Modeling and Simulation for PIG with Bypass Flow Control in Natural Gas Pipeline

Tan Tien Nguyen*, Sang Bong Kim
Department of Mechanical Engineering, College of Engineering, Pukyong National University, Pusan 608-739, Korea
Hui Ryong Yoo, Yong Woo Rho
Korea Gas Corporation (KOGAS), 638, Il-dong, Ansan, Kyunggi-do 425-160, Korea

This paper introduces modeling and simulation results for pipeline inspection gauge (PIG) with bypass flow control in natural gas pipeline. The dynamic behaviour of the PIG depends on the different pressure across its body and the bypass flow through it. The system dynamics includes: dynamics of driving gas flow behind the PIG, dynamics of expelled gas in front of the PIG, dynamics of bypass flow, and dynamics of the PIG. The bypass flow across the PIG is treated as incompressible flow with the assumption of its Mach number smaller than 0.45. The governing nonlinear hyperbolic partial differential equations for unsteady gas flows are solved by method of characteristics (MOC) with the regular rectangular grid under appropriate initial and boundary conditions. The Runge-Kuta method is used for solving the steady flow equations to get initial flow values and the dynamic equation of the PIG. The sampling time and distance are chosen under Courant-Friedrich-Lewy (CFL) restriction. The simulation is performed with a pipeline segment in the Korea Gas Corporation (KOGAS) low pressure system, Ueijungboo-Sangye line. Simulation results show us that the derived mathematical model and the proposed computational scheme are effective for estimating the position and velocity of the PIG with bypass flow under given operational conditions of pipeline.

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

Nomenclature

A : Pipe cross section [m^2]
c : Wave speed [m/s]
C : Linear damping coefficient of the PIG [Ns/m]
C_c : Convection heat transfer coefficient [W/m^{2}K]
d : Internal diameter of pipe [m]
d_{valve} : Bypass valve diameter [m]
F_b : Braking force [N]
F_f : Friction force per unit pipe length [N/m]
F_{fp} : Friction force between the PIG and pipeline's wall including [N]
-F_{fpsta} : Static friction force
-F_{fpdyn} : Dynamic friction force
F_p : The PIG driving force [N]
h : The opening height of valve [m]
k : Pipe wall roughness [m]
K : Wear factor per distance travel [N/m]
K_{SC} : Sudden constraction loss coefficient
K_{SE} : Sudden expansion loss coefficient
K_{total} : Total loss coefficient
L_{PIG} : Length of the PIG [m]
m : Hydraulic mean radius of pipe [m]
M : Weight of the PIG [kg]
p : Flow pressure [N/m2]
q : Compound rate of heat inflow per unit area of pipe wall [W/m^2]
S : Perimeter of pipe [m]

* Corresponding Author,
E-mail : tiennt@yahoo.com
TEL : +82-51-620-1606; **FAX** : +82-51-621-1411
Department of Mechanical Engineering, College of Engineering, Pukyong National University, Pusan 608-739, Korea. (Manuscript **Received** september 6, 2000; **Revised** June 4, 2001)

T : Flow temperature [K]
T_{ext} : Seabed temperature [K]
u : Flow velocity [m/s]
u_V : Flow velocity through valve [m/s]
v_{PIG} : Velocity of the PIG [m/s]
x : Distance from pipe inlet [m]
x_{PIG} : Position of the PIG [m]
X : Denote flow parameter values

Greeks

γ : The ratio of specific heat
ν : Kinetic viscosity of flow [m^2/s]
ρ : Flow density [kg/m^3]

Subscripts

L, R, M, N, S, O, P : Denote the grid points, and
$0, l$: Denote the points at inlet and outlet of pipeline

1. Introduction

It is generally agreed that pipelines provide one of the most common ways and the safest means to transport large quantities of oil and gas products. Just like any other technical component, during operation, the walls of pipelines suffer a deterioration process and the pipeline conditions get worse. Pipelines can be failed with time if they are not properly maintained. One part of a maintenance procedure of pipelines is pigging them regularly to prevent the increase of their wall's roughness and the reduction of the internal diameter. The tool used for pigging is called Pipeline Inspection Gauge (PIG). There are over 350 PIGs of all types nowaday(Cordell and Vanzant, 1999). Each type of the PIG is designed for some different desired purposes. All of the PIG is 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 typical speeds for utility pigging are about 1-5m/s for on-stream liquids and 2-7m/s for on-stream gas(Cordell and Vanzant, 1999). So, prediction and control of the PIG velocity are very important when we operate a pipeline system.

Fluid transient flows in pipelines are an interesting field in fluid mechanics and can be found in the references(White, 1999; Tannehill et al., 1997; Wylie et al., 1993; Fox, 1977). Results of research on the dynamics of the PIG in pipelines are scarcely found in the literature. Some works relating to the dynamics of the PIG without bypass flow have been reported. J. M. M. Out (1993), used Lax-Wendroff scheme for the integration of gas equations with adaptation of finite difference grid. The grid has to be continuously updated with the PIG position and the fluid values at the new grid points are estimated by interpolation. P. C. R. Lima(1999), solved this problem by using one-dimensional semi-implicit finite difference scheme. The nonlinear algebraic equations at each time step are solved by adopting Newton's method. T. T. Nguyen et al.(2001), dealt with this problem by using MOC and regular rectangular grid for upstream and downstream flows and solved the PIG dynamic equation by using Runge-Kuta method.

In the case of the PIG without bypass flow, the PIG is modelled without leakage so that upstream and downstream flows are completely separated by the PIG body. Boundary conditions at the tail and nose of the PIG for upstream and downstream flows are quite simple: the flow velocity at the PIG nose and tail equal to its velocity. In fact, there is undesired leakage flow through the PIG. Some PIGs are also designed with a flow path through their bodies. This flow is called bypass flow and varies with different pressure across the PIG. Bypass flow is not used in a sealing PIG but is often essential for an efficient cleaning operation. Bypass flow makes the PIG to slip back behind the debris that it may have scraped from the pipe wall. The purpose is to keep the debris flowing with the stream and not accumulate in front of the nose of the PIG. The presence of bypass flow reduces different pressure across the PIG and then slows down its velocity. Hence, we can also use bypass flow to control the PIG velocity. For the PIG with bypass flow, Azevedo et al.(1996), simplified the solution under the assumption of steady state and incompressibility of flow in pipeline.

This paper deals with modeling of the PIG flow in compressible, unsteady natural gas pipe-

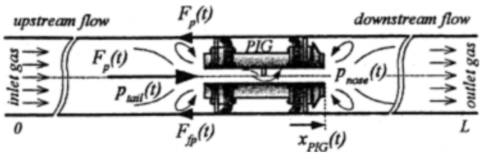

Fig. 1 PIG flow in the natural gas pipeline

line with bypass flow across its body. The PIG is driven by injected gas flow behind its tail and expelled gas flow in front of its nose. Bypass flow is controlled by opening and closing a valve placed in the PIG body. The bypass flow effects to the different pressure across the PIG and then, to its dynamic behaviour. The system dynamics includes dynamics of driving gas flow behind the PIG, dynamics of expelled gas flow in front of the PIG and movement dynamics of the PIG.

The governing nonlinear hyperbolic partial differential equations of downstream and upstream gas are solved by MOC with the regular rectangular grid under appropriate initial and boundary conditions. The Runge-Kuta method is used for solving the steady flow equations to get initial flow values and the dynamics equation of the PIG.

2. Modeling

The scheme of the PIG flow in pipeline with bypass flow is given in Fig. 1.

We assume that the PIG is designed with the central bypass hole and the velocity of the PIG is controlled by controlling the bypass flow according to opening and closing the valve.

2.1 Gas flow model

2.1.1 Governing dynamics equations

We assume for the natural gas flow in the pipeline as shown in Fig. 1.

i. the natural gas is ideal and one phase,

ii. pipeline internal diameter is constant,

iii. the pipe center line is in a horizontal or near horizontal line to ignore the effect of gravity,

iv. the friction factor is a function of wall roughness and Reynolds number. Steady state values are used in transient calculations(Wylie et al., 1993),

v. the flow of gas is quasi-steady heat flow.

The unsteady flow dynamics can be modelled based on four fundamental fluid dynamic equations: continuity equation, momentum equation, state equation and energy equation. These four nonlinear hyperbolic partial differential equations are transformed to ordinary differential equations by using MOC in the following forms(Nguyen et al., 2001)

$$\frac{du}{dt}+\frac{c}{\gamma p}\frac{dp}{dt}=E_1 \text{ along } \frac{dx}{dt}=u+c \quad (1)$$

$$\frac{du}{dt}-\frac{c}{\gamma p}\frac{dp}{dt}=E_2 \text{ along } \frac{dx}{dt}=u-c \quad (2)$$

$$\frac{du}{dt}-c^2\frac{dp}{dt}=E_3 \text{ along } \frac{dx}{dt}=u \quad (3)$$

where,

$$E_1=\frac{\gamma-1}{c}\frac{q}{\rho m}+\frac{F_f}{\rho A}\left[\frac{u(\gamma-1)}{c}-1\right] \quad (4)$$

$$E_2=-\frac{\gamma-1}{c}\frac{q}{\rho m}-\frac{F_f}{\rho A}\left[\frac{u(\gamma-1)}{c}+1\right] \quad (5)$$

$$E_3=(\gamma-1)\left(\frac{q}{m}+\frac{F_f u}{A}\right) \quad (6)$$

$$c=\sqrt{\gamma\frac{p}{\rho}} \quad (7)$$

$$q=C_c(T_{ext}-T) \quad (8)$$

$$m=\frac{A}{S}$$

$$F_f=F_f(k, Re)$$

The value of friction force, F_f, can be calculated as shown in the reference(Fox, 1977). The fluid variables p, u or ρ must be solved at each location x and time t. The sampling distance, Δx, and the sampling time, Δt, are chosen under the CFL stability constrain(Tannehill et al., 1997)

$$\Delta t<\left|\frac{\Delta x}{u\pm c}\right| \quad (9)$$

Figure 2 shows the relationship between fluid variables p, ρ, u at the time step t_j and at preceeding time step t_{j-1}.

Using Eqs. (1)-(3) under description of variables shown in Fig. 2, we can derive the variables p, ρ, u at grid point P from previous calculated grid points L, N, and O. Firstly, we

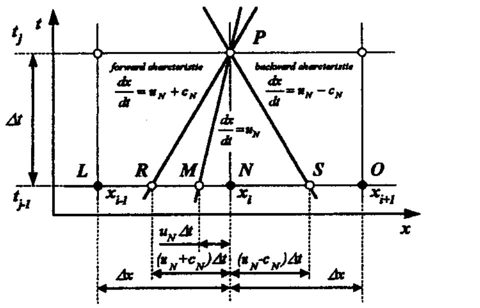

Fig. 2 Backward and forward characteristics using in MOC

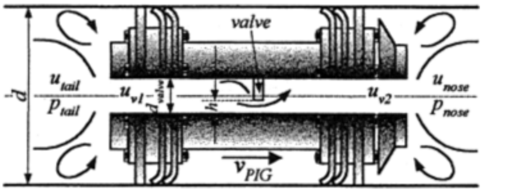

Fig. 3 Bypass flow through PIG

get flow parameters at grid points R, M, S from linear interpolation formula. Then, we integrate Eqs. (1)-(3) along the characteristic lines dx/dt to get the desired variables.

$$X_R = X_N - (X_N - X_L)\frac{(u_N + c_N)\Delta t}{\Delta x} \quad (10)$$

$$X_M = X_N - (X_N - X_L)\frac{u_N \Delta t}{\Delta x} \quad (11)$$

$$X_s = X_N - (X_N - X_O)(u_N - c_N)\frac{\Delta t}{\Delta x} \quad (12)$$

$$p_P = \frac{\gamma}{\frac{c_R}{p_R} + \frac{c_S}{p_S}} \times \left[(u_R - u_S) + \frac{c_R + c_S}{\gamma} + (E_{1R} - E_{2S})\Delta t\right] \quad (13)$$

$$u_P = u_R + \frac{c_R}{\gamma p_R}(p_R - p_P) + E_{1R}\Delta t \quad (14)$$

$$\rho_P = \rho_M + \frac{1}{c_M^2}[p_P - p_M - E_{3M}\Delta t] \quad (15)$$

The values of E_{1R}, E_{2S}, E_{3M} in Eqs. (13)-(15) are calculated from Eqs. (4)-(6) at the corresponding grid points R, S, and M.

2.1.2 Bypass flow through PIG

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. 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%(Willson and Yokota., 1994). 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

$$p_{tail} - p_{nose} = K_{total}\frac{(v_V - v_{PIG})^2}{2g} \quad (16)$$

where,

$$K_{total} = K_{SC} + K_V + K_{SE} \quad (17)$$

$$K_{SC} = 0.42\left(1 - \frac{d_{valve}^2}{d^2}\right) \quad (18)$$

$$K_{SE} = \left(1 - \frac{d_{valve}^2}{d^2}\right)^2 \quad (19)$$

$$K_V = K_V(h/d_{valve}) \quad (20)$$

Equations (18) and (19) are given in the reference(White, 1999). Valve loss coefficient K_V is a function of the opening distance ratio h/d_{valve} of a closing valve and depends on the type of valve to be used. This data can be found from valve manufacturer. From Eq. s (17)-(20), the total loss coefficient is given by

$$K_{total} = 0.42\left(1 - \frac{d_{valve}^2}{d^2}\right) + K_V + \left(1 - \frac{d_{valve}^2}{d^2}\right)^2 \quad (21)$$

2.1.3 Initial and boundary conditions

It is assumed that the steady state variable distributions are used for the initial conditions in the absence of field data concerning the initial field variable distributions(Wylie et al., 1993). The boundary conditions at pipeline inlet and outlet can be given in two ways: under a condition of flow rate $Q(t)$ or pressure $p(t)$ together with the temperature of flow $T(t)$. Both of the above conditions are given in the previous work (Nguyen et al., 2001). Here, we deal with the boundary conditions at the PIG such as its tail for upstream flow and at its nose for downstream flow. The boundary conditions here depend on

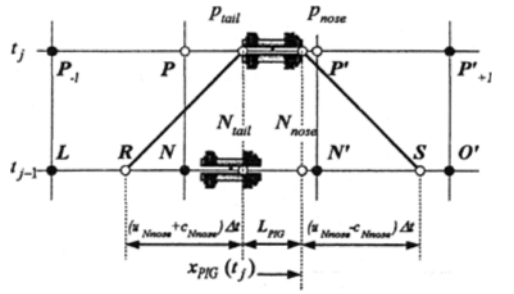

Fig. 4 Scheme for calculation of boundary values at the tail and nose of the PIG(the PIG stays in same grid space)

the dynamic behaviour of the PIG and the open state of bypass valve. At a boundary there is only one available characteristic such as a backward characteristic at an upstream boundary or a forward characteristic at a downstream boundary.

In the presence of bypass flow, the average fluid velocity at the tail of the PIG can be derived as follows

$$u_{tail}=v_{PIG}+\left(\frac{d_{valve}}{d}\right)^2(u_V-v_{PIG}) \qquad (22)$$

where,

$$u_V=u_{V1}=u_{V2} \qquad (23)$$

Equation (23) is made with assumption that the pressure drop allows the bypass flow to be treated as incompressible as it passes through the central bypass hole in the PIG. So, the velocity u_{V1} of the flow enters into valve equal to the velocity u_{V2} of the flow leaves from valve. Then, we have

$$u_{nose}=u_{tail} \qquad (24)$$

Having established a technique for finding total loss coefficient K_{total} at any position of a closing valve in Eq. (21), it is possible to calculate pressure and velocity of fluid at the tail and nose of the PIG.

From Fig. 4, using backward characteristic line at the tail of the PIG, we have

$$p_{tail}=p_R+\frac{\gamma p_R}{c_R}[-(u_{tail}-u_R)+E_{1R}\Delta t] \qquad (25)$$

And using downward characteristic line, at the nose of the PIG we have

$$p_{nose}=p_S+\frac{\gamma p_S}{c_S}[(u_{nose}-u_S)-E_{2S}\Delta t] \qquad (26)$$

Substituting Eqs. (22), (24)-(26) into Eq. (16), after some arrangements, we have the relationship

$$a_V(u_V-v_{PIG})^2+b_V(u_V-v_{PIG})+c_V=0 \qquad (27)$$

where,

$$a_V=\frac{K_{total}}{2g}\left(\frac{d}{d_{valve}}\right)^4$$

$$b_V=\gamma\left(\frac{d_{valve}}{d}\right)^2\left(\frac{p_R}{c_R}+\frac{p_S}{c_S}\right)$$

$$c_V=\gamma\left(\frac{p_R}{c_R}+\frac{p_S}{c_S}\right)v_{PIG}-(p_R-p_S)$$

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

We solve Eq. (27) under the condition of $u_V-v_{PIG}>0$ to get fluid velocity in the valve, u_V. Then, using Eqs. (22) and (24)-(26), we can derive the values u_{tail}, u_{nose}, p_{tail}, and p_{nose}. To use Eqs. (25)-(27), the fluid parameters at point R of downstream flow and at point S of upstream flow need to be calculated first and they can be derived as the following steps:

i. Calculate the flow parameters at point N_{tail} by linear extrapolating from two points L and N

$$X_{Ntail}=\frac{x_{Ntail}-x_L}{x_N-x_L}(X_N-X_L)+X_L \qquad (28)$$

ii. Calculate wave speed, c_{Ntail}, at point N_{tail} using Eq. (13)

iii. Calculate the position of point R

$$x_R=x_{PIG}-L_{PIG}-(u_{Ntail}+c_{Ntail})\Delta t \qquad (29)$$

iv. Calculate the flow parameters at point R by linear interpolating from two points L and N

$$X_R=\frac{x_R-x_L}{x_N-x_L}(X_N-X_L)+X_L \qquad (30)$$

The same steps must be done for upstream flow to find out flow parameters at point S. After finding out flow parameters at the tail of the PIG, flow parameters at point P are derived by linear interpolation from flow parameters at point P_{-1} and flow parameters at the tail of the PIG. The PIG can move to the next grid space as shown in Fig. 5. In this case, two points P and P_{+1} need to interpolate from flow values at point P_{-1} and at the tail of the PIG.

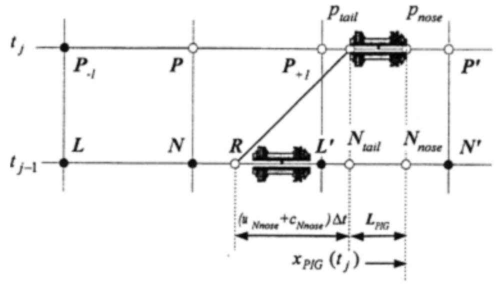

Fig. 5 Scheme for calculation of boundary values at the tail of the PIG(the PIG moves to the next grid space)

2.2 The PIG dynamics model

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

$$M\frac{d^2x(t)}{dt^2}+C\frac{dx(t)}{dt}+Kx(t)$$
$$=F_p(t)-F_{fp}(t)-F_b(t) \quad (31)$$

In the above Eq. (31), the driving force $F_p(t)$ is derived from the different pressure at the tail and nose of the PIG which are calculated from upstream and downstream flow dynamics in each computational step. The friction force $F_{fp}(t)$, the braking force $F_b(t)$, the wear factor K and the linear damping coefficient C are measured from experiment. The position and velocity of PIG can be calculated from Eq. (31) by using Runge-Kuta method.

3. Computational Scheme

The steps of computing the dynamics of the PIG are simplified by the computational scheme shown in Fig. 6.

Fist of all, the sampling distance and time are chosen and the CFL condition (9) must be checked to make sure whether the computing is stable or not. Then the initial values at grid points along pipeline are calculated. If the PIG does not reach the end of pipeline yet, the dynamics of the PIG is calculated. From the new position and velocity of the PIG, the boundary conditions at the tail and nose of the PIG are solved to get flow parameters at these points. Then the differential pressure now is derived for calculation of the PIG movement in next time step. Next, we calculate the dynamics of upstream and downstream of flows. The calculations are repeated for further time steps until the PIG reaches the end of pipeline.

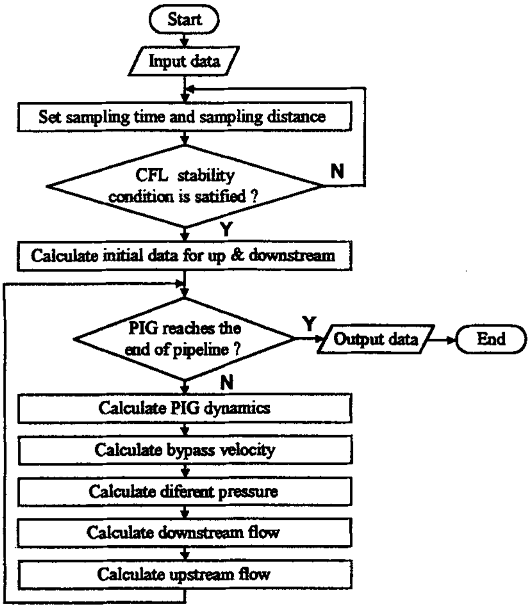

Fig. 6 Computational scheme

4. Simulation Results

Simulation was performed with data of one pipeline segment in the KOGAS low pressure system, Ueijungboo-Sangye line, which has been used in previous work(Nguyen et al., 2001). We chose the sampling time $\Delta t=0.05s$ and sampling distance $\Delta x=40$m. The boundary condition of interest is used: constant flow rate at pipeline inlet and constant pressure at pipeline outlet. The bypass valve diameter is chosen as $d_{valve}=0.1778$m. 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.

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

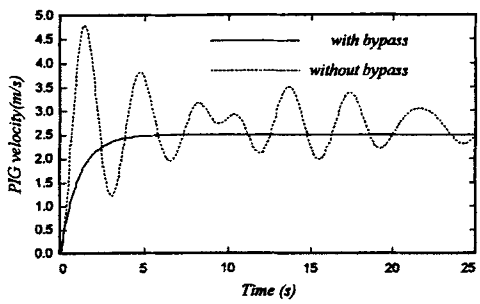

Fig. 7 PIG velocity when launching

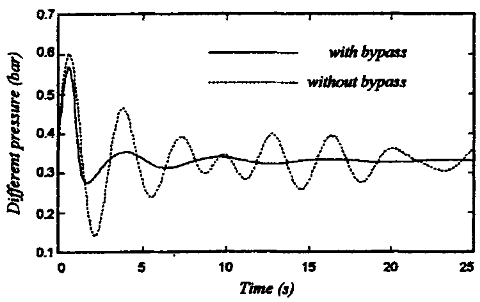

Fig. 8 Different pressure acting on the PIG when launching

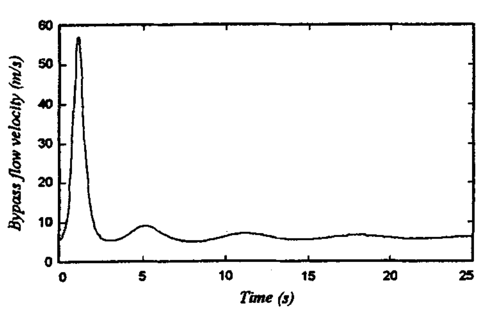

Fig. 9 Bypass flow velocity across the PIG when launching

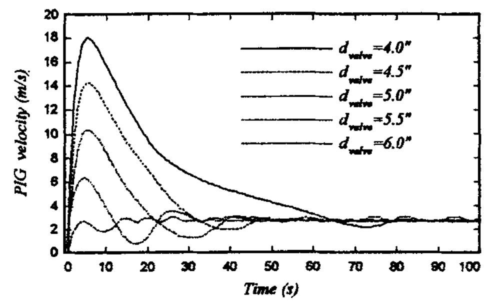

Fig. 10 PIG velocities after restart with different bypass port

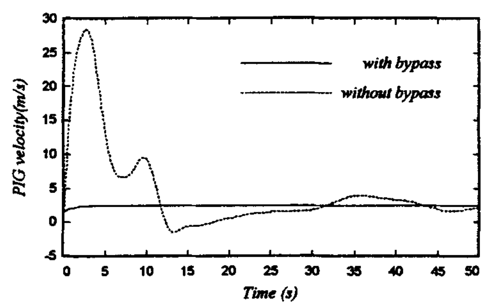

Fig. 11 PIG velocity after restarting

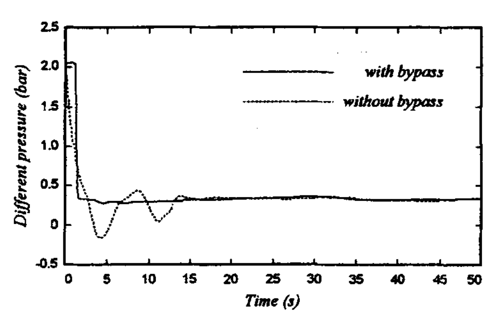

Fig. 12 Different pressure acting on the PIG after restarting

PIG is given in Fig. 8. The velocity of bypass flow across the PIG body is given in Fig. 9.

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 a 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 its velocity is reduced. This case of simulation has been done because it is the worst case in pigging operation. The bypass flow must act as fast as possible to keep the PIG velocity tracking its designed operational value. The

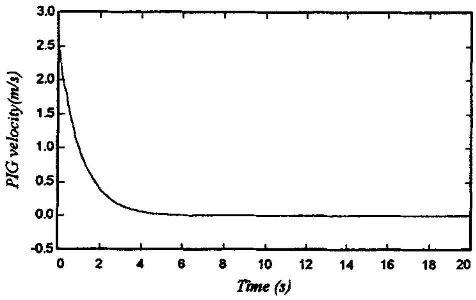

Fig. 13 PIG velocity

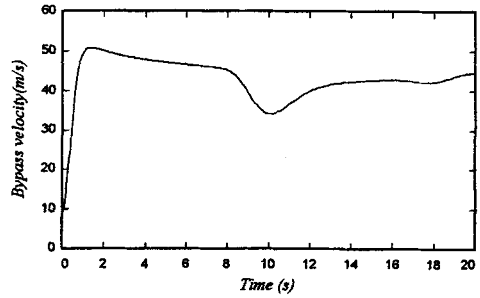

Fig. 14 Bypass velocity across the PIG

bigger bypass port is the faster the PIG velocity is reduced. Figure 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.

The different pressure acting on the PIG is shown in Fig. 12 and the PIG velocities in both cases with and without bypass can be seen from Fig. 11: with appropriate controlled bypass flow, we can eliminate the effects of friction force change and the PIG can restart with tracking well the reference speed.

The bypass flow can also be used as a brake to stop the PIG when it is reaching to its trap barrel.

Figures 13 and 14 show the PIG velocity and the velocity of bypass flow after opening bypass port to reduce the PIG speed. Different pressure acting on the PIG is shown in Fig. 15.

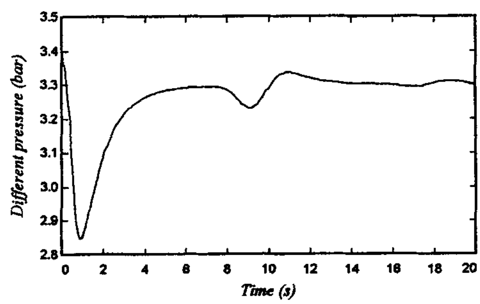

Fig. 15 Different pressure acting on the PIG

5. Conclusion

This paper presents the modeling and its simulation results for the PIG with bypass flow when it runs in natural gas pipeline. The models for flow dynamics and PIG dynamics are derived. The governing dynamic equations of upstream and downstream flows are the same in the case of the PIG without bypass flow. The computational scheme for estimating the dynamics of the PIG with bypass flow is proposed. The simulation was performed with data of one pipeline segment in the KOGAS low pressure system, Ueijungboo-Sangye line. 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. Through the simulation results, we can conclude as the following:

(1) The bypass PIG can track well the reference velocity while no bypass PIG has much oscillation.

(2) In the worst case of pigging procedure (the PIG stopped in the pipeline), the PIG accelerates until the acting different pressure abates to a level required to overcome the static and dynamic friction forces. At the same time, the bypass port must open as fast as possible to reduce the different pressure acting on the PIG and hence its velocity is reduced.

(3) By controlling the bypass flow appropriately, the PIG can track and regulate well its reference speed. The bypass flow also can be used as a brake to stop the PIG when it is reaching to its trap barrel.

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 treated in another our work.

Acknowledgement

This paper is a part of study results of "Modeling and Control of PIG Flow in Natural Gas Pipeline" which is studied by Korea Gas Corporation support. We gratefully acknowledge the contributions and suggestions of related persons.

References

Azevedo, L. F. A., Braga, A. M. B., Nieckele, A. O., Naccache, M. F. and Gomes, M. G. F. M., 1996, "Simple Hydrodynamic Models for the Prediction of Pig Motions in Pipelines," in *Proceedings of the 1996 Offshore Technology Conference*, TX. , USA, pp. 729~739.

Cordell, Jim and Vanzant, Hershel, 1999, "All About Pigging," On-Stream Systems Limited and Hershel Vanzant & Associates.

Fox, J. A., 1977, *Hydraulic Analysis of Unsteady Flow in Pipe Networks*, John Wiley & Sons Pub.

Korea Gas Corporation, 2000, "The First Stage of Development of Intelligent PIG for Low Pressure Pipeline."

Lima, P. C. R., Petrobas, S. A., and Yeoung, H., 1999, "Modeling of Pigging Operations," in *Proceedings of SPE Annual Technical Conference and Exhibition*, pp. 563~578, TX. , USA.

Nguyen, T. T., Yoo, H. R., Rho, Y. W., and Kim, S. B., 2000, "Modelling and Simulation for PIG Flow Control in Natural Gas Pipeline," in *Proceedings of the 15th Korea Automatic Control Conference*, pp. 448~451, Yong-in, Korea.

Nguyen, T. T., Yoo, H. R., Rho, Y. W., and Kim, S. B., 2001, "Modelling and Simulation for PIG Flow Control in Natural Gas Pipeline," *KSME International Journal*, Vol. 15, No. 8, pp. 1165-1173.

Out, J. M. M., 1993, "On the Dynamics of Pig-slug Trains in Gas Pipeline," OMAE, Vol. V, *Pipeline Technology, ASME*, pp. 395~403.

Sim, W. G. and Park, J. H., 1997, "Transient Analysis for Compressible Fluid Flow in Transmission Line by the Method Of Characteristics," *KSME International Journal*, Vol. 11. No. 2, pp. 173~185.

Smith, G. L., 1992, "Pigging Velocities and the Variable-Speed PIG," *Proceedings of Pipeline Pigging and Integrity Monitoring Conference*, Amsterdam, Netherlands, 28th September-2nd.

Tannehill, John C., Anderson, Dale A. and Pletcher, Richard H., 1997, "Computational Fluid Mechanics and Heat Transfer," Taylor & Francis Pub.

White, Frank M., 1999, *Fluid Mechanics*, McGraw-Hill Pub.

Willson, D. J. and Yokota, J. W., 1994, "Speed Control Research and Development," Nowsco Pipeline Service.

Wylie, E. Benjamin, Streeter, Victor L. and Suo, Lisheng 1993, *Fluid Transients in Systems*, Prentice-Hall, Inc.