VERSITA 10.2478/auoc-2013-0013
Ovidius University Annals of Chemistry Volume 24, Number 1, pp.67-72, 2013

Considerations on transport capacity of natural gas pipelines and its limits

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Abstract The paper deals with the transport capacity of the pipeline and shows its variation in accordance with working parameters. The most drastic limitation occurs when the sonic choke is reached. This should be avoided during the operation of transport systems.

Keywords: transport, gas, capacity, pipeline.

1. Introduction

In accordance with the GTE (Gas Transmission Europe) position, technical transport capacity of pipelines represents the maximum volumetric flow rate expressed in the normal state that can be transported in a pipeline between two points in which the input pressure *p*1 is the operating pressure, and, at the output, minimum acceptable pressure is defined due to technical or contractual reasons.

Transport capacity is the main parameter of a transport system around which the whole business is built. Usually, the natural gas transport company TRANSGAZ from Romania puts on the market at customers' disposal the transport capacity for a whole year. The aim is to cover with firm contracts most of the capacity, if possible all of it.

Negotiations usually cover part of the transport capacity with firm contracts (reservation capacity) for a year. The difference in capacity is put on the market at customers' disposal, this being possible to be covered by interruptible contracts.

The capacity of a transport system is a size which is determined by calculation. It depends on the used pipelines' volume and the pressure state.

This paper presents the calculation method of the transport capacity and the elements that limit it.

2. Transport capacity calculation using the classic method

The transport capacity of a pipeline is represented by the flow that can be transported safely and can be calculated with the following equations [3, 4]:

$$Q_n = \frac{\pi}{4}\frac{T_n}{p_n}\sqrt{\left(p_1^2 - p_2^2\right)\frac{R}{Z_1 T}\frac{d^5}{l\lambda}} \tag{1}$$

$$Q_n = 3600\frac{\pi}{4}\frac{T_n}{p_n}\sqrt{\left(p_1^2 - p_2^2\right)\frac{R}{Z_1 T}\frac{d^5}{l\lambda}} \tag{2}$$

Where the significance of the symbols used in the formulas is the following:

Q_n – gas flow in normal conditions, St $m^3 \cdot h^{-1}$
T_n – standard temperature, 288.15 K
p_n – normal pressure 1.01325 [bar]
p_1 – pipeline input pressure [bar]
p_2 – pipeline output pressure [bar]
R – gas constant [$J \cdot kg^{-1} K^{-1}$]
Z_1 – compressibility factor in state 1, when gas enters the pipeline
T – absolute gas temperature ($T = t + 273.15$; t –

ISSN-1223-7221

temperature in °C) [K]

d – inner diameter of the pipeline [m]

l – pipeline length [m]

λ – hydraulic loss coefficient

The pressure drop in the pipeline is calculated with the following equation:

$$p_1^2 - p_2^2 = KQ_n^2 \tag{3}$$

The following notation was used:

$$K = \frac{16}{\pi^2}\frac{p_n^2}{T_n^2}\frac{Z_1 T}{R}\frac{l\lambda}{d^5} \tag{4}$$

The calculation of pipeline capacity, which represents the maximum flow that can be transported in the pipeline under the conditions of pressures p_1 and p_2 at the pipeline's ends is not an easy task due to the hydraulic loss coefficient λ which depends on the flow rate in the pipeline [1, 5]. The equation for calculating the hydraulic loss coefficient that provides the best results is the Colebrook White equation [3, 4].

$$\frac{1}{\sqrt{\lambda}} = -2\lg\left(\frac{2.51}{\mathrm{Re}\sqrt{\lambda}} + \frac{k}{3.71D}\right) \tag{5}$$

where *k* represents rugosity and *Re* Reynolds criterion.

A correct calculation for flow determination is an iterative calculation which includes the following

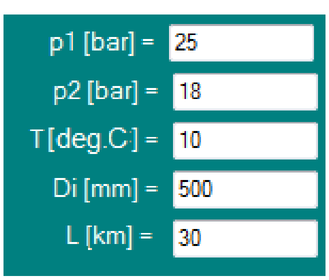

Fig. 1 Initial data of the pipeline

Steps:

1. Initial estimation of hydraulic loss coefficient λ using a simplified explicit formula, which is Weymouth's formula (6); λ depends only on the diameter of the pipeline:

$$\lambda^{(0)} = \frac{0{,}009407}{\sqrt[3]{D}} \tag{6}$$

2. The initial value of the flow is calculated: $Q_n^{(0)}$

3. The new value of the hydraulic loss coefficient $\lambda^{(1)}$ is calculated again, using for the flow rate the value $Q_n^{(0)}$

4. The new value of the flow $Q_n^{(1)}$ is determined from equation (1) and value $\lambda^{(1)}$

5. The new value of the flow is compared with the old one:

$$\left|Q_n^{(1)} - Q_n^{(0)}\right| < \varepsilon \tag{7}$$

where ε represents the absolute error.

If condition (7) is not fulfilled the initial value is replaced with the calculated value $Q_n^{(0)} = Q_n^{(1)}$ and steps 3, 4 and 5 are repeated until the desired precision is reached.

For a pipeline whose characteristics are shown in **Fig. 1**, the results of iterative calculations are presented in **Fig. 2.**

Initial Iteration
lambda ini = 0.011852
Flow rate Qn = 182,224.560 [Nmc/h]
Iteration 1
lambda = 0.0121891269597164
Flow rate Qn = 179,687.493 [Nmc/h]
Iteration 2
lambda = 0.0121920440557826
Flow rate Qn = 179,665.995 [Nmc/h]
Iteration 3
lambda = 0.0121920691112847
Flow rate Qn = 179,665.811 [Nmc/h]
Iteration 4
lambda = 0.0121920693264772
Flow rate Qn = 179,665.809 [Nmc/h]

Fig. 2 Iterative calculation of the flow

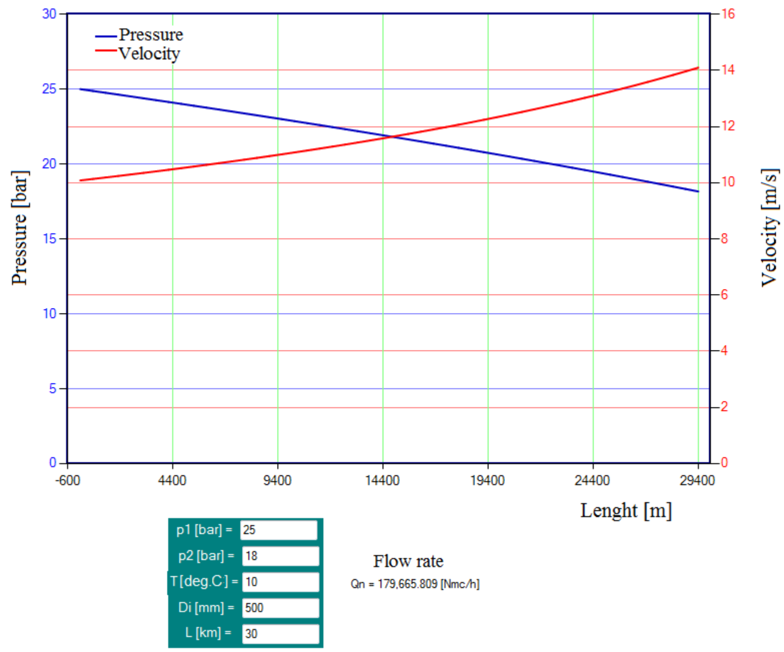

Fig. 3 Variation of pressure and gas velocity

It can be noticed that for calculating the flow 4 iterations are required to reach precision 0.1 $m^3 \cdot h^{-1}$. **Figure 3** shows the pressure and gas velocity variation along the pipeline.

3. Transport capacity limitation of a pipeline

If for the analyzed pipeline the flow rate is increased by increasing the pressure difference at the ends of the pipeline (Figures 6 and 7) it can be noticed that once the pressure drops, the transport velocity increases. This phenomenon can be explained by the fact that in order to transport more gas, the transport velocity must be increased, but brushing due to friction also increases [7]. Pressure drop increases velocity.

Figures 4 and **5** show cases where the flow rate in the pipeline is increased by raising the pressure difference at the ends of the pipeline. It is clear the correlation between increasing flow and pressure drop at the delivery end of the pipeline.

Velocity variation is influenced by the change of gas pressure in the pipeline due to pressure drop. The higher the flow is, the higher the velocity at the delivery end gets.

The flow that can be transported in the pipeline is limited by a value that leads to sonic choke of the pipeline. The formulas used to calculate flow rates are available for transport velocities of 25 ... 30 $m \cdot s^{-1}$; at higher transport velocity they cannot correctly describe the phenomenon. As shown in Figure 7 a flow of 256225.294 St $m^3 \cdot h^{-1}$is obtained at the delivery pressure of 4 bar.

Using an efficient numerical simulator (AFT Arrow) [9] shows that for this pipeline a flow of 250000 St $m^3 \cdot h^{-1}$ leads to its sonic choke flow. Calculation data are shown in **Table 1.**

From Table 1 it is observed that at 27 km from the end of the pipeline, for the flow value mentioned above, the sonic choke illustrated in **Fig. 6** and **7** is reached.

For each pipeline there is a flow leading to sonic choke flow, characterized by the fact that the gas velocity increases until it reaches the speed of sound. In this place the gas pressure drops a lot. If the local value is lower than p_2 the pipeline gets blocked. If the local pressure remains higher than p_2 the flow will be locked and its value will not exceed the choke flow value, called critical value.

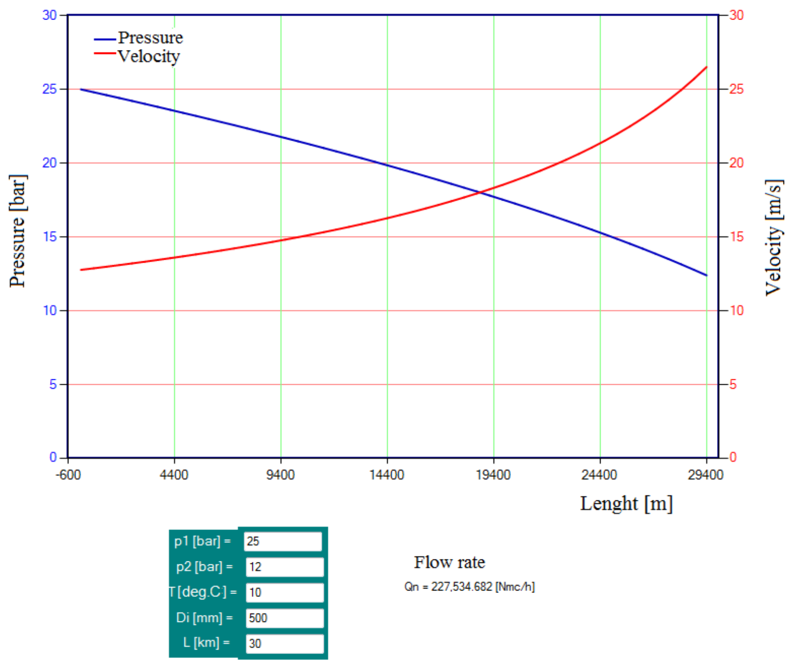

Fig. 4 Variation of pressure and gas velocity – 13 bar pressure drop

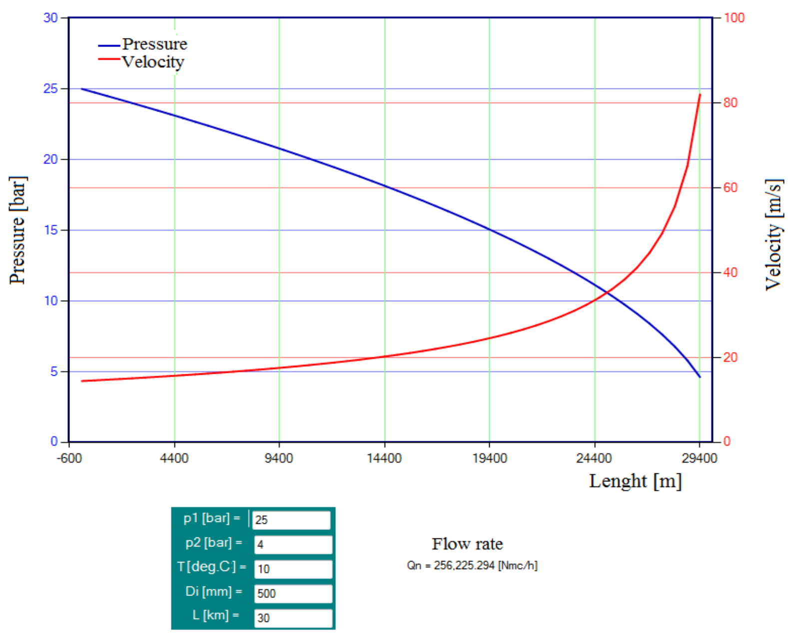

Fig. 5 Variation of pressure and gas velocity – 21 bar pressure drop

Table 1 Calculation data for a pipeline

Point	x (m)	Mass flow rate (kg/sec)	Velocity (m/s)	Static P (MPa)	Density (kg/m^3)
1	0	49.83	14.75	2.49804	17.9998
2	3,000	49.83	15.74	2.34947	16.8766
3	6,000	49.83	16.93	2.19081	15.6846
4	9,000	49.83	18.44	2.01967	14.4077
5	12,000	49.83	20.4	1.83253	13.0221
6	15,000	49.83	23.13	1.62382	11.4898
7	18,000	49.83	27.28	1.38372	9.7443
8	21,000	49.83	34.82	1.09135	7.6443
9	24,000	49.83	56.36	0.68029	4.7423
10	27,000	49.83	438.67	0.08854	0.8774
11	30,000	49.83	392.66	0.09889	0.9138

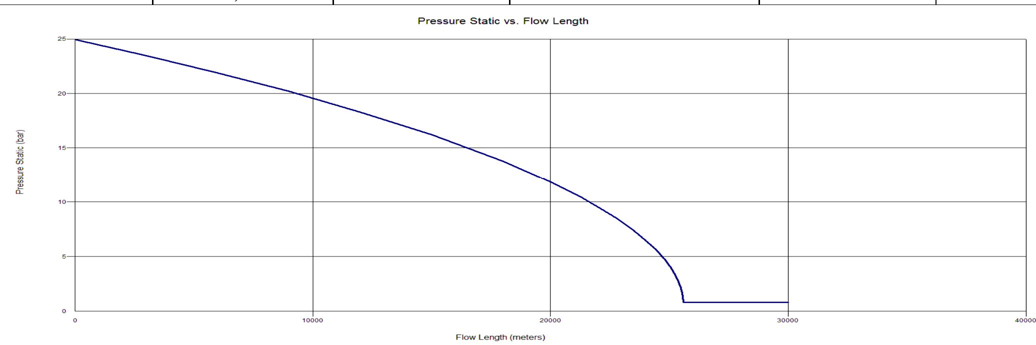

Fig. 6 Pressure variation in case of sonic choke

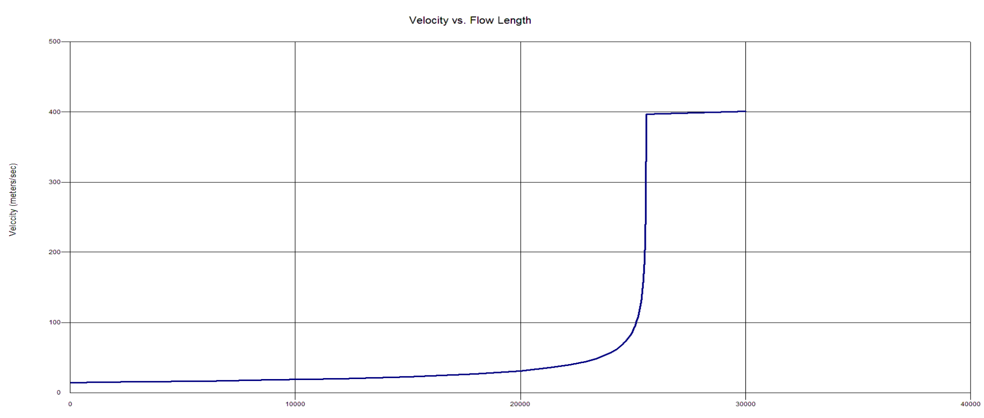

Fig. 7 Velocity variation in case of sonic choke flow

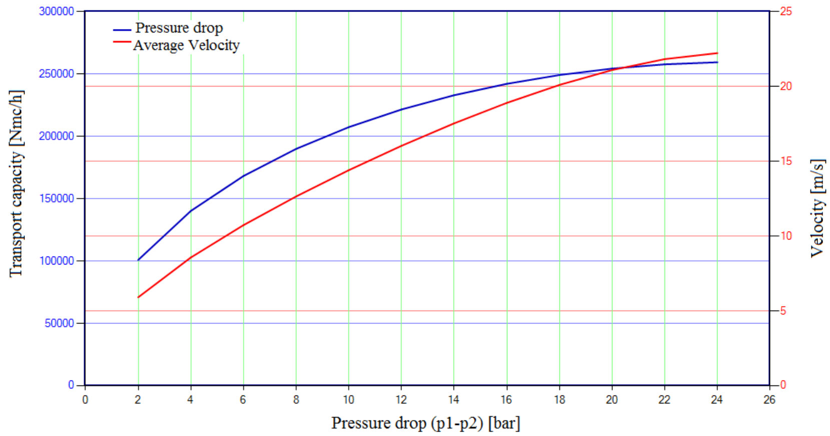

Fig. 8 Capacity variation based on pressure drop in parallel with the average velocity of gas in the pipe

All literature in the field [1, 2, 3, 8] mentions that these operating states of natural gas pipelines should be avoided. All simulators signal the locking conditions and usually stop calculation in this area recommending restoring calculation conditions.

4. Elements that allow defining transport capacity limitation

For the analyzed pipeline it is shown in Figure 8 the flow rate variation based on the difference in pressure at the end of the pipeline in parallel with the average velocity of gas in the pipeline. It is noticed that with increasing pressure difference at the ends of the pipeline the flow rate increases, but for large differences in pressure, in this case more than 14 bar, the flow rate growth remains the same, becoming almost horizontal.

This chart shows the need to transport gas flow producing moderate pressure drops, in the case of the analyzed pipeline within 10 - 12 bar. The transport velocity at the delivery end should not exceed 20 - 25 m/s. Compliance with these velocities provides safety of the transport process and also allows the existence of a reserve of 15 - 20% (flow rate growth) which does not lead to sonic choke.

5. Conclusions

Transport capacity is the main characteristic of natural gas transport systems. This is determined by calculation based on the volume of the pipelines and transport parameters, mainly pressures.

As shown in the paper there are values of transport parameters that limit the capacity. The most drastic limitation occurs when the sonic choke is reached. This should be avoided during the operation of transport systems.

Defining real technological capacity for a transport system must be determined for loads of the system that allow its safe operation, away from critical regimes that can lead to blockages.

6. References

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Submitted: May 20th 2013
Accepted in revised form: August 5th 2013