Improving the performances of the gas pipeline using the low temperature for the different climate countries.

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Abstract Currently the tendency is with the transport of increasingly significant quantities of gas at distances increasingly large (intercontinental) and under increasingly severe conditions (example future the gas pipeline Nigeria Europe while passing by Algeria (4000 km); the existing gas pipeline Urengoy - Ujgorod (4451 km including 120 km located in a cold ground) or North America which has a extremely mesh network which extends to Alaska

The need for ensuring the transport of gas at long distance passes through the development of the means of transport but this development involves exploitation and increasingly significant capital costs.

The purpose of this paper is to show what are the different parameters that affect the performance of a gas pipeline and in particular the temperature of the transported gas. Will be first a pipeline with temperature limit of gas equal to the temperature of the ground then will be the transport of gas to temperatures below freezing. It comes also to materials used in 2 cases and individuals of construction of a gas pipeline at low temperature.

The parameters that affect the performance are:

1) the diameter and pressure on the optimal parameters of transport;
2) the temperature on the optimal parameters of transport;
3) Influence low temperatures on the availability of the tubes, the effectiveness of transport and the environment;

It is a question of the impact about the generated energy saving and environment of the gas pipeline transport at sufficiently low temperatures.

In conclusion we will consider the applicability, the degrees of effectiveness obtained for various values of temperature and the limits of the temperatures according to the used tubes.

1 Introduction.

The optimal parameters choice of a gas pipe is a fairly complex problem which resolution requires taking into account an important number of factors. Nowadays the recurrent questions that are asked are: the optimisation criteria choice; the parameters to be introduced and the possible different variants.
To which does this gas transport optimisation consist of? All leads to the choice of:

- A pressure,
- A canalisation,
- Compression stations.

The pipeline represents a primitive investment, impossible to echelon in time, of a very high cost, of an important lifetime and of reduced exploitation cost. The compression station on the contrary can be differed, modified (reinforced or reduced); they have a reduced lifetime and a high exploitation cost, essentially, because of the recompression energy:

- Economising on the canalisation (by choosing a smaller diameter) or on the stations equipment (by reducing the number) increases the recompression energy expenses.
- In the same, economising the recompression energy leads to a more important investment (in canalisation for example)

The optimisation problem can be divided into 2 parts:

1) The study of the transport different factors influence including:

optimal rate flow ; space between stations and the compression ratio ; gas pipe diameter ; the working pressure ; TC type and the station scheme ; used metal mechanical properties.

2) The other approach is the study of the gas pipes construction exploitation conditions.
   (Field study; meteorological conditions etc…)

2 Diameter and pressure influence on the transport optimal parameters

The expression of the rate flow can be written:

$$Q \;=\; 0{,}785\, D^{2,5}\, \frac{Pi}{\rho} \sqrt{\frac{1-1/\varepsilon^2}{Z.R.T.\lambda.lsc}} \qquad (1)$$

Where : D- pipe internal diameter; P_i – pipe section initial pressure; $\varepsilon = P_i/P_f$ –compression ratio; P_f – final pressure; T and Z- mean values of the temperature and the compressibility coefficient; l_{sc} – pipe section length between 2 compression stations neighbours.

In this equation we note the important role attributed to the pipe diameter and its influence on the gas pipe rate flow. Nowadays this problem has been solved by the increase, due to the technological progress, of the pipe diameter up to 1420 mm for pressures of 75 kgf/cm^2 and more. However this increase doesn't occur without inconvenient. In fact the diameter increase goes with construction and exploitation problems.

1. The construction problems appear with the necessary thickness increase which increases the pipeline weight and rigidity. The increase of the thickness and mass creates welding problems and problems when installing the sections of the pipeline. The diameter increase requires a greater hold and therefore, an increase in the civil engineering works. With the canalisation diameter increase, so does the contact surface with the ground which will entrain an increase in the coating volume then a greater deterioration risk during the installation and exploitation. The coating volume increase requires a greater attention, and therefore more important expenses for the pipeline cathode protection. This has stimulated and still stimulate the emergence of new installation techniques and the elaboration new types of steel permits to diminish the steel volume and increases the pipeline reliability.
2. From a technological point of view, the pipeline diameter increase requires an increase in the installed turbocompressors power of the compression stations and the diminution of the gas temperature.

The compression station developed power can be expressed by the following thermodynamic relation:

$$N_{SC} = B\frac{m}{m-1}.Q.T_{asp}\left(\varepsilon^{\frac{m-1}{\eta.m}} - 1\right) \qquad (2)$$

m – gas adiabatic coefficient ; Q – transported volumic rate flow ; T_{asp} – admission temperature ; ε – compression ratio ; η – the efficiency if the transformation is polytropic ;
This power is directly proportional to the transported rate flow that is to the diameter power 2.5 (formula 1) which gives us this equation:

If D increases, then Q increases, then N_{SC} increases, then the compressor power increases leading to the use of a more powerful entraining turbine. This means that the temperature at the compressor discharge increases (formula 3)

$$Tref \;=\; Tasp\ .\varepsilon^{\frac{m-1}{m.\eta p}} \quad °K \qquad (3)$$

Where: T_{asp}: Admission temperature (°K); m: Specific heats ratio; η_p : Compressor polytropic efficiency.

For the turbines used nowadays (up to 25000 kW and more) the gas temperature at the station outlet is fairly great. The temperature increase influences, not only in a negative manner on the transported rate flow (formula 1) but it entrains a diminution in the pipeline reliability. In fact in one hand, the released heat will not have the time to dissipate in the environmental medium which entrains a gas temperature increase at the inlet of the next station ; on the other hand there is a difficulty in maintaining the pipeline stability and a perfect coating against the corrosion.

We can conclude that the diameter increase doesn't entrain only advantages (rate flow increase) but inconvenient on the economical side.

The realised research results have shown that:
1) With the pipeline diameter increase, transport costs decreases; but this diminution slows down with the diameter increase. This is visible for diameters 1220-1420 mm (48" -56"). From this diameter the increase doesn't give appreciable economical effects.
2) The questions of ballast, welding, laying and hydraulic tests are more difficult to resolve using a 48" diameter.

3) The economical diameter doesn't depend on the transport length, the available pressure at the origin, nor on the required pressure at arrival.
4) It only depends on the rate flow Q and the retained working pressure.

3 Service pressure influence

The other important parameter that we must take into account is the service pressure (formula 1). The gas transport in the economical conditions requires high transport pressures, and then the use of high elasticity steels. More, the installations security requires a good tenacity in order to avoid the structure destruction by rapid fissures propagation.
The increase of the service pressure necessarily entrains an increase of the transported quantity, but this increase, as for the rate flow, has its limits. In fact, studies on the gas pipes optimisation problems [56] have shown that above a pressure of 75 kgf/cm^2, the economies of transport are not evident. These studies are carried out for pressures of 55, 75 and 100 kgf/cm^2.

As we can see, the factors which influence the rate flow increase are a lot. We can cite again the pipeline roughness which influence is expressed by the following formula:

$$\lambda \cong 0{,}067\left(\frac{2.Ke}{D}\right)^{0{,}2} \qquad (4)$$

The study has shown that the roughness diminution from 30 to 10 microns can increase the flow by 4 to 6 % for a 56" diameter. The increase of the pipe rate flow entrains an increase in the supplied powers on the compression stations. This entrains an increase in the temperature at the compression station inlet and outlet. The formula can be written, for a pipe section as follows:

$$T_{ref\ i+1} = T_{asp_{i+1}}.\varepsilon^{b} \qquad \text{with } b = (m-1)/(\eta_p\ m) \qquad (5)$$

From another side, the temperature variation on the section is expressed by (neglecting the Joule-Thompson effect)

$$T_{asp_{i+1}} = T_{si} + (T_{ref\ i} - T_{si}).e^{-a\,l} \qquad (6)$$

Where: a – Choukhov coefficient: $$a = \frac{K.\pi.D_{ext}}{M.C_p} \qquad (7)$$

K – heat transfer coefficient ; M – mass rate flow ; D_{ex}t – pipe external diameter ; T_i – initial temperature ; T_a – ambient temperature ; Cp ; gas specific heat.

We can establish a link between the station outlet temperature and the surrounding ground temperature from the formulae 5 and 6.

$$T_{ref\ i+1} - T_{refi}\,\frac{\varepsilon^{b}}{e^{al}} = T_{si}.\varepsilon^{b}.\frac{e^{al}-1}{e^{al}} \qquad (8)$$

Or

$$\varphi = \frac{T_{ref\ i+1}}{T_{ref\ i}} = \left[\frac{Ts_i}{T_{ref\ i}}\left(e^{al}-1\right)+1\right]\frac{\varepsilon^{b}}{e^{al}} \qquad (9)$$

In order that the gas temperature at the inlet and outlet of two successive stations will not increase ie $\varphi \leq 1$, we obtain from formula (9) the following condition:

$$\frac{Ts_i}{T_{ref\ i}} \leq \frac{e^{al}-\varepsilon^{b}}{e^{al}-1}.\frac{1}{\varepsilon^{b}} \qquad (10)$$

The realisation of this condition in the pipeline exploitation real case, (compression ratio, discharge pressure, rate flow, diameter and ground temperature), requires that the gas discharge temperature exceeds the ground temperature of only 1.5 to 2 times. Knowing the average ground temperature we can say that this condition is impossible without gas cooling at the station exit. In the opposite case, the gas temperature increases from station to station up to a limit expressed by the relation (10). The temperature is limited by the coating type and the pipe stability conditions.

From the other side, we have to take into account the possibility of increasing the rate flow by doubling the stations (or diminution of the distance between stations) , this entrains an increase in the stations power and therefore an increase in the station entrance temperature.

From relation (1) we note that the temperature influences not only in a direct manner the rate flow but also in an indirect manner. In fact, with the gas temperature diminution the compression coefficient diminishes, this entrains a rate flow increase. We can evaluate the rate flow increase rate by the following formula:

$$\chi = \frac{Q}{Qo} = \sqrt{\frac{ZoTo}{Z.T}} \qquad (11)$$

By decreasing the temperature, at constant pressure, we reduce the transported gas specific volume, which permits to increase the canalisation transport capacity. From the curves SPE/AIME, by considering natural gas transport at 8 MPa (mega Pascal) for a transport temperature lowered of 50°C to -30°C, we observe that compressibility factor diminishes with the temperature of 0.92 to 0.72. We observe that the temperature incidence on the specific volume is clearly more important for natural gas than for a perfect gas case.

4 Pipeline thermal influence at low temperature on the environment in regions with freezing ground.

The principal problem during the pipeline study at low temperature is the choice of the admissible temperature on the pipeline external surface. This temperature determines the zone and the ground cooling intensity around the canalisation. Also the cooled ground entrains the swelling effect and the pipeline stability loss, mainly on the sections with high humidity concentration (defrost ground, rivers and water crossing, swamps etc…)

During the heat exchange process between the pipeline and the surrounding medium, we have to consider the following approaches:

1) Stationary thermal regime study i.e. the regime type for which is the canalisation exploited during a certain number of years.
2) The second approach consists to study the heat transfer dynamic effect i.e. the variation of the gas temperature field, the insulator and the ground surrounding the canalisation
3) The third approach is linked with the determination of characteristics from reciprocal thermal influences on the basis of experimental modelling with exploitation data.

There are 3 pipeline construction types: the buried pipelines; those on the ground and those which are supported.

1) Habitually the pipeline construction of the 1^{st} type is carried out when the ground is frozen because of the difficulties met when the ground is defrosted. From this fact the initial pipe state is determined by the laying and coating. The pipe being recovered by movable and frozen ground we can say that there is not a real link between the pipe and the ground; the pipe may move if tangential forces appear along it. In this case we are in presence of best exploitation conditions for the buried pipe.

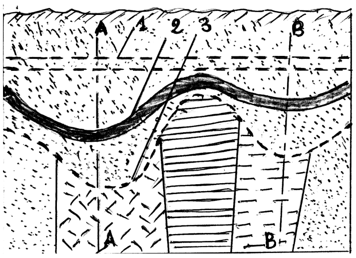
The exploitation start can be done in 2 cases:

a) The transported gas has a temperature less than 0°C.
b) The transported gas has a temperature more than 0°C.

In the 1^{st} case, the pipe exploitation conditions don’t undergo changes because there will not be any ground characteristic changes; it remains always frozen.

In the 2^{nd} case we are in presence of a heat transfer between the pipe and the ground which will defreeze the ground around the pipe (fig 1). If the surrounding ground is homogenous then we note a pipeline repositioning along its path in the heated ground layers where there isn’t any constraint. On the contrary if the ground is not homogenous the ground characteristic variations along the path influence negatively the pipe stability because of the thaw process difference of every type of ground, then a difference between the sections transversal displacements along the pipe. This is mainly the characteristic of stratified ground layers, cellular and also ground with different nature ice layers.

We assist then to a ground falling which leaves the pip suspended and this can provoke in some cases a pipe rupture.



1 – Initial pipe position after the installation;
2 – Pipe position after the thaw;
3 – Thaw zone limit.
A-A and B-B - Sections where dangerous tensions appear for the pipe resistance.

Fig.1. pipe displacement following a ground thaw.

The ground freezing and thaw cycle in function of the cooling speed and the temperature gradient can provoke the texture formation which will provoke fissures perpendicularly to the pipe axis and therefore contact constraints of the higher part of the pipe with the ground.
A buried pipe is necessarily protected by an insulator layer against corrosion. It is evident that the tangential constraints after, ground freezing and thaw provokes the insulator destruction then the necessity to take into account the insulator quality and resistance.

1) The percentage of frozen grounds (Heginbottom and Radburn, 1992) is used to define the three susceptibility classes (low, moderate, high) of the different impermeable and frozen in permanence ground. The ground instability is inversely proportional to the frozen ground percentage. We estimate that a continuous frozen ground less susceptible to the ground landslide that a discontinuous frozen ground, and is less affected by the thermal regime changes in the ground.
2) The susceptibility of grounds with different ice tenors (from null to high; Heginbottom and Radburn, 1992) is divided in tree classes: low, moderated and high. The ice in the frozen ground appears under the form of lenses, thin layers and reticulated and rectangular veins, and equally under the form of massive ice in the limonous clays. The ground with null to low ice tenor is less subject to landslide, because they have a weak risk to be under high interstitial pressure during the thawing. On the contrary, the grounds with high ice tenor contain more water, which can increase the interstitial pressure and then diminishes the ground stability.
3) The landslide can be caused by frequent movements, in the case of slope, which can open several fissures caused by the tension and the fissures would be unfiltered by water. If we again the ground is clayey, the surface clay of this zone has a tendency to fill the fissures itself without intervention, it may be that the fissures caused by tension are obturated by imprisoning an excess water volume and by avoiding the fissures detection. The imprisoned water way then increases the pressure by provoking other rapid movements. It is practically impossible to detect rapid movements.
4) It will then follow pipe torsion because of the longitudinal compression caused by the interaction of the pipe and ground during a rapid and sudden ground displacement. The pipe will then be ruptured under the effect of a greater tension than its design limit. In order to limit the natural gas emissions in case of rupture caused by a landslide, we must install a number of stop gates in case of a pressure drop near the instable grounds.

In the case of a pipe lying on embanking ground (fig.1) there is no contact between the pipe and frozen ground, but the problems remain concerning the pipe stability. In fact if the pipe lying has been done in winter when the ground is more stable, in summer during the thaw there will be an embanking collapse with pipe 2 following a non identical process in function of the ground nature. The pipe can remain suspended in certain places of the ground. If gas is transported at negative temperature there will not be any pipe problem stability; but if it is transported at positive temperatures then, with the embanking reheat there will be formation of a corona limited by line 4.

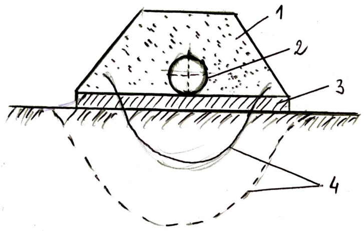


Fig.2. Pipe on embanking

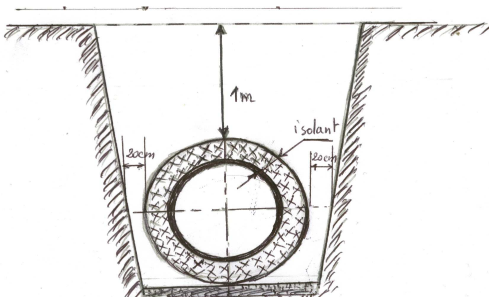


Fig.3. Pipe in trench

Gas cooling admissible level

The gas cooling during the transport by pipeline is a very efficient mean to increase the reliability and gas rate flow in the pipe. The gas cooling is habitually carried out for economical reasons, by aero refrigerant which lower the temperature up to 10 to 15°C above the air temperature. The ambient air temperature seasonal variation negatively influences the working regime of the pipe and compression station. In summer the gas temperature at station outlet attains 45-50°C even in the Northern zones of the planet.

The gas temperature in winter can attain in countries like Russia and Canada, -5 to -10 °C and more in function of the pipe metal stability when cold. From this fact, the gas pipeline functions along the year at variable thermal regimes where it undergoes thermal deformations and movements along the path. This requires an anticorrosive isolation, stability against the thermal variations and an adequate electrochemical protection.

During the lying and exploitation of the buried pipe in the highly humid zones where the ground is not capable to protect the pipe against movements due to temperature variation this can provoke in long term the anticorrosive insulator deterioration and the loss of the pipe stability. For all these reasons, it is necessary to cool the gas to a temperature near surrounding ground temperature along the year.

The choice of the convenient temperature is determined through the hydraulic and thermal calculations for gas pipeline, compression and cooling station, taking into account the influence on the ecosystem.

Following the gas temperature diminution there is discharge power diminution of the station and a power increase in the cooling stations. The great challenge is the elaboration of a metal type enough economical and with great reliability which could insure a greater resistance to deformations due to thermal constraints along the path.

The 2nd important problem is the immediate environment preservation around the pipeline. For buried gas pipe transporting gas at low temperature, this problem is aggravated by these temperatures action on the ground. It impossible to avoid the problem by an insulating matter solution because it entrains the use of great quantities of insulating layers, this entrains an increase in the laying constraints mainly in sever Northern climatic conditions. All these considerations influence the gas pipe technical and economical studies.

Gas pipe hydraulic and thermal calculations at low temperature

Let's consider the case where we desire to transport gas at sufficiently low temperatures and at pressures up to 75-120 kgf/cm^2. for such conditions it is necessary to have a look on the hydraulic and thermal calculations specificity; i.e. to consider the discrepancy effect between the real and ideal gas properties. That's why the temperature and pressure variation influence its volume V and the Joule-Thompson coefficient Dj.

The quantitative evaluation of these effects goes with the differential equations system resolution for the movement and energy. For stationary conditions they can be written under the form:

$$\rho.\frac{\partial\left(\frac{1}{2}.w^2\right)}{dx}+\frac{dp}{dx}+\lambda.\rho.\frac{w^2}{2D_0} = 0 \quad (12); \qquad M.\frac{d}{dx}\left(i + \frac{w^2}{2}\right)=q_{ext} \quad (13)$$

Where: w – flux speed; V – gas flux specific volume; i – flux enthalpy;
M – Gas mass rate flow; q_{ext} – external influx heat;

Furthermore let us write the continuity and state equations (where F – pipe transversal section)

$$M=\frac{w.F}{V}=\rho.w.F \quad \text{With} \quad V=\frac{1}{\rho} \quad (14); \qquad V=V(p,T); \quad i=i(p,T) \quad (15)$$

To determine the heat flux variation we habitually use the equation:

$$q_{ext} = K\pi D_0\left(T_s - T(x)\right) \quad (16)$$

Where K – heat transfer coefficient referred to the pipe external diameter;
Tx – gas temperature variable along the pipe path.

If in the formulae 12 and 13 we neglect the kinetic inertia factor ($w^2/2$) and if introduce the enthalpy i and the specific volume V dependence on the temperature and pressure we obtain the following relation, which expresses the pressure and temperature repartition along the pipe :

$$\frac{M^2}{gS^2}.V(p,T).\frac{\partial V(p,T)}{\partial T}.\frac{dT}{dx} + V(p,T)\left[1+\frac{M^2}{gS^2}.\frac{\partial V(p,T)}{\partial p}\right].\frac{dp}{dx} + \xi\frac{V^2(p,T).M^2}{2.g.D.M^2} = 0 \quad (17)$$

$$\frac{d}{dx}\left[\rho.w.\left(u+\frac{p}{\rho}\right)\right] = \frac{4k\left(T_s - T_{(x)}\right)}{D_0} \quad (18)$$

But:

$$\frac{\pi.D^2}{4}.\rho.w = M \quad \Rightarrow \quad d\left(u+\frac{p}{\rho}\right) = \frac{k.\pi.D_0\left(T_s - T_{(x)}\right)}{M}.dx \quad (19)$$

This equation permits to resolve the temperature repartition question along the pipe.

The expression $u+\frac{p}{\rho}=i$ enthalpy. By taking into account that i = i (T,p) we have :

$$\frac{di}{dx} = d\left(u + \frac{p}{\rho}\right) = \left(\frac{\partial i}{\partial T}\right)_p.dT + \left(\frac{\partial i}{\partial p}\right)_T.\frac{dp}{dx} \quad (20)$$

Let us examine now the term $\left(\frac{\partial i}{\partial p}\right)_T$. By posing i = const.. we can write :

$$di = \left(\frac{\partial i}{\partial T}\right)_p.dT + \left(\frac{\partial i}{\partial p}\right)_T.dp \quad \text{then} \quad . \left(\frac{\partial i}{\partial p}\right)_T. = -\left(\frac{\partial i}{\partial T}\right)_p.\left(\frac{\partial T}{\partial p}\right)_i \quad (21)$$

The terms $\left(\frac{\partial T}{\partial p}\right)_i = D_j$ - Joule-Thompson coefficient; (22)

$\left(\frac{\partial i}{\partial T}\right)p = Cp$ - Specific heat at constant pressure (23)

Then

$$di = d\left(u + \frac{p}{\rho}\right) = Cp.(dT - Dj.\,dp) \quad (24)$$

The equation (19) becomes then:

$$Cp.(dT - Dj.\,dp) = \frac{k.\pi.D_{ext}\left(T_s - T(x)\right).\,dx}{M} \quad (25)$$

On the other hand :

$$a = \frac{K.\pi.D_{ext}}{M.Cp} \quad \text{we obtain :} \quad \frac{d\left(T-T_s\right)}{dx} + a\left(T-T_0\right) = D_j\frac{dp}{dx} \quad (26)$$

Furthermore $\frac{dp}{dx} \cong \left(\frac{P_1 - P_2}{L}\right)$ we obtain after integration:

$$T(x) = T_a + (T_i - T_a).e^{-a\,x} - Dj.\frac{\left(P_1 - P_2\right)}{a.L}.\left(1 - e^{-a.x}\right) \quad (27)$$

Temperature repartition formula by taking into account the Joules-Thompson effect.

Heat exchange coefficient.

The general formula for the heat transmission coefficient is written:

$$\frac{1}{K.D_{int}} = \frac{1}{\alpha_1.D_{int}} + \sum_{i=1}^{n} \frac{1}{2.\lambda_i} \ln \frac{D_{i+1}}{D_i} + \frac{1}{\alpha_2.D_{ext}} \qquad (28)$$

Or for diameters D_{ext} > 500 mm:

$$\frac{1}{K.} \cong \frac{1}{\alpha_1} + \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2} \qquad (29)$$

D_{int} and D_{ext} – internal and external pipe diameter; n – number of insulating layers;
D_i – internal diameter of each layer; D_{i+1} – external diameter of each layer; α_1 – heat exchange coefficient between the product and the pipe wall; α_2 – heat exchange coefficient between the pipe external surface and the medium; λ_i – coating thermal conductibility coefficient.

1) Case where the gas pipe crosses unfrozen grounds (ground temperature over 0°C).

$$\alpha_2 = \frac{2\lambda_s.B_{i2}}{D_{ext}(1+A_0.B_{i2})} \quad (30); \qquad B_{i2} = \frac{\alpha_a.C}{\lambda_s} \quad (31); \quad C = \sqrt{h^2 - R_{ext}^2} \qquad (32)$$

$$A_0 = \ln\left[\frac{2h}{Dext} + \sqrt{\left(\frac{2h}{Dext}\right)^2 - 1}\right] \qquad (33)$$

Bi_2 – bio criterion; α_a – transmission coefficient from the ground surface to the atmosphere;
h – Laying depth up to the pipe axis;

For this type of ground we should only decrease the gas temperature to the ground temperature (10 - 15°C) then in this case ($T_i = T_a$) from formula (27):

$$T_f \approx T_a - Dj\frac{(P_i - P_f)}{a.l}.\left(1 - e^{-a.l}\right) \rightarrow T_f < T_a \qquad (34)$$

Example:
For l = 118 km; P_i = 73 kgf/cm^2; P_f = 49 kgf/cm^2; T_a = 287 °K; al = 0.83; K = 1.7 N/m^2 °K; D_j = 0.35 °K/kgf/cm^2 we obtain $T_f \approx$ 281 °K and T_m = 289 °C rather than 313 °K, if Ti = 330 °K which gives a pipe rate flow increase of 4 %.

The heat transmission coefficient in the preceding formulae is written for two distinct cases:

a) For a gas pipe with a good quality insulator we can neglect the gas and ground thermal resistance. In this case for one insulator layer :

$$K = \frac{1}{\frac{R_0}{\lambda is} \ln \frac{R_n}{R_0}} \qquad (35)$$

With λ_{is} – insulator thermal conductibility coefficient, D0 – pipe internal diameter, D_{ext} – insulator external diameter.

2) If the pipe transporting the gas at low temperature doesn't have thermal insulator the coefficient K is determined by taking into account the frozen area resistance and the thermal exchange with the ground.

$$K = \frac{1}{\frac{R_0}{\lambda_T}(A_0 - A_s) + \frac{1}{\alpha'_2}} \qquad (36)$$

With:

$$\alpha'_2 = \frac{2\lambda_d.B_{i2}}{Di_{nt}(1+A_s.B_{i2})} \quad ; \qquad (37) \qquad A_s = \frac{A_0 - \frac{\lambda_g}{\lambda_d.B_{i2}}.\frac{T_{ext}-T_e}{T_e-T_a}}{1 + \frac{\lambda_g}{\lambda_d}.\frac{T_{ext}-T_e}{T_e-T_a}} \quad ; \qquad (38)$$

$$B_{i2} = \frac{\alpha_a.C}{\lambda_s} \quad (39); \qquad R^*_g = \frac{R_0}{\lambda_g}(A_0 - A_s) \quad (40); \qquad R^*_d = \frac{R_0}{\lambda_d}.A_s \quad (41)$$

Where: λ_g – frozen ground thermal conductivity coefficient; λ_d – the one for thawed ground ;
T_a – air temperature; T_e – freezing temperature of water contained in the ground ;($\approx$0°C)

In function of the available data we can:

- Either determine the insulator thickness δ_{is} for a given temperature T_{ext} ;
- Or determine the pipe temperature at the ground contact for a given insulator thickness $\delta_{is.}$

In the following table are represented the calculus results for the determination of the required insulator thickness (in metres) for a gas pipe at low temperature with a diameter of 1420 mm for different values of T_{ext} and T_{gas} [2]

T_{gas} °C	T_{ext}				
	0°C	-1°C	-2°C	-5°C	-10°C
-30	0.4	0.28	0.21	0.11	0.06
-70	0.77	0.58	0.26	0.26	0.13
-120	1.1	0.9	0.42	0.42	0.25

Lying depth: 1.7 m (up to the axis); λ_d = 0.86 kcal/m.h°C; α_a = 8.6 kcal/m^2.h°C; λ_g = 1.03 kcal/m.h.°C ; T_a = +2°C ; α_1 = 400 kcal/m^2.h.°C ; T_s = 3.2 °C.

From theses figures we can say that the realisation of a pipe transporting gas at -30°C requires an insulating layer of 40 cm to maintain a ground contact temperature equals 0°C.

This will entrain the realisation of a trench at least 3m wide and 3.22 m depth. From a civil engineering point of view, the works are enormous and there is a negative impact on the environment with so much displaced earth and possible corona formation due to frozen ground. The advised solution is to build a suspended gas pipe.

Let's cite at the end the different type of solicitations which act on the pipeline:

- Pipeline proper weight; insulating coating weight; initial constraint due to pipe elastic flexion; ground pressure on the pipe; axial and circumferential constraints; transported gas weight; thermal constraints; snow charge etc.

Conclusion

1) The calculations have shown that the gas transport at temperatures from 5 to 10°C influences the rate flow in a neglecting manner (around 4° increase). The cooling advantage resides on the contrary in the amelioration of the gas pipe exploitation reliability.
2) The gas cooling at lower temperatures (-2 $\div$-5°C) finds its necessity during the pipe laying in frozen regions in order to face the thaw and then stabilise the pipe.
3) The temperature diminution up to -30°C permits :
   - A rate flow increase of 12 $\div$ 14 %
   - A transport reliability amelioration.

The economic influence is:

1) An increase in the total cost of 10 to 12 % because of the compression, the gas cooling and the thermal insulator.
2) The necessity to use special pipes able to withstand low temperatures.

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