

Research note

Looped Pipeline System for Increasing the Capacity of Natural Gas Transmission

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Abstract

At present, gas engineers use the simple Campbell's equation to determine the proper length of parallel gas pipelines. The Campbell's equation was proposed for horizontal pipelines with the assumption that the gas compressibility factor and temperature throughout the pipeline are constant. Therefore, the Campbell's equation has a notable error for an inclined pipeline. In this paper, the Campbell's equation was extended in a way that it can be used for inclined pipelines. In order to make a comparison between the extended and original equations, a pipeline with different slopes was used. The results show that in the case of using a pipeline with more than 2 degrees in slope, the resultant error is increased to 11 percent by using the original Campbell's equation. For validation of the extended Campbell's equation, the results of this equation are compared to the results of HYSYS software (version 3.1) in which the temperature and gas compressibility factor are not considered constant. The results indicate that the average error of the extended equation is less than 2 percent.

Keywords: Natural Gas pipeline, Looped Pipeline, Optimization

1. Introduction

In the past, the gas pipeline networks were designed based on a simple formula such as Weymouth and Panhandle [1, 2], but in recent years the use of engineering software such as PIPEPHASE [3], PIPESYS [4] and HYSYS [5] has increased. In general, for the prediction of flow rate, pressure and temperature variation of gas along the pipelines, three equation of mass, momentum and energy balances should be solved simultaneously [6]. These equations for a pipeline with angle θ from horizontal are as follows:

Mass balance equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0 \quad (1)$$

Momentum balance equation

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2 + P)}{\partial x} = -\rho g \sin \theta - 2 \frac{f \rho u |u|}{D} \quad (2)$$

Energy balance equation

$$q \rho A dx = \frac{\partial}{\partial t} \left[(\rho A dx) \left(C_v T + \frac{u^2}{2} + gz \right) \right] + \frac{\partial}{\partial x} \left[(\rho A u dx) \left(C_v T + \frac{u^2}{2} + gz + \frac{P}{\rho} \right) \right] \quad (3)$$

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In the above equations, the density of the real gas could be estimated as follows.

$$\rho = \frac{P}{ZRT} \quad (4)$$

Different numerical methods such as explicit and implicit finite difference, the method of characteristics and the method of lines [7] can be used to solve the above mentioned equations. At steady state the above partial differential equations (2 and 3) are converted to ordinary differential equations and an initial value method such as Euler and Runge-Kutta can be used for the calculation of pressure and temperature along the pipeline. In HYSYS software, the explicit finite difference method is used for dynamic gas pipeline and the Euler method is used for steady state gas pipeline calculations [5].

One of the most important difficulties for gas transport companies in recent years has been the increase of gas pressure drop results from the increase of gas flow rate through the pipeline network. In order to solve this problem the establishment of new pipelines, the increase in the number and capacity of compressor stations, and strengthening of the old gas pipelines using a parallel pipeline are applied [1].

The strengthening of gas transport pipelines by using parallel pipes known as looped pipelines was first investigated by Campbell. The results of these investigations are available in most gas engineering textbooks [1, 2, 8]. In the equation presented by Campbell to determine the pipeline length, the assumptions of horizontal pipelines, isothermal flow, and constant gas compressibility factor are used. In the

presented article, Campbell's equation is extended in a way that it can be used for inclined pipelines as well.

This article is arranged as follows. First, the accuracy of Campbell's equation is compared with the results of HYSYS software (in appendix, an algorithm is proposed for simulation of looped pipelines with given diameter and unknown length in HYSYS software). In the next part of this article, after presenting the way of extending the Campbell's equation for inclined pipelines, the angle range of inclined pipelines for which the extended equation must be used, is determined. Then, two real pipeline case studies are used for comparison of original and extended Campbell's equations. Finally, a method is presented for the determination of optimal length and diameter of parallel pipelines using the original or extended Campbell's equation.

2. Campbell's equation

In a looped pipeline system, which is shown in Fig. 1, the length of the parallel pipeline (*B*) is determined in a way that, in spite of the increase in gas flow rate, the amount of pressure drop in the main pipeline (*A+C*) was not changed. Of course, it should be pointed out that the length and diameter of the parallel pipeline are interrelated. In other words, only the length or the diameter of the pipeline can be considered as a design parameter.

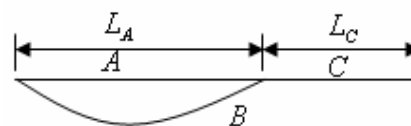


Figure 1. Looped pipeline system

Campbell was the first one to present an equation to determine the length of the parallel pipeline in a loop system [8]. In Campbell's equation, some assumptions like horizontal pipeline, isothermal and steady state flow, and constant gas compressibility factor are applied. In the case of using Weymouth formula to determine the friction factor, Campbell's equation will be as follows [1]:

$$x_f = \frac{1 - \left(\frac{Q_{new}}{Q_{old}}\right)^2}{1 - \frac{1}{\left[1 + \left(\frac{D_B}{D_A}\right)^{8/3}\right]^2}} \quad (5)$$

Where x_f represents a fraction of the length of the main pipeline ($A+C$) which is looped with a parallel pipe B , Q_{old} is the old gas flow rate and Q_{new} is the new (increased) gas flow rate. x_f is defined as follows:

$$x_f = \frac{L_A}{L_A + L_C} \quad (6)$$

Before extending the Campbell's equation, its accuracy was compared with the results obtained from HYSYS software. For this purpose a horizontal pipeline with a length of 107.4 kilometers, diameter of 54.76 inches, inlet pressure of 1000 psia, inlet temperature of 45 °C and flow rate of 80 million standard cubic meters per day (MMSCMD) is simulated (Fig. 2). The steps used for simulation of a looped pipeline in HYSYS software are illustrated in the appendix. The composition of the inlet gas is shown in Table 1. Then, in order to increase the gas flow rate up to 110 MMSCMD, a parallel pipeline with a 42 inch diameter is used. By using Campbell's equation and HYSYS software, the length of the parallel pipeline is calculated as 89.68 and 91.77 kilometers respectively. The resulting error from using Campbell's equation in comparison to HYSYS software is about 2.3 percent. Therefore, we can conclude that, in the case that changing the height of the pipeline is ignorable, Campbell's equation can be used with acceptable accuracy.

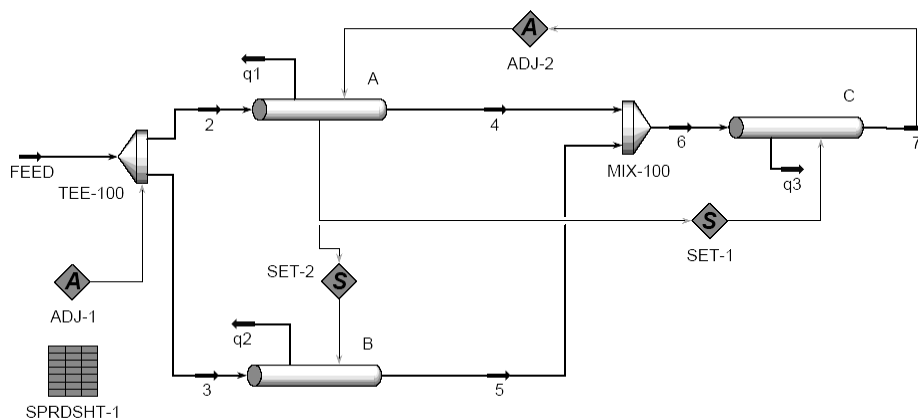


Figure 2. The simulated diagram of a looped pipeline system.

Table1. The mole percent of inlet gas

Methane	Ethane	Propane	i- Butane	n-Butane	i-Pentane
88.3	3.84	1.18	0.24	0.33	0.13
n-Pentane	Hexane	n-Heptane	Nitrogen	Carbon monoxide	
0.09	0.09	0.16	5.58	0.06	

3. Generalization of Campbell's equation

As it has already been discussed in the previous section, Campbell's equation can be used for horizontal looped pipeline systems with desirable accuracy. But the most important question is how the accuracy of the Campbell's equation is changed with changing the pipeline slope. To answer this question, first the Campbell's equation is extended for inclined pipelines. Then the accuracy of the Campbell's equation and extended equation are compared by using an inclined pipeline with different angles.

In general, the equations governing the inclined pipelines are different from the equations of horizontal pipelines. In the calculation of inclined pipelines, the concept of equivalent length (L_e) instead of real length (L) is used. Briefly, the equation

governing the inclined pipelines network (Fig. 3), while considering the isothermal and steady state flow, and assuming the constant gas compressibility factor is as follows [1].

$$P_1^2 = e^S P_{n+1}^2 + \left(\frac{16 \rho_{sc}^2 Q^2 Z_{av} T_{av} R f}{\pi^2 g_c D^5 M} \right) L_e \quad (7)$$

where

$$L_e = \sum_{i=1}^n L_i \frac{(e^{S_i} - 1) e^{\sum_{j=1}^{i-1} S_j}}{S_i} \quad (8)$$

$$S_i = \frac{2M g z_i}{g_c Z_{av} T_{av} R} \quad (9)$$

$$S = \sum_{i=1}^n S_i \quad (10)$$

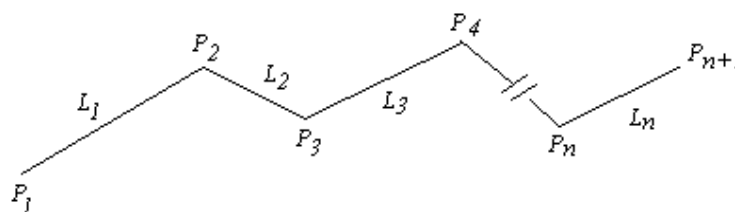


Figure 3. A typical network of inclined pipelines

The extended Campbell's equation is obtained if the length of pipeline A and C is replaced by the equivalent lengths (L_{Ae} and L_{Ce}) in equations 5 and 6. Therefore the fraction of the equivalent length of the main pipeline (x_{fe}) that must be looped with a new parallel pipeline can be calculated by the following equation.

$$x_{fe} = \frac{L_{Ae}}{L_{Ae} + L_{Ce}} = \frac{1 - \left(\frac{Q_{new}}{Q_{old}}\right)^2}{1 - \frac{1}{\left[1 + \left(\frac{D_B}{D_A}\right)^{8/3}\right]^2}} \quad (11)$$

Having used the above equation and determined the equivalent length of the required parallel pipelines, the real length of the parallel pipeline can be calculated by trial and error and by using equation 8.

The results of Campbell's equation and its extended form are compared for an inclined pipeline with different angles. For this purpose, a pipeline with the length of 100 kilometers, 40 inch diameter, inlet pressure of 1200 psia and inlet temperature of 50 °C is considered. Moreover, a parallel pipeline with a 35 inch diameter is used to remove the problem of pressure drop created due to the increase of flow rate from 50 to 60 MMSCMD. The general perspective of the mentioned pipeline is shown in Fig. 4. The calculations for angles from zero to 50 degrees are repeatedly done and the obtained results are shown in Table 2. It is necessary to mention that, in all calculations, the gas compressibility factor is considered to be equal to 0.9, average temperature of gas equal to 40°C, and molecular weight equal to 16.04. With regard to the offered results in

Table 2, we can conclude that, when the slope of the pipeline is less than 0.5 degrees, the resulted error of Campbell's equation will be less than 3 percent. Therefore, for an inclined looped pipeline with angles less than 0.5 degrees, the changes in the elevation of the pipelines can be ignored. However, for inclined pipelines with more than 2 degrees, the resulted error will increase to more than 11 percent if we ignore the changes in the elevation of the pipelines. Therefore, in this case, the extended Campbell's equation is advisable. In addition, as in the previous section, the accuracy of the extended Campbell's equation was compared to the results of HYSYS software. The results show that, the average error of the extended equation is less than 2.3 percent.

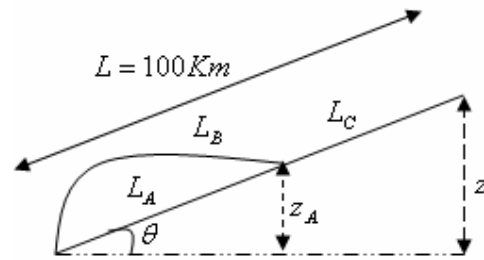


Figure 4. The diagram of inclined looped pipeline

4. Case studies

In this section the results of original and extended Campbell's equations are compared for two real gas transport networks of Iran. The first case study is a part of the gas pipeline between Tehran and Qum, and the second is the gas transport pipeline from Aliabad Katol to Shahrood. The second case study pipeline has the higher elevation change compared to the first one.

Table 2. The obtained lengths of parallel pipeline for an inclined looped pipeline system with different angles.

Angle (degree)	Length of parallel pipeline (km)	Resulted error in comparison to horizontal looped system (%)
0	46.700	-----
0.25	47.430	1.54
0.5	48.162	3.03
1	49.623	5.90
2	52.540	11.12
3	55.403	15.70
5	60.836	23.20
10	71.856	35.00
20	83.673	44.19
30	88.682	47.34
50	92.599	49.57

4.1. Gas transport pipeline between Tehran and Qum

This pipeline has a length of 107.4 km and average inside diameter of 55 inches (Fig. 5). Other specifications of the selected pipeline which included six pipe segments are presented in Table 3. The mole fraction of gas transmitted in this pipeline is also presented in Table 1. To increase the capacity of the network from 80 to 100 MMSCMD, a parallel pipeline with an inner diameter of 45 inches is used. The length of the needed parallel pipeline is calculated first by Campbell's equation, while ignoring the changes in the elevation of each pipe, and then by using the extended Campbell's equation, while the real slope of each pipe is taken into consideration. In the case of using

Campbell's equation and its extended form, the calculated length of the parallel pipe will be 63.67 and 64.23 kilometers, respectively. As it can be observed, the length of the parallel pipeline obtained through these two equations will be almost the same. The first reason is that the elevation changes for all pipelines are small, and the second reason is that the elevation changes of some pipes are positive and the others are negative. The former reason causes the effects of the slope on calculations for the length of the parallel pipelines to be neutralized (Fig. 5). Therefore, when the changes in the elevation of the pipes are rather low, the application of Campbell's equation with regard to its simplicity is more preferable than the extended form.

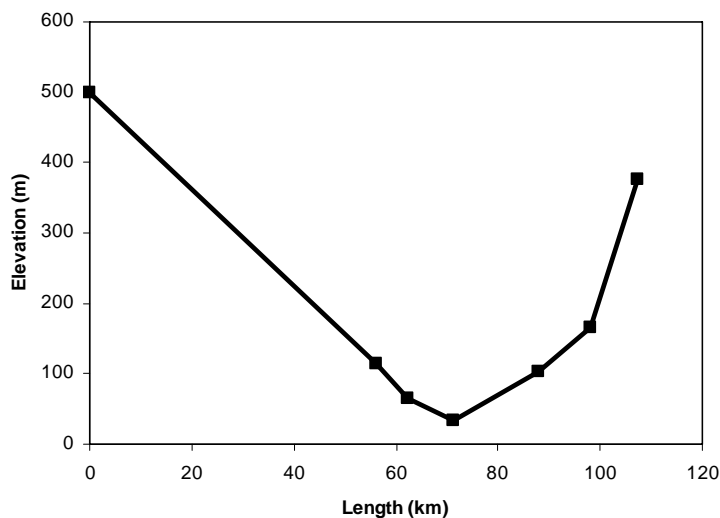


Figure 5. Gas transport pipeline between Tehran and Qum.

Table 3. Specification of the gas transport pipeline between Tehran and Qum.

Pipe number	Length (km)	Elevation change (m)	Average temperature (°C)	Slope from horizontal (degree)
1	56	-386	45.0	-0.395
2	6.2	-50	44.1	-0.462
3	9.0	-30	43.45	-0.190
4	16.8	70	42.3	0.239
5	10.2	61	41.2	0.343
6	9.2	211	40.45	1.314

4-2. Gas transport pipeline between Aliabad Katol and Shahrood

This pipeline has a length of 69 km and an average inside diameter of 15 inches (Fig. 6). Other specifications of this pipeline, which included five pipe segments, are presented in Table 4. The mole fraction of gas transmitted in this pipeline is shown in Table 5. To increase the capacity of the pipeline from 2.0 to 2.5 MMSCMD, a parallel pipeline with an inner diameter of 12.0 inches is used. The length of the needed parallel pipeline, which

is calculated by using Campbell's and extended Campbell's equations, is 42.49 and 44.28 km respectively. As it can be observed, the calculated length of the parallel pipeline by using the Campbell's equation has about 4 percent error in comparison to extended Campbell's equation. Therefore, for this pipeline, which has an average slope of about 0.75 degree, the use of extended Campbell's equation is more preferable than the Campbell's equation.

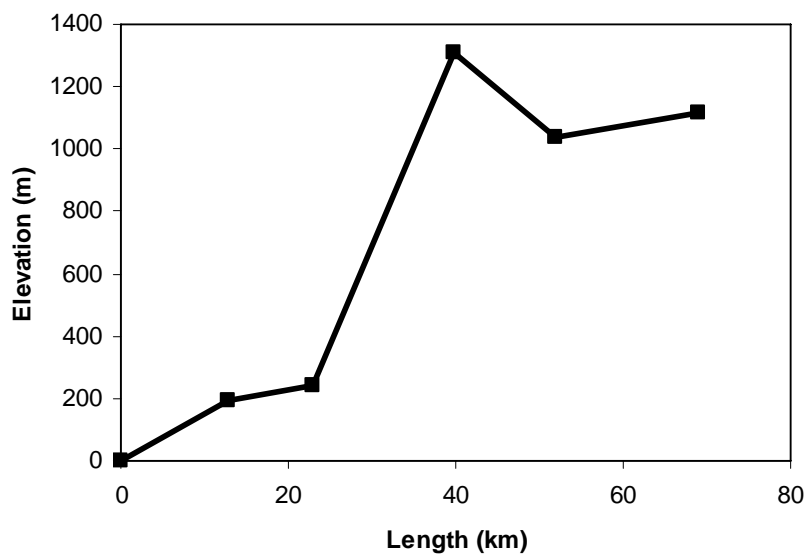


Figure 6. Gas transport pipeline between Aliabad and Shahrood.

Table 4. Specification of the gas transport pipeline between Aliabad and Shahrood.

Pipe number	Length (km)	Elevation change (m)	Average temperature (°C)	Slope from horizontal (degree)
1	12.9	193.3	14.28	0.859
2	10.10	45.8	12.52	0.257
3	16.9	1070	8.69	3.630
4	12.20	-270.4	7.54	-1.270
5	16.9	77.25	9.47	0.262

Table 5. The mole percent of inlet gas

Methane	Ethane	Propane	i- Butane	n-Butane	i-Pentane
98.510	0.669	0.079	0.020	0.073	0.026
n-Pentane	Hexane⁺	Nitrogen	Carbon dioxide		
0.020	0.095	0.480	0.028		

5. The optimization of looped pipeline system

As previously mentioned, in the looped pipeline system, in order to determine the length of the parallel pipeline, the diameter of the parallel pipeline is considered as an independent variable. In other words, in the case of changing the diameter of the parallel pipeline, its length will also be changed according to equation 5 or 11. In this section, a method is introduced for the determination of the optimal diameter (and length) of the parallel pipeline. For this purpose the total cost of purchasing and installing the parallel pipe are considered as an objective function. The purchasing and installation costs of pipelines with a diameter of more than one inch can be calculated as follows [9]:

$$C_B = C_p \left(\frac{D_B}{0.0254} \right)^{1.5} L_A \quad (12)$$

In this equation, C_p represents the purchasing price and the installation cost of steel pipelines with a one inch inside diameter and one meter length, and D_B is the inner diameter of the looped pipeline. The inner diameter of the parallel pipeline must be determined based on the minimization of the objective function. Of course, with regard to the dependence of the length and diameter of the parallel pipeline (referring to equation 5 or 11), the optimization should be carried out numerically or graphically. For example, the values of the objective function versus the inner diameter of the parallel pipeline for the gas transport network explained in section 4-1 are shown in Fig. 7. As it can be seen, for the mentioned network, the parallel pipeline

has an optimal diameter of 42 inches. The length of this pipeline, according to equation 11, is almost 70.2 km.

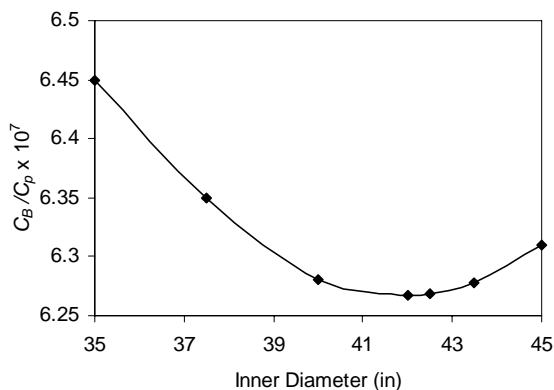


Figure 7. Values of the objective function versus the diameter of the parallel pipeline

6. Conclusions

The Campbell's equation is a simple and popular equation for calculating the length of horizontal looped pipelines. Before extending the Campbell's equation, its accuracy was compared to HYSYS software. The obtained results show that the Campbell's equation has the acceptable accuracy in determining the length of the parallel pipeline used in horizontal networks (the obtained error is less than 2 percent). But with increasing the slope of the pipeline, the accuracy of the Campbell's equation was decreased. In the next step, the Campbell's equation was extended in a way that it can be used for inclined pipelines. The comparison between the extended Campbell's equation and HYSYS software show that the obtained error in calculating the length of the parallel pipeline is less than 2 percent. In addition, the results show that when changes in the elevation of the pipelines are rather low (the average slope is less than 0.5 degree), the

application of Campbell's equation with regard to its simplicity is more preferable than the extended form (the obtained error is less than 3 percent).

Notation

A	Cross-sectional area of pipe (m^2)
C_B	Purchase and installation cost of pipe
C_P	A constant equal to the purchase and installation cost of a 1-in diameter of a steel pipe per meter of pipe length
C_V	Specific heat at constant volume (J/kg K)
D	Inner diameter of the pipe (m)
f	Moody friction factor
g	Gravitational acceleration (m/s^2)
L	Length of the pipe (m)
M	Molecular weight of the gas (kg/kmol)
P	Pressure (Pa)
Q	Gas flow rate at standard condition (MMSCMD)
q	The added heat per unit mass per unit time (W/kg)
R	Gas constant (J / kmol K)
T	Gas temperature (K)
t	Time (s)
u	Gas velocity (m/s)
x_f	Fraction of the length of the main pipeline which is looped with a parallel pipe
Z	Gas compressibility factor
z	Elevation change of the pipeline (m)
θ	Angle of pipeline from horizontal
ρ	Gas density (kg/m^3)

Subscripts

s.c	Standard condition
a.v	Average
i	i^{th} pipe segment
e	Equivalent

Appendix: Proposed algorithm for simulation of looped pipelines in HYSYS

When the diameter of the parallel pipeline is known, the following algorithm is used for simulation of the looped pipeline system using the HYSYS software:

- First, the main gas pipeline is simulated without increasing the gas flow rate ($Q = Q_{old}$). To do so, the PIPE SEGMENT or PIPESYS elements in the HYSYS software must be used [4, 5]. Of course, it is necessary to simulate the main pipeline by using two separate pieces of pipe known as A and C .
- A pipeline B (parallel pipeline) with a known diameter is added to the above system. Then by using two SET (an element of HYSYS software [5]) the pipeline B and pipeline A with the same length is set, the length of pipeline C is set equal to the total length of the main pipeline minus the length of pipeline A . Now, the input of gas flow rate is set according to the new amount ($Q = Q_{new}$).
- By using the ADJUST element of the HYSYS software [5], the gas flow rate between the pipelines A and B is divided into such a way that the pressure of the two pipelines is the same at the junction.
- Now, by using another ADJUST element, the length of pipe A should be changed in a way that the outlet pressure of pipeline C is the same as the main pipeline before increasing the gas flow rate.

The diagram of the mentioned algorithm in HYSYS is shown in Fig. 2.

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