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Simulation of Ultrasonic Wave Velocity Flow of Fluid in Pipe System

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Abstract Ultrasonic flow meter is a measurement tool with method of indirect measurement (inferential), because sensor does not measure the speed of the fluid in the pipe directly, instead, it measures difference in time of transit (differential transit time), by measuring time of transit of the sound pulse with high-frequency (high-frequency sound pulses) which travels in the pipe with fluid flow. Time of transit or transit time is the time needed by the sound pulse to travels along the pipe in two directions, in the same direction as the flow and the opposite direction. The difference in time between the two equals the average speed of the fluid flow. Because of its measurement based on transit time, this method also called ultrasonic transit time flow meter. Engineers need to know the model and type of flow meter that is going to be used, with first choosing what model compatible with the production process and the purpose of installation of the flow meter. The model and type of flow meter usually also chose based on the purpose and benefits of the flow meter itself.

Keywords Simulation, ultrasonic wave, velocity, flow, fluid, pipe system

Introduction

The research is to demonstrate the liquid or gas flow through pipes and the usefulness of measuring instrument as a common devise used in ascertaining variation in the desired functional variables in terms of heating and cooling applications and fluid distribution networks [1]. Study on the fluid in such applications is usually forced to flow by a fan or pump through a flow section as well as the terms pipe, duct, and conduit are usually used interchangeably for flow sections. In general, researchers revealed that flow sections of circular cross section are referred to as pipes(especially when the fluid is a liquid), and flow sections of noncircular cross section as ducts (especially when the fluid is a gas) as well as the small diameter pipes are usually referred to as tubes [2].
The fluid velocity in a pipe changes from zero at the surface because of the no-slip condition to a maximum at the pipe center was investigated and the in fluid flow characteristics were observed. In this case, it is convenient to work with an average velocity V_{avg}, which remains constant in incompressible flow when the cross-sectional area of the pipe is constant. The average velocity in heating and cooling applications may change somewhat because of changes in density with temperature [3]. But, in practice, we evaluate the fluid properties at some average temperature and treat them as constants. Most researchers are convenience of working with constant properties usually more than justifies the slight loss in accuracy in a given process [4].
Also, the friction between the fluid particles in a pipe does cause a slight rise in fluid temperature as a result of the mechanical energy being converted to sensible thermal energy. But this temperature rise due to frictional heating is usually too small to warrant any consideration in calculations and thus is disregarded [5]. For example, in the absence of any heat transfer, no noticeable difference can be detected between the inlet and outlet temperatures of water flowing in a pipe. The primary consequence of friction in fluid flow is pressure drop, and thus any significant temperature change in the fluid is due to heat transfer, which result to frictional effect as shown in Figure 1.

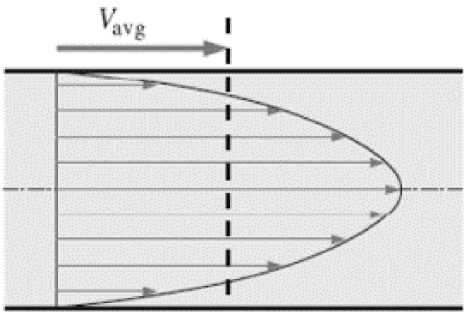

Figure 1: Demonstration of Fluid Flow in a Pipe with Internal Friction Effect [5]

The value of the average velocity V_{avg} at some stream wise cross-section is determined from the requirement that the conservation of mass principle be satisfied by recalling equation (1a). That is,

$$m = \int_{A_r} \rho u(r) dA_c = \int_{A_r} \rho u(r) dA_c \quad (1a)$$

Where, m is the mass flow rate, r is the density, Ac is the cross-sectional area, and u(r) is the velocity profile. Then the average velocity for incompressible flow in a circular pipe of radius R can be expressed as:

$$V_{avg} = \frac{\int_{A_r} \rho u(r) dA_c}{\rho A_c} = \frac{\int_0^R \rho u(r) 2\pi r dr}{\rho \pi R^2} = \frac{2}{R^2}\int_0^R u(r) r dr \quad (1b)$$

Therefore, when we know the flow rate or the velocity profile, the average velocity can be determined easily using the mathematical expression in equation (1b).

Flow velocity in a pipe is an important process parameter that quantifies the volume or mass flow rate as well as monitors the process safety. Efficient electricity generation in nuclear and thermal power plants is reliant on flow rate measurements in connecting pipes. Highly accurate flow rate measurements might improve the plant performance and reduce the impact of plant discharge on surrounding environments. In turbine cooling systems, flow rate measurements are used to monitor temperature increases in the discharge water and improve the performance of steam condensers.

However, flow meters are not generally used in circulation water loops, and they are difficult to install once the plant operation has commenced because most of the pipe sections are buried underground. A grounded pipe section contains many elbows and insufficient regions of straight pipe. The length between the elbow and a flow metering point is typically only a few times of the pipe diameter. This short length induces spatiotemporal fluctuations in the velocity profile. In addition, large pipe diameters (2–3 m) are required for circulation water.

Ultrasonic Flow Meter

An ultrasonic flow meter is a type of flow meter that measures the velocity of a fluid with ultrasound to calculate volume flow can be estimated using Figure 2 as shown below:

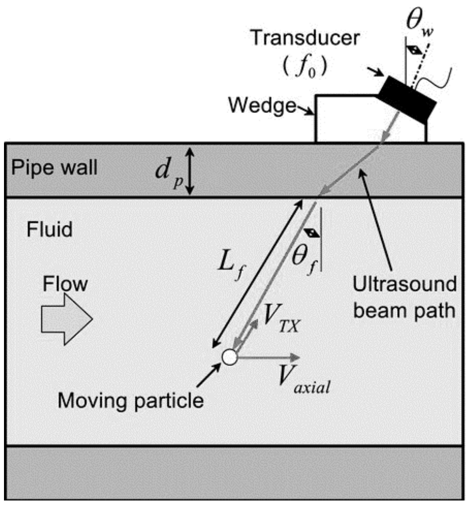

Figure 2: A Simple Application of Ultrasonic Transducer [6]

Using ultrasonic transducers, the flow meter can measure the average velocity along the path of an emitted beam of ultrasound, by averaging the difference in measured transit time between the pulses of ultrasound propagating into and against the direction of the flow or by measuring the frequency shift from the Doppler Effect *(the change in wave frequency during the relative motion between a wave source and its observer).*

Ultrasonic flow meters are affected by the acoustic properties of the fluid and can be impacted by temperature, density, viscosity and suspended particulates depending on the exact flow meter [7]. Compared with the conventional flow meter, the ultrasonic flow meter has a better performance since it has no moving parts, no pressure loss, wide measuring range, excellent repeatability, and high precision, and it is widely used in industrial production, especially for large diameter pipes and larger flows [8]. The ultrasonic flow meter is mainly comprised of an ultrasonic transducer installed on the measuring pipe and the related sensors of temperature and pressure [7-10].

The ultrasonic transducer has two installations: intrusive and nonintrusive. With the nonintrusive installation, the signal emitted by the ultrasonic transducer needs to go through the pipe wall twice, which will weaken the strength of the signal largely, while the low SNR will affect the stability and accuracy of signal receiving [11]. The intrusive installation is currently used in normal situations. For the single-path ultrasonic flow meter, the intrusive installation requires a through-hole in the pipe wall, where the ultrasonic transducer can be built. This structure and ultrasonic transducer generate disturbance in the flow field, because measuring errors, and may be the key problem in the measurement of ultrasonic flow meter.

Ultrasonic flow sensors operate using two slightly different approaches. In the first approach, pair of ultrasonic transducers generates a signal that is directed into the fluid flow from two locations. Each signal generated by a transmitter is reflected back to the receiver of the other transducer using a set of mirrors. The orientation of the transducers and mirrors is such that one signal is traveling for part of its path with the fluid flow while the other is traveling against the fluid flow. The receiver electronics measures the transit time of each signal and computes the time difference between the two [12]. When the fluid is not in motion, the transit times are the same for each signal – when the fluid is moving, the signal that is moving with the flow will have a shorter transit time, and therefore the difference between the two signal transit times reflects the velocity of the fluid. These types of ultrasonic flow sensors are sometimes called transit time ultrasonic flow sensors.

In a second variation of the design, ultrasonic energy is transmitted into the fluid and is reflected back to a receiver. Under the zero-flow condition, the frequency of the ultrasonic wave is unchanged [13]. When the fluid is in motion, there is a frequency shift that occurs as a result of the doppler effect, which is linear with respect to the fluid velocity. Detecting and reporting the shift in ultrasonic frequency allows for the computation of the fluid's flow rate [13].

The advantages of ultrasonic flow sensors are that they may be used with both conductive and non-conductive fluids, they can handle high temperatures and pressures, and some models may be clamped to the exterior eliminating the need for pipe penetration [14]. They also can be non-wetted and, in many cases, will not result in pressure drops or otherwise interfere with the flow. Transit time style sensors can be used in the measurement of gas or vapor flow. The primary limitations of these flow sensors are that fluids that have air bubbles and other fluids like slurries that do not pass ultrasonic energy well will cause difficulty with the readings. Additionally, high vibration installations may cause difficulty when using this type of flow sensor [15]. When externally mounted, transducer contact with the pipe wall needs to be made carefully to eliminate reflections that can interfere with the readings.

Materials and Methods

The aim of this study is to measure the flow rate (velocity) of fluid in a pipe using the *ultrasonic velocity profile (UVP)* method. The UVP method allows an instantaneous velocity profile to be obtained along the ultrasonic beam path, which is then integrated over the pipe diameter.

Operational Principle of the Single-Path Ultrasonic Flow meter

The basic principle is based on measuring the propagation time of an ultrasonic wave to propagate inside a liquid medium from the transmitting to the receiving sensor. The transit time depends both on the fluid and the flow regime in the pipe. The measured transit time is influenced by the velocity of the waves, c, in the fluid, and by the distribution of the axial velocities, V, of the flow along the path of the measurement line, l, according to the integral expression of figure 2. The method commonly used in the ultrasonic flow meters is to calculate the flow rate from measurements of the above transit time [6].

We can see the measurement principle of transmission speed difference method in the single-path ultrasonic flow meter from Figure 3. The diameter of the pipe is represented by D, ultrasonic transducers are installed on A and B sides, which could emit and receive the ultrasonic signals, L represents the distance of A and B, and Θ is the angle of AB with the pipe axis. It will need time t1 for the signal from A to B and the circuit delay is τ1. For the same reason, the signal will cost time t2 from B to A and the circuit delay is τ2; in addition, the actual pressure is P and the actual temperature is T.

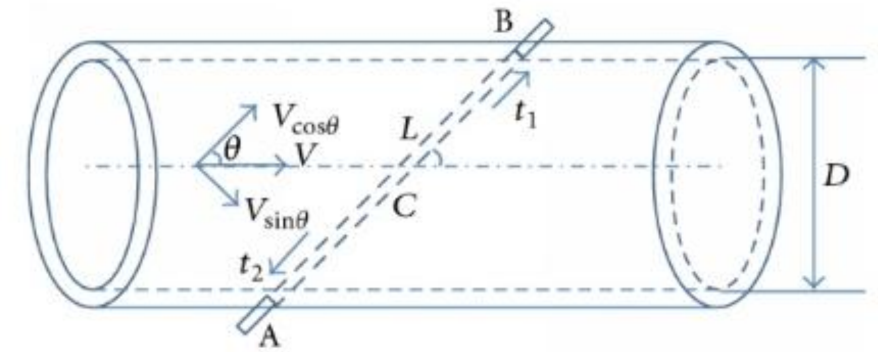

Figure 3: Measurement Principle of Transmission Speed Difference Method in the Single-Path Ultrasonic Flow Meter [6]

It is assumed that the fluid will flow with velocity V and the direction is parallel to the axis to the right, so on the channel L the propagation velocity of the ultrasonic signal is composited by the acoustic velocity C and component of flow velocity $V\cos\theta$, then the propagation time of ultrasonic signal in both downstream and upstream directions can be shown, respectively in the various equations shown below

Downstream: $t_1 = \frac{L}{C + \cos\theta}$ (1)

Upstream: $t_2 = \frac{L}{C - \cos\theta}$ (2)

The linear mean velocity V_L will be calculated by:

$$V_L = \frac{L}{2\cos\theta}\left(\frac{1}{t_1 - \tau_1} - \frac{1}{t_2 - \tau_2}\right) \quad (3)$$

Because of the presence of the actual fluid velocity distribution in the pipe cross-section, linear mean velocity V_L is not equal to the cross-section mean velocityV_A. Assume that there is a power correction factor K between the linear mean velocity $V_L$and the cross-section mean velocityV_A, the expression is shown in equation (4) to (5), that:

$$K = \frac{V_L}{V_A} \quad (4)$$

Then we can get that the flow of the pipe is:

$$Q = K\frac{\pi D^2}{4}V_L \quad (5)$$

Considering the influences of pressure and temperature, the flow can be converted under the standard working conditions:

$$Q = K\frac{\pi D^2}{4}V_L\frac{P}{P_0}\frac{T_0}{T} \quad (6)$$

Model of Ideal Channel

Based on the hydrodynamic theory, the fluid has viscosity so that the fluid shows different velocities at the points of different diameter in the cross-section. And the Reynolds number can be the only parameter that distinguishes moving patterns of viscous fluid. Whether the fluid moving as laminar or turbulent flow can be decided by the value of Reynolds number, there is a lower bound around 2000 for the critical Reynolds number, which transits laminar flow to turbulence. In the moving of laminar flows, the tiny disturbance in the flow field such as the roughness of pipe wall and free changes of surface will attenuate gradually so that the fluid flows as laminar flow. However, the tiny disturbance can be increased and flow becomes unstable if Reynolds number is bigger, so it is difficult to make sure the final status after disturbance increased as the equations are of nonlinearity, we can only conclude that the final stage is connected with structure of flow field and Reynolds number.

To the fluid, the Reynolds number can be estimated using equation (7) by stating that:

$$R_e = \frac{\rho VR}{\eta} \quad (7)$$

WhereR_e is the Reynolds number, ρ is the density of gas,V is velocity of flow, and R means the radius of the pipe.

With regard to the ideal laminar flow shown in Figure 1, the fluid may flow symmetrically if the gravity effects are ignored, and the velocity will be a function of radius r in the horizontal direction. Presume that the pressure drop on the pipe is ΔP and the radius of the pipe R = D/2, the velocity distribution at cross-section can be shown by the Hagen-Poiseuille formula:

$$u = \frac{\Delta P}{4\mu L}(R^2 - r^2) \quad (8)$$

Based on the equation above, each point velocity distributed parabolically with radius r; the largest velocity is on the pipe axis as r=0:

$$u_{max} = \frac{\Delta P}{4\mu L}R^2 = \frac{\Delta P}{16\mu L}D^2 \quad (9)$$

According to the distribution of flow velocity, the cross-sectional area of the flow can be calculated as:

$$dQ = udA = \frac{\Delta P}{4\mu L}(R^2 - r^2)2\pi rdr \quad (10)$$

After integration of equation (10), we have

$$Q = \int_0^R \frac{\Delta P}{4\mu L}(R^2 - r^2)2\pi rdr = \frac{\pi\Delta P}{128\mu L}D^4 \quad (11)$$

The mean flow velocity at cross-section can be presented as:

$$V_A = \frac{Q}{A} = \frac{\Delta P}{32\mu L}D^2 = \frac{1}{2}u_{max} \quad (12)$$

Under the normal circumstances, the path of ultrasonic flow meter is installed in the middle of the pipe, and then the linear mean velocity is:

$$V_L = \frac{1}{L}\int_0^L u(r)dL = \frac{1}{R}\int_0^R u_{max}\left(1 - \frac{r^2}{R^2}\right) = \frac{2}{3}u_{max} \quad (13)$$

Hence, from the above equations we can compute the power correction factor K:

$$K = \frac{V_A}{V_L} = \frac{3}{4} \quad (14)$$

We can achieve the relationship between the cross-section mean velocity, linear mean velocity, and the maximum flow rate based on the above theory; meanwhile the relationship between the cross-section mean velocity and linear mean velocity is obtained. However, the magnitude and position of maximum velocity cannot be measured directly in practice and engineering application.

In engineering, we can get the power correction factor generally from the test when correcting the flow meter against the fluid with low Reynolds number, if, considering the actual shape, structure of pipe, and the influences on the measurement of the non-axis-parallel flowing fluid, the relationship between flow field that affects power correction factor and measurement error of pipe flow can be analyzed.

Reflux makes the linear average velocity less so that the measurement is lower and the error is negative. Now considering the influences of reflux, we can rewrite:

$$V_L = \frac{L - L_A - L_B}{2\cos\theta}\left(\frac{1}{t_1 - t_{A1} - t_{B1} - \tau_1} - \frac{1}{t_2 - t_{A2} - t_{B2} - \tau_2}\right) \quad (15)$$

$$V_L = \frac{L - L_A - L_B}{2\cos\theta}\frac{t_2 - t_{A2} - t_{B2} - \tau_2 - t_1 + t_{A1} + t_{B1} + \tau_1}{(t_1 - t_{A1} - t_{B1} - \tau_1)(t_2 - t_{A2} - t_{B2} - \tau_2)} \quad (16)$$

$$V_L = \frac{L - L_A - L_B}{2\cos\theta}\frac{\Delta T_{sim} - \Delta T_A - \Delta T_B + (\tau_1 - \tau_2)}{(t_1 - t_{A1} - t_{B1} - \tau_1)(t_2 - t_{A2} - t_{B2} - \tau_2)} \quad (17)$$

Considering that the type and size of the transducer in part A are generally the same as part B, so the hardware delay can be regarded as the same: $\tau_1 = \tau_2$. Then:

$$V_L = \frac{L - L_A - L_B}{2\cos\theta}\frac{\Delta T_{sim} - \Delta T_A - \Delta T_B}{(t_1 - t_{A1} - t_{B1} - \tau_1)(t_2 - t_{A2} - t_{B2} - \tau_2)} \quad (18)$$

Results and Discussion

Through the simulation, we can obtain the flow results with parabolic distribution in Figure 4; the distribution is shown clearly.

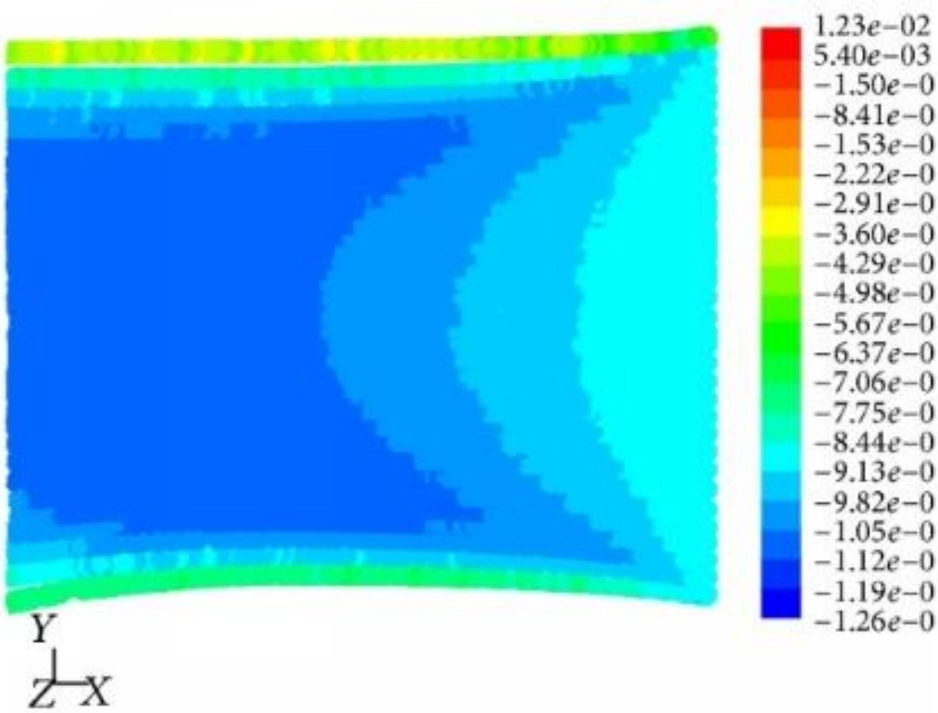

Figure 4: Simulation of Velocity versus Time

According to the simulation output data we can get t_1, t_{A1}, t_{B1}, t_2, t_{A2}, and t_{B2}. Since $\tau 1$ and $\tau 2$ are errors caused by circuit board delay, which can be ignored, getting the linear average velocity by calculation, then the power correction factor is calculated.

```
%Matlab Simulation Coding
Length_of_pipe=60 [m]
Gravitational_constant=9.82 [m/s2]
Pipe_diameter=0.1 [m]
Fluid_density=998.6 [kg/m3]
Initial_upstream_pressure=1000700 [Pa]
Initial_downstream_pressure=1000000 [Pa]
Fluid_density=998.6 [kg/m3]
Speed_of_sound_in_water=1483.8 [m/s]
Measured_wave_speed=1248.4 [m/s]
Friction_factor=0.023
Water_bulk_modulus=2.1_109 [Pa]
Young's elasticity_modulus=180-210)_109 [Pa]
Pipe_thickness=0.003 [m]
Number_of_nodes_in_MOC=601
Increment_of_x=(_x) 0.1 [m]
Increment_of_t=(_t) 8.01 105 [s]

h_cond_ideal=zeros(size(Zx,2),size(Ax,2),size(flow,2));
for f=1:1:size(flow,2)
for i=1:1:size(Ax,2)
for j=1:1:size(Zx,2)
AZ=[Ax(i); Zx(j)];
```

```
h_cond_ideal(j,i,f)=spread_cond_func(c(:,f), AZ);
end
          end
                    end
clearf i j AZ;
```

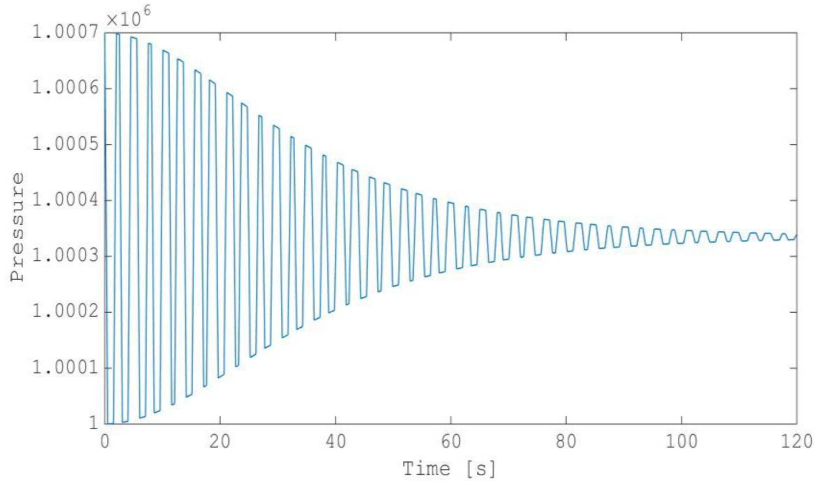

Figure 5: Effect of Upstream Pressure on Flow versus Time

Figure 5 demonstrates the effect of pressure on the flow characteristics of the pipe with increased time as well as pressure change in the middle of the pipe until steady state condition was researched. The variation in the pressure can be attributed to the variation in time.

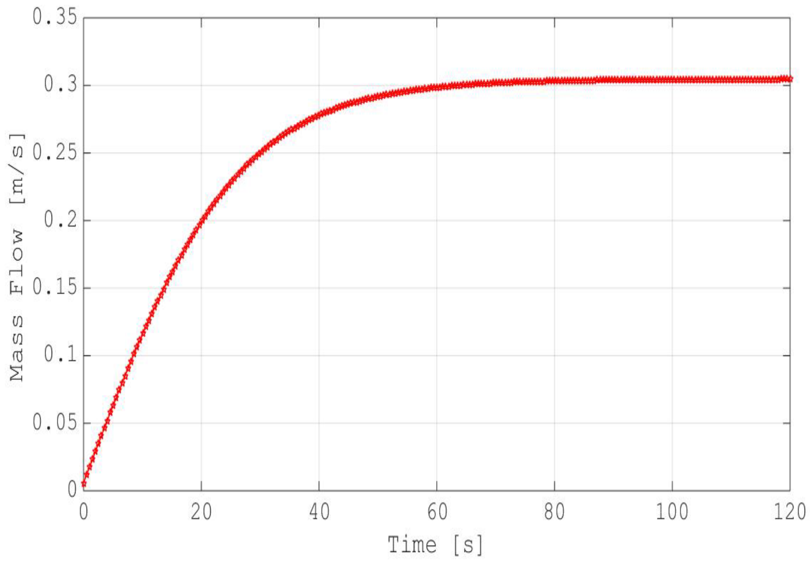

Figure 6: Effect of Molar Flow versus Time

Figure 6 showcases the effect of molar flow on the fluid characteristics with time. The variation of the molar flow can be attributed to the variation in time. These changes are monitored by the ultrasonic instrument stored along the flow line and through wave mechanism transduce the output signal to the controller.

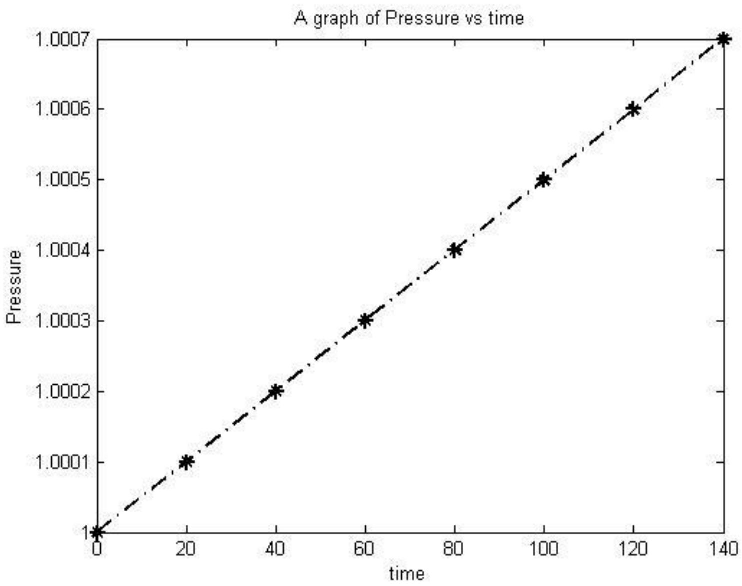

Figure 7: Effect of Downstream Pressure on Flow versus Time

From Figure 7 it is seen that increase in downstream pressure was observed with increase in time. The variation in the effect of the downstream pressure can be attributed to the variation in time.

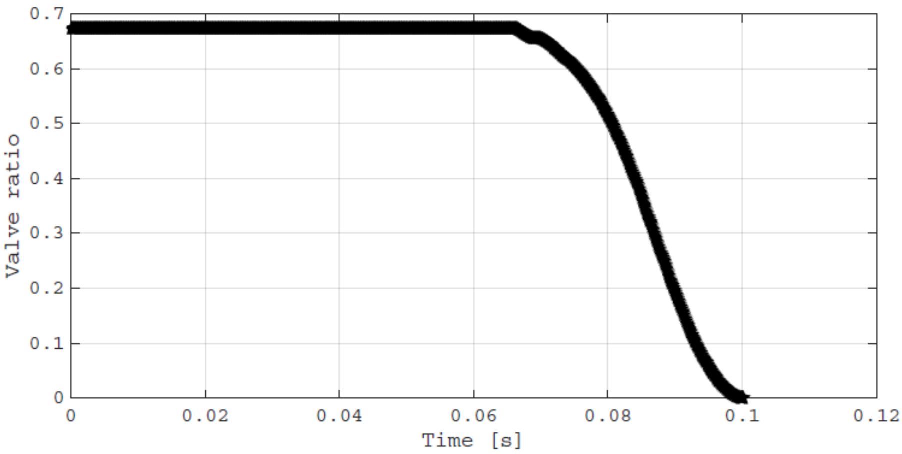

Figure 8: Effect of Valve Ratio on Flow versus Time

Figure 8 illustrates the effect of valve ration on flow characteristics of fluid flowing inside the pipe with incremental increase in time. The variation the effect of valve ratio on the fluid flow could be attributed to the variation in time.

Conclusion

In this paper, we analyze the flow field of ultrasonic mono flow meter with small diameter and low flow and discuss the influences on the flow field and power factor of exact pipe structure and the variation using different Reynolds number. The main conclusions are as follows.

(1) The installation point of ultrasonic transducer and temperature/pressure sensor will disturb the laminar flow field, the velocity will not be standard parabolic distribution any longer, and the reflux is generated at the transducer; the length of reflux has the same trend with Reynolds number.

(2) Near the transducer, the reflux decreases the linear average velocity and makes the measurement of flow lower; the errors will be negative.

(3) The expression of power correction factor by simulated data is fit.

(4) Through the test, the effectiveness of simulation is tested. Numerical simulation method can be a good reaction to flow state of flow field; it may be an important way to design and develop ultrasonic flow meter.

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