Impact of Different Parameters on the Hydraulic and Flow Capacity of Gas Transmission Pipelines

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Abstract

Hydraulic and flow capacity of a gas transmission pipeline is usually affected by different parameters. These parameters are pipeline parameters, gas parameters, system parameters, heat transfer parameters, compression parameters and compressor fuel consumption parameters. Pipeline parameters are diameter, length, effective pipeline roughness and drag factor. Gas parameters are specific gravity, flowing gas compressibility factor and gas viscosity. System parameters are inlet pressure, outlet pressure, flowing gas temperature and elevation change. Heat transfer parameters are burial depth, soil temperature, soil thermal conductivity, and insulation thickness and insulation thermal conductivity. In this study the effect of these parameters on pipeline hydraulics has been investigated and results show that the change of inlet pressure (about 1%) has the greatest effect on flow change (is about 1% to 10%) in pipeline conditions.

Keywords: Gas Transmission Pipeline, Flow Capacity, Pipe Parameters, Gas parameters, System parameters, Heat transfer parameters.

1. Introduction

Oil and gas are the most important sources of energy in the world. They have prepared about 90% of total energy that is used in industries, homes and etc. Modern people's lives are based on an environment in which energy plays a main role. Oil and gas are major participants in the study of energy, and pipelines are the primary means by which they are transport. These pipelines are mostly buried and operate without distributing normal pursuits. They carry large volume of natural gas, crude oil, and other products in continuous streams.

During the last 60 years, the transportation of natural gas from wells to city distribution systems has developed from a single low pressure line 25 miles long, made of short lengths of 8 inch diameter wooden pipe, to one of the most important branches of the petroleum and natural gas industry. Thousands of miles of large diameter steel pipe are carrying natural gas between the sources of supply and points of consumption [1-3].

Many factors have been contributed in the engineering and design of long distance pipelines, including the nature and volume of fluid to be transported, the length of the pipeline, the type land traversed, and environmental constraints. The engineering problems involved have multiplied and become more difficult as the length, size, and operating pressures of natural gas transmission lines have increased.

2. World Natural Gas Outlook

As seen from Figure 1, The IEO2006 reference case projects increased world consumption of marketed energy from all sources over the next two and one-half decades [4].

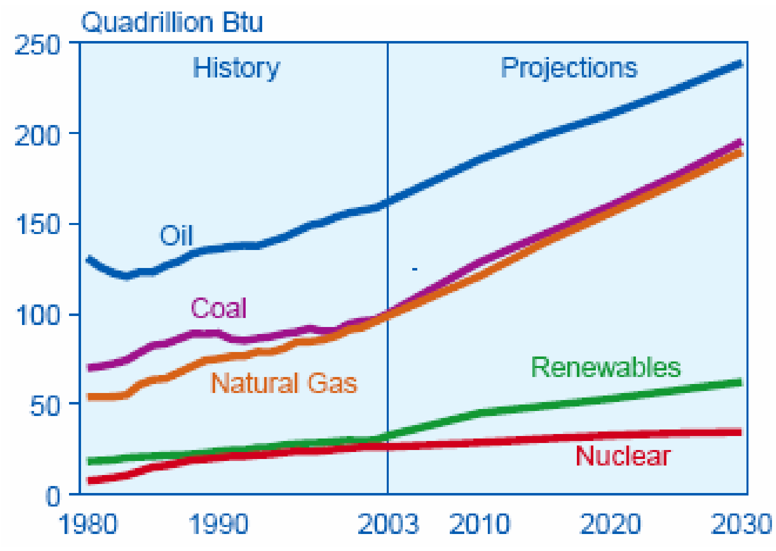

Fig1. World marketed energy use by fuel type, 1980-2030 [2]

Consumption of natural gas worldwide increases from 95 trillion cubic feet in 2003 to 182 trillion cubic feet in 2030 in the IEO2006 reference case. Higher world oil prices in IEO2006 increase the demand for and price of natural gas, making coal a more economical fuel source in the projections[3-6].

Historically, world natural gas reserves have, for the most part, trended upward. As of January 1, 2006, proved world natural gas reserves, as reported by Oil & Gas Journal, 5 were estimated at 6,112 trillion cubic feet—70 trillion cubic feet (about 1 percent) higher than the estimate for 2005. Iran has the second place in the country of the world [7].

3. Gas Transmission Methods

Gas is difficult to store because of its physical nature and needs high pressures and/or low temperatures to increase the bulk density. Gas, as a result of the storage difficulties, needs to be transported immediately to its destination after production from a reservoir. There are a number of methods of exporting gas energy from an isolated field for use elsewhere. Methods include: Pipelined Natural Gas(PNG), Liquefied Natural Gas (LNG), Gas to Liquids (GTL), Gas to Commodity (GTC), Gas to Wire (GTW), Compressed Natural Gas (CNG), Gas to Solids (GTS)[8].

4. Gas Physical Properties Prediction

The physical properties of a natural gas may be obtained directly either by laboratory measurements or by prediction from the known chemical composition of the gas. In the latter case, the calculations are based on the physical properties of individual components of the gas and upon physical laws, often referred to as mixing rules, relating the properties of the components to those of the gas mixture. For gas compressibility factor calculation used Standing-Katz chart that curve-fitted by Gopal. For calculation of pseudo critical pressure and temperature and apparent molecular weight and heat capacity of gas mixtures used Kay's rules. For calculation of gas thermodynamic properties and density of gas mixtures used real gas laws. For calculation of gas viscosity used Lee-Gonzales-Eakin method.[9-12].

5. Flow Equations and Correlations for Gas Transmission Pipelines

In this section, the general flow equation for compressible flow in a pipeline will be presented. Different flow regimes in gas transmission systems (i.e., partially turbulent and fully turbulent flow) will be presented. Some of the widely used transmission equations and their applications, advantages, and limitations will be outlined.

5.1 General Flow Equation - Steady State

Consider a pipeline that transports a compressible fluid (natural gas) between points 1 and 2 at steady-state condition. The impact of all existing forces (i.e., pressure, weight, friction, etc.) exerted on a particle of gas in a non-horizontal pipeline [Figure. 2] can be considered as follows[12, 13]:

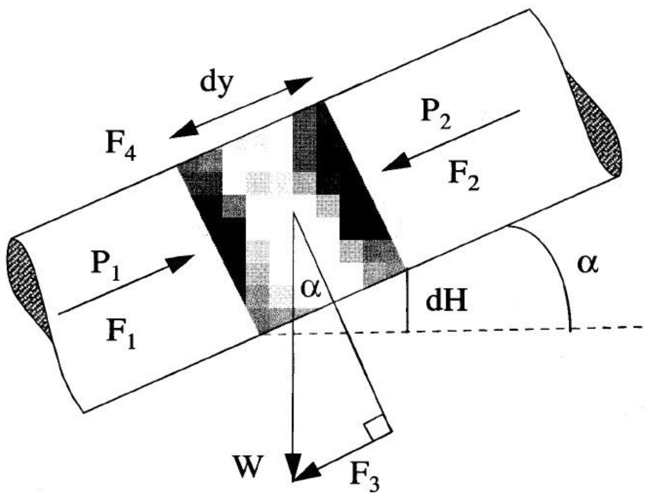

Fig 2. Demonstration of all forces acting on a gas particle moving in a non-horizontal pipeline[10]

The forces F_1 and F_2 acting on the gas particle due to the gas pressure. The force F_3 exerted on the gas due to the weight W of the gas particle. F_4 is friction force. The general form of the flow equation is obtained by adding all the terms together and setting them equal to zero:

$$\frac{C^2}{gc}\ln\frac{u_2}{u_1}+\frac{M}{2RZ_{ave}T_{ave}}\left(P_2^2-P_1^2\right)+\frac{M^2.P_{ave}^2}{R^2.T_{ave}^2.Z_{ave}^2}\mathrm{D}H+\frac{2fC^2}{gc.D}L=0 \quad (1)$$

Where the first term is kinetic energy, the second term is pressure energy, the third term is potential energy and the fourth term is friction loss.

The general flow equation of natural gas in a pipeline in Imperial Units can be written as follows[13]:

$$Q_b = 38.774\frac{T_b}{P_b}\sqrt{\frac{1}{f}}\sqrt{\frac{P_1^2 - P_2^2 - 0.0375 G.DH.\frac{P_{ave}^2}{R.T_{ave}Z_{ave}}}{Z_{ave}.T_{ave}.G.L}}.D^{2.5} \quad (2)$$

Where Q_b is gas flow rate at base conditions, SCFD, g_c is proportionality constant, 32.2 $lb_m \cdot ft/lb_f \cdot sec^2$, T_b is temperature at base condition, 520 oR, P_b is pressure at base condition, 14.7 psia, P_1 is gas inlet pressure to the pipeline, psia, P_2 is gas exit pressure, psia, G is gas gravity, dimensionless, DH is elevation change, ft, P_{ave} is average pressure, psia, R is gas constant, 10.73, $psia \cdot ft^3/lbmoles \cdot °R$, T_{ave} is average temperature, oR, Z_{ave} is compressibility factor at P_{ave}, T_{ave}, dimensionless, L is pipeline length, ft or miles, f is friction coefficient, dimensionless, $\sqrt{\frac{1}{f}}$ is transmission factor, dimensionless, D is inside diameter of the pipeline, inch, Z_b is compressibility factor at the base condition (at standard condition and low pressure for simplifying, compressibility factor is near to 1) Z_b » 1[14].

5.2 Flow Regimes

In high-pressure gas transmission lines with moderate to high flow rates, two types of flow regimes are normally observed[13]:

1. Fully Turbulent Flow (Rough Pipe Flow)
2. Partially Turbulent Flow (Smooth Pipe Flow)

Flow Regime is defined by the Prandtl -Von Karman equation as follows[13]:

$$\sqrt{\frac{1}{f}} = 4\log_{10}\frac{Re}{\sqrt{\frac{1}{f}}} - 0.6 \quad (3)$$

Where f is friction factor, dimensionless; and Re is Reynolds number, dimensionless.

Equation (3) is plotted on a semi-log graph, where the straight line shows the maximum limit of partially turbulent flow (see Figure. 3). All points to the right-hand side of the line exhibit fully turbulent flow, and those to the left side remain partially turbulent. Points located on the line are in the transition zone.

The simplified equation that gives the Re number in terms of pipeline parameters with reasonable accuracy is:

$$Re = 20\frac{Q_{sG}G}{mD} \quad (4)$$

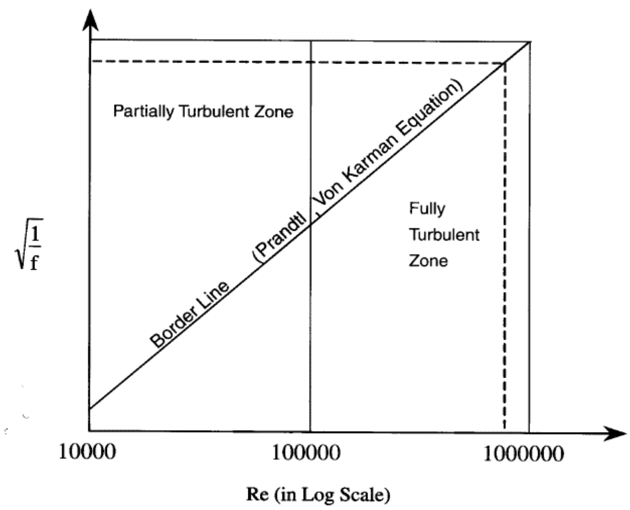

Fig 3. Representation of fully turbulent/partially turbulent zones by the Prandtl- Von Karman Equation [11]

5.3 Fully Turbulent Equations

The Panhandle B equation is normally suitable for high-flow-rate, large-diameter (i.e., pipes larger than NPS 24), and high-pressure systems. The transmission factor of this equation is defined in Imperial Units as: [10]

$$\sqrt{\frac{1}{f}} = 16.49(\mathrm{Re})^{0.01961} \tag{5}$$

The Weymouth equation is normally used for high-flow-rate, large-diameter, and high pressure systems. The transmission factor of this equation is defined in Imperial Units as[13]:

$$\sqrt{\frac{1}{f}} = 11.19D^{\frac{1}{6}} \tag{6}$$

The AGA fully turbulent is the most frequently recommended and widely used equation in high-pressure, high-flow-rate systems for medium- to large-diameter pipelines. It predicts both flow and pressure drop with a high degree of accuracy, especially if the effective roughness values used in the equation have been measured accurately. The transmission factor of this equation is defined in Imperial Units as[13]:

$$\sqrt{\frac{1}{f}} = 4\log\frac{3.7D}{Ke} \tag{7}$$

The Colebrook-White equation combines both partially turbulent and fully turbulent flow regimes and is most suitable for cases where the pipeline is operating in the transition zone. This equation is again used for large-diameter, high-pressure, and medium- to high-flow-rate systems. It predicts a higher pressure drop or lower flow rates than the AGA fully turbulent equation. The transmission factor of this equation is defined in Imperial Units as[13]:

$$\sqrt{\frac{1}{f}} = -4\,log\left[\frac{K_e}{3{,}70D} + \frac{1{,}4126\sqrt{\frac{1}{f}}}{Re}\right] \tag{8}$$

6. Impact of Different Parameters on the Hydraulic and Flow Capacity of Gas Transmission Pipelines

The hydraulic parameters are essentially those parameters which affect the flow behavior of the gas during transmission. They come under four broad headers that shown in Table. 1

Table 1. Pipeline hydraulic parameters

	Pipe Parameters		Heat Transfer Parameters
1	Diameter	1	Burial Depth
2	Length	2	Soil Temperature
3	Roughness	3	Soil Thermal Conductivity
4	Drag Factor	4	Insulation Thermal Conductivity
	System Parameters	5	Insulation Thickness
1	Inlet Pressure		Gas Parameters
2	Outlet Pressure	1	Specific Gravity
3	Flowing Gas Temperature	2	Viscosity
4	Elevation Change	3	Compressibility Factor

7. Case Study

For the sensitivity analysis, the special part of the IGAT IV pipeline selected that has maximum change in parameters. So the following part of IGAT IV chooses for sensitivity analysis with properties that shown in Tables 2 to 6.

Table 2. Gas composition of refinery outlet

Gas Composition	Mole Percent	Gas Composition	Mole Percent
Methane	0.9	n-Hexane	2.00E-04
Ethane	5.00E-02	n-Heptanes	2.00E-04
Propane	6.00E-03	Nitrogen	3.20E-02
n-Butane	1.00E-03	CO_2	1.00E-02
n-Pentane	6.00E-04		

Table 3. Pipe parameters for pipe#2 of IGAT IV pipeline

Pipe Parameters	
Diameter(in)	56
Length(ft)	29408
Roughness(in)	0.0006
Drag Factor	0.96
Wall Thickness for ID Calculation=0.733in	

Table 4. System parameters for pipe#2 of IGAT IV pipeline

System Parameters	
Inlet Pressure(psia)	1244
Outlet Pressure(psia)	1153
Elevation Change(ft)	2390
Flowing Gas Temperature(R)=[(Tin+Tout)/2]	570

Table 5. Gas parameters for pipe#2 of IGAT IV pipeline

Gas Parameters	
Specific Gravity	0.61
Viscosity(cp)	1.43E-02
Compressibility Factor	0.8673

Table 6. Heat transfer parameters for pipe#2 of IGAT IV pipeline

Heat Transfer Parameters	
Pipe Wall Thickness(in)	0.733
Soil Temperature(R)	527.67
Soil Thermal Conductivity (BTU/hr ft F)	0.43334175
Burial Depth(ft)	3.018
Insulation Thermal Conductivity (BTU/hr ft F)	0.4044523
Insulation Thickness(ft)	0.03281

8. Sensitivity Results

The data from IGATIV pipeline were introduced to the written program by Microsoft visual basic. At first the physical properties of gas calculated. Then sensitivity analysis was performed for each parameter. The sensitivity results from the generated program were investigated in the following sections. It is notable that, in the present study, for examining the effect of each parameter on flow ratio, all of parameters keeps constant excepted one.

• Pipe parameters:

In Table 7 and Fig 4 to7, the pipe parameter effects on flow were shown.

Table 7. Summary of Results, Design Criteria and Parameters Impact Study

Pipe Parameters	Variation in Parameter	Change in Flow (MMSCFD) For AGA Fully Turbulent	Remarks
Diameter	30 in<D<64 in Stepsize=2 in Change=6.6666% increase	745.1317<Q<5642.234 Average change per step-size=38.6596 % increase	--------
	5.7989% flow change for 1% parameter change		
Length	20000 ft<L<30000 ft Stepsize=1000 ft Change=5% increase	4807.315>Q>3925.157 Average change per stepsize= 1.8350% decrease	--------
	0.3670% flow change for 1% parameter change		
Effective Roughness	0.0001 in<Ke< 0.001 in Stepsize=0.0001 in Change=100% increase	4522.631>Q>3805.307 Average change per step-size=1.7623% decrease	$K_e = K_s + K_i + K_d$
	0.0176% flow change for 1% parameter change		
Drag Factor	0.92<Df<0.98 Stepsize=0.01 Change=1.0869% increase	4462.411<Q<4753.446 Average change per step-size=1.0869% increase	Drag Factor varies from 0.92-0.98 for typical operating pipelines in the partially turbulent flow regime
	1% flow change for 1% parameter change		

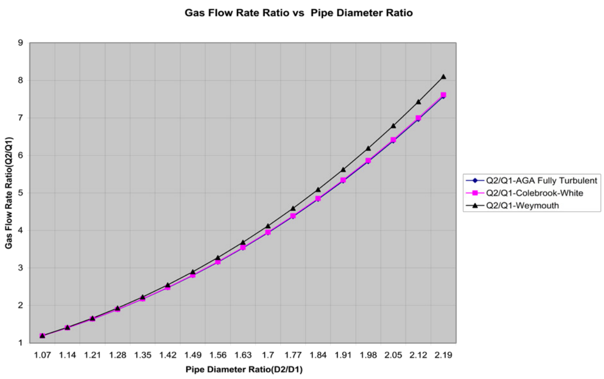

Fig 4. The impact of pipe diameter ratio change on gas flow ratio

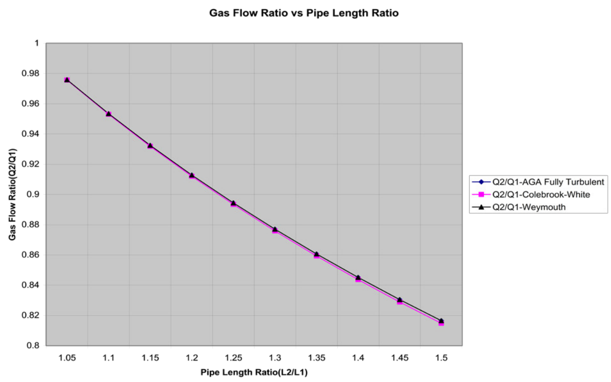

Fig 5. The impact of pipe length ratio change on gas flow ratio

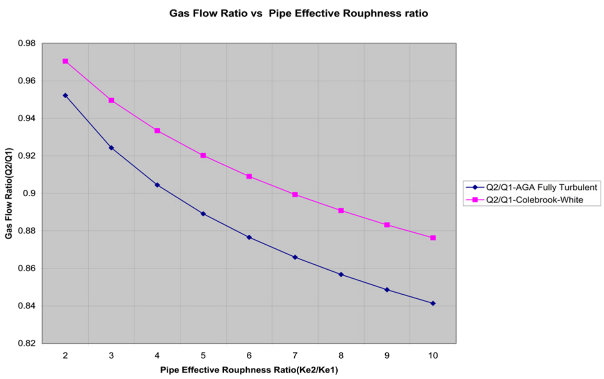

Fig 6. The impact of pipe effective roughness ratio change on gas flow ratio

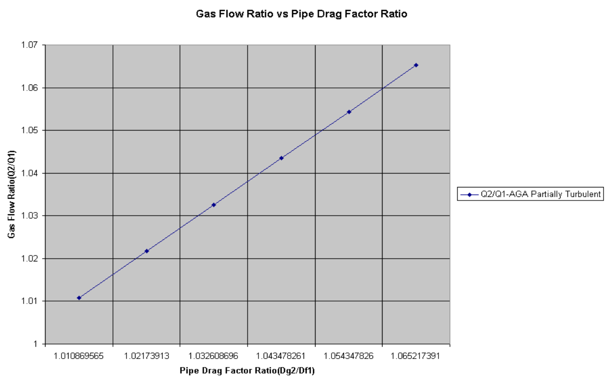

Fig 7. The impact of pipe drag factor ratio change on gas flow ratio

As seen from fig 4 and 7, with increasing pipe diameter and pipe drag factor, as the diameter and drag factor increases, due to a decrease in the pressure drop, the flow value can be increased to maintain the same conditions. On the contrary, this is visible in Fig 5 and 6 with increasing length and effective roughness, due to increased pressure drop, it was necessary to reduce the fluid flow for decreasing the pressure drop.

• **System operating parameters:**

In the Table 8 and Fig 8 to 11, the system operating parameter effects on flow were shown.

Table 8. Summary of Results, Design Criteria and Parameters Impact Study

System Operating Parameters	Variation in Parameter	Change in Flow(MMSCFD) For AGA Fully Turbulent	Remarks
Inlet Pressure	1240 psia<Pin<1840 psia Stepsize=100 psia Change=8.0645% increase	3641.288<Q<21974.82 Average change per stepsize=83.9150% increase	average pressure of pipeline, Average compressibility factor, Density, viscosity change due to change of Inlet Pressure
	10.4054% flow change for 1% parameter change		
Outlet Pressure	750 psia<Pout<1150 psia Stepsize=100 psia Change=13.3333% increase	15014.43>Q>4198.961 Average change per stepsize=18.0085% decrease	average pressure of pipeline, Average compressibility factor, Density, viscosity change due to change of outlet Pressure
	1.3506% flow change for 1% parameter change		
Flowing Gas Temperature	500 R<Tave<600R Stepsize=20R Change=4% increase	2950.542<Q<4165.229 Average change per stepsize=9.2440% increase	Average compressibility factor, Density, viscosity change due to change of Flowing Gas Temperature
	2.3110 % flow change for 1% parameter change		
Elevation Change	500 ft<E<3000 ft Stepsize=500 ft Change=100% increase	6963.95>Q>2268.642 Average change per stepsize=13.4846% decrease	------------------
	0.1348% flow change for 1% parameter change		

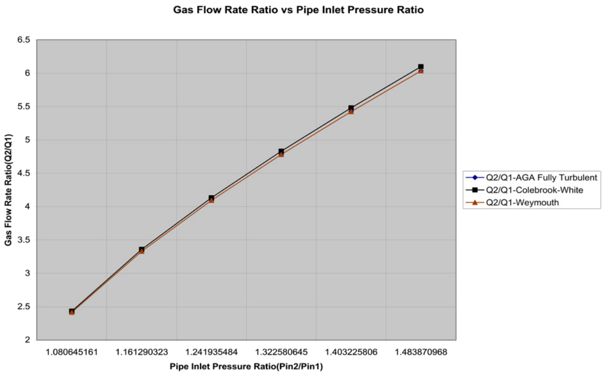

Fig 8. The impact of gas pipe inlet pressure ratio on gas flow ratio

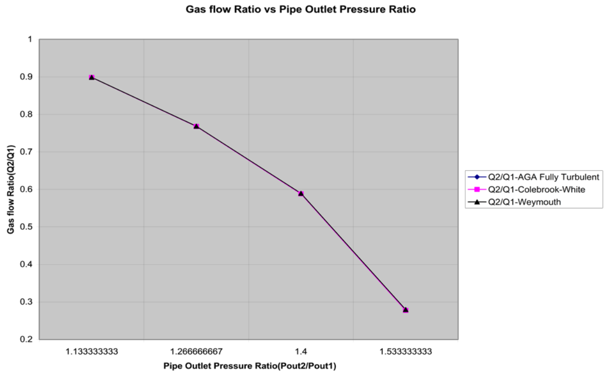

Fig 9. The impact of pipe outlet pressure ratio change on gas flow ratio

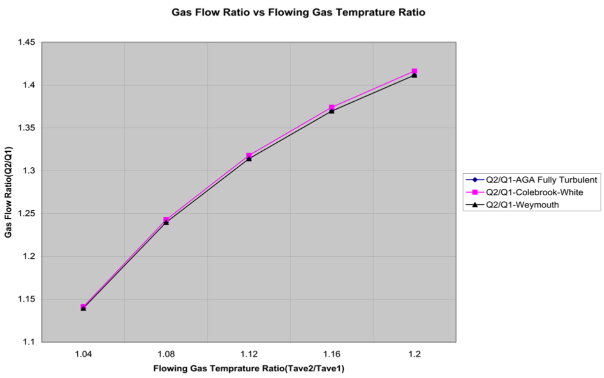

Fig 10. The impact of flowing gas temperature ratio change on gas flow ratio

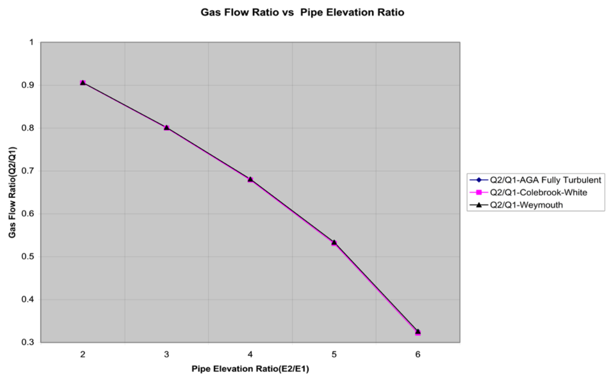

Fig 11. The impact of elevation ratio change on gas flow ratio

As shown in Figures 8 and 9, with increasing inlet pressure and gas flowing temperature, the gas flow increases. And vice versa, according Figures 10 and 11, by increasing the outlet pressure and increasing the elevation change, the passing flow from the pipeline is decreased.

As known and also according to equation 2, with increasing inlet pressure and gas temperature in a specific length, the energy loss is decreased and you can pass more flow through the pipeline. Vice versa, with the increasing outlet pressure and height of elevation the loss is increased and flow capacity should be decreased.

- **Gas parameters:**

In Table 9 and Fig 12 to14, the gas parameter effects on flow were shown.

Table 9. Summary of Results, Design Criteria and Parameters Impact Study

Gas Parameters	Variation in Parameter	Change in Flow (MMSCFD) For AGA Fully Turbulent	Remarks
Specific Gravity	0.56<SG<0.76 Stepsize=0.02 Change=3.8461% increase	5113.017>Q>1951.27 Average change per step-size=5.6215% decrease	pseudo critical pressure and temperature, Average compressibility factor, Density, viscosity of change due to change of specific gravity
	1.4616% flow change for 1% parameter change		
Flowing Gas Compressibility Factor	0.75<Zave<1.1 Stepsize=0.05 Change=6.6666% increase	3221.719<Q<4388.809 Average change per step-size=5.1750% increase	Density, viscosity of change due to change of Flowing Gas Compressibility Factor
	0.7762% flow change for 1% parameter change		
Viscosity	0.01 cp<μ<0.01 cp Stepsize=0.001 cp Change=10% increase	3929.613>Q>3898.286 Average change per step-size=0.0797% decrease	AGA fully turbulent is independent of viscosity so Colebrook –white equation used
	0.0079% flow change for 1% parameter change		

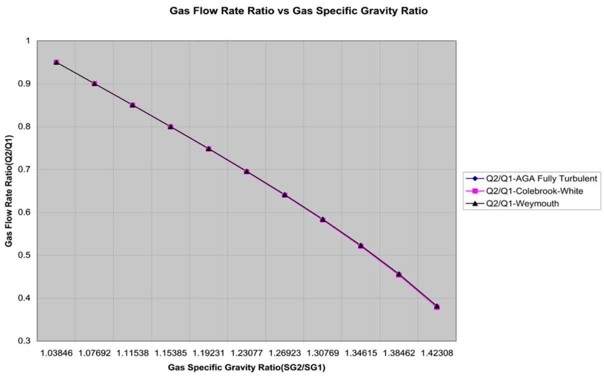

Fig 12. The impact of gas gravity ratio change on gas flow ratio

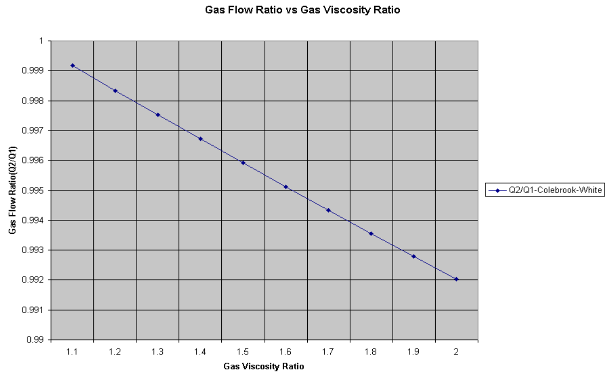

Fig 14. The impact of gas viscosity ratio change on gas flow ratio

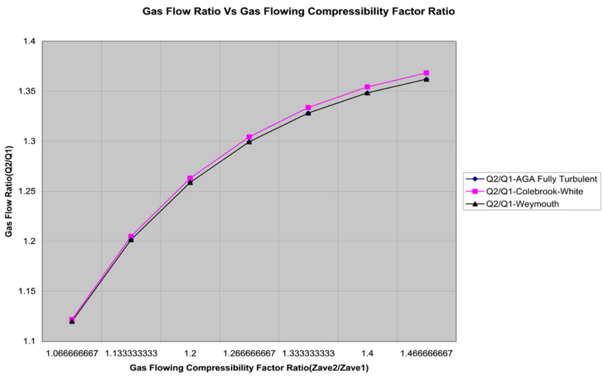

Fig 13. The impact of gas flowing compressibility factor ratio change on gas flow ratio

As shown in Figures 12 and 14, with increasing gas gravity and viscosity, due to increasing losses in the pipeline, the flow capacity should be decreased for compensation these losses.

For compressibility factor, based on equation 2, with increase this factor the losses are decreased and the term under radical increases so the flow capacity increase.

• Heat transfer parameters:

Table 10. Summary of Results, Design Criteria and Parameters Impact Study

Heat Transfer Parameters	Variation in Parameter	Change in Flow(MMSCFD) For AGA Fully Turbulent	Remarks
Buried Depth	3 ft<BD<5 ft Stepsize=0.5 ft Change=16.6666% increase	3964.413<Q<3966.285 Average change per step-size=0.0118% increase	-------------
	0.0007% flow change for 1% parameter change		
Soil Temperature	500 R<Ts<550 R Stepsize=10 R Change=2% increase	3961.923<Q<3966.510 Average change per step-size=0.0231% increase	-------------
	0.0115% flow change for 1% parameter change		
Soil Thermal Conductivity	0.1 (BTU/hr Ft F)<Stc<1.6 (BTU/hr Ft F) Stepsize=0.3(BTU/hr Ft F) Change=300% increase	3967.448>Q>3955.035 Average change per step-size=0.0625% decrease	-------------
	0.0002% flow change for 1% parameter change		
Insulation Thermal Conductivity	0.1 (BTU/hr Ft F)<Itc<1.6 (BTU/hr Ft F) Stepsize=0.3(BTU/hr Ft F) Change=300% increase	3964.689>Q>3964.406 Average change per step-size=0.0014% decrease	-------------
	0.000004% flow change for 1% parameter change		
Insulation Thermal Conductivity	0.67 ft<It<0.72 ft Stepsize=0.01 ft Change=1.4925% increase	3960.635>Q>3958.114 or 3958.24<Q<3958.481 Average change per step-size=0.0318% decrease or0.0030% increase	This variation is because of Critical Radius of insulation that the insulation thickness is equal to 0.69 ft
	0.020% flow change for 1% parameter change		

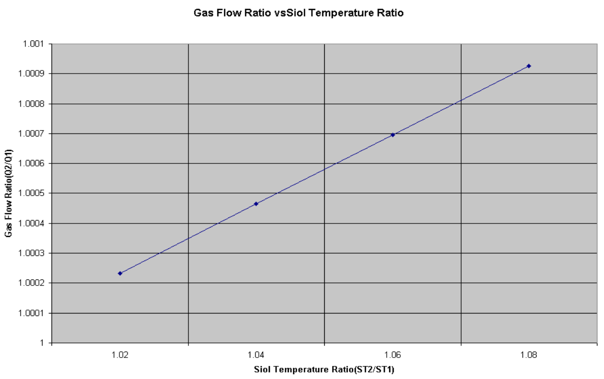

Fig 15. The impact of soil temperature ratio change on gas flow ratio

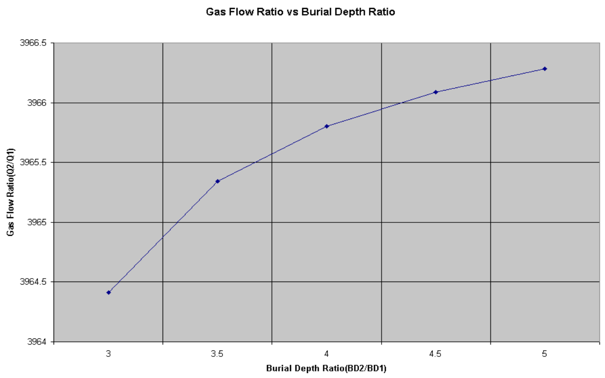

Fig 16. : The impact of burial depth change on gas flow ratio

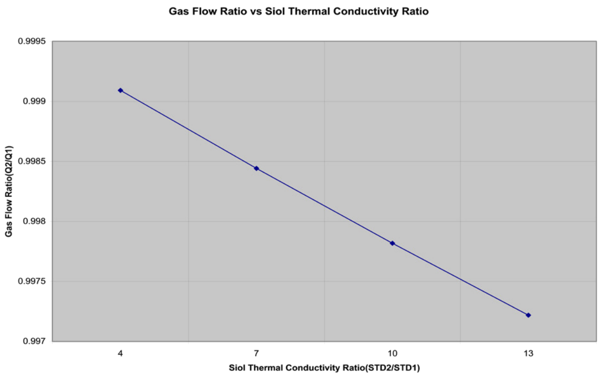

Fig 17. The impact of soil thermal conductivity ratio change on gas flow ratio

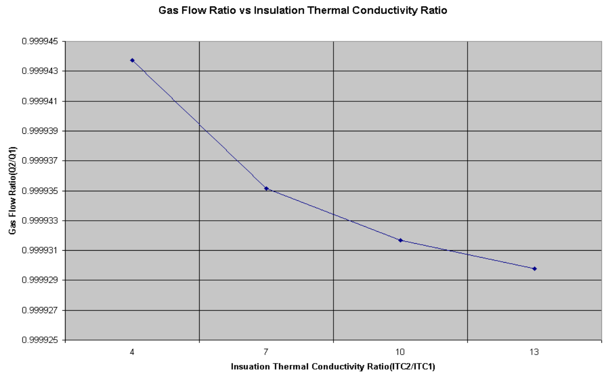

Fig 18. The impact of gas flowing compressibility factor ratio change on gas flow ratio

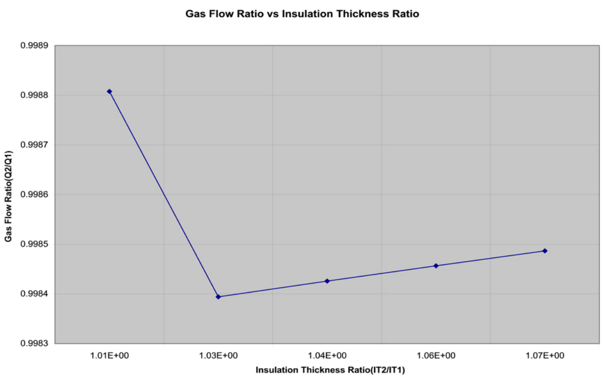

Fig 19. The impact of insulation thermal conductivity ratio change on gas flow ratio

In Table 10 and Fig 15 to19, the heat transfer parameter effects on flow were shown.

It is notable that, by reducing heat transfer to the surrounding environment And reduce the tendency to form liquid and phase change, the losses decrease and from equation 2 the flow capacity in pipeline increase. This behavior is visible in Figures 15 and 16, but on the contrary, in Figures 17 and 18, by increasing the heat transfer, the flow passes from the pipeline has decreased.

Figure 19 consists of two distinct regions in terms of heat transfer. In this figure, to critical radius, the heat transfer is decrease and after that with adding external surface, the convection with surrounding is increased and so according to the above justifications, the flow capacity is decreased.

9. Conclusions

The main objective of this work was to investigate the impact of different parameters on the hydraulic and flow capacity of a gas transmission pipelines. To achieve these objectives, the impact of pipe parameters, system parameters, gas parameters and heat transfer parameters on the physical properties of gases was firstly studied. The results of this study was introduced into general flow equation of gas transmission pipelines equations, for estimating the effect of these changes on the hydraulic and flow capacity of pipelines. From the present investigation, concluded that AGA Fully Turbulent, Colebrook-White and Weymouth have the best prediction of flow rate in gas transmission pipelines. It was determined from the study that the changing gas inlet pressure has large effect on the flow capacity (10.4054% flow changes due to 1% inlet pressure change).

10. Acknowledgement

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تاثیر پارامترهای مختلف بر ظرفیت هیدرولیک و جریان گاز خطوط انتقال گاز

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چکیـــــده

ظرفیت هیدرولیک و جریان گاز خطوط انتقال، معمولا تحت تأثیر پارامترهای مختلف قرار می گیرد که این پارامترها شامل پارامترهای خط لوله(پارامترهای گاز، پارامترهای سیستم، پارامترهای انتقال گرما، پارامترهای فشرده سازی و پارامترهای مصرف سوخت کمپرسور)، پارامترهای گاز(گرانروی موثر، جریان فشرده سازی گاز و ویسکوزیته گاز)، پارامترهای سیستم (فشار ورودی، فشار خروجی، دمای گاز جریان و تغییر ارتفاع)، پارامترهای انتقال گرما(عمق دفن، درجه حرارت خاک، هدایت حرارتی خاک، ضخامت عایق و هدایت حرارتی عایق)، پارامترهای فشرده سازی و پارامترهای مصرف سوخت کمپرسور هستند. در این مقاله تأثیر این پارامترها بر هیدرولیک خط لوله مورد بررسی قرار گرفته اند و نتایج نشان می دهد که تغییر فشار ورودی (حدود ۱٪) بیشترین تاثیر را در تغییر جریان (در حدود ۱٪ تا ۱۰٪) در شرایط خط لوله دارد.

واژگان کلیدی: خطوط لوله انتقال گاز، ظرفیت جریان، پارامترهای لوله، پارامترهای گاز، پارامترهای سیستم، پارامترهای انتقال حرارت