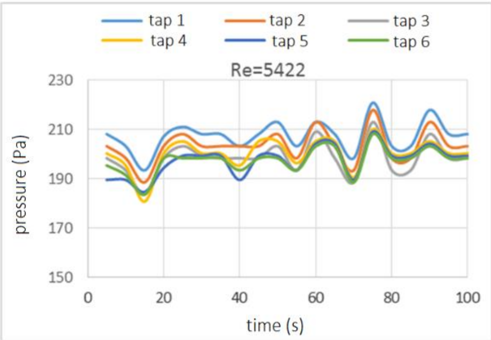
Figure 4. Calming section, test pipe and distances between pressure taps

Table 1. The rougness values found from the experimental measurements for five pipe types

	Aluminium pipe	Copper pipe	Steel pipe	Galvanized pipe	Plastic pipe boru
D (mm)	26	26	28	28	21
Relative roughness: ε/D	0.00159	0.000163	0.00236	0.00256	0.000331

Static Pressure Fluctuations

In a steady experimental water flows, which is carried out in a horizontal and circular pipe, variation of static prssures in the entrance and fully devloped flow regions of a pipe was investigated in this section. In ech pipe flow, water heights in piezometer pipes were recorded for a three minutes with a camera. The pressure at the tap locations are found from the water column heights in piezometer pipes through correlation of $P = \rho g h$. Her *"h"* is the water column height in piezometer pipe. As can be mentioned above, a total of 25 snapshots were recorded at 5-second intervals from the camera recording of each pipe flow. The water heights in the piezometer pipes were read from these snapshots. Through this way, the time-dependent values of pressure values at each tap location has been obtained. For example, Fig.5 has shown the time-dependent variation of the static pressures in the first six pressure taps for close Reynolds numbers of two pipes. When the pressure variations across time are examined, it is seen that the pressures at all tap locations is fluctuated in the same phase, frequency and amplitude as depicted in Fig.5.



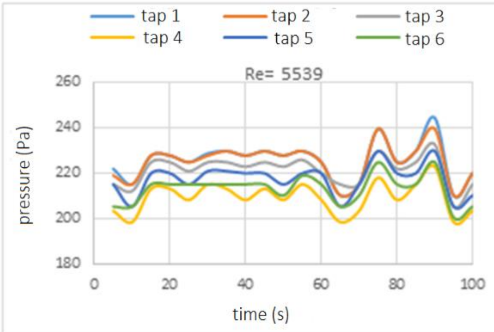


Figure 5. The time-denpendent variations of pressure values at each tap at low Reynolds numbers of two pipes

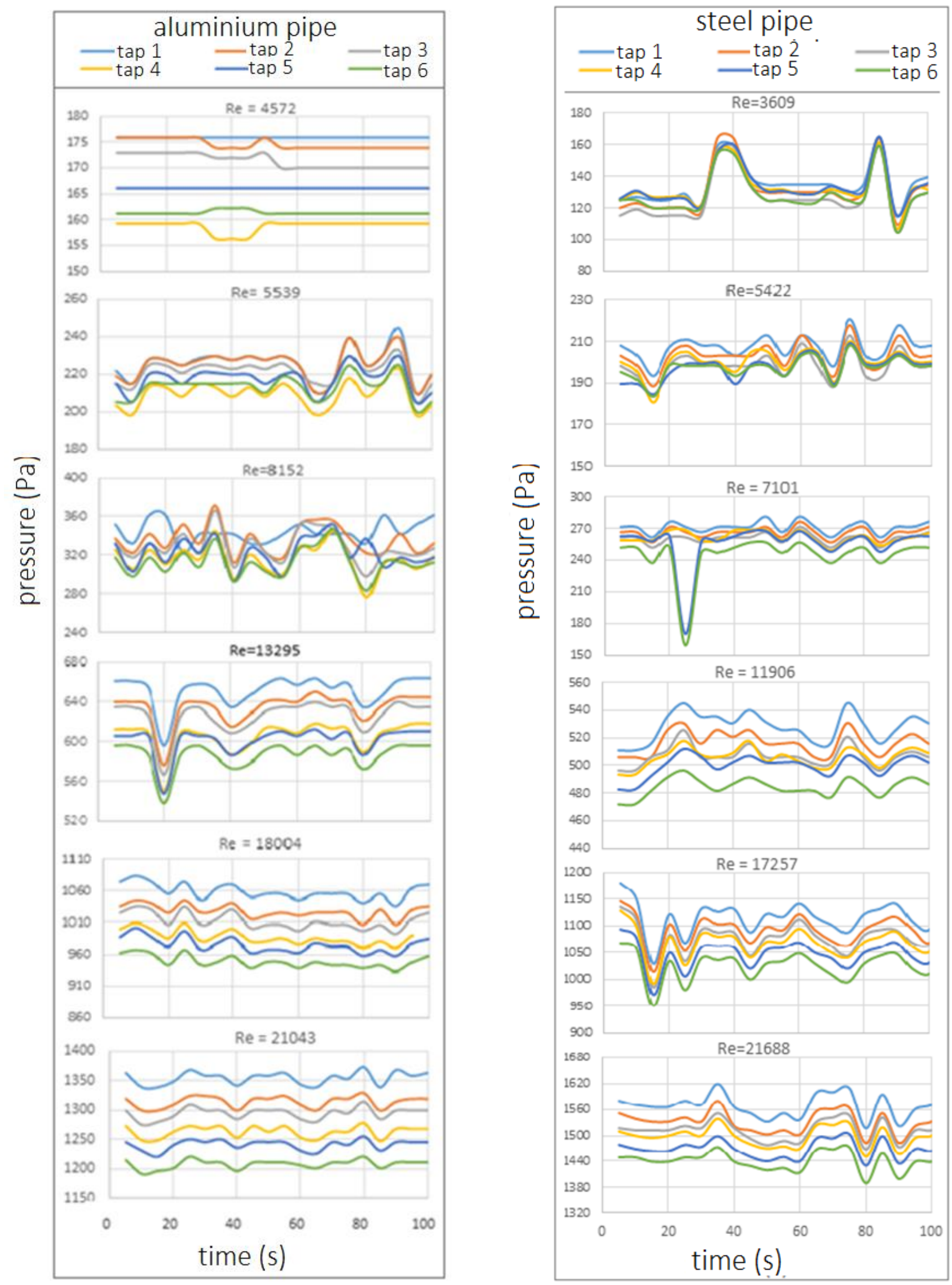


Figure 6. Time dependent variation of pressures at each taps location in different Reynolds numbers

Fig. 6 also shows the time-dependent variations of the pressures at the taps at different Reynolds numbers for two pipes. As can be seen from the figure, the pressure fluctuations are not observed in the lowest Reynolds numbers, but are observed in bigger Reynolds numbers. It is also seen that all presure taps have pressure fluctuations in the same phase, frequency and amplitude for all Reynolds numbers. Pressure fluctuations in the taps indicate that the friction resistance of the flow increases and decreases over the time also. The variation of the flow resistance over the time indicate that the flow rate fluctuates in time with the same phase and frequency also. The reason why the flow resistance variate in time is that the inertia forces are greater than the viscous forces. Inertial forces are forces due to flow velocity while the viscous forces are the bonding forces between liquid molecules. The inertial force of the flow is getting stronger near pipe walls than viscous forces in turbulent flows. The difference between both forces are being stronger intermittently due to some imbalances exists in the flow so that the laminer flow stability are broken down then the flow becomes turbulent.

Viscous forces suddenly failed in the near-wall flow region across inertial forces and fluid vortices exists by this phenomenon which moves from the wall into the pipe flow core region while spinning its around. These eddy fluid clusters as well as carry heat and momentum together with, agitate and mixing the flow also. For this reason, the flow energy is converted to sensible heat in the flow by these vortex motions. Fig. 7 has shown the variations of pressures with the time at each taps including all the five pipe types at close Reynolds numbers. When these variations are examined, it can be seen that the pressure fluctuations are in the same phase, frequency and amplitude for all six tap locations.

Figure 7. Variation of pressures across the time at each tap locations of five pipe type flows at close Reynolds numbers

The amplitude of swing motion of water in the piezometer tubes is directly proportional to the flow resistance encountered in the piezometer hose. The amplitude of the swing motion will be lower in the hose of which the flow resistance is high. As can be seen from Fig. 3, the length of the piezometer hose used on tap 7 is about 1.6 times longer than others. So that, as can be seen in Fig. 8, the pressure variation at tap 7 is slightly different from the pressure variation at tap 6. It is seen that the amplitude of the tap 7 is lower than tap 6 as shown in Fig. 8. This is indicated by the root mean square (RMS) value of the amplitudes given in Table 2 in the last column. Whereas Table 2 has shown the RMS values of the pressure amplitudes in all tap locations of aluminium pipe at a given Reynolds number.

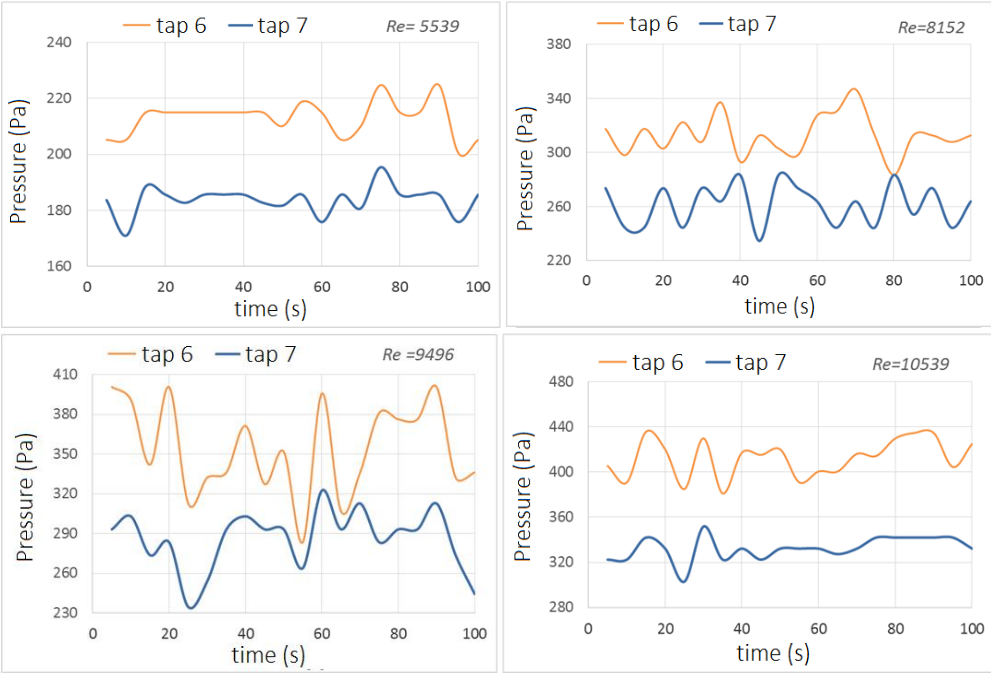


Figure 8. Comparision of pressure variations in pressure taps 6 and 7 at four different Reynolds numbers

Effective Static Pressure

In the pipe flow, for the variation of the pressure over the time, the amount of deviation from the average pressure value of the instantaneous pressure is called the pressure amplitude or fluctuate value. To find out whether the pressure amplitude is related to pipe diameter, roughness and Reynolds number, the pressure amplitude values can be calculated as below.

$$P' = \left| P - \overline{P} \right|$$

P' : pressure amplitude value *P:* instantaneous pressure value $\overline{P}$: time mean pressure value

The RMS values of the pressure amplitude which shows the time mean effective value are calculated as follows.

$$P'_{RMS} = \sqrt{\sum_{i=1}^{N} \frac{(P - \overline{P})^2}{N}}$$

Here, N is the time step number. 21 images has been taken from each camera recordings so the total time step must be N = 21. In Table 2, the pressure fluctuating values of all pressure taps are given for the Reynolds number of 5539 of aluminum pipe flow. Similar tables are prepared for other pipe types which is not given here. In Table 2, the RMS values of each tap are given in the last row. When the RMS value of tap 7, which is given in the last column, is observed it is seen that it is lower than the RMS values of other taps. As stated above, the longer the piezometer hose in the tap 7 is the reason. The longer the hose in the oscillation movement, the more friction creates resistance.

Tablo 2. Absolute deviations from the time averaged pressure values of the pressures at all taps and their time averages in the aluminum pipe flow

absolute pressure amplitude values P'(Pa) Re=5539							
t (s) / L (m)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**1.7**
5	3.567	6.058	6.106	5.911	2.296	7.768	0.049
10	10.406	9.966	9.038	10.797	12.067	7.768	12.751
15	2.296	2.736	3.664	3.860	2.589	2.003	4.837
20	2.296	2.736	3.664	3.860	2.589	2.003	1.905
25	0.636	0.196	0.244	1.026	2.296	2.003	1.026
30	3.273	2.736	3.664	5.814	3.566	2.003	1.905
35	4.250	4.690	3.664	3.860	3.566	2.003	1.905
40	2.296	2.736	1.710	1.026	2.589	2.003	1.905
45	4.250	4.690	3.664	3.860	2.589	2.003	1.026
50	2.296	2.736	1.710	1.026	2.296	2.883	2.003
55	4.250	4.690	4.642	5.814	2.589	5.911	1.905
60	0.636	0.196	1.221	1.026	2.589	2.003	7.865
65	15.292	14.852	6.106	10.797	12.067	7.768	1.905
70	10.406	9.966	6.106	5.911	2.296	2.883	2.980
75	14.021	14.461	8.550	8.745	12.360	11.773	11.676
80	0.636	0.196	0.733	1.026	2.589	2.003	1.905
85	4.250	4.690	3.664	5.814	2.589	2.003	1.905
90	18.906	14.461	11.481	13.630	12.360	11.773	1.905
95	15.292	14.852	15.877	10.797	12.067	12.653	7.865
100	5.521	5.081	6.106	5.911	7.182	7.768	1.905
P'_{RMS}	8.327	7.893	6.316	6.645	6.686	6.206	3,334

Table 3 has shown the RMS values of the pressure amplitudes which is determined from each taps on aluminium pipe at all Reynolds numbers studied. Similar tables are also prepared for other pipes which is not given here. RMS values of the tap 7 are not shown in the table since it has not the same fluctuation conditions with other taps. So it will be enough to use the inputs of the first six taps to determine the overall RMS values. When Table 3 is seen, it is seen that the RMS values of any tap are different at Reynolds numbers. When the variation of RMS value in each tap is examined across Reynolds, no any relation are observed between RMS and Reynolds numbers it can be said that RMS values do not depend on the Reynolds number. The last column in Table 3 shows the mean RMS values in each Reynolds numbers. In addition, an overall average value is taken from the mean tap RMS values as shown in the last row. These overall average RMS values are given in Table 4 for all pipe types.

Table 3. RMS values of the pressure amplitutes for aluminium pipe

Aluminium Pipe, P'_{RMS} (Pa)							
Re / L (m)	0.2	0.3	0.4	0.5	0.6	0.7	**Mean**
4572	0.004	0.932	1.357	1.047	0.003	0.349	0.615
5539	8.327	7.893	6.316	6.645	6.686	6.206	7.012
8152	15.105	15.119	16.074	15.453	15.404	14.735	15.315
9496	37.110	35.226	35.319	34.888	32.091	34.147	34.797
10539	16.053	18.329	17.691	15.785	18.300	16.651	17.135
11371	24.309	21.235	21.452	20.164	17.903	18.876	20.657
12172	24.209	24.282	25.814	25.768	24.173	24.548	24.799
13295	15.619	15.607	16.394	15.483	14.340	13.535	15.163
15712	15.127	10.904	19.012	15.625	14.028	14.109	14.801
18004	12.513	10.645	13.134	11.183	11.980	9.964	11.570
21043	10.798	9.523	9.892	9.661	8.726	7.584	9.364
				Overall Mean			15.56

Table 4. Overall mean RMS values of the pressure amplitudes for whole pipe types.

Overall RMS values				
Aluminium pipe (D=26mm)	Copper pipe (D=26mm)	Steel pipe (D=28mm)	Galvanised pipe (D=28mm)	Plastic pipe (D=21mm)
15.56	15.27	13.16	11.63	21.75

The overall average RMS values given in Table 4 were obtained from the flows in a certain numbers experimented in the Reynolds numbers between 2000 and 25000 for each pipe type. Even though the pipe flows were not provided at the same Reynolds numbers for each pipe type, the flows performed at a certain number have had nearly a uniform Reynolds distribution in the Reynolds range studied. Hence, due to the overall average values are obtained from the statistical values in the Reynolds numbers between 2000 and 25000, which is not improtant to be the same or not of the Reynolds numbers so that the comparisons can be made. In Table 4, the diameters of each pipe type are given in parentheses. The diameter of the plastic pipe is the smallest one however the overall average RMS value is seen the highest one. Similarly, when the RMS values are observed to be related to the pipe diameter, it is seen that the aluminum and copper pipe diameters are the same and their RMS values are close each other and iron and galvanized pipe have the same diameters also and their RMS values has been close to each other. Here it is seen that the overall RMS values are inversely proportional to the pipe diameter. The reason is that the flow velocity is higher in the small pipe diameter for the same Reynolds number considered. It is seen that the higher the flow velocity, the more the pressure amplitudes are affected. However to learn the effect of pipe roughness on RMS values, aluminium and copper pipes can be compared, since both have the same pipe diameters. Even though pipe diameter are te same the roughnesses are different as shown in Table 1. However, the ov arall average RMS values are very close to each other. So roughness can not be said to have much effect on the oscillation amplitude. So roughness can not be said to have much effect on the oscillation amplitude. As a result, the pressure fluctuation amplitudes seem to have an increasing relationship with flow velocity.

Conclusion

In this study, experimental water flows were performed for the Reynolds numbers ranged from 2000 to 25000 with five pipe types made of different materials. Pipe diameters and pipe surface roughness also is different. Approximately 12 different pipe flow rates were carried out evenly in the Reynolds number range studied. From the pipe inlet, seven pressure taps were drilled on the pipe at different locations longitudinal. The pressure in the pipe flows is measured by observing the water heights in the piezometer hoses inserted to these pressure taps. Measurements were time-dependent, so each pipe flow was recorded with camera for three minutes of time. Twenty one snapshots were obtained from each camera recordings at equal time intervals. The pressures at each tap locations are read from these snapshot pictures. These pressures are examined for any flow rate and it is seen that the pressures at each top locations fluctuate with time. When the pressures at all tap locations are compared to each other for any flow rate, it is seen that pressure values fluctuate with time in the same phase, frequency and amplitude. The time dependent RMS values of the turbulent pressures amplitudes were obtained. The RMS values of the pressure amplitudes, which is the amount of deviation from the time mean value, are obtained. When the variation of RMS values were examined across the Reynolds number, it was found that there was no relation with the Reynolds number. The same RMS values were found to be independent of the pipe surface roughness. An overall average value of the RMS values of all flow rates were obtained. In the Reynolds number range studied, it is seen that this is the largest in the small pipe diameter according to the overall average RMS value. The reason for this is that the velocity is being higher in the small pipe diameter for the same Reynolds number considered. Consequently, the flow valocity appears to have a significant impact on the pressure amplitudes

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