THERMAL INSULATION OF CRYOGENIC, MODERATE DIAMETER PIPELINES

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Different methods of superposing thermal insulation were tested on a 3-mm-diameter liquid-nitrogen pipeline and the influence of different factors on the heat-transfer components through screen-vacuum thermal insulation (SVTI) was studied experimentally.

Investigations performed in recent years showed [1-3] that the possibilities of screen-vacuum thermal insulation (SVTI) achieved on cryogenic vessels ($\lambda_i \cong 1$ μW/cm·K) are not realized completely successfully on cryogenic pipelines. Especially significant is the increase in SVTI heat conductivity observed in moderate diameter pipelines (∿5 mm), where its efficiency was reduced 5-10 times [1]. In order to determine the reasons for degradation of the SVTI characteristics and to search for means to improve them, different methods of superposing the SVTI on a 3-mm-diameter pipeline were tested and the heat-transfer components through it were experimentally studied.

The apparatus and research methodology described earlier [1] were used in the experiments. The pipeline had a total length of 1210 mm and was cooled by liquid nitrogen. Films of PET GOST 24234-80, aluminized on both sides (PET-DA) and hole diffraction screens (porosity ∿3%) from this film [4], coated by aluminum (HDA) or copper (HDC) on both sides, were used as SVTI screens. Glass-paper SBSh-T TU21-RSFSR-26-76-76 was used as packing material.

Insulation was superposed on the pipeline in [1] in layers by using 10-15-mm-wide strips in a spiral method [5]. Such a method (modification of assembly No. 1) does not permit a winding density less than 25-30 scr/cm because of the displacement of the spiral turns along the pipeline at lower densities. Consequently, to study the SVTI characteristics at moderate packing densities, the following SVTI winding methods were tested. Modification No. 2 is a layer by layer spiral winding of 35-40 mm wide strips. Modification No. 3 is layer-by-layer winding in the form of 25-30 mm long cylinders that overlap 3-5 mm. Screens of 400-mm-wide aluminum foil were also used in this method. Adjacent PET film cylinders were connected by masking tape TU-6-17-703-75, while the foil cylindrical layers were encircled "crosswise" by two glass threads along the whole length of the pipeline. Modification No. 4 is a screen superposed by the method of No. 3 while the packing layer cylinders were stacked with an 8-10 mm gap.

A spiral method of assembling 10-12-μm aluminum foil screens was also tested in the preliminary experiments, but it turned out to be unacceptable for practice. This is because large gaps are formed during assembly of the foil strips on the band junctions for moderate tensile forces, which results in high heat influxes to the cold carrier. As the winding density increases (in order to diminish the gap) breaks occur in the aluminum foil.

Comparative data about the magnitude of the heat influxes to the nitrogen pipeline are presented in Table 1 for different methods of SVTI superposition. It is seen therefrom that the minimal value of the heat influxes for all the assembly methods is achieved in conformity with the results of [2] for a 3-5 screen SVTI packet thickness. And only for a spiral winding do the compositions PET DA + SBSh-T reach a minimum for 9 screens per packet, which is apparently related to the high packing density of the layers (∿37 scr/cm).

The lowest value of the heat influx (Q_{hi} = 0.31 W) is obtained for a cylindrical method of assembly (modification No. 4) of the PET DA + SBSh-T composition. This is apparently

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TABLE 1. Heat Influx to a Cold Conductor with Liquid Nitrogen for Different Superposition Methods and Numbers of Insulation Screens

Number of screens	Kind of insulation							
	PET DA + SBSh-T				HDA + SBSh-T			
	modification							
	№ 1		№ 3		№ 1		№ 3	
	ρ, scr/cm	Q, W	ρ, scr/cm	Q, W	ρ, scr/cm	Q, W	ρ, scr/cm	Q, W
1	—	0,71	—	0,73	—	0,60	—	—
2	—	—	—	—	—	—	—	—
3	33 (10)*	0,74 (0,55)*	17 (10)	0,51 (0,31)*	33	0,57	12	0,56
5	36	0,73	15	0,31	36	0,65	10	0,57
7	37	0,66	15	0,40	37	0,66	10	0,56
9	37	0,42	—	—	37	0,67	—	—

Number of sections	Kind of insulation					
	HDM + SBSh-T				aluminum foil + SBSh-T	
	modification					
	№ 2		№ 3		№ 3	
	ρ, scr/cm	Q, W	ρ, scr/cm	Q, W	ρ, scr/cm	Q, W
1	—	0,62	—	0,79	—	0,80
2	—	—	—	—	29	0,82
3	9	0,57	11	0,47	20	0,78
5	8	0,51	10	0,48	23	0,72
7	8	0,60	11	0,55	—	—
9	9	0,65	—	—	—	—

*Packings from SBSh-T are arranged with 8-10-mm discontinuities (modification No. 4).

associated not only with the method of assembly which assures a diminution in contact heat transfer because of the reduction in the contact area between the packing and the screen [6], but also with the assurance of an optical packing density of the layers (∿15 scr/cm). Such a deduction follows from a comparison of the data for the compositions HDA + SBSh-T and HDM + SBSh-T. It follows from the data for the last composite (where similar layer packing densities are used in the spiral and cylindrical assembly methods) that the cylindrical winding method assures a 6-25% reduction in the heat influx. The large difference between these methods for the composite PET DA + SBSh-T is evidently associated with the large difference in the layer packing density.

It follows from a comparison of modifications Nos. 2 and 4 (spiral and cylindrical methods of PET DA film assembly) that the superposition of packings with discontinuities along the length of the pipeline permits a 1.5-2 times reduction in the heat influx for an identical layer packing density.

Values of the SVTI packet heat conduction are presented in Table 2 for different assembly methods. As follows from Table 2, the heat-conduction coefficient already reaches the values 2-6 μW/cm·K, which exceeds the SVTI characteristic in vessels by almost an order [7], for a 2-6 screen packet thickness. Since very thin layers (less than 5-6 mm thickness) wound with narrow tape (10-30 mm) and with high gas permeability were used, then the heat transmission therein over the residual gas cannot evidently exceed the total heat influx through a 5-10-mm-thick packet in the vessels (the component 0.5 μW/cm·K [7]). This quantity is small compared to the values 2-6 μW/cm·K and, consequently, the heat transfer over the gas in the layers of the SVTI packets investigated can be neglected. Therefore, the elevated heat influxes to small-diameter cryogenic pipelines can be related just to increased values of the contact and radiant heat transfer.

According to [2], one reason for the degradation of the radiation characteristics of the screens in moderate thickness SVTI screens is the formation of a thick layer or cryodeposits thereon. Either oil vapors from the vacuum exhaust system or products of SVTI gas

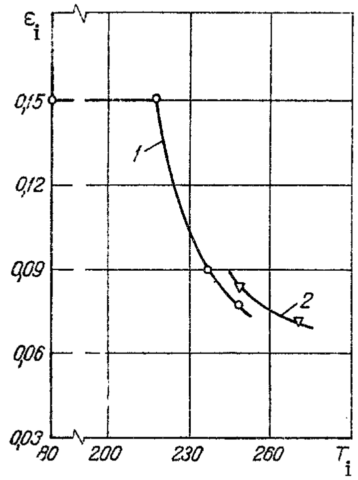

Fig. 1

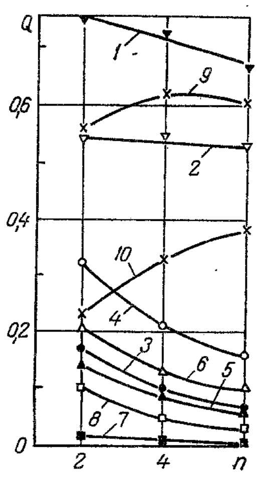

Fig. 2

Fig. 1. Dependence of the insulation screen emissivity ε_i on the screen temperature T_i (K) for the composites: 1) PET DA + MKV (1, 3, 7, and 9 screens), spirally (modification No. 1); 2) HDA + SBSh-T (3 and 5 screens), cylinders (modification No. 3).

Fig. 2. Dependence of the total and radiant heat influx Q(W) on the number of screens n (scr) for insulating the cooling line from the composite PET DA +MKV, ρ = 40 scr/cm (1, 3, 5, 7) and HDA +SBSh-T, ρ = 10 scr/cm (2, 4, 6, 8): 1, 2) total heat influx; 3, 4) total radiant heat influx; 5, 6) heat influx by radiation taking only the cryogenic settling into account; 7, 8) heat influx by radiation with only slots taken into account; 9, 10) heat influx due to the contact component for high and low packing densities, respectively.

liberation, among which water vapor comprises up to 95% [8], can be condensed on the cold screens. It is known that condensed water vapor has a significantly higher emissivity than the PET DA film. The change in PET DA screen emissivity as a function of their temperature was therefore studied experimentally in the 77-300°K range. To this end, one screen was superposed on the pipeline and its temperature was determined (by using a copper—constantan thermocouple), as were the heat influxes to the pipeline. The screen temperature was varied by first winding a layer of SBSh-T glass paper of different thickness on the pipeline. Results of the experiments are represented in Fig. 1.

It is seen from the figure that a practically analogous nature is observed for the change in emissivity ε with temperature for the PET DA (curve 1) and the aluminized hold diffraction screens. In contrast to the known data, the quantity ε diminishes monotonically with the rise in temperature. It must be noted that a sharp rise in ε is observed at temperatures below 230°K (where the vapor pressure is less than 10 Pa) and reaches the value 0.15. However, a definite change in the emissivity is already observed at temperatures less than 250°K, which permits the assumption of the presence of not only condensed water on the screens, but also of products of oil vapor decomposition.

Special tests were performed in which the water vapor pressure in the SVTI vacuum cavity was raised to 10^{-2} Pa and then evacuated to a pressure of 10^{-4} Pa were performed to study the degree of influence of the water vapor pressure. During these tests, the heat influxes to the cold line, which increased 10-15% with the rise in pressure and then decreased gradually to the initial level, were monitored continuously. This result indicates the reversible condensation and sublimation of the water vapors on the screens as the water vapor partial pressure changes in the SVTI packet.

It should be noted that an increase in ε with the reduction in temperature is also observed for screens based on hole diffraction screens with a copper coating, but the absolute

TABLE 2. Components of Heat Transfer in Cryogenic Pipeline Insulation

Number of screens	Packing density, scr/cm	Screen emissivity	Total heat influx, W	Effective heat-conduction coeff. λ_{ef}, μW/cm·K	Total heat-transfer components, μW/cm·K			
					$\lambda_{r\Sigma}$	radiant heat-transfer components		λ_{κ}
						λ_{rcr}	λ_{rsl}	
HDA + SBSh-T, spirally								
2	13	0,17	0,55	3,27	1,84	1,25	0,59	1,43
4	12	0,14	0,55	4,88	1,76	1,23	0,53	3,12
6	12	0,11	0,54	5,76	1,54	1,07	0,47	4,22
PET DA + MKV, spirally								
2	40	0,15	0,74	1,81	0,45	0,40	0,047	1,36
4	40	0,12	0,73	2,67	0,39	0,35	0,040	2,28
6	40	0,10	0,68	3,17	0,36	0,32	0,037	2,81

TABLE 3. Emissivity of One Insulation Shield of the Cold Conductor ε_i as a Function of the Shield Temperature With and Without Slots Therein

No.	Kind of insulation	Insulation temp., T_i, °K	Shell temp., T_{shell}, °K	Heat influx, Q_{tr}, W	Insulation emissivity	Remark
1	PET film without deposition, 1 layer superposed spirally in ϕ 3 mm	100	295	1,62	0,35	
2	One PET DA shield, spirally without slots in ϕ 3 mm	155	295	0,52	0,12	Shield superposed on PET film without deposition
3	One PET DA shield with 2 mm (6%) slots between cylinders in ϕ 3 mm	148	296	0,95	0,2	Same
4	Glass paper SBSh-T between STEF-1 washers in ϕ 24 mm; slots 5-6 mm	268	297	2,05	0,16	
5	One PET DA shield, with 2 mm (6%) slots between cylinders in ϕ 24 mm	269	293	1,46	0,126	Shield superposed on glass paper SBSh-T
6	One PET DA shield, spirally in ϕ 24 mm, without washer, without slots	280	297	0,63	0,074	Shield superposed on glass paper SShB-T
7	One PET DA shield, spirally in ϕ 24 mm, with slots (6%), without washers	281	297	0,65	0,083	

values of the quantity ε is much higher. This is apparently associated with the elevated emissivity of the copper coating (which had visually observable black spots) because of the atmospheric action during prolonged storage (more than 1.5 years).

Another essential factor in the increase of radiation heat transfer in SVTI layers should be the appearance of slots at the junction of two turns of the screen with a spiral winding or along the generator of the pipeline for a cylindrical winding. For a winding density of 10 scr/cm, the maximal slot width cannot exceed 1 mm, i.e., the distance between adjacent screens. For a 10-20 mm width of the spiral the slots can occupy 5-10% of the total screen area. If it is assumed that the slot emissivity is one, then the presence of the mentioned slots is equivalent to a 0.05-0.1 increase in the degree of blackness.

To confirm these deductions, the degree of blackness of a screen is studied here as a function of the temperature (as described earlier) in the presence of a slot of a previously assigned width and area. To this end, a PET DA film screens 20-25 mm long with a 2-mm gap between adjacent segments were superposed on the pipeline in cylindrical segments. To increase the slot emissivity, a continuous layer of nonmetallized PET film was wound on the pipeline in the gap between the screen segments before the superposition.

Results of the experiments are presented in Table 3 from which it follows that the emissivity of such a film is 0.35 even at nitrogen temperatures. Comparing the results of experiments Nos. 2 and 3, it can be seen that a slot of 6% area results in an 0.08 increase in the emissivity. Since this addition exceeds the theoretical limit value 0.06, a deduction can then be made about an additional increase in the slot area because of the loose contact between the shield edges and the pipeline surface. It is hence seen that it will be quite difficult to assure the absence of a gap at the turn junctions when winding the shields on a soft substrate of several SVTI layers rather than on the pipeline.

However, it was established in the experiment at room temperature (test No. 7) that the effective emissivity of a shield with slots is just 0.083, which is close to its emissivity in the absence of slots ($\varepsilon \approx 0.074$, test No. 6). Since the PET film is transparent in the IR domain, and there is a thick layer of glass paper (24 mm) beneath it, we then arrive at a deduction about the significant IR reflection by this layer.

To confirm this assumption, a new series of experiments was conducted in which washers (24 mm in diameter and 0.5 mm thick) from glass textolite STÉF-1 were mounted on the pipeline in pairs with a 5-6-mm gap. The spacing between each of these pairs was 25-30 mm and was filled by a layer of glass paper SBSh-T. The emissivity presented for such a layer was 0.16 (test No. 4), and the superposition of a shield with 6.6% slot area (with a 2 mm width and in agreement with the free gap between adjacent washers) changed this quantity insignificantly ($\varepsilon = 0.126$). Hence, the addition to the cited emissivity because of the slots (of 6.6% area) in tests Nos. 5 and 6 was 0.052, which corresponds approximately to an increase in the slot emissivity to $\varepsilon = 1$.

The experiments performed showed that there is a considerable increase in the reduced emissivity of the shielding layers and, therefore, the radiation heat transfer in the SVTI. To estimate its contribution to the total heat flux, computations were carried out, whose results are given in Table 2. The computation of the radiation heat flux (multishield system formed by coaxial cylinders mounted at equal distances from each other, with 3-mm inner diameter and outer equal to the outer diameter of the SVTI packet) is performed by using the relationship [9]:

$$Q_r = \xi E_0 \sigma_s 10^8 F_i \left[\left(\frac{T_{shell}}{100} \right)^4 - \left(\frac{T_{pi}}{100} \right)^4 \right],$$

while the shielding factor is determined from the relationship

$$\xi = \left[1 + E_0 f_1 \left(\frac{1 - t_1}{t_1} \right) + E_0 f_1 f_2 \left(\frac{1 - t_2}{t_2} \right) + \ldots + E_0 f_1 \ldots f_n \left(\frac{1 - t_n}{t_n} \right) \right]^{-1}.$$

The computed curves are shown in Fig. 2. Analysis of the design data shows that the radiant heat influx diminishes with the increase in the number of shields, while the fraction of contact heat transfer increases.

The radiant heat influx for the composition PET DA + MKV with high packing density is considerably less than $Q_{r\Sigma}$ for the composition PET HAD + SBSh-T with low shield packing density (curves 3 and 4). It is also seen from Fig. 2 that the radiant heat influx $Q_{r\Sigma}$ consists of the radiant heat influx due to the available cryodeposit on the shields Q_{rcr} (curves 5 and 6) and the radiant heat influx through the shield slots Q_{rs} (curves 7 and 8). To estimate the influence of the cryodeposit, the shield emissivities ε_i as a function of the temperature were taken off from the data in Fig. 1. The change in radiant heat transfer due to the number of shields is presented in Table 2 for two compositions. To take account of the influence of the slots, it was assumed that their width equaled the gap between adjacent shields, and determined the radiant heat transfer in multishields systems for $\varepsilon_i = \varepsilon_{cr} + \varepsilon_s$, where ε_s is the addition to the effective emissivity because of the presence of a slot in each shield. The total values of $\lambda_{r\Sigma}$ are also presented in Table 2.

It follows from the data in Table 3 that the effective emissivity of the shields in the SVTI packets of moderate pipelines will reach the magnitude 0.1-0.16, which results in a value of its effective heat conductivity coefficient determined by the radiation heat transfer of 2-3 μW/cm·K. This quantity exceeds by 3-10 times the value of the emissivity of the PET DA films determined under calorimetric conditions [10]. The main reason for the increase in emissivity is the presence of cryopressurization in the shields, and in this connection further investigations are necessary to clarify the conditions for its formation.

It is also seen from Table 2 that for a small number of shields (1-2) the radiant heat transfer is 60-70% of the total heat flux. But even for a number of shields equal to 5-6, its fraction is reduced to 30-50%, and the main role is played by contact heat transmission, whose magnitude grows from 1 to 3-4 μW/cm·K, in thicker SVTI packets as the number of shields increases from 2-6, and is approximately identical for both low-density layer packing (8-12 shields/cm) and high-density packing (30-40 shields/cm). The values found for λ_k also exceed the contact heat transfer in the SVTI of cryogenic vessels with the same packet thickness by 3-10 times. This is apparently associated with the large deformations and the appearance of significant forces during winding of the shields on moderate diameter pipelines.

NOTATION

E_0, reduced emissivity of a system of two boundary surfaces; $f_1, f_2, \ldots, f_n$, fractions of reflected radiation of the incident; F_i, insulation surface area, m²; n, number of shields; T_i, T_{sh}, T_{pi}, insulation, shell, pipeline temperature, °K; $t_1, t_2, \ldots, t_n$, reduced emissivities; Q_{tot}, Q_r, total and radiant heat fluxes, W; ε, ε_i, ε_{cr}, ε_s, emissivities of the surface, insulation, due to cryodeposits, slots; σ_3, Boltzmann constant, W/m²·K⁴; λ_i, $\lambda_{r\Sigma}$, λ_{rcp}, λ_{rs}, λ_k, effective heat conductivity coefficient of the insulation, due to the radiant heat transfer, the cryodeposit, the slots, the contact heat transfer, μW/cm·K; ρ, shield packing density, shields/cm; ξ, shielding efficiency factor; PET, polyethylene terephthalate film; PET DA + MTF, polyethylene terephthalate film, two-sided aluminized and glass paper of microthin fiber; DDA + SBSh-T, diffraction two-sided-aluminized film and glass paper of staple fiber for thermal insulation purposes.

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