Evaluation of Losses Of Cold Energy of Cryogen Products in The Transport Systems

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Abstract. At present, there are problems of energy saving in various areas of human life and in power complexes of industrial plants. One possible solution to the problem of increasing energy efficiency is the use of liquefied natural gas and its cold energy. Pipelines for fuel or gas supply in cryogen supply systems have different length depending on the mutual position of storage and cryogen consumption devices relatively to a start construction. Cryogen supply and transport systems include a lot of fittings of different assortment. Reservoirs can be installed on different elevation points. To reduce heat inleak and decrease cold energy of cryogen product different kinds of thermal insulation are used. Cryogen pipelines provide required operation conditions of storage and gasifying systems. The aim of the thermal calculation of cryogen transport and supply systems is to define the value of cryogen heat. In this paper it is shown values of cryogen temperature rise due to heat inleaks at cryogen’s transfer along transport systems for ethane, methane, oxygen and nitrogen were calculated. Heat inleaks also due to hydraulic losses were calculated. Specific losses of cold energy of cryogen product for laminar and turbulent flow were calculated. Correspondences of temperature rise, critical pipeline’s length and Reynolds number were defined for nitrogen, argon, methane and oxygen.

1. Introduction
At present, there are problems of energy saving in various areas of human life and in power complexes of industrial plants[1,2]. One possible solution to the problem of increasing energy efficiency is the use of liquefied natural gas and its cold energy [3].

Some aspects of cryogen supply and transportation are investigated in works of A.M. Arharov, I.D. Kunis [4], N.V. Filin [5], M.P. Malkov [6]. On the ground of their proceedings short description of their works can be made.

Pipelines for fuel or gas supply in cryogen supply systems have different length depending on the mutual position of storage and cryogen consumption devices relatively to a start construction. Cryogen supply and transport systems include a lot of fittings of different assortment. Reservoirs can be installed on different elevation points. To reduce heat inleak and decrease cold energy of cryogen product different kinds of thermal insulation are used.

Thermal and hydraulic calculations should be made to design cryogen supply and transport systems.
Cryogen pipelines provide required operation conditions of storage and gasifying systems. Cryogen pipe is a coaxial two-walled pipe with a screen-vacuous insulation. Cryogen pipeline sections are welded.

A right-of-way of the cryogen pipeline is assembled according to the location with the following elements:
- sections of cryogen pipelines;
- compensation elements (compensators, metal hoses); reducing fitting (joint sleeves, lens etc.);
- adsorptive sections;
- vacuum ports for connection to evacuation and vacuum control equipment;
- supports, membrane protectors, safety grounding devices.

The aim of the thermal calculation of cryogen transport and supply systems is the definition of the value of cryogen heat. There are two reasons for the calculation:
- maintenance of the cryogen temperature that a consumer needs;
- single-phase condition of the cryogen.

When calculating, the system is considered to be absolutely preliminary chilled to the temperature of a liquid product.

2. Calculation methods
The increase of the cryogen temperature is given by the expression:

\[ \Delta T = \frac{\Sigma Q}{c_p G} \]  \hspace{1cm} (1)

Heat of temperature rise is comprised of:
- temperature rise due to the heat inleak from the environment;
- temperature rise due to the hydraulic friction in pipelines and the throttling effect.

Thus, temperature rise of the cryogen can be defined by the following expression:

\[ \Delta T_S = \Delta T_{o.c.} + \Delta T_{w} \]  \hspace{1cm} (2)

where \( \Sigma Q \) – overall heat inleak to the system from the environment, \( V \); \( c_p \) – product thermal capacity, \( J/kg \cdot K \); \( G \) – consumption of fuel component, \( kg/s \).

Specific overall heat inleak to the cryogen product for 1 m is defined by the following expression:

\[ q_{\Sigma} = q_t + q_{mp}, \]  \hspace{1cm} (3)

where \( q_t \) – heat inleaks through thermal insulation layer and pipelines (sleeves), \( V/m \); \( q_p \) – hydraulic losses in pipelines, \( V/m \).

3. Heat inleaks calculation
For computational convenience a filling system is divided into separate sections. Heat inleaks are defined for every section and system’s element separately, and then they are summed up. Formulae for calculation of heat inleaks through some filling system’s elements are given below.

Heat inleaks through thermal insulation layer and sleeves are defined as

\[ q_t = K_t \cdot (T_{o.c.} - T_e) = \frac{T_{w} - T_{e}}{\frac{1}{a_1} \cdot \frac{d_1^{d_2}}{d_1^{d_2}} + \frac{d_1^{d_2}}{d_1^{d_2}}} \]  \hspace{1cm} (4)

where \( T_{env} \) – environment temperature, \( K \); \( T_e \) – component temperature, \( K \); \( \alpha_1 \) – heat-transfer from the wall to the cryogen product coefficient, \( W/(m^2 \cdot K) \); \( \alpha_2 \) – heat-transfer from environment to the wall coefficient, \( W/(m^2 \cdot K) \), that equals 10 \( W/(m^2 \cdot K) \) according to [1]; \( d_1 \) and \( d_2 \) – inside and outside diameter of the pipe, \( m \); \( d_{ins} \) – outer insulation diameter, \( m \); \( \lambda_{ins} \) – thermal conductivity coefficient of the insulation layer, \( W/(m \cdot K) \):
- for a powder-vacuous insulation \( \lambda_i = 2,1 \cdot 10^{-3} \hspace{0.5cm} W/ (m \cdot K) \);
- for a screen-vacuous insulation \( \lambda_i = (1,1...1,2) \cdot 10^{-3} \hspace{0.5cm} W/ (m \cdot K) \);
for a non-vacuum insulation of ATIMS -10 $\lambda t = 4.2 \cdot 10^{-3}$ V/(m·K), and ATIMS-3-15 $\lambda t = 3.5 \cdot 10^{-3}$ V/(m·K) (more accurate data of coefficients depending on pressure and number of insulation layers are given in references);

Heat-transfer coefficient from the wall to the cryogen is defined by the value of Nu criterion:

$$\alpha_1 = \frac{Nu \cdot \lambda_w}{d_1} = \frac{0.21 \cdot Re_f^{0.8} \cdot Pr_f^{0.43} \cdot \lambda_w}{d_1}$$  \hspace{1cm} (5)

Nusselt criterion is defined by the flow regime. At laminar fluid flow, $Re_f < 2 \cdot 10^3$, to define average heat transfer coefficient the following formula is suggested:

$$\overline{Nu_f} = 0.15 \cdot Re_f^{0.8} \cdot Pr_f^{0.43} \cdot \left(\frac{Pr_f}{Pr_w}\right)^{0.25}.$$  \hspace{1cm} (6)

At developed turbulent flow, $Re_f > 10^4$, the calculation formula is as follows:

$$\overline{Nu_f} = 0.21 \cdot Re_f^{0.8} \cdot Pr_f^{0.43} \cdot \left(\frac{Pr_f}{Pr_w}\right)^{0.25}.$$  \hspace{1cm} (7)

The definiens are a pipe’s diameter $d$, defining temperature $t_f$, average fluid velocity $W$.

In cryogen supply systems heat inleaks can appear in the following elements:

- Heat inleak through bayonet joints of cryogen pipelines;
- Heat inleak along a butt joint through a bellows;
- Heat inleak along supporting structures of pipe utilities (pin supports);
- Heat inleak along fittings.

After the calculation of heat inleaks of separate elements and system sections, the results are presented in tables. To consider all losses at totaling the values, coefficient that equals 1.3-1.5 is used.

As the calculations and experience of working with cryogen pipelines show, the basic heat of cryogen fluid, transported along supply system, is conditioned by temperature heat due to heat inleaks from environment. Heat of hydraulic losses is somewhat smaller.

The temperature of the liquid component at the inlet to the cryogenic systems:

$$\Delta T_{f,i} = \Delta T_{res} + \Delta T_{heat},$$  \hspace{1cm} (8)

where $\Delta T_{res}$ – change of temperature in the tank of the filling system, K;
$\Delta T_{heat}$ – heat value of hydraulic losses, K.

According to references about pipelines, designed and produced in company “Cryogenmash”[11], calculation of specific inleaks per meter run of pipelines of different diameter is made. The values of specific heat inleaks are presented in the table 1 and in the figure 1.

$q$, W/m

![Figure 1](image)

**Figure 1.** Correspondence of a specific heat inleaks per 1 meter of a pipeline and its inside diameter

4. Heat inleaks calculation caused by hydraulic losses

Figure 2 shows transport scheme of cryogen liquid at a distance. In that system heat, supplied to the cryogen in a pump, is given to fluid under low pressure in a heat exchanger, and discharged fluid
under a pressure (higher than bubble pressure) is supplied to the pipeline. The problem was considered with fluid approaching a valve at saturation.

![Figure 2. Transport system of cryogenic liquid: 1 — fluid flow; 2 — steam return or release; 3 — pipeline; 4 — pump; 5 — pump reservoir; 6 — heat exchanger; 7 — to a consumer; 8 — distant storage.](image)

Fluid heat due to hydraulic losses can be found by the following formula:

$$\Delta T_h = \frac{\Delta P}{\rho c_p}$$

(9)

where \(\Delta P\) — pressure losses, MPa (defined by hydraulic calculation of the system); \(\rho\) — air density, kg/m\(^3\).

Cryogen pressure losses at cryogen’s transposition inside a pipeline are defined by flow regime, specifically by Reynolds number \((Re)\). While flow velocity is defined as follows:

$$w = \frac{Q}{S} = \frac{4Q}{\pi d^2},$$

(10)

where \(Q\) — cryogen volume flow rate; \(S\) — line flow area.

Pressure losses on friction in general are defined as follows:

$$\Delta p = \frac{\lambda}{d} \cdot \frac{\rho w^2}{2},$$

(11)

where \(\lambda\) — specific friction coefficient; \(\rho\) — cryogen density; \(l\) — pipeline section’s length.

Correlation for pressure losses on friction per one meter run calculation is defined as follows:

$$\Delta p_l = \frac{\lambda}{d} \cdot \frac{\rho w^2}{2} \cdot |\frac{pa}{m}|.$$  

(12)

Specific losses of low temperature heat of cryogen flow per 1 meter of a pipeline are defined as follows:

$$q^k_l = \frac{\lambda}{d} \cdot \frac{w^2}{2} \cdot |\frac{f}{kg \cdot m}|;$$

(13)

$$q^k_l = \frac{\lambda}{d} \cdot \frac{16Q^2}{2d^4} = \frac{8\lambda Q^2}{\pi^2d^5};$$

(14)

$$q^k_l = \frac{8\lambda Q^2}{\pi^2d^5 \rho^2}.$$  

(15)

The last correlation has mass flow:

$$G_m = \rho \cdot Q.$$  

(16)

Friction coefficient \(\lambda\) is defined by a flow regime. For a laminar cryogen flow:

$$\lambda = \frac{64}{Re} = \frac{64 \cdot v}{w \cdot d} = \frac{64 \cdot v \cdot \pi d^2}{4Q} = \frac{64d^2 \cdot \rho \cdot m}{4G_m}.$$  

(17)

For turbulent cryogen flow:

$$\lambda = \frac{0.3164 \cdot v^{0.25}}{Re^{0.25}} = \frac{0.3164 \cdot v^{0.25}}{(w \cdot d)^{0.25}} = \frac{0.3164 \cdot v^{0.25}}{(\frac{4Q \cdot d}{\pi \cdot w})^{0.25}} =$$

$$= \frac{0.3164 \cdot v^{0.25}}{(\frac{4Q \cdot d}{\pi \cdot w})^{0.25}} =$$
Considering calculation expressions for definition of friction coefficient, specific energy losses of cryogen flow are defined as follows:

For a laminar flow:

$$ q_{l, \text{lam}}^k = \frac{8 \cdot 64 d^2 \nu \rho G_m^2}{\pi d^4 \rho^2} = \frac{128 \nu G_m}{\pi d^3 \rho}. $$

For a turbulent flow:

$$ q_{l, \text{turb}}^k = \frac{8 \cdot 0,3164 d^{0,25} \rho^{0,25} G_m^{0,25} \rho^2}{\pi d^{4,25} \rho^{1,75}} = 0,24 \nu^{0,25} G_m^{1,75} d^{4,25} \rho^{1,75}. $$

In general losses of cold energy due to friction will be defined by the following expression:

$$ g_l = f(G_m, \nu, d, \rho). $$

### Table 1. Heat of cryogen evaporation

| Fluid       | Empirical expression |
|-------------|----------------------|
| Nitrogen    | $r = 200,1 \cdot e^{-0,02p}$ |
| Argon       | $r = 160,2 \cdot e^{-0,01p}$ |
| Oxygen      | $r = 212,9 \cdot e^{-0,01p}$ |
| Methane     | $r = 516,2 \cdot e^{-0,02p}$ |

Critical pipeline’s length, when cryogen gasifies, is defined by the following expression, considering heat of cryogen evaporation, depending on pressure $r = r(p)$ (table 1):

$$ l_{cr} = \frac{r G_m}{q_x}. $$

Based on given expressions heat flows and critical cryogen pipelines’ length were calculated. Using this methodology it has been calculated the dependence of Specific overall heat inleak, the dependence of the temperature change of the liquid component and the dependence of the critical cryogen pipelines length on the Reynolds number. The results are shown at figures 3-5.
Figure 4. The dependence of the temperature change of the liquid component on the Reynolds number.

Figure 5. The dependence of the critical cryogen pipelines length on the Reynolds number.

5. Conclusions
In the result of the work:
1) Values of cryogen temperature rise due to heat inleaks at cryogen’s transfer along transport systems for ethane, methane, oxygen and nitrogen were calculated.
2) Heat inleaks due to hydraulic losses were calculated.
3) Specific losses of cold energy of cryogen product for laminar and turbulent flow were calculated.
4) Correspondences of temperature rise, critical pipeline’s length and Reynolds number were defined for nitrogen, argon, methane and oxygen.

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