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천연가스배관내 피그흐름의 동적모델링

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Dynamic Modeling of PIG Flow in Natural Gas Pipelines

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Key Words : Pipeline Inspection Gauge (PIG), Method Of Characteristic (MOC), Pipeline, Bypass Flow

Abstract

This paper introduces modeling and solution for the dynamics of pipeline inspection gauge (PIG) flow in natural gas pipeline. Without of bypass flow, the dynamic behavior of the PIG depends on the different pressure between the rear and nose parts, which is generated by injected gas flow behind the tail of the PIG and expelled gas flow in front of its nose. With bypass flow, the PIG dynamics also depends on the amount of bypass flow across its body. The mathematical model are derived for unsteady compressible flow of the PIG driving and expelled gas, and for dynamics of the PIG. The bypass flow is assumed to be incompressible with the condition of its Mach number smaller than 0.45. The method of characteristic (MOC) and the Runge-Kutta method are used to solve the system governing equations. The simulation is performed with a pipeline segment in the Korea Gas Corporation (KOGAS) low pressure system, Ueijungboo-Sangye line. The simulation results show that the derived mathematical model and the proposed solution are effective for estimation the dynamics of the PIG with and without bypass flow under given operational condition.

Nomenclatures

A	pipe cross section	$[m^2]$
c	wave speed	$[m/s]$
C_C	convection heat transfer coefficient	$[m^2]$
C	linear damping coefficient of PIG	$[Ns/m]$
d	internal diameter of pipeline	$[m]$
d_{valve}	bypass valve diameter	$[m]$
F_f	friction force per unit pipe length	$[N/m]$
F_{fp}	friction force between the PIG and pipe's wall	$[N]$
F_p	force due to different pressure acting on the PIG	$[N]$
g	gravity acceleration	$[m/s^2]$
h	opening height of bypass valve	$[m]$
K	wear factor of PIG	$[N/m]$
K_{SC}	sudden contraction loss coefficient	
K_{SE}	sudden expansion loss coefficient	
K_{total}	total loss coefficient of bypass system	
K_V	average-loss coefficient of valve	
L	length of pipeline	$[m]$
L_{PIG}	length of the PIG	$[m]$
m	hydraulic mean radius of pipe	$[m]$
M	mass of the PIG	$[kg]$
p	flow pressure	$[N/m^2]$
q	compound rate of heat inflow per unit area of pipe's wall	$[W/m^2]$
R	gas constant	$[J/kgK]$
Re	Reynolds number	
S	perimeter of pipe	$[m]$
T	flow temperature	$[^0C]$
T_{ext}	seabed temperature	$[^0C]$
u	flow velocity	$[m/s]$
x_{PIG}	PIG position	$[m]$
v_{PIG}	PIG velocity	$[m/s]$
v_{ref}	reference velocity of PIG	$[m/s]$
v_V	absolute velocity of bypass flow	$[m/s]$

Greeks:

γ	the ratio of specific heat	
ν	kinetic viscosity of flow	$[m^2/s]$
ρ	flow density	$[kg/m^3]$
β	angular between PIG velocity and gravity force	$[rad]$

Subscripts:

$_{0, L}$ denote the points at inlet and outlet of pipeline

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1. Introduction

The use of in-line tools for inspection and cleaning is accepted as essential for the safe and profitable operation of all pipelines. A device that moves through the inside of a pipeline for the purpose of cleaning, dimensioning, or inspecting is called Pipeline Inspection Gauge (PIG). PIGs can perform a number of tasks including cleaning debris from pipeline, removal of residual product in, and gauging the internal bore of the pipeline. There are different types of PIG and each type is designed for some different desired purposes. All of the PIGs are the most effective when they run at a near constant speed but will not be effective in case that they run at too high speed. The velocity is generally in the range of 1-5m/s in liquid pipelines, and 2-7m/s in gas pipelines. The optimal speed range for intelligent pigs is more defined depending on the accurate of data acquisition. Ranges of between 0.5-4m/s are recommended for corrosion tools, and slightly higher for caliper tools[14]. Hence estimate the PIG dynamics and control of the PIG velocity is very important when we operate a pigging procedure in a pipeline.

Results of research on the dynamics of the PIG in pipelines are scarcely found in the literature. Some works relating to the estimation of the PIG dynamics have been reported. J.M.M. Out[9], 1993, used Lax-Wendroff scheme for the integration of gas equations with adaptation of finite difference grid. Azevedo et al.[7], 1996, simplified the solution with assumption of incompressible and steady state of flow in pipeline. P.C.R. Lima[6], 1999, solved the problem by using one-dimensional semi-implicit finite difference scheme. In previous works[1-4], we solve the PIG dynamics problem by using MOC and proposed a simple computational scheme.

This paper summarizes our work on the dynamics of the PIG flow in natural gas pipeline. Some analysis is given for the PIG with bypass and without bypass flow across it body. Without of bypass flow, the dynamic behavior of the PIG depends on the different pressure between the rear and nose parts, which is generated by injected gas flow behind the tail of the PIG and expelled gas flow in front of its nose. With bypass flow, the PIG dynamics also depends on the amount of bypass flow across its body. The mathematical models are derived for unsteady flow of the PIG driving and expelled gas, and for dynamic of the PIG in the general case. The nonlinear hyperbolic partial differential equations are solved by method of characteristics (MOC) with the regular rectangular grid under appropriate initial and boundary conditions. The Runge-Kuta method is used when we solve the steady flow equations to get initial flow values and the dynamic equation of PIG. The simulation is performed with a pipeline segment in the Korea Gas Corporation (KOGAS) low pressure system, Ueijungboo-Sangye line. The simulation results show that the derived mathematical model is effective for estimating the PIG dynamics with and without bypass flow under given operational conditions of pipeline.

2. Modeling

The scheme of PIG flow in natural gas pipeline can be described in Fig. 1.

2.1 Gas Flow Model

We assume as the following:

i. the natural gas is ideal,
ii. flow is one phase,
iii. the pipeline diameter is constant,
iv. the flow is quasi-steady heat flow,
v. the friction factor is a function of wall's roughness and Reynolds number. Steady state values are used in transient calculations.

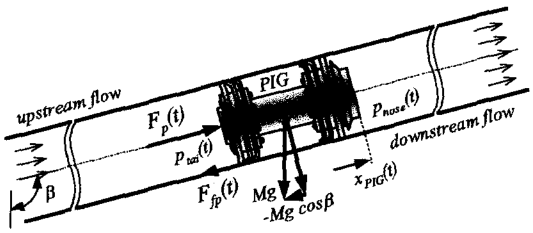

Fig. 1 PIG without bypass flow in the pipeline

The unsteady flow of natural gas in pipeline can be modeled based on four fundamental fluid dynamic equations: continuity equation, momentum equation, state equation and energy equation as the following

$$\frac{\partial \rho}{\partial t}+u\frac{\partial \rho}{\partial x}+\rho\frac{\partial u}{\partial x}=0 \tag{1}$$

$$\frac{\partial p}{\partial x}+\rho u\frac{\partial u}{\partial x}+\rho\frac{\partial u}{\partial t}+\frac{F_f}{A}-\rho g\cos\beta=0 \tag{2}$$

$$\frac{p}{\rho}=(\gamma-1)C_V T \tag{3}$$

$$\frac{\partial}{\partial t}\left[\rho\left(C_V T+\frac{u^2}{2}\right)\right]+\frac{\partial}{\partial x}\left[\rho\left(C_V T+\frac{u^2}{2}\right)u\right]+\frac{\partial}{\partial x}(pu)-\frac{qS}{A}=0 \tag{4}$$

These four non-linear hyperbolic partial differential equations can be transformed to ordinary differential equations by using MOC in the following forms[1-3]:

$$\frac{du}{dt}+\frac{c}{\rho p}\frac{dp}{dt}=E_1 \quad \text{along} \quad \frac{dx}{dt}=u+c \tag{5}$$

$$\frac{du}{dt}-\frac{c}{\rho p}\frac{dp}{dt}=E_2 \quad \text{along} \quad \frac{dx}{dt}=u-c \tag{6}$$

$$\frac{du}{dt}-\ c\frac{dp}{dt}=E_3 \quad \text{along} \quad \frac{dx}{dt}=u \tag{7}$$

where,

$$E_1=\ \frac{\gamma-1}{c}\frac{q}{\rho m}+\left(\frac{F_f}{\rho A}-g\cos\beta\right)\left(\frac{\gamma-1}{c}u-1\right) \tag{8}$$

$$E_2=-\frac{\gamma-1}{c}\frac{q}{\rho m}-\left(\frac{F_f}{\rho A}-g\cos\beta\right)\left(\frac{\gamma-1}{c}u+1\right) \tag{9}$$

$$E_3=\ (\gamma-1)\frac{q}{m}+\left(\frac{F_f}{\rho A}-g\cos\beta\right)(\gamma-1)u\rho \tag{10}$$

$$c=\sqrt{\gamma p/\rho} \tag{11}$$

$$m=A/S \qquad F_f=F_f(k,\mathrm{Re})$$

To attain a stable solution for the above equations, the sampling time and distant must be chosen to satisfy the Courant-Friedrich-Lewy condition

$$\Delta t<|\Delta x/(u\pm c)| \tag{12}$$

In the case of PIG without bypass, the PIG separates the flow in pipeline into two parts: upstream and downstream flows as shown in Fig. 1. The above Eqs. (5)-(7) can be used to describe both unsteady dynamics of upstream and downstream flows. In the bypass PIG, there is another flow through its body as shown in Fig. 2.

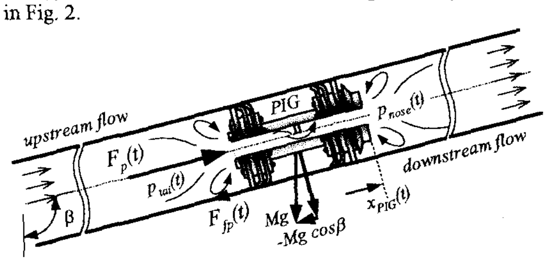

Fig. 2 PIG with bypass flow in the pipeline

The amount of bypass flow through the PIG depends on the opening height of valve, h, and the different pressure across the PIG as shown in Fig. 3. The pressure loss across the PIG includes the pressure loss of valve and the pressure loss caused by sudden contraction of flow at the tail of the PIG and sudden expansion of flow at the nose of the PIG.

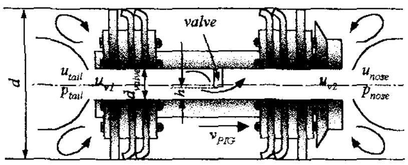

Fig. 3 Bypass flow through the PIG

When the velocity of natural gas in the range of 200m/s or its Mach number is less than 0.45, it can be treated as incompressible with an error less than 5%[10]. Hence in this paper, the pressure drop allows the bypass flow to be assumed as incompressible as it passes through the central bypass hole in the PIG. The bypass flow through valve causes the pressure drop across the PIG is given by:

$$p_{tail} - p_{nose} = K_{total}\frac{(v_V - v_{PIG})^2}{2g} \tag{13}$$

where

$$K_{total} = K_{SC} + K_V + K_{SE} \tag{14}$$

$$K_{SC} = 0.42\left(1 - \frac{d_{valve}^2}{d^2}\right) \tag{15}$$

$$K_{SE} = \left(1 - \frac{d_{valve}^2}{d^2}\right)^2 \tag{16}$$

$$K_V = K_V(h / d_{valve}) \tag{17}$$

In Eq. (17), the pressure loss of valve is a function of the opening height of valve and depends on the structure of used valve. Usually this value can get from the manufacturer. The value of total pressure loss in Eq. (14) can also get from experimental data in laboratory with the designed bypass valve system to be used. From Eqs. (14)-(17) we can see

$$\min(K_{total}) = \left(1 - \frac{d_{valve}^2}{d^2}\right)\left(1.42 + \frac{d_{valve}^2}{d^2}\right) \tag{18}$$

The bypass valve diameter can be obtained from this equation.

2.2 The PIG dynamic model

Forces acting on the PIG are shown in Fig. 1. The dynamic equation of the PIG can be written from the Newton's Second Law as follows:

$$M\frac{d^2 x_{PIG}(t)}{dt^2} + C\frac{d x_{PIG}(t)}{dt} + K x_{PIG}(t) = F_p(t) - F_{fp}(t) + Mg\cos\beta \tag{19}$$

In the above Eq. (19), the driving force is derived from the different pressure at the tail and nose of the PIG that are calculated from upstream and downstream flow dynamics in each computational step. J.M.M. Out[12] proposed three models for friction between the PIG and pipeline's wall: static-dynamic model; logarithmic model; and quadratic model. In our case, a natural gas pipeline is used to transport dry natural gas. Hence, in this paper, we use the static-dynamic friction force model. The friction force $F_{fp}(t)$, the wear factor K and the linear damping coefficient C are measured from experiment.

3. Solution of the PIG dynamics

The steps for solving the PIG dynamics together with upstream and down stream flow dynamics by using MOC were presented in the previous work[1-3] and is briefly summarized by the following computational scheme

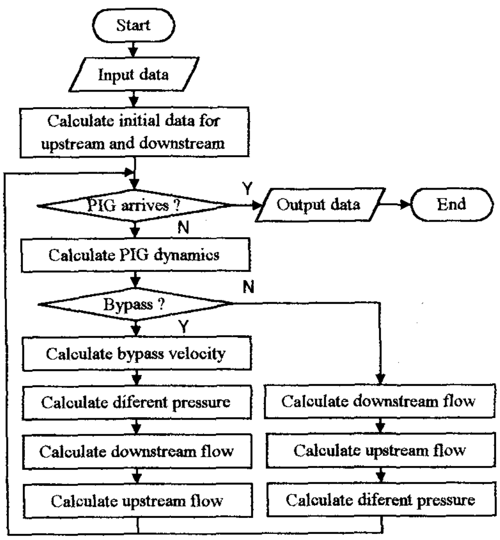

Fig. 4 Computational scheme

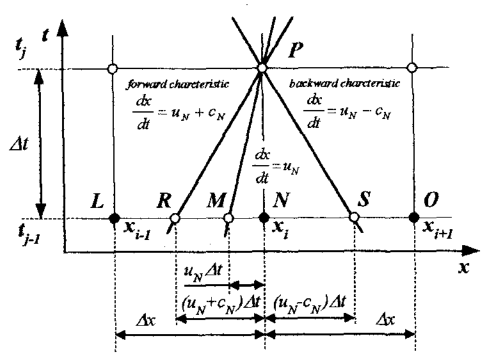

Fig. 5 Backward and forward characteristics using in MOC

At each computational step, the flow dynamics are solved using MOC. The relationship between flow variables p, ρ, u at the time step t_j and at the preceding time step t_{j-1} can be seen through Fig. 5. Using Eqs. (5)-(7) under the description of variables shown in Fig. 5, we can derive the variables p, ρ, u at grid points *P* from the previous calculated values at grid points *L*, *N*, *O*. First, we get flow parameters at *R*, *M*, *S* from linear interpolation formula. Then, we integrate Eqs. (5)-(7) along their characteristic lines dt/dx to get the desired variables.

$$p_P = \frac{\gamma}{\frac{c_R}{p_R}+\frac{c_S}{p_S}}\left[(u_R - u_S)+\frac{c_R + c_S}{\gamma}+(E_{1R}-E_{2S})\Delta t\right] \quad (20)$$

$$u_P = u_R + \frac{c_R}{\gamma p_R}(p_R - p_P)+E_{1R}\Delta t \quad (21)$$

$$\rho_P = \rho_M + \frac{1}{c_M^2}(p_P - p_M - E_{3M}\Delta t) \quad (22)$$

3.1 Initial condition

In the absence of field data concerning the initial field variable distributions, it is assumed that the steady state variable distributions can be used as the initial values. These values can be obtained using the analytical Eqs. (1)-(4)

$$\frac{\partial p}{\partial x} = -\frac{F_f}{A}+\rho g\cos\beta + Xu \quad (23)$$

$$\frac{\partial u}{\partial x} = -\frac{X}{\rho} \quad (24)$$

$$\frac{\partial \rho}{\partial x} = \frac{X}{u} \quad (25)$$

where

$$X = \frac{1}{u^2 - c^2}\left(\gamma\frac{F_f u}{A} - \gamma\rho g\cos\beta u + (\gamma - 1)\frac{q}{m}\right)$$

3.2 Boundary conditions at pipeline inlet and outlet

At a boundary, there is only one available characteristic such as a backward characteristic at upstream boundary or a forward characteristic at downstream boundary. Depending on the given condition, we will used appropriate characteristic line to solve the flow values at boundary. Usually, the boundary conditions at inlet and outlet of pipeline are given as pressure or flow rate together with flow temperature.

3.2.1 Given flow rate at pipeline inlet and out let

First, we get flow velocity from flow rate using $u_P = Q/A$. The pressure at inlet and outlet are as the following, respectively

$$p_P = p_S + \frac{\gamma p_S}{c_S}[(u_P - u_S) - E_{2S}\Delta t] \quad (26)$$

$$p_P = p_R + \frac{\gamma p_R}{c_R}[-(u_P - u_R) - E_{1R}\Delta t] \quad (27)$$

3.2.2 Given pressure at pipeline inlet and out let

When boundary pressure is given, flow velocity at inlet and out let are calculated as follows, respectively

$$u_P = u_S + \frac{c_S}{\gamma p_S}(p_P - p_S) + E_{2S}\Delta t \quad (28)$$

$$u_P = u_R + \frac{c_R}{\gamma p_R}(p_P - p_R) + E_{1R}\Delta t \quad (29)$$

Flow density at inlet and outlet can be derived form state equation.

3.3 Boundary condition at the tail and nose of the PIG

Without bypass flow, the boundary condition at the PIG is quite simple: flow velocities at the PIG nose and tail equal to the PIG velocity. The boundary at the tail (nose) of the PIG is identical to the problem of given flow rate at outlet (inlet) of pipeline. In the presence of bypass flow, the average flow velocity at the tail of the PIG can be derived as follows

$$u_{tail} = v_{PIG} + \left(\frac{d_{valve}}{d}\right)^2 (u_V - v_{PIG}) \quad (30)$$

The above assumption of incompressible bypass flow yields

$$u_V = u_{V_1} = u_{V_2} \Rightarrow u_{nose} = u_{tail} \quad (31)$$

With a known value of K_{total}, we can calculate the bypass flow velocity and then the flow velocity at the tail and nose of the PIG.

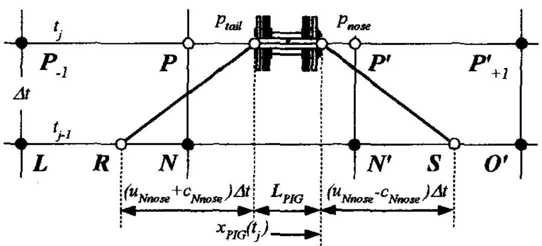

Fig. 6 Scheme for calculation of boundary values at the PIG

From Fig. 6, using backward characteristic line at the PIG nose and using forward characteristic line at the PIG tail, we have

$$p_{tail} = p_R + \frac{\gamma p_R}{c_R}[-(u_{tail} - u_R) + E_{1R}\Delta t] \quad (32)$$

$$p_{nose} = p_S + \frac{\gamma p_S}{c_S}[(u_{nose} - u_S) + E_{2S}\Delta t] \quad (33)$$

Substituting Eqs. (32)-(33) into Eq. (13), using assumption (31), after some arrangements we have the relationship

$$a_V (u_V - v_{PIG})^2 + b_V (u_V - v_{PIG}) + c_V = 0 \quad (34)$$

where

$$a_V = \frac{K_{total}}{2g}\left(\frac{d}{d_{valve}}\right)^4, \quad b_V = \gamma\left(\frac{d_{valve}}{d}\right)^2\left(\frac{p_R}{c_R}+\frac{p_S}{c_S}\right)$$

$$c_V = \gamma\left(\frac{p_R}{c_R}+\frac{p_S}{c_S}\right)v_{PIG} - (p_R - p_S) - \gamma\left(\frac{p_R}{c_R}(u_R + E_{1R}) + \frac{p_S}{c_S}(u_S + E_{2S})\right)$$

From the solution of Eq. (34) with $u_V - v_{PIG} \geq 0$, we get the flow velocity in valve, u_V and then u_{tail} and u_{nose}. The problem now is identical to the case without bypass.

4. Simulation results

The simulation is performed with numerical values from a pipeline segment in the Korea Gas Corporation (KOGAS) low pressure system, Ueijungboo-Sangye line, which used in previous work[4]. We choose the sampling time $\Delta t = 0.05s$, sampling distance $\Delta x = 40\ m$, and bypass valve diameter d_{valve}=*0.1778m*. The boundary condition of interest is used: constant flow rate at pipeline inlet $u_0(t) = u_0$, and constant pressure at pipeline outlet $p_L(t) = p_L$.

The first simulation has been done with the PIG when we launch it. The initial velocity is given to overcome the static friction force acting on the PIG. These simulation results are given in Figs. 7-9.

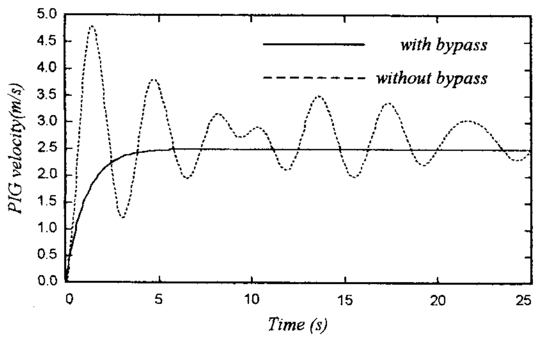

Fig. 7 The PIG velocity

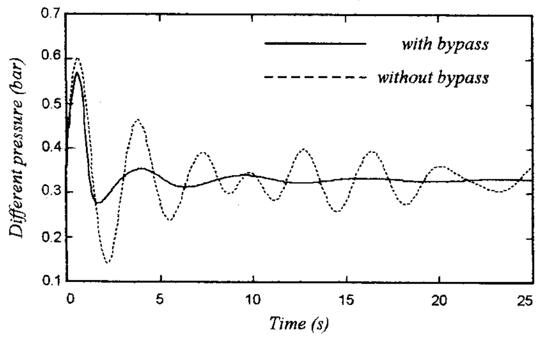

Fig. 8 Different pressure acting on the PIG

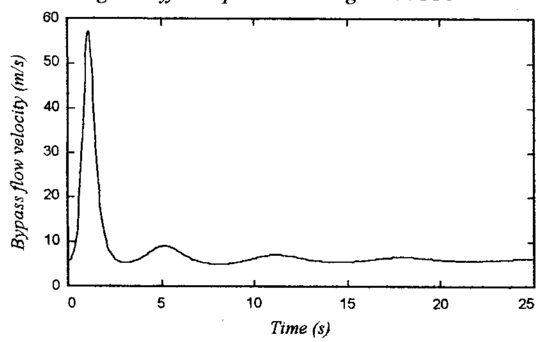

Fig. 9 Bypass flow velocity across the PIG

The effect of using bypass flow can be seen from Fig. 7: the bypass PIG tracks well the reference velocity while no bypass PIG has much oscillation. The different pressure acting on the PIG is given in Fig. 5. The velocity of bypass flow across the PIG body is given in Fig. 7.

The second simulation has been done with assumption that the PIG was stopped at the one third of pipeline length by obstruction (debris or deposit). This worst situation rarely happens with regular pigged pipeline. Once the PIG is stopped, the pressure at the tail of the PIG increased while the pressure at its nose decreased. As the result, the different pressure across the PIG is increased until overcoming both obstructions causing the stoppage and the static friction. Then, the PIG accelerates until the different pressure abates to a level required to overcome the static and dynamic friction. Once the PIG restarts, the friction force reduces from static value to dynamic value and the PIG velocity increases very fast. At this time, the bypass port must be opened to reduce the different pressure acting on the PIG and hence reduce its velocity. The bigger bypass port is the faster the PIG velocity reduces. Fig. 10 shows the PIG velocities vs. the bypass port diameters. From this figure, we can choose the bypass diameter when designing bypass system for the PIG.

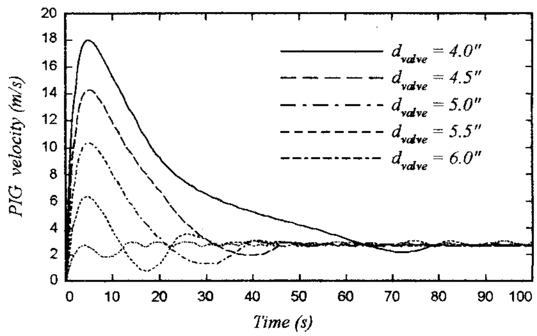

Fig. 10 PIG velocities after restart with different bypass port

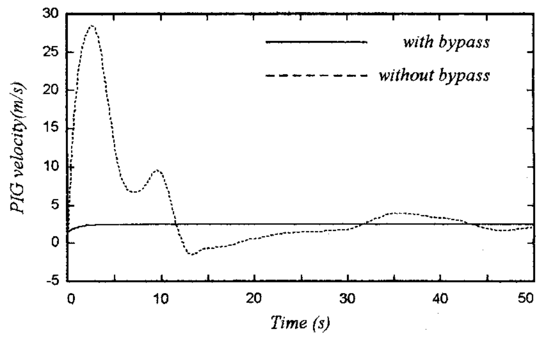

Fig. 11 The PIG velocity after restarting

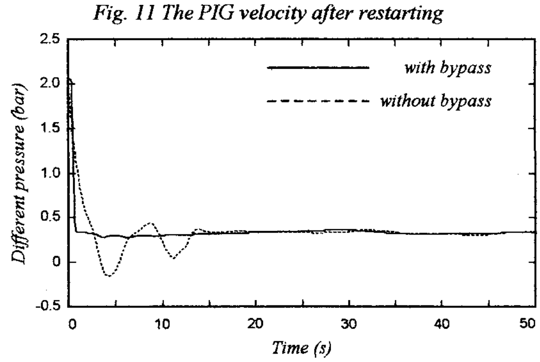

Fig. 12 Different pressure acting on the PIG

Fig. 11 shows the PIG velocity and Fig. 12 shows the different pressure acting on the PIG in both cases with and without bypass. With appropriate controlled bypass flow, the PIG restarts with tracking well the reference speed as shown in Fig. 12.

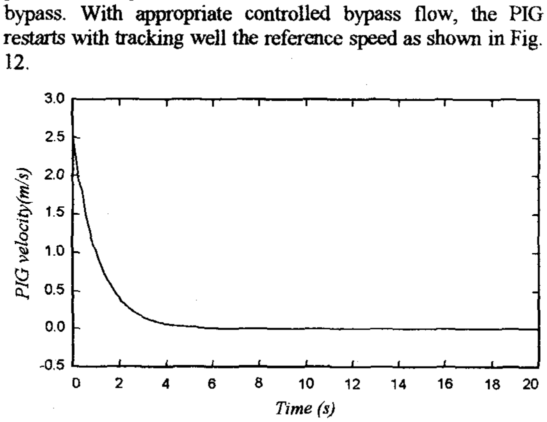

Fig. 13 PIG velocity after restart

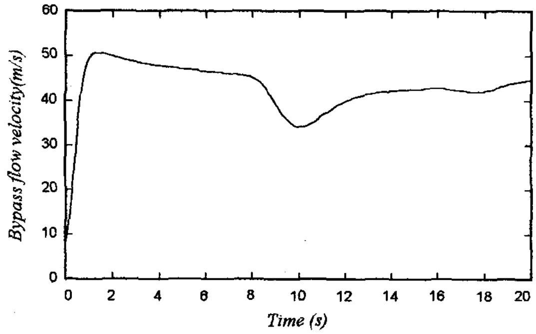

Fig. 14 Bypass velocity across the PIG

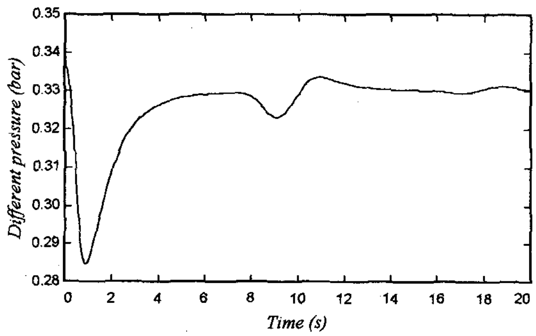

Fig. 14 Different pressure acting on the PIG

The bypass flow can also be used as a "brake" to stop the PIG when it is reaching to its trap barrel. Fig. 13 shows the PIG velocity and the velocity of bypass flow after opening bypass port to reduce its speed. Different pressure acting on the PIG is shown in Fig. 14.

To attain the good performance of the PIG system using bypass flow, we need to control the amount of bypass flow appropriately. This paper does not concern to the problem of designing the controller for the PIG operational system. The PIG velocity control problem is in another our work[4].

5. Conclusion

This paper summarizes our work on the dynamics of the PIG flow in natural gas pipeline. Some analysis is given for the PIG with bypass and without bypass flow across it body. The models of flows and the PIG are derived. The solutions based on MOC and Runge-Kutta method are proposed. The simulation has been done in three cases: the PIG starts to move at its launcher, the PIG arrives at its receiver and the PIG restarts after stopping at the middle of pipeline. The simulation results show that with the models and the solution can be used for estimating the dynamics of the PIG when it flows through natural gas pipeline.

Acknowledgment

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