Gas Transmission Europe

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Definition of available capacities at cross-border points in liberalized markets

GTE report

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Executive summary

The conclusions of the 6th meeting of the European Gas Regulatory Forum, held in Madrid on the 30-31 October 2002, in order to "provide network users with the information that network users need for efficient access to the TSOs networks", asked GTE to continue in the implementation of Guidelines for Good Practice adopted in the 5th meeting of the Madrid Forum, in particular with the publication of the available capacities at least at the cross-border entry and exit points, and to propose a methodology for calculating available capacities.

According to the GTE definition, available capacities are the net of maximum physical operating capacity, already existing capacity commitments incl. public service obligations and the operational margin necessary for safe and reliable operation of the system.

The paper shows how, based on the physical laws of gas transmission in pipelines, that the maximum physical operating capacity depends on the technical system as well as on the assumptions about deliveries to and off takes from the system and that it can be calculated for a well defined set of the technical system as well as deliveries to and off-takes from the system.

The methodology to determine maximum physical operating capacities and then the available capacities is applied internationally and is "state of the art" from the engineering perspective and is specific to each TSO from the flow scenarios perspective, due to the existing differences in the systems.

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1 Introduction

Information about available transmission capacity at cross border nodal points is an important indicator for market participants to plan their cross border transactions in gas. Against this background GTE already published on its website a map of the European natural gas transmission grid containing information about the maximum physical operating capacities and available capacities at cross border nodal points (GTE grid map). Moreover GTE members have decided to publish information about available capacities at cross border nodal points in their respective websites. The general principle is publication of numerical figures. If confidentiality problems prevail indications about the available capacities are provided in the form of a traffic light system. Links from the GTE grid map have been implemented that lead to the respective websites of the individual TSOs.

As capacities at cross border nodal points are one important factor that determine the possibilities of access to market regions in Europe and thus of the international trade it remains critical that the TSOs do the calculations and the assessments in the most transparent way and that the calculations used are all well understood by all market participants and well applicable by all decision making bodies.

Therefore GTE decided to improve the transparency of calculating available capacities by explaining the fundamentals of calculating capacities in gas transmission as well as the dynamic view that has to be taken as regards the determination of available capacities. The paper starts with a description of the basic differences between electricity and gas. In the second part a definition of available capacity at cross border nodal points is provided. The third part describes the main technical background for the calculation of transmission capacities and finally an illustration is given of the dynamics that determine the amount of capacity that can be made available at cross border nodal points.

It is worth noting that there has been no difference between European TSOs as regards the application of the general principles to calculate available capacities at cross border nodal points.

2 Differences between natural gas and electricity transmission

Parallels are often drawn between gas and electricity transmission systems. Although some parallels exist there are some significant differences between electricity and gas systems from a technical point of view.

Natural gas is a primary energy that can only be produced from natural gas fields. Other supply points for natural gas pipeline systems include gas storage facilities. If any the contribution of domestic gas production to the supply of natural gas is restricted in most Member States. Most of the gas required is imported from other countries and the distances involved are very long in some cases. The location of natural gas storage facilities is also determined by geological factors. In contrast, power stations are generally subject to logistical optimisation and can be distributed fairly evenly with the aim to reduce average transportation distances.

Flows through gas transmission systems can be controlled from an operational point of view relatively easily using compressors, pressure or flow control stations and to a certain extent valves. In electric power systems load flow control facilities are only available to a very limited extent.

Generally, electricity transmission systems normally should not represent a limiting factor on power station output and systems are designed to ensure that supply bottlenecks are only of secondary importance.

Moreover natural gas is a product of nature and hence TSO’s have to transport different qualities of gas in theirs systems. For this reason pipeline systems often have to be operated separately. Combined network operation is only possible to a relatively limited extent. In contrast, the same quality of electric power is supplied throughout Western Europe, allowing the use of extensive, closely meshed systems.

Energy transmission through gas systems is inseparably linked with the physical transportation of volumes of gas, a process which can only take place at a finite flow velocity, typically 5–10 m/s. The properties of gas as a substance mean that it can be stored. On the other hand, energy transmission through electric power systems is not coupled with the transfer of any mass of a substance and electric power cannot be stored directly. Discrepancies in the energy balance therefore call for rapid reaction: the output of a power station must be adapted within a few seconds.

Especially because electricity cannot be stored, the construction of large power station blocks only became possible as a result of the development of an integrated western European grid. The rules for cooperation between power transmission system operators in Western Europe have therefore been established for several decades although the amount of physical exchange between different grids has been restricted.

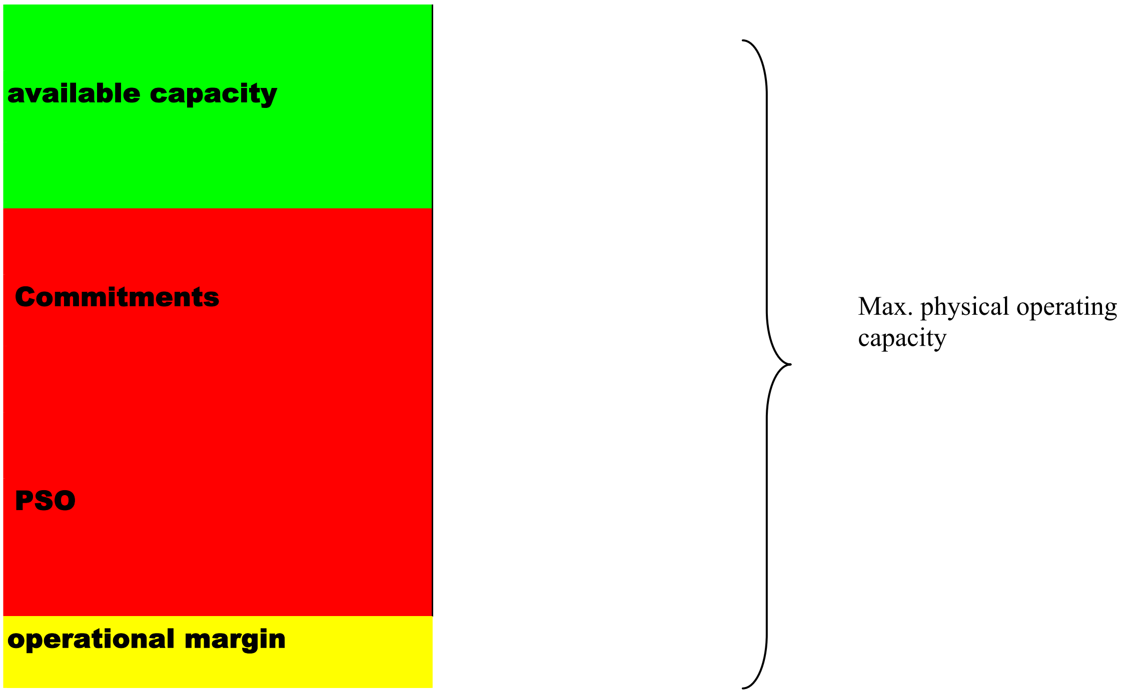
Due to the import dependence of various European gas industries and the physical flow needs in gas transmission significant cross border capacities have been established in the past.

3 Capacity in gas transmission

In its Capacity and Congestion Management Report dated 20. June 2001 GTE gave the following definition of available capacity: “Available capacity means the maximum physical operating capacity less the physical operating capacity

- necessary for the fulfilment of commitments under any valid and legally binding agreements and including the capacity necessary for non-discriminatory transportation of natural gas owned by the owner and/or operator of the system;
- necessary to fulfil any domestic laws and regulations relating to supply security (PSO [1]);
- necessary for the efficient operation of the transportation facilities including any operating margin necessary to ensure the security and reliability of the system. “

This can be illustrated as follows:



From a technical perspective the maximum physical operating capacity is determined by a number of design parameters as well as the underlying flow scenario. The main design parameters influencing pipelines capacity are described in chapter 3 and 4 of this paper. The influences of variations in flows and grid configuration on the maximum physical operating capacity of a complex network are described in chapter 5.

The booked capacity may consist of legally binding contracts and other agreements as well as the capacity that has to be reserved for the fulfilment of public service obligations.

The operational margin is necessary for the safe and reliable operation of the system.

Although different commercial models exist for selling capacity to the market no basic differences exist with respect to the principles for the calculation of available capacities.

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[1] - Public Service Obligation

4 Design parameters for the calculation of the technical capacity: pipelines

In the following section the calculation of the technical capacity of a single pipeline is described.

From a technical perspective the capacity of a pipeline is determined by a complex set of different technical design parameters like e.g. the pipeline diameter, the pressure conditions and the pipeline length and other, less significant factors which are also described below.

The determination of technical design capacities is subject to the relevant physical laws. In that context a reference is made to the basic transmission formula of Darcy/Weisbach [2] for expanding gas transmission in the high-pressure range.

In a simplified form for horizontal pipes, this formula can be expressed as follows:

$$p_1^2 - p_2^2 = \frac{16}{\pi^2} \cdot \lambda \cdot \frac{\rho_0 \cdot P_0}{T_0} \cdot \frac{T}{d^5} \cdot l \cdot K \cdot q_0^2 \qquad (1)$$

where (all values in SI units):

p_1, p_2	absolute pressures at inlet and outlet end of pipeline
λ	Pipe friction factor[3]
ρ_0	density of flowing fluid at normal conditions
P_0	normal pressure (1013.25 mbar)
T_0	normal temperature (273.15 K)
T	transmission temperature
d	inside diameter of pipeline
l	length of pipeline
K (Z/Z_0)	gas law deviation coefficient[4]
q_0	Flow rate at normal conditions[5]

This formula is based on a model of steady-state flow conditions, a reasonable approximation for design and capacity calculation purposes as the pressure potential between the pipeline inlet and outlet is fully used for gas transmission. For pipelines used for distribution purposes, the transmission temperature (average

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[2] - Also other formulas described in scientific and technical literature are currently adopted by TSO (i.e. Fergusson Formula). The results of all of them can be considered equivalent for the design of high pressure transportation pipelines.

[3] – The derivation of the friction factor can be done using Colebrook formula or other equivalent formulas (e.g. Serghides formula).

[4] – The derivation of the gas law derivation coefficient can be done using Van der Waals formula or other equivalent formulas (e.g. Redlich-Kwong, Soave-Redlich-Kwong, Peng-Robinson, Schmidt-Wenzel, London Research Station, Riazi-Mansoori, Benedict-Webb-Rubin-Starling, Lee-Kessler, AGA8).

[5] – Expressed in Nm³/h or Nm³/d (through appropriate coefficient) in case of calculation of daily capacity (according to balancing period).

temperature of the fluid) can be assumed to be equal to the soil temperature at the depth of burial of the pipeline. On gas transmission pipelines with compressor station, the gas temperature is increased by compression and it is necessary to determine the average fluid temperature over the pipeline route.

In case of significant differences in the height along the pipeline, an additional factor has to be taken into account; the contribution is an additional pressure drop in case of increase of the height, while there is an increase of the gas pressure in the pipe in case of decrease of the height.

The formula is based on a parabolic (square) function for the pressure drop during pipeline transmission. The gas industry uses the term "expanding" transmission as the pressure drop during transmission leads to an increase in the volume flow rate at flowing conditions in accordance with the equation of state for real gases. In view of the continuity law (the mass flow rate through any pipeline cross section remains constant at steady-state conditions), this leads to an increase in flow velocity over the length of the pipeline.

If the inlet pressure p_1 is taken as the maximum admissible operating pressure of the pipeline and the outlet pressure p_2 is taken as the minimum pressure that is acceptable for technical or contractual reasons, the volume flow q_0 is equal to the capacity of the pipeline. The capacity can be calculated by transforming equation (1) as follows:

$$q_0 = \frac{\pi}{4} \cdot \sqrt{\frac{(p_1^2 - p_2^2) \cdot T_0}{P_0 \cdot \rho_0 \cdot l \cdot K \cdot T}} \cdot \sqrt{\frac{d^5}{\lambda}} \qquad (2)$$

In accordance with equation (2), the relationship between the capacity q_0, the diameter d and the friction factor λ of a pipeline may be expressed in the following form:

$$q_0 \sim d^{2.5} \cdot \lambda^{-0.5} \qquad (3)$$

As the friction factor λ is an implicit function of the diameter d, λ can be expressed as a power of d and the relationship between capacity and diameter is given by the following equation:

$$q_0 \sim d^{\gamma} \qquad (4)$$

where $\gamma = 2.595$ for a roughness k of 0.07 mm (a typical value for steel pipelines without epoxy resin lining is in the range between 0.02 and 0.07 mm)

where $\gamma = 2.580$ for a roughness k of 0.006 mm (a typical value for steel pipelines with epoxy resin lining is in the range between 0.006 and 0.02 mm)

The relationship between the carrying capacities of pipelines of different diameters can be expressed as follows if the other parameters remain unchanged:

$$\frac{q_{0,1}}{q_{0,2}} = \left(\frac{d_1}{d_2}\right)^{\gamma} \qquad (5)$$

where d_1 ; d_2 [m] pipeline diameter for cases 1 and 2 (comparison case)

$q_{0,1}$; $q_{0,2}$ [Nm^3/h] (see footnote 5) capacity at normal conditions for diameters d_1 and d_2

The effect of pipeline diameter on pipeline capacity is therefore very pronounced, with an exponent of approx. 2.6. This effect may be illustrated by a specific example. The figure shows the capacity increase as a function of increasing diameter (from DN 300 to DN 1100) for an 80 km pipeline section with an inlet pressure of 52 bar and an outlet pressure of 40 bar.

The graph clearly shows that the capacity increases very steeply with increasing diameter (as a function of rather more than the square of the diameter). The capacity of a DN 1100 pipeline is some 30 times higher than that of a DN 300 pipeline.

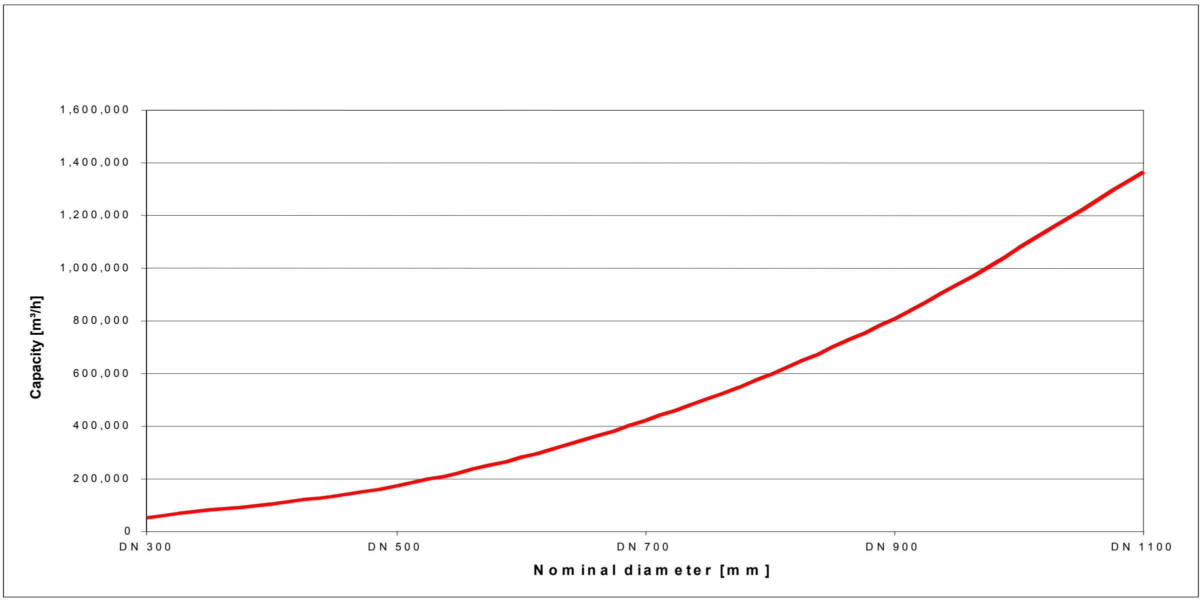

Fig. 1: Transportation capacity as a function of pipeline diameter for the selected example of an 80 km pipeline[6]

In accordance with equation (2), the relationship between the capacity and the pressure drop in a pipeline may be expressed in the following form:

$$q_0 \sim \sqrt{p_1{}^2 - p_2{}^2} \qquad (6)$$

The inlet pressure p_1 considered here is the pressure that is reliably available at the inlet of a pipeline section (i.e. the pressure laid down in contracts with the gas supplier or the pressure limited by technical factors, such as the maximum admissible operating pressure). The outlet pressure is the minimum pressure that must be maintained on the basis of gas delivery contracts with customers or for technical reasons. There may be significant variations in the inlet pressure as a function of the load situation. In this connection, it is important to consider the situation at maximum gas flow, the case used as a basis for the sizing of the pipeline. In order to express the effect of pressure on pipeline capacity, it is convenient to transform the quadratic expression of inlet and outlet pressure in equation (6)

$$p_1^2 - p_2^2 = (p_1 - p_2) \cdot (p_1 + p_2)$$

as indicated in equation (7).

$$= \Delta p \cdot 2 \cdot \overline{p} \qquad (7)$$

The quadratic pressure drop is equal to the product of the linear pressure drop and twice the

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[6] For more details please refer to „gwf Gas Erdgas Nr. 3 of 1996, „Einfluß der Rohrrauhigkeit und der Rohrreibungszahl auf die Transportkapazität und die spezifischen Kosten von Gasrohrleitungen"" from . Fasold and Wahle

average operating pressure $\bar{p}$, the average of inlet and outlet pressure. Taking into account equation (6), the capacity of the pipeline is given by a function of the following type:

$$q_0 \sim \sqrt{\Delta p} \cdot \sqrt{\bar{p}} \qquad (8)$$

With a constant linear pressure drop, the pipeline capacity increases with the square root of the available pressure drop and the square root of the average operating pressure. In practice, pipelines are typically designed for a maximum pressure drop $\Delta p/l$ of between 0.1 and 0.2 bar/km for technical and economic reasons. Under these conditions, the average operating pressure $\bar{p}$ can be seen as a variable that is relevant to pipeline capacity.

The general equations (1) and (2) indicate that there are other factors which affect pipeline capacity in addition to inlet and outlet pressure and diameter. These include:

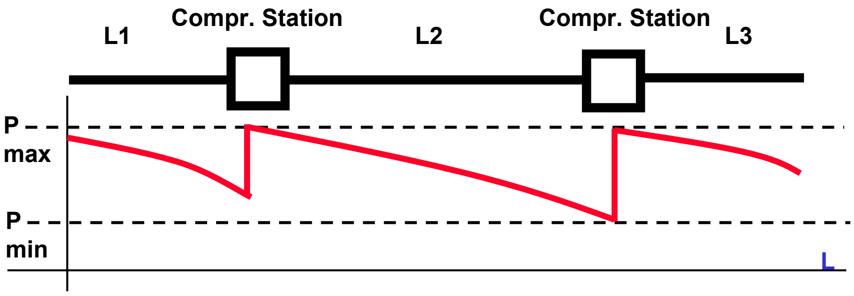
- the average gas temperature;
- the physical properties of the gas (density and gas law deviation coefficient);
- the friction factor (mainly determined by the pipe wall roughness).

It should be noted that environmental parameters like ground temperatures, heat exchange coefficients and air temperatures have an impact on pipeline capacities, i.e. the necessity for providing an operational margin.

In general, it can be stated that these factors either are only subject to variation in a very narrow range (as in the case of gas temperature and properties) or only have a relatively minor effect compared with diameter and average operating pressure. If a maximum pressure drop $\Delta p/l$ has been taken into consideration for the design of the pipeline, the effects of pipeline length may be neglected. Pipeline diameter and average operating pressure are therefore the key factors which affect the transportation capacity of gas pipelines.

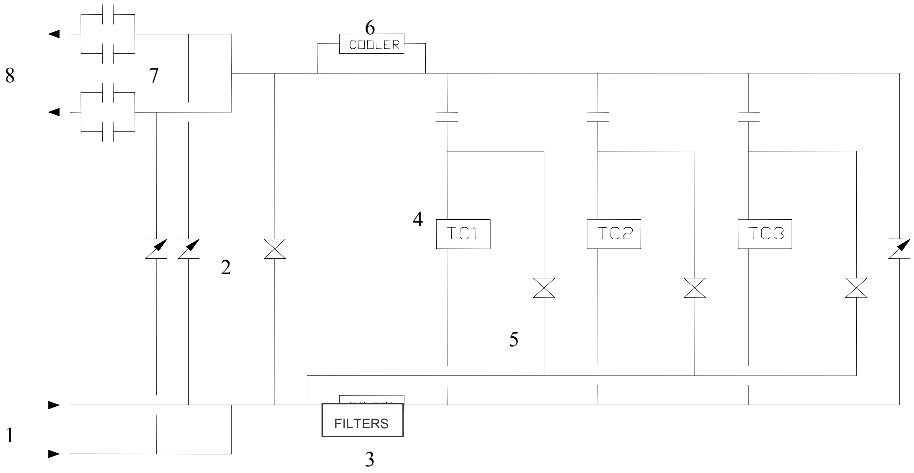
5 Design parameters for the calculation of the technical capacity: compressor stations

In the transmission networks the restoring of the necessary pressure for transportation of gas after each section of pipeline is provided by the compressor stations.



The compressor units, the equipment and associated plants in compressor stations are designed and operated to ensure a high level of reliability and safety of compressor stations.

A typical layout of a compressor station is given in the picture below.



From this sketch is possible to identify some section:

1) inlet section
2) station's by-pass
3) filters
4) compressor units
5) antisurge system
6) coolers
7) measurement section
8) outlet section

Compressor stations are connected to pipeline or near manifolds and are equipped with compression units working in parallel.

The compression process is usually made through a centrifugal compressor whose duty is to transfer mechanical energy (from a prime mover i.e. gas turbine) in terms of pressure increase.

The maximum performance of such compressor station can influence the capacity of the pipelines in many cases:

- the installed power must be enough to compress the gas from the inlet pressure provided by the upstream pipeline, to the maximum pressure in the downstream pipeline. In case of lack of power, this could result in a limitation of the minimum pressure in upstream pipeline, of the maximum pressure in the downstream pipeline or both;
- the operational curves of the compressors must be adequate to the flow and or to the inlet/outlet pressure ratio requested by the pipelines;
- all the components of the plant (filters, manifolds, gas coolers …), must be adequate to the flow requested by the pipelines.

In the next paragraphs are described the formulas used to calculate the operational parameters of the compressor station.

5.1 Process parameters

It is possible to characterize the compression process with few parameters such as the isentropic and polytropic head, isentropic and polytropic efficiency and adsorbed power.

The effective head H_{eff} is the specific real work which is supplied from the compressor station and is given by the following equation:

$$H_{eff} = L_{1,2} = \int_{P1}^{P2} v\, dp + L_L$$

where:

- $L_{1,2}$ is the work to do to move from point 1 (compressor inlet) to point 2 (compressor outlet),

P_1 and P_2 are respectively the compressor inlet and outlet pressure,

v is the specific volume of gas,

L_L is the work done to win the resistance due to gas motion.

The compressor power to be installed in compressor station is calculated taking into account pressure losses in suction and discharge sections of compressor station piping (mainly such losses are located in filters, valve, bends etc):

$$\begin{cases} P_1 = P_i - \Delta P_i \\ P_2 = P_o + \Delta P_o \end{cases}$$

The polytropic head represents the energy accumulated in the fluid as increase in thermodynamic energy, and it is given by the following equation:

$$H_{pol} = \int_{P1}^{P2} v \, dp$$

Using the relation between pressure and specific gas volume, generally of the type $pv^n = const$ where n is average exponent of the polytropic transformation between points 1 and 2, we obtain:

$$H_{pol} = \frac{n}{n-1} Z_1 R T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

where:

Z_1 is the compressibility gas coefficient in the inlet section[7],

R is the gas constant characteristic,

T_1 is the inlet temperature.

The polytropic efficiency is the ratio between the polytropic and the effective head

$$\eta_{pol} = \left(\frac{H_{pol}}{H_{eff}} \right)$$

In the design of compressor stations the value of the polytropic efficiency have to be valued on technical knowledge, while, during the check it can be calculated by the relation:

$$\eta_{pol} = \frac{k-1}{k} \cdot \frac{\ln\left({}^{P_2}\!/_{P_1} \right)}{\ln\left({}^{T_2}\!/_{T_1} \right)}$$

where k is the exponent of the isentropic-adiabatic transformation relative, with the same compression ratio, to the real transformation.

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[7] The compressibility gas coefficient is calculated using formulas described in scientific and technical literature.

The compressor adsorbed power can be estimated by the following energetic balance:

$$W = Q \cdot L_{1,2} + P_f + P_m = \left(\frac{H_{pol}}{\eta_{pol}} \right) + P_f + P_m$$

where

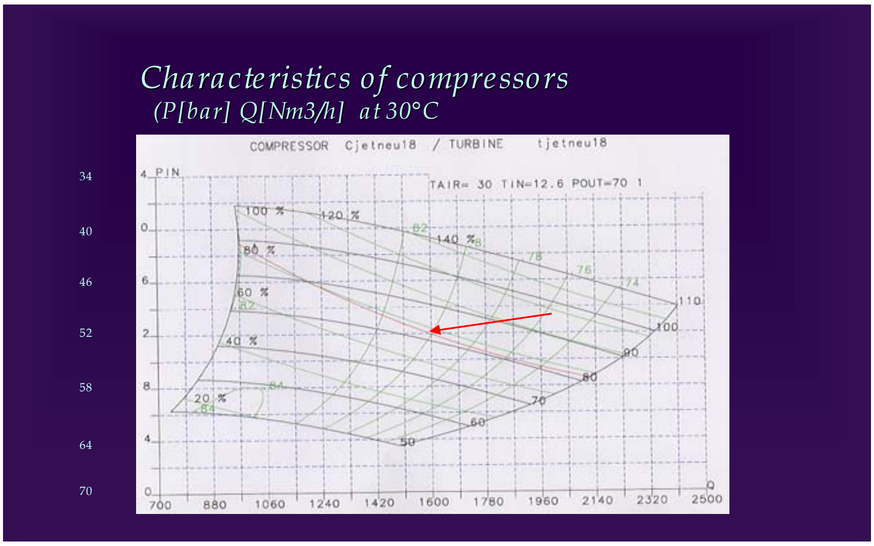
- Q is the gas flow,
- P_f is the power loss due to gas leak,
- P_m is the power loss due to mechanical friction.

In choosing the number of compression units to be installed, besides the necessary power for the compression process, the provision of spare units and the available size of gas turbine shall to be taken into account.

However the installed power has to be greater than the demanded one to have a “spare” capability to satisfy unexpected situations.

There is also an environmental influence on the available maximum power of the turbine which is illustrated in the following example demonstrating the influence of the air temperature:

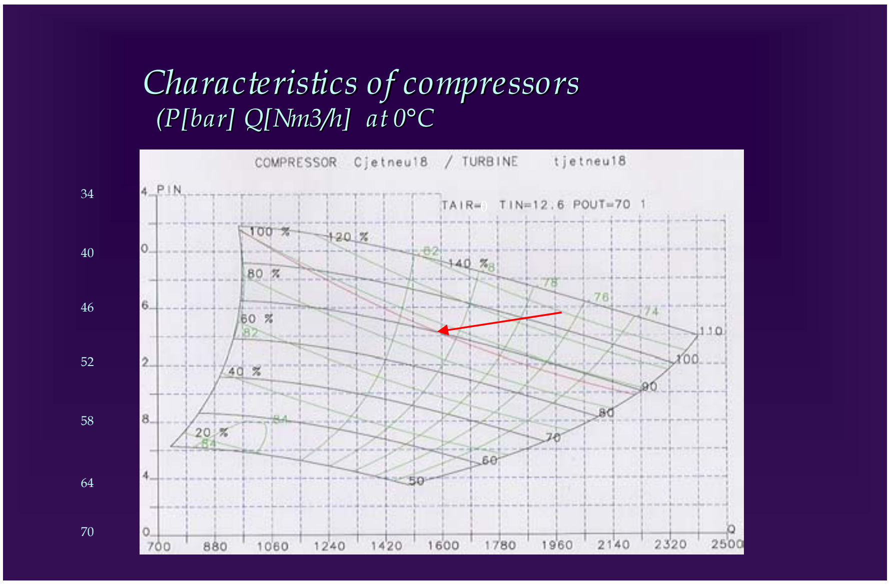
The red curve characterizes the maximum available power reducing the available operating range of the compressor.



Characteristics of compressors

(P[bar] Q[Nm3/h] at 30°C

Maximum turbine line at 30°C



Characteristics of compressors
(P[bar] Q[Nm3/h] at 0°C

Maximum turbine line at 0°C

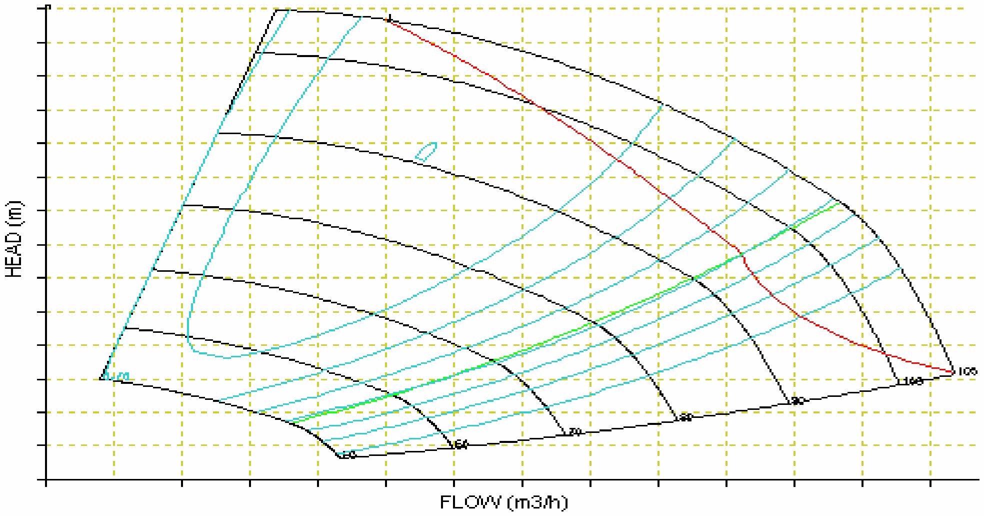
5.2 Characteristics of compressors

For each compressor the supplier makes a map where isospeed and isoefficiency are drawn on the head/flow diagram. On the y-axis, instead of the head, the compression ratio can be indicated.

The following picture shows a typical map of a centrifugal compressor for pipeline application. It is possible to identify some curves which define the map contours:

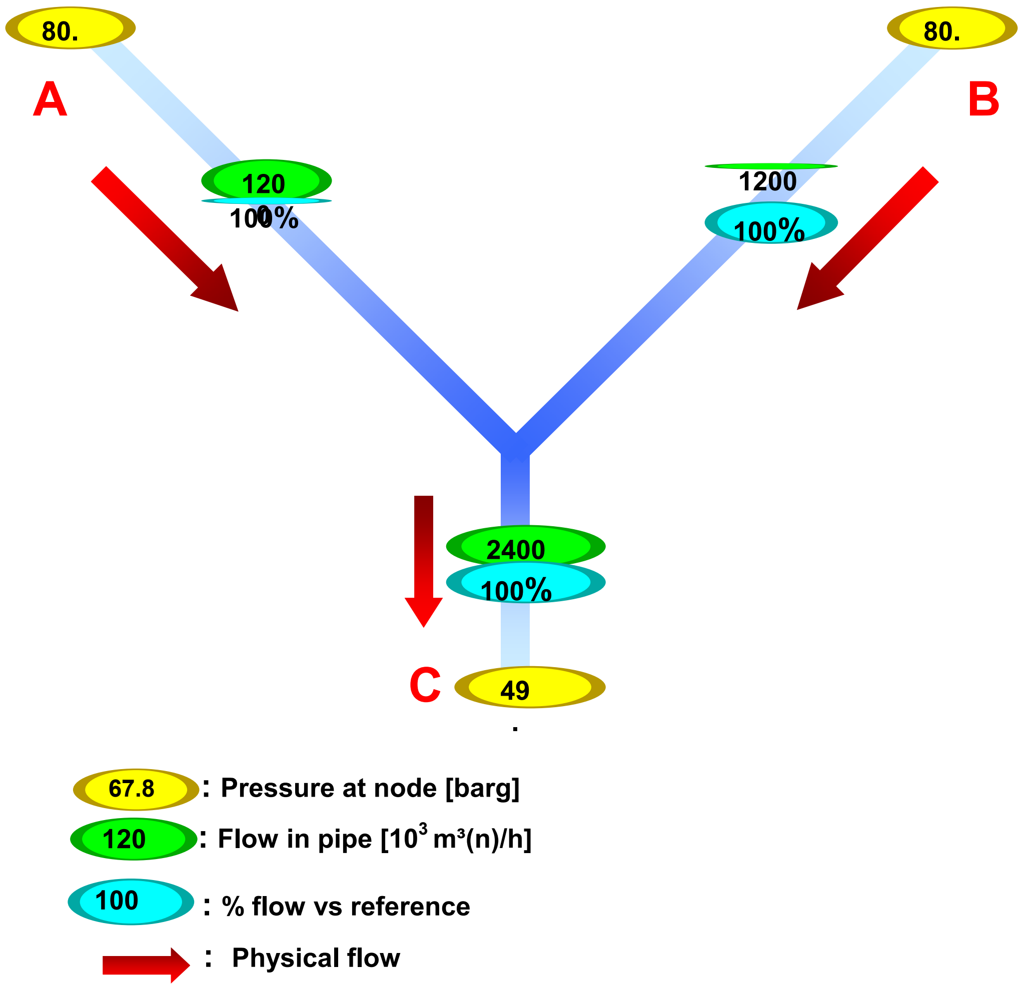
- surge line;
- maximum speed;
- minimum speed;
- chocking line.

These curves define the operation area of the centrifugal compressor. In the same picture is indicated, in red, the maximum available power, over which the turbine can’t drive the compressor.



6 The influence of variations in the flow patterns on maximum physical operating capacity

It has already been stressed that the prevailing flow pattern in the system have a great influence on maximum physical operating capacity. The following examples illustrate that although the hardware of the system is always the same, completely different maximum physical operating capacities may result as a consequence of variations in the underlying flows of the grid, i.e. the grid configuration. This grid is composed of three nodes A, B and C – possibly cross-border points– and three pipelines that are interconnected at one point as shown in the following picture. The pressure at the nodes must be between 49.0 and 80.0 barg.



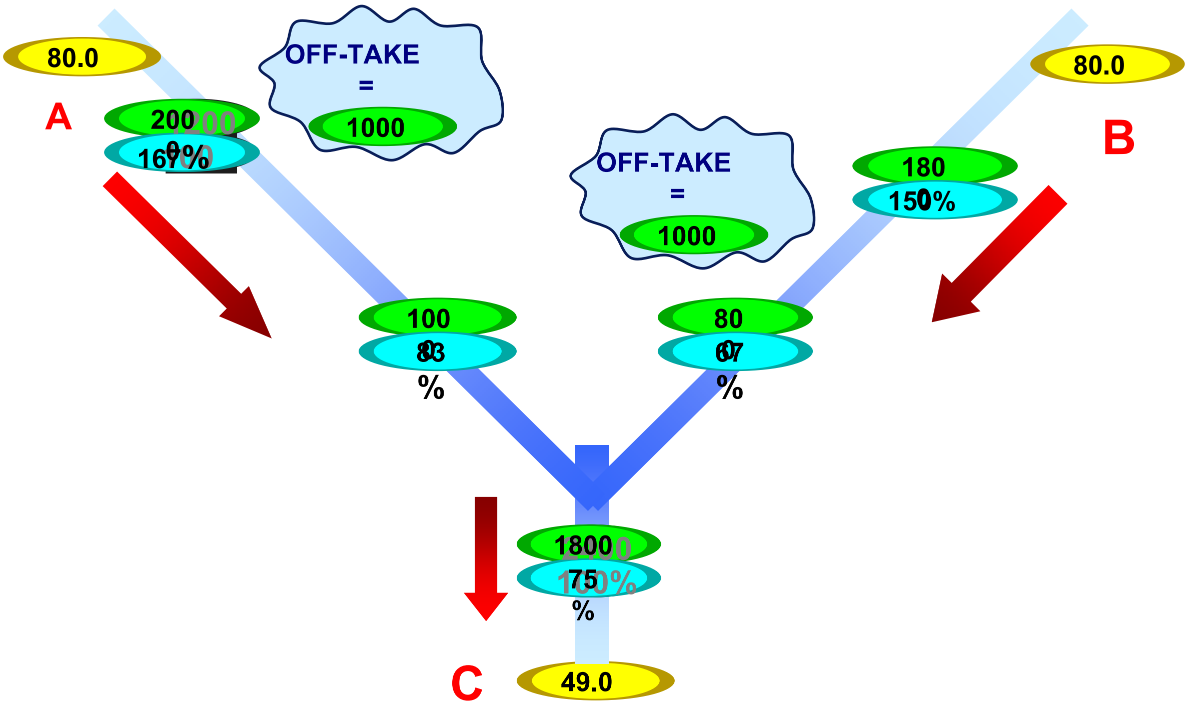
First example: reference situation

In the first example (see previous picture), the flow pattern of the previous picture is assumed. Gas is flowing from A to C and from B to C. There is no off-take between the three nodes of the grid.

In this case, the capacity of the grid is determined only by the pressure at nodes A, B, C. The maximum physical operating capacity is achieved when the pressure is highest at nodes A and B (80 barg), and lowest at node C (49 barg). Under these conditions, the capacity of the grid can be determined precisely at each interconnection point: 1200*10^3m³(n)/h from A, 1200*10^3m³(n)/h from B and 2400*10^3 m³(n)/h to C. This situation is called the reference situation.

Second example: intermediate off-take

In the second example (see next picture), an off-take of 1000*10³m³(n)/h is added at some place between node A and the interconnection point, and an off-take of 1000*10³m³(n)/h at some other place between node B and the interconnection point.

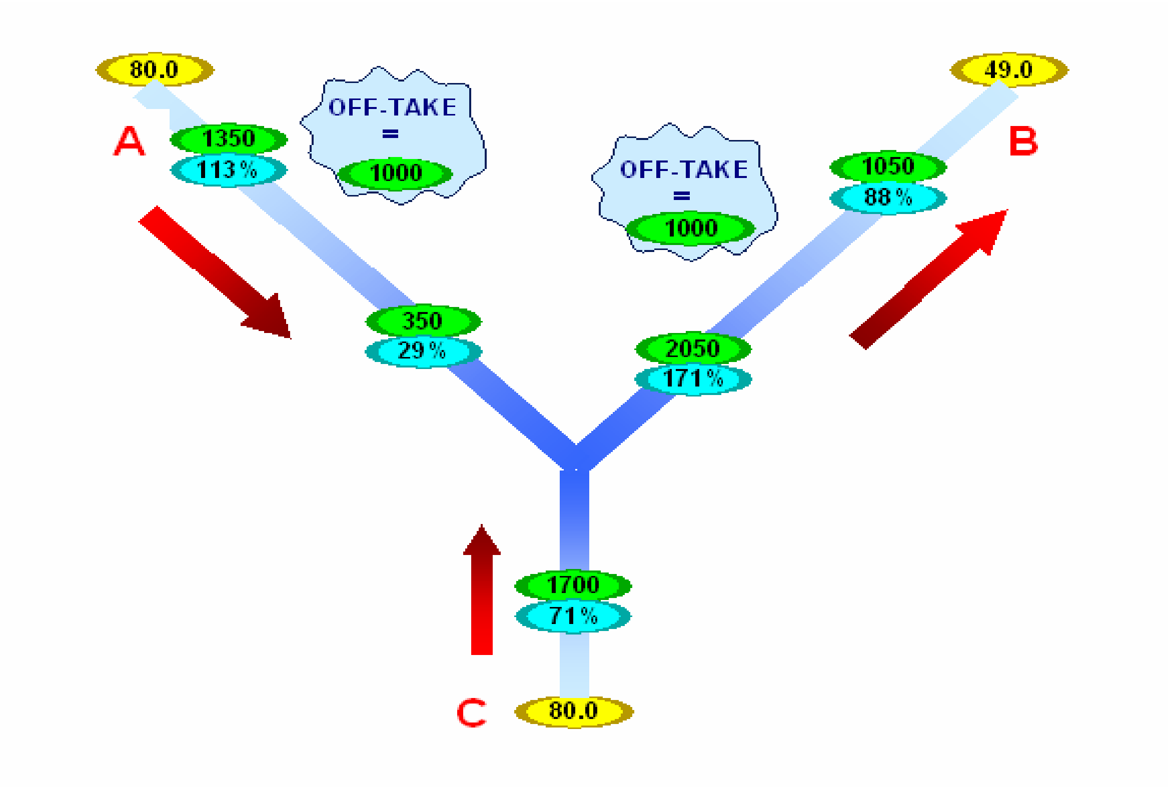


In this case, the maximum physical operating capacity of the grid is achieved under the same node pressures as in the first example: 80 barg at nodes A and B, and 49 barg at node C. But, due to the additional off-take on the grid, the capacity at the node C is reduced to 1800*10^{3}m³(n)/h instead of 2400, or 75% of the capacity calculated in the first example. On the contrary, capacity at nodes A and B is increased, due to the additional off-take at a shorter distance than node C : 2000 and 1800*10^{3}m³(n)/h, respectively, instead of 1200*10^{3}m³(n)/h, or 167% and 150% respectively of the capacities at nodes A and B. But capacity further in the grid is reduced significantly with respect to the previous example : 75% on the leg near the C node.

The second example shows that an additional off-take at some place of the grid increases the capacity at the nodes from where the gas is flowing (A and B), but reduces capacity further in the grid to the nodes where the gas is delivered (C). In addition, the increase or decrease of capacity depends on the location and amount of the off-take.

Third example: reverse flow in one leg

In the third example (see next picture), another flow pattern is assumed: gas is now flowing from A to B and from C to B: the flow is reversed at B and C. The off-take of $1000*10^3$m³(n)/h is still assumed at some place between node A and the interconnection point. The off-take of $1000*10^3$m³(n)/h at some place between node B and the interconnection point is also assumed. Gas to this last off-take point is provided by nodes A and C, instead of B.



In this case, the maximum physical operating capacity of the grid is achieved when the pressure is highest at nodes A and C (80 barg), and lowest at node B (49 barg). At node A, the capacity is increased to 113% of the initial capacity, but the capacity flowing into the node C is reduced to 71% (absolute value) of the initial capacity and the capacity flowing from the node B is reduced to 88% (absolute value) .

The third example shows that a different flow pattern (reverse flow) leads to a strongly different capacity distribution in the grid and at the nodes. This means that the maximum physical operating capacity of a grid is strongly influenced by the grid configuration.

7 Conclusion

Available capacities at cross border nodal points are the net of maximum physical operating capacity, already existing capacity commitments incl. public service obligations and the operational margin necessary for safe and reliable operation of the system.

Based on the physical laws of gas transmission in pipelines the maximum physical operating capacity can be calculated for a given flow pattern, i.e. a well defined set of technical system and deliveries to and off-takes from the system.

The methodology to determine maximum physical operating capacities and then the available capacities is applied internationally and is “state of the art” from the engineering perspective.

The choice of flow scenarios is specific to each TSO due to the existing differences in the systems. The main factors are:

- number, location and level of use of the different sources
- number and size of interruptible customers
- transit ratio
- market participants behaviour

Even the predictability of these factors is different from system to system.

In general terms the flows delivered to the internal market with a restricted number of sources, a limited number and size of interruptible customers and of transit flows are more predictable.

This implies that in some cases the assessment of the maximum physical operating capacity has to be based on several flow scenarios.