Journal of Applied Fluid Mechanics, Vol. 12, No. 5, pp. 1497-1509, 2019.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.29252/jafm.12.05.29869

Simulation of Pigging with a Brake Unit in Hilly Gas Pipeline

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(Received November 24, 2018; accepted January 19, 2019)

ABSTRACT

Pigging is a routine operation in the oil and gas industry. In this paper, the governing equation of pig speed was combined with the gas flow equations. The transient equations of gas flow are solved by the method of characteristics (MOC). An experiment was carried out to test the proposed pigging model. The measured speed of the pig coincides with the calculated speed well. The process of a pig carrying a brake unit to pass over a hilly gas pipeline is simulated. The results indicate that the brake unit would lead to a sharp increase of the pressure on the tail of the pig, because the pig is dragged by the brake unit and thus prevented to accelerate together with the gas column in a downhill gas pipeline. This way, the pig speed in a downhill gas pipeline is much lower by using a brake unit, but the speed of pig still can hardly be controlled in the desired range. Furthermore, response surface methodology (RSM) is used to study the maximum speed of pig with/without a brake unit in downhill gas pipeline. Based on the results of the RSM simulations, two equations are present to predict the maximum speed of a pig in a downhill gas pipeline.

Keywords: Method of characteristics; Gas pipe; Hammer effect; Runge-Kutta method; Response surface methodology; Speed control.

NOMENCLATURE

c	sound speed	q	rate of heat inflow
d	diameter of the pipe	Re	Reynolds number
F_d	drag force of brake unit	S	pipe inner perimeter
F_{fp}	friction force between of pig	t	time
F_p	derived force of pig	u	velocity of gas
f	friction factor	x	distance
g	gravity parameter		
K_d	coefficient of drag force	μ	coefficient of friction force
k	pipe wall roughness	θ	angle of pipe
m	pig mass	ρ	density of gas
p	gas pressure	γ	ratio of specific heat

1 INTRODUCTION

Regular pigging for the gas pipelines has become one standard procedure for the operators. Generally, a pig is a plug that is installed in the pipe to perform certain operations such as liquid removal, inspection of the pipe and cleaning out debris (Tolmasquim and Nieckele, 2008; Zhang *et al.*, 2015). Fluid is pumped upstream of the pig to drive the pig in motion. Regardless of what the aim of the pigging, it is generally accepted that the pigs are more effective at a near constant, moderate speed. This pig speed is in the range of 2-7 m/s in gas pipelines and 1-5 m/s in liquid pipelines (Nguyen *et al.*, 2001b).

Because of the compressibility of natural gas, the speed of pigs in natural gas pipelines can be erratic (Mirshamsi and Rafeeyan, 2012; Zhu *et al.*, 2014). In gas pipelines, there are occasions that the pig speed is much faster than the allowable value, which is dangerous for the pipe and the pig itself (Zhang *et al.*, 2018). Therefore, the control of the pig's speed is critical to the pigging operation (Hendrix *et al.*, 2017; Lesani *et al.*, 2012).

Currently, the main method of pig speed control is to use a bypass valve (Lesani *et al.*, 2012; Mohamad and Fakhruldin, 2012). In the pigging operations using a pig with a bypass valve, an amount of the fluid passes through the bypass valve, building up a pressure difference at the front and rear of the pig. The control strategy is to adjust the open extent of the valve that changes the driving pressure of the pig and then changes the speed of the pig. To date, some works about pig speed control using bypass valve have been down, which involves the structure and mechanical characteristics of bypass valve, pigging model, control strategy, algorithm and applications (Groote *et al.*, 2015; Mirshamsi and Rafeeyan, 2012; Nguyen *et al.*, 2001b; Tan *et al.*, 2011).

In the field, bypass control strategy is widely used in smart pigs for pipeline inspection, while normal (i.e. non-bypass) pigs for cleaning operation barely use an adjustable bypass valve. In order to control the speed of the pig, Stoltze invented a brake device. (Stoltze, 2009). The brake unit moves together with the pig and provides a drag force that changes with pig speed automatically (Liang *et al.*, 2017). In this way, it is possible to prevent the pig from moving at an undesired high speed. The brake unit has been used in horizontal pipelines and shows a good performance for controlling the speed of the pig. However, there are few studies on the application or simulation of the brake unit in hilly gas pipelines.

In order to understand the dynamic behavior of the pig in the pipeline, the pig dynamic equation must be solved together with the flow equation (Nieckele *et al.*, 2001). Liquid-gas flows in pipeline can occur in different forms that make the simulation of the pigging for liquid removal very complicated. A lot of research has been done on the model of pigging for liquid-gas flows (Ayati *et al.*, 2014; Ayati *et al.*, 2015; Birvalski *et al.*, 2014; Holmas, 2010; Kumara *et al.*, 2009; Strazza *et al.*, 2011). It's generally accepted that a pig in liquid-gas pipelines runs at a lower and more stable speed than it is in gas pipelines. The pigging models for gas pipelines deal the gas as transient flow, and therefore can predict the dynamic behavior of the pig accurately. The method of characteristics (MOC) was used to transform the equations of flows to ordinary differential equations. This method is quite efficient to solve the governing equations of transient gas flows.

There are already some works related to the dynamics of natural gas pipeline pigs. Esmaeilzadeh *et al.* proposed a pigging model for gas pipelines (Esmaeilzadeh *et al.*, 2009). In this research, the gas pipeline was considered as a two-dimensional curve. The process of a pig restarting from a stoppage in a horizontal gas pipe was simulated by Nguyen *et al.* In this paper, the gas equations were solved by MOC. Runge-Kutta method was employed to solve the speed equation of the pig and to solve the ordinary differential equations of the steady state equations of gas (Nguyen *et al.*, 2001a). The dynamics of a pig with a fixed bypass in gas pipeline was studied by (Hosseinalipour *et al.*, 2007). Mirshamsi *et al.* considered the pig train as a chain rather than a particle in gas pipelines (Mirshamsi and Rafeeyan, 2015). Xu and Li developed a pigging mathematical model coupling with the quasi-steady state flow model (Xu and Li, 2011).

Literature surveys show that few papers pay attention to the applications or simulations of the brake unit in hilly gas pipelines. Also, there are few calculations or simulations for estimating the pig speed in a downhill gas pipeline. This paper deals with the dynamic model for the process of a conventional pig carrying a brake unit to move in a hilly gas pipeline. The transient gas equations are solved by MOC. Then the different pressure between pig tail and nose is acquired from MOC results. Thus dynamic equation of the pig can be solved by Runge-Kutta method. The process of a pig moving through a hilly gas pipeline is simulated. The results demonstrate the coupling effect of the pig and the gas well. Furthermore, RSM is used to study the maximum speed of pig in downhill gas pipeline. Based on the results of the RSM simulations, two equations are present to predict the maximum speed of a pig in a downhill gas pipeline.

2 MATHEMATICAL MODELING

2.1 Dynamic Equation of Pig Carrying a Brake Unit

Figure 1 shows the rig of pig and brake unit, i.e. a pig carries a brake unit to travel through pipeline. The simplified working principle of the brake unit is presented in Fig. 2. Several speed-acquiring wheels are urged against the pipe wall so as to roll on the wall. Each wheel drives a hydraulic pump to produce an oil flow through a throttle, thereby building up a pressure which counteracts the brake wheel rotation. With sufficient force to push the speed-acquiring wheel against the pipe wall, the reaction force is transmitted as a braking force to the pipe wall. Therefore, the braking force increases as the pig speed increases. In this way, an undesirably high speed of the pig can be prevented in a simple and reliable manner (Liang *et al.*, 2017; Stoltze, 2009).

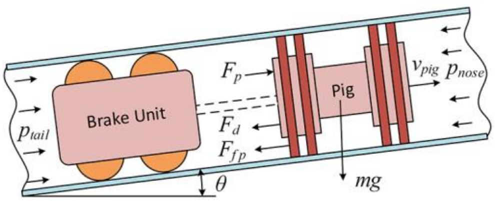

Fig. 1. Pig carries a brake unit in pipeline.

The dynamic equation of the pig is as follows:

$$mv'_{pig} = F_p - \text{sgn}(\dot{x})F_{fp} - mg\sin\theta - F_d \qquad (1)$$

In this equation, m is the pig mass, F_{fp} is the friction force between the pig and the pipeline wall. The driving force F_p is derived from the differential pressure at the rear and front of the pig. The differential pressure is calculated from the upstream and downstream flow dynamics in each calculation step. As shown in the Appendix, the drag force F_d produced by the brake unit can be expressed as follows (Liang *et al.*, 2017),

$$F_d = K_d v_{pig}^2 \tag{2}$$

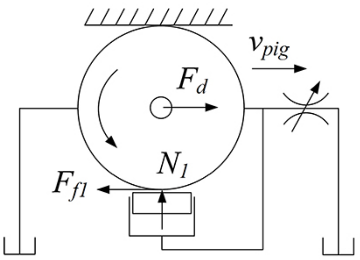

Fig. 2. Schematic principle of the brake unit.

where, K_d is the coefficient of drag force. The value of K_d generally ranges from 200 to 800 and is determined by the control system parameters, such as the cylinder area, the throttle area, number of brake wheels and radius of brake wheel.

As is known, the sealing disc of the pig must be enlarged to fit the inner wall of the pipe in order to build up a pressure difference. The normal force generated by the compressed disc is noted as N_0. In addition, when the pig moves through a bend, the centrifugal force of the pig would contribute to the contact force. Lastly, the gravity of the pig generates friction force too. Assuming $f(x)$ is a function of the centerline of the two-dimensional pipeline, the total friction force F_{fp} can be rewritten as follows:

$$F_{fp} = \frac{m\mu \left| f''(x) \right| v_{pig}^2}{\left[1 + f'^2(x) \right]^{1.5}} + \frac{m\mu g}{\sqrt{1 + f'^2(x)}} + \mu N_0 \tag{3}$$

where μ is the coefficient of friction force. In this equation, the first item on the right side of the equal sign indicates the friction generated by the centrifugal force of pig, and the second item represents the friction force caused by the gravity of the pig.

In general, a pipeline curve can be expressed as a number of discrete points. Thus $\sin\theta$ in Eq. (1) of each point can be expressed by the adjacent points. At each time step, inclination parameter $\sin\theta$ of the current pig position can be obtained by interpolation of the adjacent points. Then the speed and position of the pig can be solved from Eq. (1) by using Range-Kuta method. Additionally, the inclination parameter $\sin\theta$ in the gas equations can be calculated in the same way.

2.2 Gas Flow Model in Hilly Pipeline

The unsteady flow dynamics can be modeled based on the continuity equation, momentum equation, and energy equation respectively as follows (Esmaeilzadeh *et al.*, 2009 Nguyen *et al.*, 2001a; Xie *et al.*, 2018):

$$\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + \rho\frac{\partial u}{\partial x} = 0 \tag{4}$$

$$\frac{\partial p}{\partial x} + \rho u\frac{\partial u}{\partial x} + \rho\frac{\partial u}{\partial t} = -\frac{F_f}{A} - \rho g \sin\theta \tag{5}$$

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} + \gamma p\frac{\partial u}{\partial x} = \frac{\gamma - 1}{A}\left(F_f u + qS + \mathrm{A}u\rho g \sin\theta \right) \tag{6}$$

where, u, ρ, p, x, g and t are the velocity, density, pressure, distance, gravity parameter and time, respectively. In addition, Ff, Ap, γ, S and q are the friction force, cross-sectional area of the pipe, ratio of specific heat, pipe perimeter and rate of heat inflow, respectively.

From the perspective of the fluid mechanics books and papers, the friction factor and the friction force are given respectively as follows (Dale *et al.*, 2012):

$$f = 0.11\left(\frac{k}{d} + \frac{68}{\mathrm{Re}} \right)^{0.25} \tag{7}$$

$$F_f = f\rho \frac{A}{d}\frac{u^2}{2} \tag{8}$$

where, Re, d, k, and f are the Reynolds number, diameter of the pipe, pipe wall roughness, and friction factor, respectively. Equations (4) ~ (6) can be rewritten in the following form:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{A}\frac{\partial \mathbf{u}}{\partial x} = \mathbf{B} \tag{9}$$

where,

$$\mathbf{u} = \begin{bmatrix} \rho \\ u \\ p \end{bmatrix}, \mathbf{A} = \begin{bmatrix} u & & \\ & u & \frac{1}{\rho} \\ & \gamma p & u \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ -\frac{F_f}{\rho A} \\ \frac{\gamma - 1}{A}\left(uF_f + qS + \mathrm{A}u\rho g\sin\theta \right) \end{bmatrix}$$

Equation (9) can be transformed into ordinary differential equations which can be integrated by finite differences. Matrix **A** has 3 real eigenvalues λ:

$$\lambda = \begin{cases} u \\ u + c, \\ u - c \end{cases} \quad c = \sqrt{\frac{\gamma p}{\rho}}$$

where c is the sound speed. A compatible equation is obtained by multiplying the eigenvectors of the system. The eigenvectors of matrix **A** are:

$$\upsilon=\left[\begin{bmatrix} u/\rho \\ 0 \\ -u/(\gamma p) \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ c/(\gamma p) \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ -c/(\gamma p) \end{bmatrix}\right]$$

For each pair of λ and υ, Eq. (7) can be rewritten as:

$$\upsilon^T\left(\frac{d\mathbf{u}}{dt}-\mathbf{B}\right)=0 \tag{10}$$

By writing Eq. (9) along the characteristics line, now we get the compatibility equations as follows.

Along $dx/dt=u+c$, we get:

$$\frac{du}{dt}+\frac{c}{\gamma p}\frac{dp}{dt}=\frac{\gamma-1}{c}\frac{qS}{\rho A} +\left(\frac{F_f}{\rho A}+g\sin\theta\right)\left[\frac{u(\gamma-1)}{c}-1\right] \tag{11}$$

Along $dx/dt=u-c$, we get:

$$\frac{du}{dt}-\frac{c}{\gamma p}\frac{dp}{dt}=-\frac{\gamma-1}{c}\frac{qS}{\rho A} -\left(\frac{F_f}{\rho A}+g\sin\theta\right)\left[\frac{u(\gamma-1)}{c}+1\right] \tag{12}$$

And along $dx/dt=u$, we get:

$$\frac{dp}{dt}-c^2\frac{d\rho}{dt}=(\gamma-1)\frac{qS}{A} +\left(\frac{F_f}{\rho A}+g\sin\theta\right)(\gamma-1)u\rho \tag{13}$$

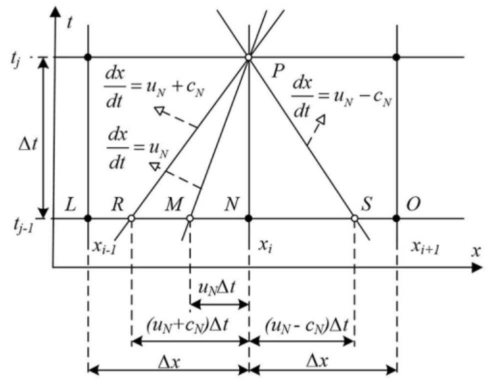

Fig. 3. Characteristics used in MOC.

Figure 3 shows the relationship between gas parameters *u*, *p*, and ρ at the time step t_{j-1} and at following time step t_j. At the time step t_{j-1}, variables *u*, *p*, and ρ at points *S*, *M* and *R* are obtained by linear interpolation of the data on *O*, *N* and *L*. Then, using the characteristic lines, the gas flow parameters at point *P* are obtained from the previously calculated *S*, *M* and *R* grid points.

According to the characteristic lines in Fig. 3, using linear interpolation, we get Eqs. (14) ~ (16) (Esmaeilzadeh *et al.*, 2009). In these equations, *X* represents the desired values *u*, *p*, or ρ.

$$X_R=X_N+(X_L-X_N)\frac{(u_N+c_N)\Delta t}{\Delta x} \tag{14}$$

$$X_M=X_N+(X_L-X_N)\frac{u_N\Delta t}{\Delta x} \tag{15}$$

$$X_S=X_N-(X_O-X_N)\frac{(u_N-c_N)\Delta t}{\Delta x} \tag{16}$$

According to Eqs. (11) ~ (13), we get

$$p_P=\frac{\gamma}{\frac{c_R}{p_R}+\frac{c_S}{p_S}}\left[\begin{matrix}(u_R-u_S)+ \\ \frac{c_R+c_S}{\gamma}+(E_{1R}-E_{2S})\Delta t\end{matrix}\right] \tag{17}$$

$$u_P=u_R+\frac{c_R}{\gamma p_R}(p_R-p_P)+E_{1R}\Delta t \tag{18}$$

$$\rho_P=\rho_M+\frac{1}{c_M^2}\left[p_P-p_M-E_{3M}\Delta t\right] \tag{19}$$

where,

$$E_{1R}=\frac{\gamma-1}{c_R}\frac{qS}{\rho_R A}+ \left(\frac{F_f}{\rho A}+g\sin\theta\right)\left[\frac{u_R(\gamma-1)}{c_R}-1\right] \tag{20}$$

$$E_{2S}=-\frac{\gamma-1}{c_S}\frac{qS}{\rho_S A}- \left(\frac{F_f}{\rho A}+g\sin\theta\right)\left[\frac{u_S(\gamma-1)}{c_S}+1\right] \tag{21}$$

$$E_{3M}=(\gamma-1)\frac{qS}{A}+ \left(\frac{F_f}{\rho_M A}+g\sin\theta\right)(\gamma-1)u_M\rho_M \tag{22}$$

The time step, Δt, and the space interval, Δx, are chosen under the CFL stability condition, which can be expressed as follows (Dale *et al.*, 2012):

$$\Delta t<\frac{\Delta x}{u+c} \tag{23}$$

Due to the drastic changes in gas parameters and pig speed in the hilly gas pipeline, a small space step should be chosen, but the calculation load will increase significantly. Therefore, the step size should be modified before calculation to achieve better efficiency.

2.3 Boundary and Initial Conditions

In this paper, the boundary condition of constant inlet flow rate and constant outlet pressure is used, simulating the releasing of a stuck pig by increasing upstream pressure. It is assumed that the upstream and downstream gas flows are fully coupled to the pig. Therefore, the gas velocity at the tail and nose of the pig is equal to the speed of the pig. (Esmaeilzadeh *et al.*, 2009; Nguyen *et al.*, 2001a).

The steady state momentum Eq. (5) and

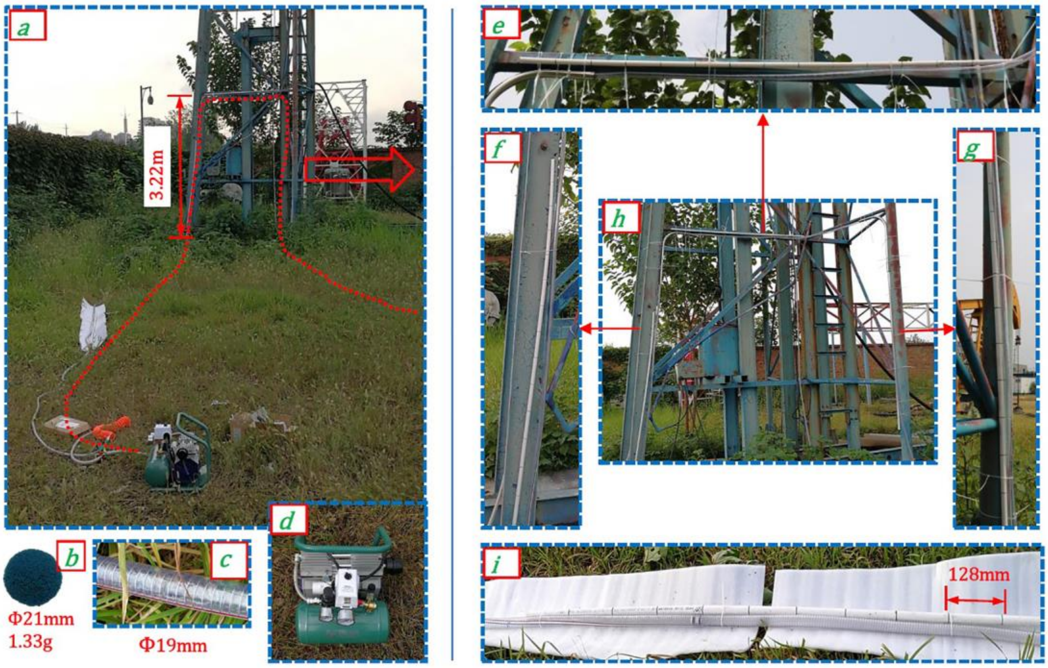

Fig. 4. Schematic diagram of the experiment.

(***a.*** Overview of the setup; ***b***. Foam pig; ***c***. Pipe; ***d***. Air compressor; ***e***. Top section for measuring pig speed; ***f***. Uphill section for measuring pig speed; ***g***. Downhill section for the measurement of pig speed; ***h***. View of the hilly pipe; ***i***. Horizontal section for the speed measuring.)

energy Eq. (6) for gas flow can be transformed to ordinary differential equations, by assuming $\partial/\partial t = 0$. Now we get the steady state equations:

$$\rho u = \rho_o u_o \tag{24}$$

$$\frac{\mathrm{d}u}{\mathrm{d}x} = \frac{\gamma F_f u}{\rho A\left(c^2 - u^2\right)} + \frac{(\gamma - 1)qS}{\rho A\left(c^2 - u^2\right)} + \frac{\gamma u \rho g \sin\theta}{\rho\left(c^2 - u^2\right)} \tag{25}$$

$$\frac{\mathrm{d}p}{\mathrm{d}x} = \mathrm{sgn}(u)\frac{(1-\gamma)u^2 - c^2}{c^2 - u^2}\frac{F_f}{A} - \frac{(\gamma - 1)qSu}{A\left(c^2 - u^2\right)} + \frac{(1-\gamma)u^2 - c^2}{c^2 - u^2}\rho g \sin\theta \tag{26}$$

The initial fluid variables u, p, and ρ for both up-stream and down-stream gas flows can be calculated by solving Eqa. (24) ~ (26) using Runge-Kutta method.

2.4 Numerical Solution

To simulate the pigging process in gas pipeline, the pipeline is divided into two sections: one behind the pig and the other in front of it. At time step t_{i+1}, the dynamic equations for both upstream and downstream gas flows are solved, to get the differential pressure between the rear and front of the pig.

In the next step, the Runge-Kutta method is used to solve the speed equation of the pig, to obtain the speed and the new position of the pig.

As the pig moves across one or more grids during time step t_{i+2}, the grids on upstream and downstream of flows must be updated for calculating the gas parameters. Then the differential pressure between the rear and front of the pig is derived to calculate the pig motion at time step t_{i+3}. The calculations are repeated until the time step reaches the end.

3 Experimental Study on the Pigging Model

For the purpose of testing the proposed pigging model, an experiment is designed to simulate the process of pigging for a hilly gas pipeline. A schematic view of the setup is shown in Fig. 4. As shown in Fig. 4(a), the pipeline contains an uphill section and a downhill section, which is figured out in Fig. 5. A foam pig is installed in the transparent pipeline and driven by an air compressor. Figure 4 (e ~ i) shows the four positions for the measurement of the pig speed: horizontal, uphill, top and downhill section, in sequence. A ruler is set near the pipe section for measuring the speed of pig. Then a camera is used to record the process of pigging through the specific section of the pipeline. Thus, the time taken by the pig to pass the scales on the ruler can be read from the videos. This way, the speed of the pig can be figured out.

Values of the parameters used in this pigging experiment and simulation are shown in Table 1. The pig speeds of the simulation and the experiment

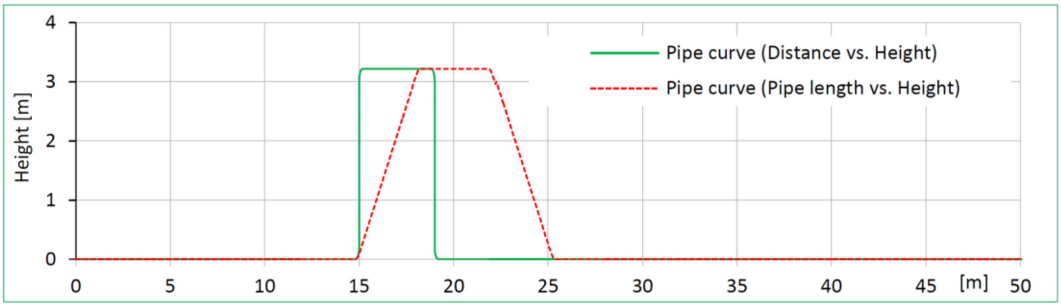

Fig. 5. Pipe curve used for the experiment.

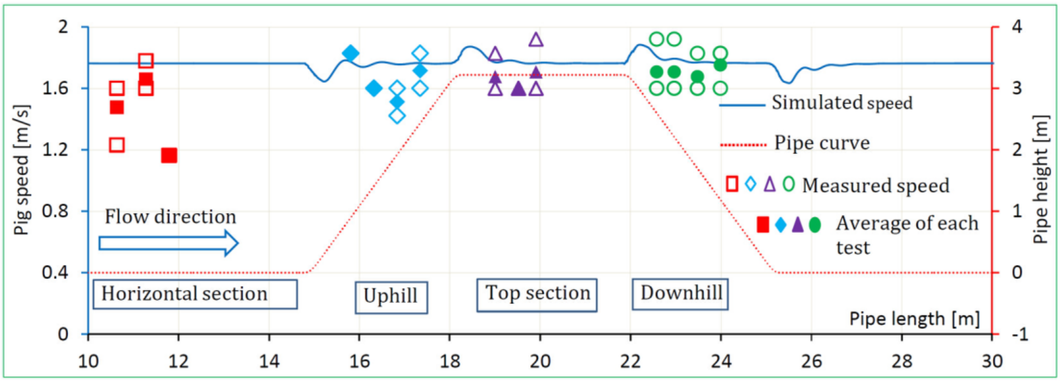

Fig. 6. Pig speed of the measurement vs. the speed of the simulation.

are figured out in Fig. 6. The results show that the measured speed is in good agreement with the simulated speed. In addition, the fluctuation of the simulated speed coincides with the shape of pipeline well. Therefore, the effectiveness and reliability of the pigging model adopted are verified to a certain extent.

Table 1 Numerical values of the experiment

Parameter	Unit	Valve
D	m	0.019
F_{fp}	bar	0.5
g	m/s^2	9.8
k	mm	0.03
l	m	50
m_p	g	1.33
p_i	bar	1
Q_i	m^3/s	0.0005
q	w/m^2	0
Δt	s	0.002
Δx	m	0.1
ν	m^2/s	1.45×10^{-5}
ρ_i	Kg/m^3	1.3
γ	-	1.4

4 Simulation of Pigging for a Hilly Natural Gas Pipeline

The pipe curve used in the simulation is shown in Fig. 7, in which the uphill or downhill slope is about 11 degrees. The parameters of both the pigging system and the brake unit are listed out in Table 2. In this simulation, the outlet pressure remains at 7MPa or 2MPa, while the pig carries a brake unit or without control, is discussed.

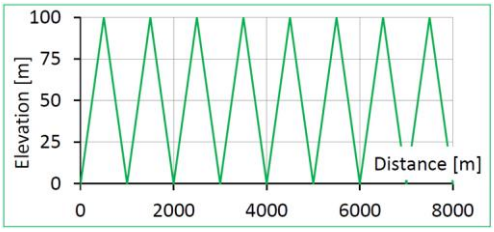

Fig. 7. Pipe curve for the simulation.

As the outlet pressure remains at 2MPa, the distributions of gas pressure and speed are figured out in Fig. 8, which shows that the shock wave of the gas speed, generated by a high speed of the pig, will continue to move forward. When the pig moves to the uphill section, the gas pressure on the nose of the pig increases because of the compression generated by the pig. Additionally, the pressure rise at the nose of the pig is more obvious due to the action of gravity, i.e. the gas gravitational potential energy is converted into pressure energy because of the upward compression produced by the pig. This way, the pig slows down and requires a higher upstream pressure to drive it in motion. In terms of the downhill section, the action of gravity reverses, leading to an increase of pig speed and a decrease of the gas pressure.

As shown in Fig. 8(B), a cuspidal point appears in the distribution of gas pressure, when the pig carries

Table 2 Numerical values for simulation

Parameters of the pigging system						
Parameter	Unit	Valve		Parameter	Unit	Valve
p_i	bar	20	70	D	m	0.5
ρ_i	Kg/m^3	13.4	54.2	F_{sta}	bar	0.25
ν	m^2/s	8.6×10^{-7}	2.4×10^{-7}	Q_i	m^3/s	0.8
γ	-	1.37	1.57	q	w/m^2	0
μ_2	-	0.3		k	mm	0.03
T	℃	25		m_b	Kg	100
Δt	s	0.04		m_p	Kg	200
Δx	m	40		N_0	N	10000
Parameters of the brake unit						
Parameter	Unit	Valve		Parameter	Unit	Valve
A_c	m^2	2.83×10^{-3}		V_o	m^3	2.5×10^{-5}
A_t	m^2	1.96×10^{-5}		r	m	0.1
C_t	-	0.72		μ_1	-	0.1
n	-	6		ρ_{oil}	kg/m^3	900

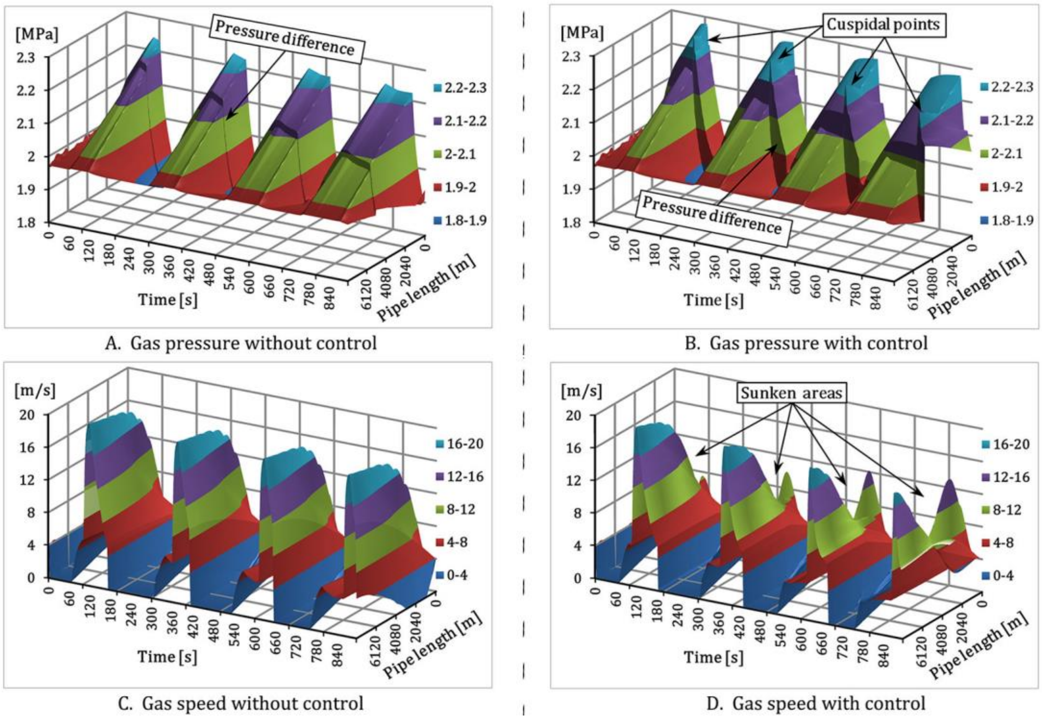

Fig. 8. Distributions of gas parameters.

a brake unit to move into a downhill section of the pipeline. Simultaneously, the plot of gas speed shows a sunken area at the corresponding area, which is figured out in Fig. 8 (D). The results indicate that the brake unit hinders the acceleration of the pig in the downhill segments, which leads to a hammer effect on the tail of the pig. It means the pressure at the rear of the pig suffers a sharp increase, because the pig is dragged by the brake unit and prevented to accelerate together with the gas column. This way, the pressure difference between the rear and front of the pig increases to a high level when the pig carries a brake to move into the downhill, which is shown in Fig. 9. Additionally, the maximum pressure difference is about 5bar when the outlet pressure remains at 7MPa, while the maximum pressure difference is about 2.5bar as the outlet pressure remains at 2MPa. It means that the hammer effect increases significantly with the increase of gas pressure.

As shown in Fig. 9, without the brake unit, the pressure difference between the rear and front of the pig remains at about 0.2bar, excepting its fluctuations generated by the changes of pipe inclination. When the pig rushes into an uphill section, the driving pressure of the pig reverses, which means the pressure on the nose of the pig is higher now. This way, the pig stops running and even moves backward in a short time.

The pig speeds of the four calculations are illustrated in Fig. 10 and Fig. 11, which shows that the pig without control reaches a maximum speed of about 18m/s in the downhill section of pipeline.

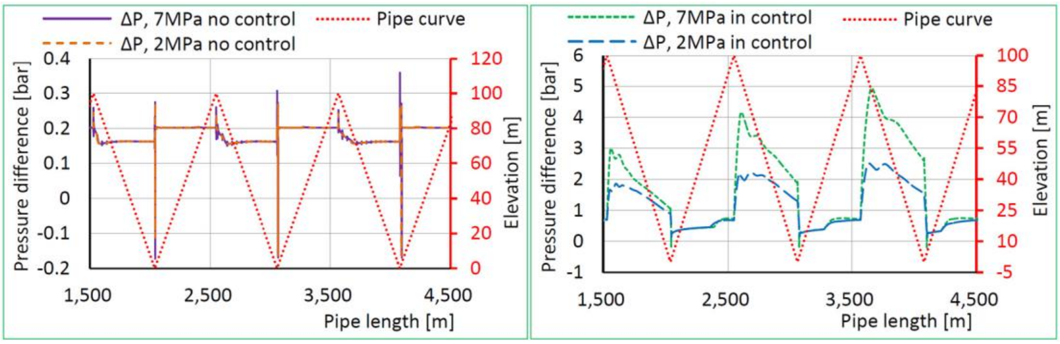

Fig. 9. Pressure difference between pig tail and nose.

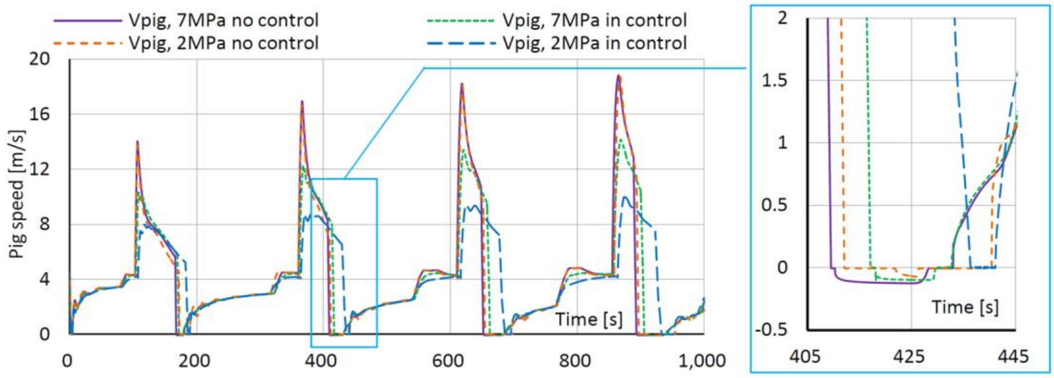

Fig. 10. Pig speeds vs. Time.

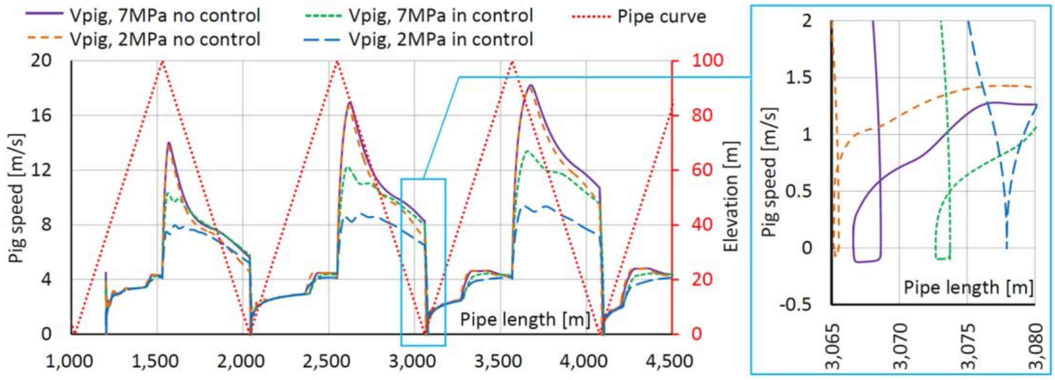

Fig. 11. Pig speeds vs. Pipe length.

In the 2MPa pipeline, the maximum speed of the pig reduces to about 10m/s by using a brake unit, while the maximum speed reduces to about 14m/s as the gas pressure is about 7MPa. The results indicate that the brake unit would show a better performance for controlling the pig speed in a hilly pipeline of lower pressure. Two partial enlarged views of Fig. 10 and Fig. 11 show the backward movement of the pig, because it rushes into the uphill and generates a negative driving pressure (shown in Fig. 9).

As shown in Fig. 12, in the boundary conditions adopted in this paper, the inlet pressure increases by 12% to push the pig through the uphill section, and decreases by 6%~10% when the pig runs at the downhill sections of the pipeline. Additionally, the inlet pressure increases by about 0.4bar because of the brake unit.

In order to discuss the effects of the mass and contact force of the pig on the results, two calculations were performed: (1) double the mass of pig, (2) double the contact force of the pig. According to the numerical valves of parameters presented in Table 2, the pig speeds are figured out in Fig. 13. The results shows that the mass and contact force of the pig make little difference to the pig speed in the hilly gas pipeline.

5 CALCULATION OF MAXIMUM PIG SPEED IN DOWNHILL GAS PIPELINE

In general terms, a downhill gas pipeline starts from

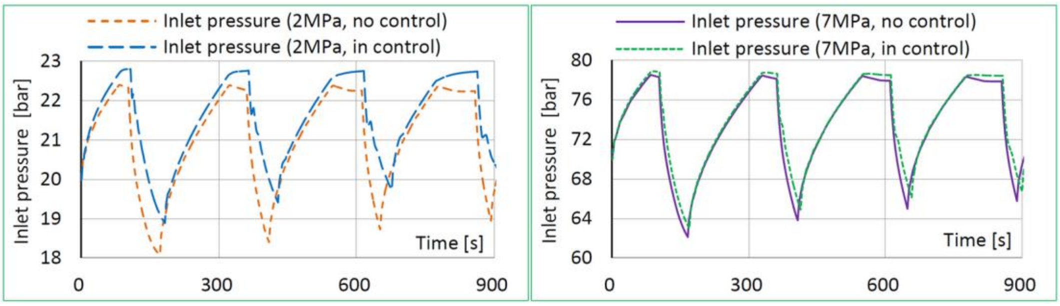

Fig. 12. Inlet pressure during the pigging.

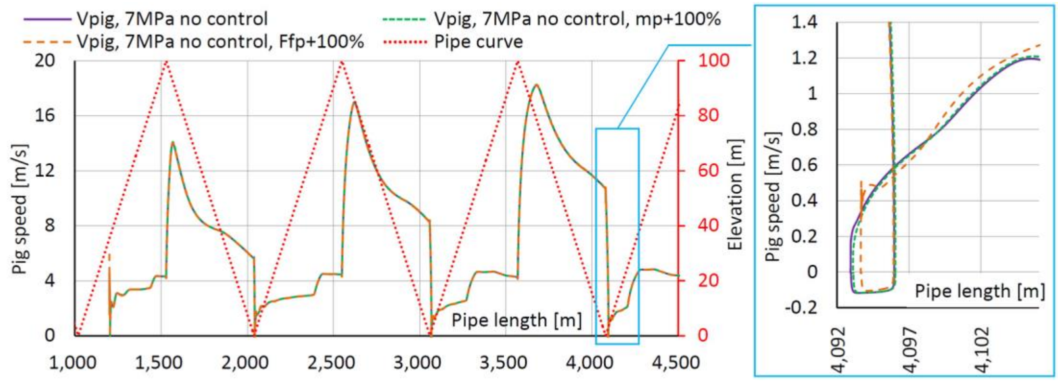

Fig. 13. Pig speeds vs. Pipe length (the mass or the contact force of the pig is doubled).

a horizontal section, which would lead to an acceleration of the pig in the downhill segment. The downhill pipe curve for the pigging simulations is shown in Fig. 14. The parameters of both the pigging system and the brake unit are listed out in Table 2, excepting that the gas pressure adopted in this simulation is 40bar and the gas flow rate is 0.95m^3/s (average flow speed is 5m/s).

The pipeline with an inclination of 27.5 degrees is adopted. The speeds of the pig are shown in Fig. 15. The results indicate that a maximum speed of the pig is achieved in the downhill pipeline, and the pig speed exceeds the allowable range. Additionally, the maximum speed of the pig is greatly reduced, by using the brake unit.

Table 3 Numerical values of the gas parameters

Par.	Unit	Valve		
p_i	bar	40	70	100
ρ_i	Kg/m^3	27.7	54.2	80.6
ν	m^2/s	4.33×10^{-7}	2.4×10^{-7}	1.77×10^{-7}
γ	-	1.439	1.57	1.705

Response surface methodology (RSM) is used to study the maximum speed of a pig in downhill pipe. Three pipe curves adopted in this calculation are shown in Fig. 14, and the gas parameters of three conditions are listed out in Table 3. Without the brake unit, the simulations of the maximum speed of pig are shown in Table 4. The simulations of the maximum speed of pig with a brake unit are listed out in Table 5.

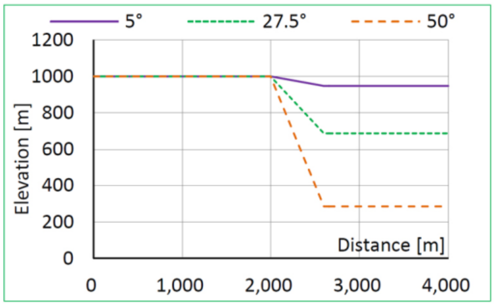

Fig. 14. Pipe curves for the simulation.

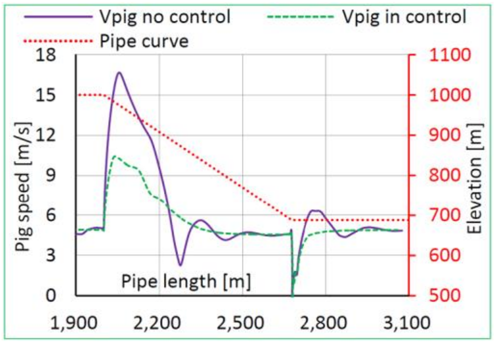

Fig. 15. Pig speed in control vs. no control.

Two equations for estimating the maximum speed of a pig in a downhill gas pipeline, obtained from the results of the RSM simulations, are as follows.

Table 4 Simulations of the maximum speed of pig without a brake unit using RSM

Run number	Flow rate [m/s]	Pipe inclination [degree]	Gas pressure [MPa]	Actual value of maximum pig speed [m/s]	Predicted value of maximum pig speed [m/s]
1	5	5	7	7.88	7.84
2	8	5	4	10.50	10.42
3	8	27.5	7	19.00	19.28
4	2	50	10	19.65	19.69
5	2	50	4	19.40	19.35
6	5	27.5	10	16.75	16.78
7	2	5	10	5.28	5.32
8	8	5	10	10.52	10.53
9	8	50	10	22.90	22.78
10	5	27.5	4	16.40	16.56
11	2	5	4	5.18	5.25
12	8	50	4	22.50	22.41
13	2	27.5	7	15.25	15.15
14	5	50	7	20.80	21.02
15	5	27.5	7	17.30	16.93

Table 5 Simulations of the maximum speed of pig with a brake unit using RSM

.	nlet flow rate [m/s]	Pipe inclination [degree]	Gas pressure [MPa]	Coefficient of drag force [Ns^2/m^2]	Actual value of maximum pig speed [m/s]	Predicted value of maximum pig speed [m/s]
1	5	5	7	200	7.25	7.74
2	2	27.5	7	200	12.80	12.49
3	5	27.5	10	800	12.00	12.07
4	5	50	7	800	12.85	12.46
5	8	27.5	7	200	15.90	15.78
6	5	5	7	800	6.50	6.55
7	8	27.5	7	800	12.60	12.78
8	8	5	7	500	9.30	9.10
9	8	27.5	10	500	14.80	14.83
10	5	27.5	7	500	12.10	12.10
11	8	27.5	4	500	12.05	12.34
12	5	5	4	500	6.34	5.92
13	2	5	7	500	4.54	4.75
14	5	27.5	7	500	12.10	12.10
15	5	27.5	4	800	9.26	9.36
16	2	27.5	7	800	9.60	9.59
17	2	50	7	500	13.30	13.53
18	5	50	10	500	15.74	16.03
19	5	27.5	4	200	12.60	12.56
20	2	27.5	4	500	9.06	9.14
21	8	50	7	500	15.83	15.65
22	5	27.5	7	500	12.10	12.10
23	5	27.5	7	500	12.10	12.10
24	2	27.5	10	500	11.74	11.55
25	5	27.5	10	200	14.82	14.75
26	5	5	10	500	7.10	6.98
27	5	50	7	200	17.10	17.16
28	5	50	4	500	12.20	12.19
29	5	27.5	7	500	12.10	12.10

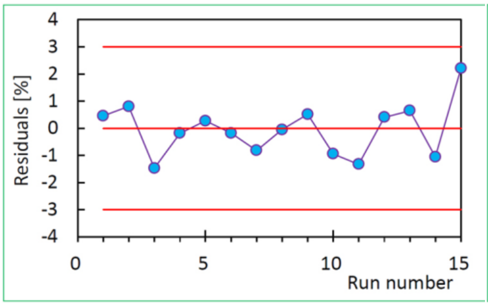

Fig. 16. Residuals vs. Run (without brake unit).

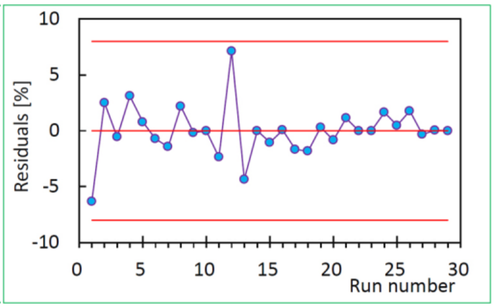

Fig. 17. Residuals vs. Run (with brake unit).

$$v_{max1} = 3.8\times10^{-3} + 0.5716v + 0.5958\beta + 0.4065p - 7.8\times10^{-3}v\beta + vp\times10^{-3} + \beta p\times10^{-3} + 0.0325v^2 - 0.005\beta^2 - 0.0286p^2 \quad (27)$$

$$v_{max2} = 1.5073 + 0.5785v + 0.3688\beta + 0.5194p - 6.5\times10^{-3}K_d - 8.3\times10^{-3}v\beta + 1.9\times10^{-3}vp - 2.78\times10^{-5}vK_d + 0.01\beta p - 10^{-4}\beta K_d + pK_d 10^{-4} + 0.0189v^2 - 0.003\beta^2 - 0.034p^2 + 4.33\times10^{-6}K_d^2 \quad (28)$$

In the two equations, v_{max1}, v_{max2}, v, β, p and K_d are maximum speed of pig without brake unit in downhill pipe [m/s], maximum speed of pig with a brake unit in downhill pipe [m/s], average flow rate [m/s], pipe inclination [degree], gas pressure [MPa] and coefficient of drag force [Ns^2/m^2], respectively. The residuals of Eqs. (27) and (28) are figured out in Fig. 16 and Fig. 17 respectively. The residuals show that the two equations obtained are in good agreement with the results of the RSM simulations.

6 CONCLUSION

A calculation scheme using MOC to solve the equations of gas flow for estimating the pig dynamics has been shown. An experiment was carried out to test the proposed pigging model. Then, the process of pigging in a hilly gas pipeline with/without a brake unit was simulated. The maximum speed of a pig in a downhill gas pipeline was studied using RSM. Some conclusions can be drawn as follows.

a) The results indicate that the brake unit would lead to a hammer effect in the downhill gas pipelines. It means the pressure on the tail of the pig would suffer a sharp increase, because the pig is dragged by the brake unit and thus prevented to accelerate together with the gas column. This way, the speed of pig in downhill gas pipelines is much lower by using a brake unit, but the speed of pig still can hardly be controlled in the desired range.

b) The hammer effect in hilly gas pipelines becomes more apparent with the increase of gas pressure. Thus, the brake unit would show a worse performance in a gas pipeline with higher pressure. Therefore, the application of the brake unit in the hilly gas pipeline has limitations.

c) Two empirical formulas for estimating the maximum speed of a pig in a downhill pipeline are obtained from the results of the RSM simulations. These formulas could be guidable for the design of a pigging operation with a brake unit in hilly gas pipeline. Furthermore, the proposed method and solution can be used to predict the gas pressure, the position and speed of the pig with/without a brake unit in hilly gas pipelines.

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