NUMERICAL MODEL OF SINGLE PHASE TURBULENT FLOWS FOR CALCULATION OF PRESSURE DROP ALONG GAS PIPELINES

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ABSTRACT: *Calculation of pressure drop along gas pipelines is an important activity in order to ensure safety and effectiveness in petroleum gas transportation. We can't control the transportation process unless we understand that technology. In reality, it's very difficult to calculate exactly parameters from flow equations because they are concerned with a lot of complex chemiphisical and dynamic progresses. So, some experimental equations originated from the flow equation and related physical quantities are used in calculating the pressure drop along the gas pipelines. The result in each case is compared with the real value of the pipeline practice. Basing on that, we can draw a suitable calculation method applied for the gas pipeline from Bach Ho mine to Dinh Co station.*

1.INTRODUCTION

Up to now, there have been many researches in calculating petroleum gas transportation technology by experimental equations. But when these equations are applied in specific cases (even with commercial software), the results are different from each others and from reality[3].

Associated gas is a mixture of hydrocarbon and some admixtures such as nitrogen (N_2), hydrogen sulfite (H_2S), dioxide carbon (CO_2). Gas containing an amount of H_2S or CO_2 is called acid gas. Hydrocarbons are methane, ethane, propane, butane, pentane, a small amount of hexane and heptanes as well as some other heavy hydrocarbons.

Although calculation of transportation technology has been done many times all over the world [1], [2], [5], it is still rather new to our petroleum branch. Through this research work, the authors would like to introduce a new research direction in transportation technology in our country which still has many unsolved practical problems. Numerical solution is based on the correlations between flow equation and fluid flow. These equations are formed on the basis of conservation law of mass, momentum and energy.

Initial data used in calculation is from the 110 km practical gas pipeline with diameter of 406.4 mm from "Bach Ho" Oil Field to the onshore. This pipeline is now transporting an average amount of 5.5million m^3 gas per day. Figures of temperature, pressure, flux and gas components come from direct measuring and sample analyzing. Calculation of pressure drop along the pipeline is chosen because the pressures at two ends of the pipeline can be measured accurately. So it will be easy to compare the result of calculation with reality.

2. MATHEMATICAL MODEL

In associated gas transportation technology, the fluid not only flows inside the pipeline but also changes its physical state because of its participation in other complex chemical reactions. However, this fluid flow still follows the laws of conservation. The energy equation is used to calculate pressure drop of associated gas inside the pipeline. After rewriting this energy equation and changing it into a more specific form, we receive the equation of pressure drop along pipeline for the stable fluid flow as follows[1]:

$$\frac{dp}{dL} = \frac{g}{g_c}\rho\sin\theta + \frac{f\rho\upsilon^2}{2g_c d} + \frac{\rho\upsilon d\upsilon}{g_c dL} \qquad (1)$$

Where:

$\left(\frac{dp}{dL}\right)_{el} = \frac{g}{g_c}\rho\sin\theta$ - component concerning the change of potential energy.

$\left(\frac{dp}{dL}\right)_{f} = \frac{f\rho\upsilon^2}{2g_c d}$ - component concerning the effect of friction.

$\left(\frac{dp}{dL}\right)_{acc} = \frac{\rho\upsilon d\upsilon}{g_c dL}$ - component concerning the change of kinetic energy due to convection.

In case of vertical flow in the pipeline, the loss of energy is essential due to friction and changing of kinetic energy. With assumption of isothermal stable flow and little change in velocity, the equation (2-1) becomes:

$$\frac{dp}{dL} = \frac{f\rho\upsilon^2}{2g_c d} \qquad (2)$$

With gas flow, specific mass ρ can be defined from equation of state:

$$\rho = pM/(ZRT)$$

The gas velocity *v* is calculated with the formula:

$$v = q_{sc}\left(\frac{ZTp_{sc}}{pT_{sc}}\right)\left(\frac{4}{\pi d^2}\right)$$

Inserting the above terms to equation (2-2), we have:

$$dp = \left(\frac{f}{2g_c d}\right)\left(\frac{pM}{ZRT}\right)\left(\frac{16q_{sc}^2 Z^2 T^2 p_{sc}^2}{p^2 T_{sc}^2 \pi^2 d^4}\right)dL$$

Or

$$\frac{pdp}{Z} = \left[\frac{8fMT^2 p_{sc} q_{sc}^2}{R\pi^2 d^5 g_c T_{sc}^2}\right]dL \qquad (3)$$

Where, the averaged temperature T_{av} is used, instead of T:

$$T_{av} = \frac{T_1 - T_2}{\ln(T_1/T_2)}$$

Coefficient of compressibility Z can be defined with the equation proposed by Dranchuk and Abou-Kassem (1975) basing on Starling equation[4]:

$$Z = 1 + \left(A_1 + \frac{A_2}{T_r} + \frac{A_3}{T_r^3} + \frac{A_4}{T_r^4} + \frac{A_5}{T_r^5}\right)\rho_r + \left(A_6 + \frac{A_7}{T_R} + \frac{A_8}{T_r^2}\right)\rho_r^2 - A_9\left(\frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right)\rho_r^5 +$$
$$+ A_{10}(1 + A_{11}\rho_r^2)\frac{\rho_r^2}{T_r^3}\exp(-A_{11}\rho_r^2)$$

Where: $p_r = p/p_c$ and $T_r = T/T_c$; $\rho_r = \frac{Z_c p_r}{ZT_r}$. And Z_c is assumed[4] to be equal to 0.270; A_1 = 0.3265; A_2=-1.0700; A_3=-0.5339; A_4=0.01569; A_5=-0.05165; A_6=0.5475; A_7=-0.7361; A_8=0.1844; A_9=0.1056; A_{10}=0.6134; A_{11}=0.7210.

Integrating equation (2-3) through the pipeline length from 0 to L corresponding to p_1 (at L=0) and p_2 (at L=L), we obtain:

$$(p_2^2 - p_1^2) = -\left(\frac{8 \times 28.9 p_{sc}^2}{R\pi^2 g_c T_{sc}^2}\right)\left(\frac{q_{sc}^2 \gamma_g Z_{av} TfL}{d^5}\right) \quad (4)$$

Where:

- q_{sc}: gas flow measured at standard condition, m^3/h.
- p_{sc}: pressure at standard condition, kPa.
- T_{sc}: temperature at standard condition, K.
- T_c, p_c: critical temperature and pressure of gas mixture.

$$T_c = \sum y_j T_{cj}\ ,\ p_c = \sum y_j p_{cj} \quad (5)$$

They can be defined with the equations[4]:

$$T_c = 170.491 + 307.344\ \gamma_g \quad (6)$$

$$p_c = 709.604 - 58.718\ \gamma_g \quad (7)$$

- y_i: molarities of mixture.
- p_1: input pressure, kPa.
- p_2: output pressure, kPa.
- d: diameter of pipeline, m.
- γ_g : gas density, kg/m^3
- T: temperature of fluid flow, K.
- Z_{av}: averaged coefficient of compressibility.
- f: Moody friction coefficient.
- L: pipeline length, m.

Friction coefficient varies in a wide range with Reynolds number (over 2000) and interface roughness rate, so a suitable friction coefficient needs to be chosen when employing these equations. According to that, we develop equations calculating pressure which are based on various formulas to calculate friction coefficient:

- Weymouth equation

Weymouth proposed the following relationship for friction coefficient f, as a function of dimentionless pipe diameter d=d/d_o (d_o=$1m$)[1]:

$$f = 0.00235(d)^{1/3}$$

Putting this friction coefficient into equation (2-4), we have:

$$(p_2^2 - p_1^2) = -\left(\frac{0.54332 p_{sc}^2}{R\pi^2 g_c T_{sc}^2}\right)\left(\frac{q_{sc}^2 \gamma_g Z_{av} T_{av} L d_o^{0.333}}{d^{5.333}}\right) \quad (8)$$

- Panhandle A equation

This equation assumes that friction coefficient is a function of Reynolds number as[1]:

$$f = 0.0768 / \mathrm{Re}^{0.1461}$$

Putting this friction coefficient into equation (2-4) we obtain:

$$\left(p_2^2 - p_1^2\right) = -\frac{Z_{av} T_{av} L q_{sc}^{1.8539}}{1.3269 \times 10^{13}} \times \left(\frac{p_{sc}}{T_{sc}}\right)^2 \times \gamma_g^{0.8539} \times \frac{\mu_g^{0.1461}}{d^{4.8539}} \quad (9)$$

- Modified Panhandle equation (Panhandle B)

This equation assumes that friction coefficient is a function of Reynolds number as[1]:

$$f = 0.015 / \mathrm{Re}^{0.03922}$$

Putting this friction coefficient into equation (2-4):

$$\left(p_2^2 - p_1^2\right) = -\frac{Z_{av} T_{av} L q_{sc}^{1.9608}}{8.4138 \times 10^{13}} \times \left(\frac{p_{sc}}{T_{sc}}\right)^2 \times \gamma_g^{0.9725} \times \frac{\mu_g^{0.0392}}{d^{4.9608}} \qquad (10)$$

- Clinedinst equation

Friction coefficient, *f*, is defined through the equation[4]:

$$\frac{1}{\sqrt{f}} = 1.14 - 2\log\left(\frac{э}{d} + \frac{21.25}{\mathrm{Re}^{0.9}}\right)$$

Where: э is absolute roughness of pipeline.

Rewriting the above equation for gas flow in the pipeline:

$$\left(p_2^2 - p_1^2\right) = -0.2510 \times \frac{q_{sc} p_{sc} Z}{p_{pc} T_{sc}} \times \left[\frac{\gamma_g T_{av} L f}{d^5}\right]^{0.5} \qquad (11)$$

3. PRESSURE DROP ALONG THE GAS PIPELINE:

In order to obtain more accurate results of the above equations, we divide the pipeline to a number of sections (ΔL), so that we can calculate the pressure drop (Δp) and value *p* at each point more accurately (Fig. 1).

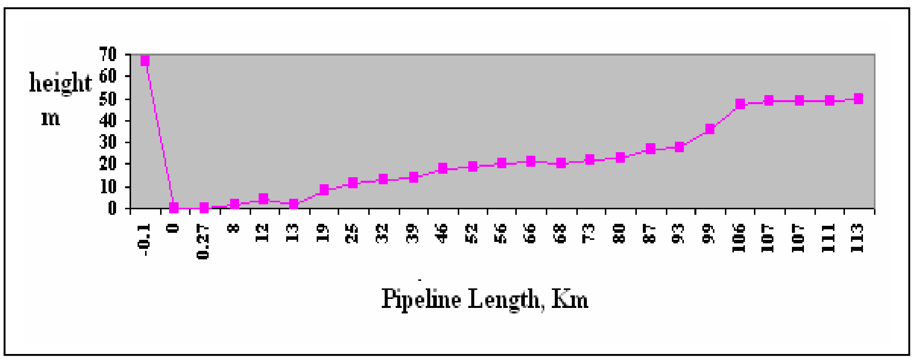

Figure 1. Gas pipeline arrangement scheme

Calculating pressure drop along pipeline is performed with the following steps:

1. Starting with the known pressure, p_1 , at L_1
2. Estimating a pressure increment Δp, corresponding to length ΔL.
3. Calculating the average pressure and, for nonisothermal cases, the average temperature.
4. From laboratory data or empirical correlations, determine the necessary fluid and p,V,T properties at conditions of average pressure and temperature (ρ_g υ_g μ_g).
5. Calculating the pressure gradient dp/dL at average conditions of pressure, temperature, and pipe inclination.
6. Calculating the pressure increment corresponding to the selected section, Δp= ΔL(dp/dL).
7. Comparing the estimated and calculated values of Δp obtained in steps 2 and 6, if they are not sufficiently closed, using a new pressure increment and return to step 3. repeating steps 3 through 7 until the estimated and calculated values are sufficiently closed.

With this calculating order, establishing a program for pressure drop calculation along pipeline will be done according to the scheme in Fig. 2.

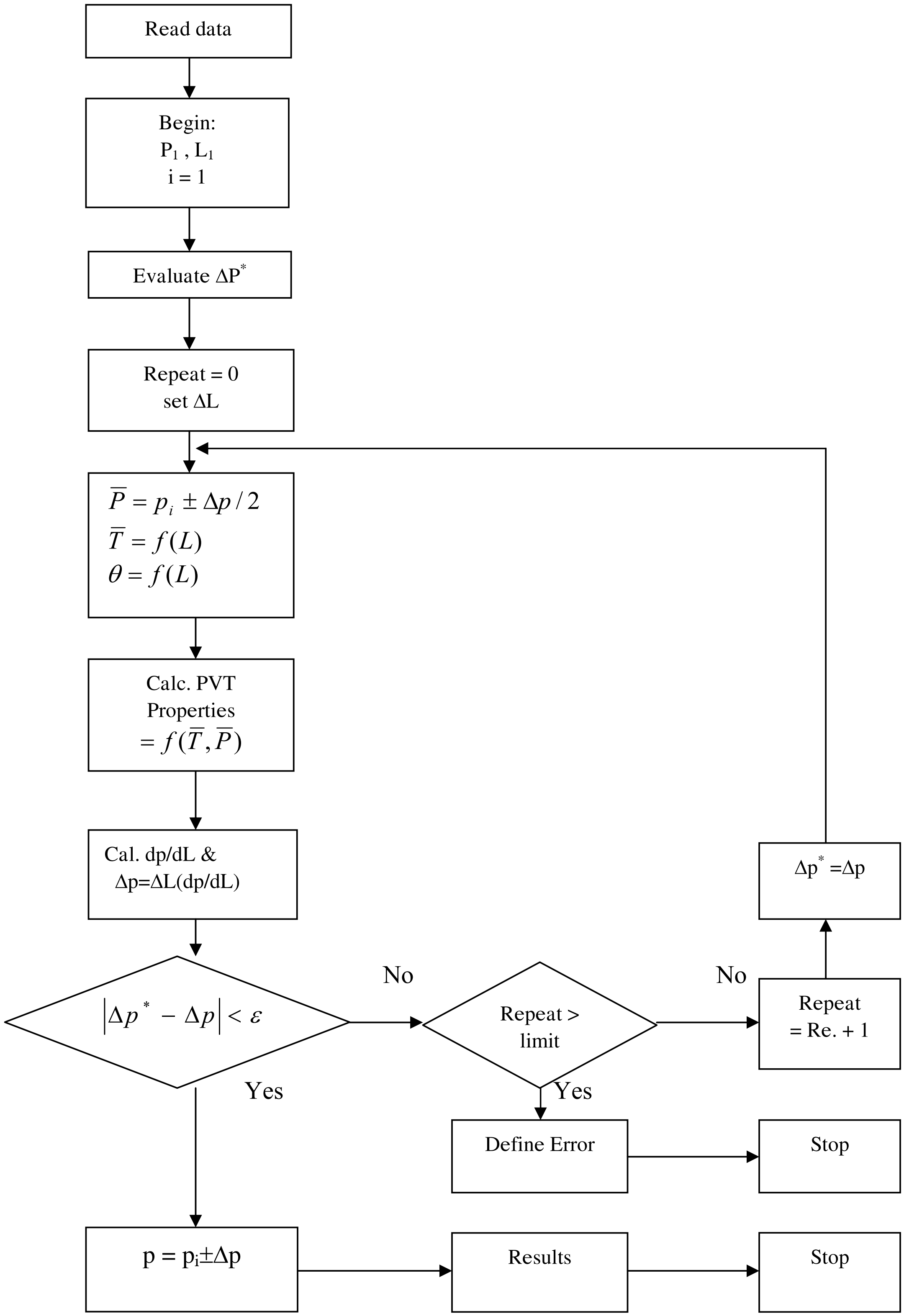

Figure 2. Flow chart for calculating a pressure traverse

The program calculating pressure drop along the associated gas pipeline is constructed in Matlab environment, the software interface is introduced in Fig. 3.

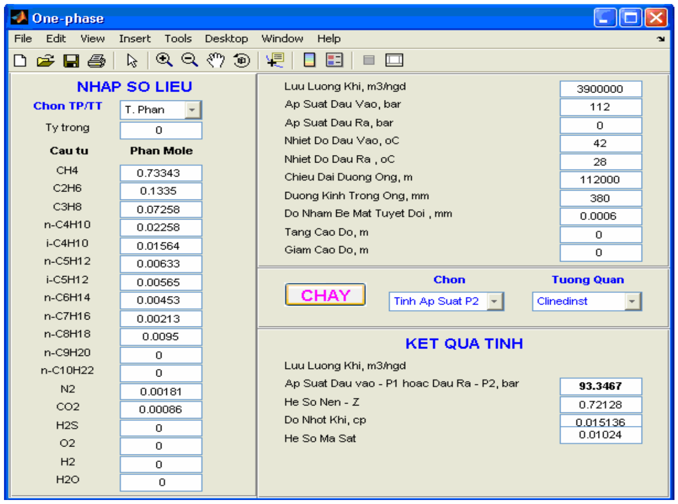

Figure 3. Interface of pressure drop calculation in Matlab Environment

- Result with data in table 3.1[6]:

Table 3.1. Input data			
Description	**Sample 1**	**Sample 2**	**Sample 3**
Inlet Temperature (^{0}C)	42	45	46
Inlet gas pressure, (kPa)	10130	10860	120
Outlet Temperature (^{0}C)	29	27	28
Outlet gas pressure, (kPa)	7730	7040	6970
Gas Flow, m^3/day	3975600	5091360	6426480
Inlet gas compositions (mole fraction)			
Compound	0.73037	0.75396	0.7380
Ethane (C_2H_6)	0.12989	0.12138	0.1219
Propane (C_3H_8)	0.07436	0.06905	0.073
i-Butane (C_4H_{10})	0.016752	0.015021	0.0161
n-Butane (C_4H_{10})	0.024459	0.021609	0.0234
i-Pentan (C_5H_{12})	0.006284	0.005295	0.0061
n-Pentan (C_5H_{12})	0.007038	0.005594	0.0068
Hexanes (C_6H_{14})	0.004874	0.003584	0.0055
Heptanes (C_7H_{16})	0.002331	0.001664	0.0032
Octan-plus (C_8H_{18})	0.000711	0.000517	0.0012
Nonanes (C_9H_{20})	0.000313	0.000257	0.0004
Decanes ($C_{10}H_{22}$)	0.00008	0.000079	0.0001
Nitro (N_2)	0.00168	0.00151	0.0032
Dioxide carbone (CO_2)	0.00087	0.00049	0.0011
Sulfide (H_2S), ppm	9	9	10
Water (H_2O), g/m^3	0.111	0.12	0.115

The results with input data-sample 1 in table 3.1 along the associated gas pipeline of flow equations of Weymouth, Panhandle A, Panhandle B and Clinedinst are stored in table 3.2a and 3.2b.

Table 3.2a. Pressure along associated gas pipeline with input data - sample 1 from table 3.1

Location along pipeline (m)	**Method**					
	Weymouth			Panhandle A		
	Pressure, kPa	Coeff. of Compressibility – Z	Friction Coeff.	Pressure, KPa	Coeff. of Compressibility – Z	Friction Coeff.
0	10130			10130		
71	10128	0.7577	0.01301	10129	0.7575	0.00812
339	10120	0.7577	0.01301	10125	0.7519	0.00812
25071	9431	0.7577	0.0129	9812	0.7359	0.00814
52071	8630	0.7577	0.0129	9467	0.7256	0.00813
73071	7951	0.7577	0.0129	9193	0.7319	0.00810
105771	6760	0.7577	0.0129	8742	0.7398	0.00807
112971	**6433**	0.7577	0.01301	**8628**	0.7462	0.00803
Average		**0.7577**	**0.01295**		**0.7413**	**0.00890**
Real Pressure at 112971m of the end of pipeline is **7730 kPa**						

Table 3.2b.Pressure along associated gas pipeline with input data – sample 1 from table 3.1

Location along pipeline (m)	**Method**					
	Panhandle B			Clinedinst		
	Pressure, kPa	Coeff. of Compressibility – Z	Friction Coeff.	Pressure, KPa	Coeff. of Compressibility - Z	Friction Coeff.
0	10130			10130		
71	10129	0.7577	0.00799	10128	0.7578	0.01240
339	10125	0.7519	0.00799	10122	0.7520	0.01240
25071	9818	0.7359	0.00799	9640	0.7394	0.01235
52071	9482	0.7254	0.00799	9098	0.7336	0.01235
73071	9210	0.7317	0.00799	8647	0.7440	0.01235
105771	8765	0.7393	0.00798	7877	0.7597	0.01235
112971	**8651**	0.7457	0.00796	**7673**	0.7692	0.01234
Average		**0.7411**	**0.00798**		**0.7508**	**0.01236**
Real Pressure at 112971m of the end of pipeline is **7730 kPa**						

The results with input data - sample 2 in table 3.1 along the associated gas pipeline of flow equations of Weymouth, Panhandle A, Panhandle B and Clinedinst are stored in table 3.3a and 3.3b.

Table 3.3a. Pressure along associated gas pipeline with input data – sample 2 from table 3.1

Location along pipeline (m)	**Method**					
	Weymouth			Panhandle A		
	Pressure, kPa	Coeff. of Compressibility – Z	Friction Coeff.	Pressure, KPa	Coeff. of Compressibility - Z	Friction Coeff.

0	10860			10860		
71	10857	0.7694	0.01301	10858	0.7706	0.007878
339	10844	0.7692	0.01301	10852	0.7623	0.007882
25071	9771	0.7692	0.01292	10383	0.7479	0.00790
52071	8498	0.7692	0.01292	9869	0.7337	0.007883
73071	7357	0.7692	0.01292	9447	0.7422	0.007851
105771	5094	0.7692	0.01292	8742	0.7532	0.007812
112971	**4360**	0.7692	0.01301	**8560**	0.7626	0.007763
Average		**0.7692**	**0.0130**		**0.7532**	**0.00785**
Real Pressure at 112971m of the end of pipeline is **7040 kPa**						

Table 3.3b. Pressure along associated gas pipeline with input data – sample 2 from table 3.1

Location along pipeline (m)	**Method**					
	Panhandle B			Clinedinst		
	Pressure, kPa	Coeff. Of Compressibility – Z	Friction Coeff.	Pressure, KPa	Coeff. Of Compressibility – Z	Friction Coeff.
0	10860			10860		
71	10858	0.7733	0.00792	10858	0.7706	0.0124
339	10853	0.7679	0.00792	10849	0.7623	0.0124
25071	10382	0.7479	0.00793	10107	0.7492	0.0123
52071	9865	0.7337	0.00792	9252	0.7450	0.0123
73071	9439	0.7422	0.00791	8512	0.7606	0.0123
105771	8724	0.7534	0.00790	7162	0.7862	0.0123
112971	**8538**	0.7630	0.00789	**6781**	0.8037	0.0124
Average		**0.7530**	**0.00791**		**0.7682**	**0.01234**
Real Pressure at 112971m of the end of pipeline is **7040 kPa**						

The results with input data - sample 3 in table 3.1 along the associated gas pipeline of flow equations of Weymouth, Panhandle A, Panhandle B and Clinedinst are stored in table 3.4a and 3.4b.

Table 3.4a. Pressure along associated gas pipeline with input data – sample 3 from table 3.1

Location along pipeline (m)	**Method**					
	Panhandle B			Clinedinst		
	Pressure, kPa	Coeff. Of Compressibility – Z	Friction Coeff.	Pressure, KPa	Coeff. Of Compressibility – Z	Friction Coeff.
0	12000			12000		

71	11995	0.8037	0.01301	11998	0.7498	0.00766
339	11977	0.8037	0.01301	11990	0.7440	0.00766
25071	10402	0.8037	0.0129	11341	0.7224	0.00769
52071	8400	0.8037	0.0129	10622	0.7075	0.00767
73071	6425	0.8037	0.0129	10021	0.7181	0.00742
105771				8992	0.7332	0.00756
112971				**8719**	0.7471	0.00750
Trung bình		**0.8037**	**0.01294**		**0.7317**	**0.007594**
Real Pressure at 112971m of the end of pipeline is **6970 kPa**						

Table 3.4b. Pressure along associated gas pipeline with input data – sample 3 from table 3.1

Location along pipeline (m)	**Method**					
	Panhandle B			Clinedinst		
	Pressure, kPa	Coeff. Of Compressibility – Z	Friction Coeff.	Pressure, KPa	Coeff. Of Compressibility – Z	Friction Coeff.
0	12000			12000		
71	11998	0.7498	0.00786	11997	0.7499	0.01239
339	11989	0.7440	0.00786	11984	0.7441	0.01239
25071	11325	0.7224	0.00787	10914	0.7280	0.01234
52071	10585	0.7079	0.00786	9648	0.7239	0.01233
73071	9963	0.7189	0.00785	8497	0.7474	0.01234
105771	8885	0.7348	0.00783	6137	0.7935	0.01233
112971	**8596**	0.7496	0.00781	**5367**	0.7296	0.01234
Trung bình		**0.7325**	**0.00785**		**0.7452**	**0.01235**
Real Pressure at 112971m of the end of pipeline is **6970 kPa**						

Table 3.5. Summary of numerical results of oulet pressure p_2

Method	**Results of outlet pressure and its differences with the real value**					
	Input data Table 3.2, (samp. 1)		Input data Table 3.3, (samp. 2)		Input data Table 3.4, (samp. 3)	
	Pressure, kPa	% diff.	Pressure, kPa	% diff.	Pressure, kPa	% diff.
Weymouth	6433	16.8	4360	38.1	-(*)	-
Panhandle A	8628	-11.6	8560	-21.6	8719	-25.1
Panhandle B	8651	-11.9	8538	21.3	8596	23.3
Clinedinst	7673	0.7	6781	3.7	5367	23.0

(*) Pressure –p_2 is not converged

Summarization of the numerical results for output pressure is listed in Table 3.5. From the results, it is clear that:

- None of those calculations gives the same result as practical data, but the result is acceptable when we combine all the one-phase flow equations of Weymouth, Panhandle A, Panhandle B and Clinedinst in calculating pressure drop along the associated gas pipeline.
- The first group of input data gives the most suitable results in comparison with measured values.
- Coefficient of compressibility Z in different calculating methods doesn't vary much, but friction coefficient does. It proves that, friction coefficient is the key cause of different results.

4. CONCLUSION

From the research, it is believed that, the combination of all the flow equations of Weymouth, Panhandle A, Panhandle B and Clinedinst in calculating pressure drop along the associated gas pipeline is very helpful to establish the mutual relationship between technical statistics. Friction coefficient is the main cause of different results in calculation. This brings about a need to determine a new correlation for friction coefficient to make it suitable for the associated gas pipeline in practice. The authors are very gracious to the Basic Studies Fund of Natural Science Committee from which our works receives precious support.

MÔ HÌNH SỐ DÒNG MỘT PHA TRONG TÍNH TOÁN TỔN THẤT ÁP SUẤT DỌC ĐƯỜNG ỐNG DẪN KHÍ

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TÓM TẮT: *Để công việc vận chuyển dầu khí an toàn và hiệu quả, điều cần phải quan tâm đầu tiên đó là tính toán suy giảm áp lực dọc theo tuyến ống dẫn khí. Nếu chúng ta không tính suy giảm áp lực dọc theo tuyến ống dẫn khí thì sẽ không thể kiểm soát được qúa trình vận chuyển. Trong thực tế việc tính toán chính xác các thông số từ các phương trình dòng chảy là rất khó thực hiện vì chúng liên quan tới nhiều qúa trình hóa lý và diễn biến động học phức tạp. Do vậy, một số phương trình thực nghiệm có nguồn gốc từ phương trình dòng và các đại lượng vật lý liên quan đã được sử dụng để tính suy giảm áp lực dọc theo tuyến ống dẫn khí. Kết qủa tính cho từng trường hợp được kiểm tra lại với số liệu của đường ống thực tế. Từ đó rút ra phương pháp tính phù hợp nhất áp dụng cho tuyến ống dẫn khí từ mỏ Bạch hổ về trạm Dinh cố.*

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