Radiant heat transfer reduction methods in heat insulation of power equipment

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Abstract

One common challenge for designers of power equipment to be operated at high temperatures is the reduction of radiation heat transfer. As the emissivity factor of radiating heated surfaces of such equipment in most cases can be reasonably approximated by a constant, the power emitted by them is directly proportional to the fourth power of their absolute temperature. A solution of this problem is the use of thermal radiation shields made from low-emissivity and highly reflective materials. Traditionally heat insulation structures employ aluminum foil as such a shield. However, aluminum is soft and rather expensive, and it also has a low tensile strength. An alternative to the use of aluminum foil is the application to the external surface of the thermal insulation structure of a reflective metal layer via ion-plasma spraying (bombardment) in vacuum or metal spraying (metalizing) by means of an electric arc. In order to find out which method of reduction of radiation heat transfer offers the best results, we have compared a number of methods of thermal radiation shielding (foil winding, ion-plasma spraying in vacuum or electric arc wire spraying) in terms of thermal resistance of proper heat insulation structure. In our paper we have used heat insulation structures with thin-film heat insulation coatings. The experiments were carried out in conditions simulating real conditions of operation of pipelines and power equipment in Russia. The results of the experiments show that the alternative methods of thermal radiation shielding are more efficient than the traditional one (aluminum foil winding). In particular, the use of an aluminum coating applied to the surface of a heat insulation structure via ion-plasma spraying allows the thermal resistance

to increase by 35%; in case of metalizing via electric arc wire spraying the thermal resistance increased by 15% or more.

Keywords: radiation heat transfer, thermal insulation, power equipment, pipelines, shields, thermal resistance, thin-film heat insulating coatings.

1   Introduction

In case of power equipment the radiation heat transfer to the environment can account for 25–80% the total heat loss depending on the temperature [1]. As a rule, in order to reduce the radiation heat loss designers use thermal radiation shields made from materials with high reflection coefficient ($R \geq 90\%$) and low emissivity in the infrared wavelength range $(0.8 \cdot 10^{-3} \div 0.8 \text{ mm})$ [2]. Electromagnetic waves interact with the atoms of the thermal radiation shield and their energy is partly transferred into heat energy. Therefore the shield absorbs the energy and is heated; as a heated body it begins to emit electromagnetic waves as thermal radiation. In a simplified model the electromagnetic waves emitted by the shield's external (reciprocal, not contacting the protected source) surface is symbolically regarded as the thermal radiation of the shielded source, which has passed through the shield.

Traditionally heat insulation structures of heat or power equipment and pipelines employ aluminum foil for thermal radiation reflection. However, aluminum is soft and rather expensive, and aluminum foil has a low tensile strength.

An alternative to the use of aluminum foil is the application to the external surface of the thermal insulation structure of a reflective metal layer via ion-plasma spraying (bombardment) in vacuum or metal spraying (metalizing) by means of an electric arc.

This study aims at determination of the efficiency of the reduction of radiation heat transfer when using various methods of thermal radiation shielding (aluminum foil winding, ion-plasma spraying and electric arc wire spraying).

2   Description of the samples used in experiments

In our experiments we used as samples of heat insulation structures steel cylinders 1100 mm long with external diameter of 89 mm with a thin-film heat insulation coating (THIC). The THIC is a syntactic foam made of glass microspheres and an acrylic matrix. It is regarded as a material with good prospects for future use in heat insulation structures of power equipment [3–5]. The THIC layer was 8 mm thick, i.e. it was thick enough to ensure compliance with sanitary regulations and protection of the workers from burns resulting from contact with hot surfaces.

The reduction of radiation heat transfer from said samples was carried out with the use of aluminum thermal radiation shields produced by the following methods: foil winding, ion-plasma spraying and electric arc wire spraying.

In case of foil winding we used standard aluminum foil 240 μm thick.

The ion-plasma spraying of aluminum to said samples has been carried out in a vacuum chamber. The aluminum was deposited at a room chamber.

In case of electric arc spraying we used two wire electrodes that were melted by an electric arc between them; a jet of compressed air blew and sprayed the molten aluminum.

In both cases, i.e. in plasma spraying and electric arc spraying the thickness of the Al layer was equal to ~ 10 µm [6].

Figure 1 shows typical appearance of the surfaces of the shielded samples.

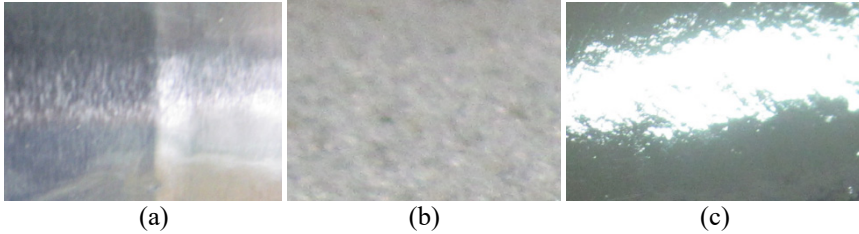(a)   (b)   (c)

Figure 1:   Typical appearance of the surfaces of the shields: (a) foil winding, (b) surface metalized by means of an electric arc, (c) deposition via ion-plasma spraying.

3   Description of experiments

The efficiency of the shielding methods has been compared in terms of the thermal resistance of shielded and unshielded test samples. The experiments were carried out on a special test stand in a thermostatic room [7]. Figure 2 shows a conceptual sketch of this test stand.
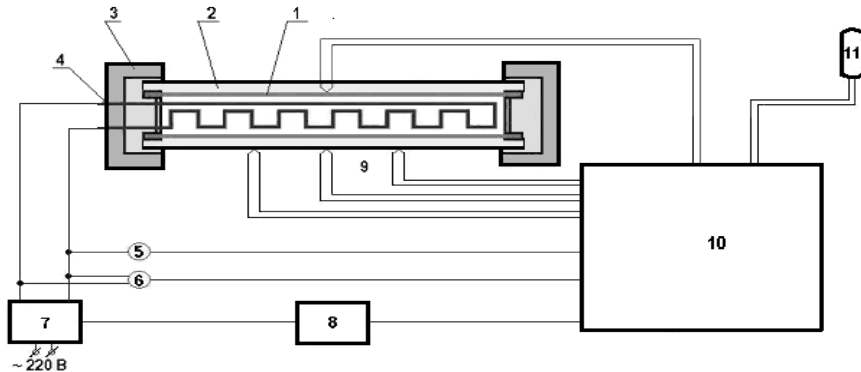

Figure 2:   Conceptual sketch of the test stand for determination of the thermal resistance of the samples tested. 1. Steel cylinder, 2. THIC, 3. Cap, 4. Electric heater, 5. Current sensor, 6, Voltage sensor, 7. Power supply unit, 8. Electronic temperature regulator, 9. Thermocouples, 10. Module for measurements and data processing, 11. Climate control system.

The flat ends of the detachable samples of heat insulation structures consisting of a steel cylinder (1) with a deposited layer of THIC (2) were covered with caps (3) for insuring a homogeneous temperature distribution over the surface of the sample of proper heat insulation structure. The test stand was equipped with current sensors and voltage sensors (6). It was switched on and off with the use of power supply unit (7). The temperature on the surface of steel cylinder 1 was regulated with the use of electronic regulator (8). The temperature on the surface of the samples of heat insulation structures was measured with the use of thermocouple elements (9), positioned in four cross sections (five thermocouples in each of the cross sections). The thermocouples were connected to multichannel module for measurements and data processing (10) that displays temperature, current and voltage values. The parameters of the ambient air in the room are regulated with the use of climate control system (11).

In the course of the experiments we have measured the distribution of the temperature over the surface of the test samples. The temperature on the surface of the steel cylinder was maintained in the range, which is typical for the operation of the equipment and pipelines used in Russian heat supply systems (+110°C - +160°C).

In order to calculate the thermal resistance we have used equation (1), which is derived from the Fourier's heat conduction equation [8]:

$$R_\lambda = \frac{t_1 - t_2}{q} \tag{1}$$

where q is the heat flux density, W/m^2, t_1, t_2 is the temperatures on the external surface of the steel cylinder and on the external surface of the test sample, °C, respectively.

We have measured the thermal resistance of test samples of heat insulation structures without shielding and of those shielded through aluminum foil winding, ion-plasma spraying and electric arc wire spraying.

4 Results and their discussion

The efficiency of heat insulation structures of pipelines and power equipment has been determined in terms of their thermal resistance, i.e. their capacity to reduce the heat transfer to the environment via conduction, convection and radiation.

The total heat resistance of a heat insulation structure is equal to the arithmetical sum of the resistances of the elements connected in series:

$$R = R_p + R_{ins} + R_s \tag{2}$$

where R_p, R_{ins}, R_s is the thermal resistances of the wall of the pipeline or power equipment, heat insulation layer and external surface of the heat insulation structure, respectively.

The thermal resistance of the wall of the pipeline or power equipment R_p, as well as the thermal resistance of the layer of heat insulation R_{ins} determine the conduction component of heat transfer. As a rule, pipelines and power equipment

are made from metal and their thermal resistance is negligible because of the high thermal conductivity coefficient.

The thermal resistance of the layer of heat insulation R_{ins} was calculated based on the equations derived from the Fourier's equation. In case of a cylindrical wall proper equation can be written as follows:

$$R_{ins} = \frac{1}{2 \cdot \pi \cdot \lambda} \, ln \, \frac{d_2}{d_1}, \qquad (3)$$

where d_1, d_2 is the internal and the external diameters of the layer of heat insulation, m respectively; λ is the thermal conductivity coefficient of the layer of heat insulation, (W/m·K).

The thermal resistance of the external surface of the heat insulation structure determines both the conduction and the convection components of heat transfer and in case of a cylindrical surface it can be calculated using the following formula:

$$R_s = \frac{1}{\pi \cdot d_2 \cdot \alpha}, \qquad (4)$$

where α is the surface coefficient of heat transfer, (W/(m^2·K^4)).

The coefficient of heat transfer from the external wall to the ambient air is a sum of two components:

$$\alpha = \alpha_r + \alpha_\kappa \qquad (5)$$

where α_r is the radiation heat transfer coefficient; α_κ is the convection coefficient.

The radiation heat transfer coefficient was calculated using the Stefan–Boltzmann's formula:

$$\alpha_r = C \frac{\left(\frac{t_2+273}{100}\right)^4 - \left(\frac{t_0+273}{100}\right)^4}{t_2 - t_0} \qquad (6)$$

where C is the radiation coefficient, (W/(m^2·K^4)); t_2 is the temperature of the surface, °C; t_0 is the temperature of the environment °C.

In a thermostatic room α_κ is negligible and in our approximation it could be set equal to zero.

The radiation coefficient C for THIC is equal to ~ 5.0 W/(m^2·*K^4), for aluminum ~ 0.34 W/(m^2·*K^4) [2]. If all other conditions are the same, the thermal resistance R_s of the external surface of a shielded heat insulation structure (characterizing the efficiency of the reduction of radiation heat transfer) will be higher than the thermal resistance of the unshielded heat insulation structure.

Figure 3 shows the efficiency of various methods of shielding of heat insulation structures in terms of reduction of radiation heat transfer in the temperature range from +110°C to +160°C.

In case of thermal insulation materials the thermal conduction coefficient usually increases with increase of temperature. Formula (3) provides evidence that thermal resistance of an unshielded sample of heat insulation structure (R_{THIC}) decreases with increase of temperature, and the results of the experiments have proved it (see R_{THIC} in Figure 3).
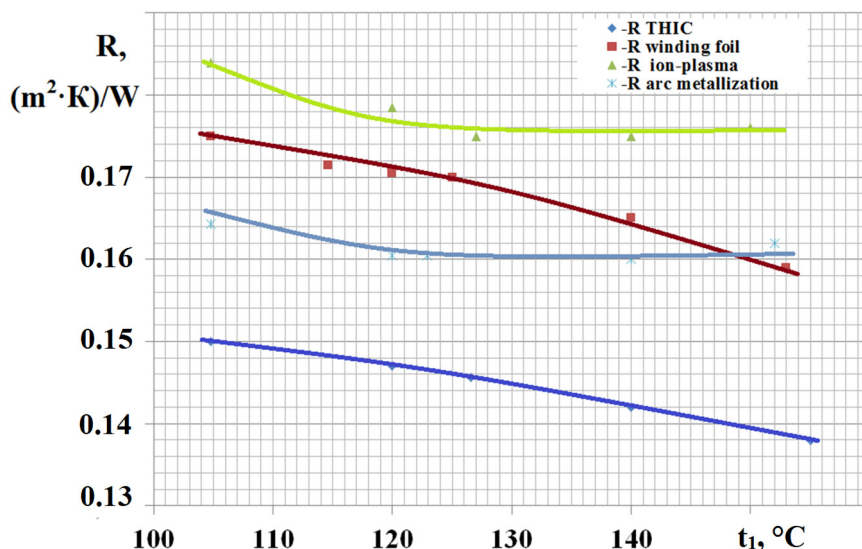
Figure 3:   Thermal resistance resulting from the use of various methods of shielding of heat insulation structures.

The trend toward the decrease of thermal resistance also exists in case of the test sample that has been shielded with the use of aluminum foil (see $R_{winding\ foil}$ in Figure 3). Here it is noteworthy to mention that as the temperature increases the shield absorbs more and more energy and, when heated, it begins to emit electromagnetic waves and therefore loses energy so that thermal resistance decreases.

In the temperature range from 110°C to 150°C the thermal resistance of the test sample of the heat insulation structure that has been shielded via electric arc wire spraying is lower than the thermal resistance of the samples that have been shielded differently (see $R_{arc\ metallization}$ in Figure 3). When the metal is deposited via electric arc wire spraying, the surface is rough and therefore the area of contact with the ambient air increases thus leading to enhancement of heat transfer. However, as the temperature of the isolated metal increases, the thermal resistance R_{ins} decreases because of the increase of the thermal conductivity of the heat insulation layer, so that heat transfer takes place mainly through radiation.

At a certain stage the specific thermal resistance of the external surface of the heat insulation structure R_s exceeds the other component of the total thermal resistance R, i.e. the specific thermal resistance R_{ins}. If the temperature is above 130°C, we observed a trend toward stabilization of the thermal resistance of the test sample of the heat insulation structure that was shielded via electric arc wire spraying. If the temperature is equal to 150°C or higher, the thermal resistance of the heat isolation structure shielded via electric arc wire spraying exceeds the thermal resistance of test samples shielded via aluminum foil winding. This effect is due to a lower (by an order of magnitude) metal content in a shield formed via

electric arc wire spray if compared with aluminum foil winding. The quantity of heat Q, transferred to the shield during heating is given by the formula:

$$Q = c_p \cdot m \cdot \Delta t \tag{7}$$

where c_p is the specific heat capacity of aluminum, (kJ/(kg·K)); m is the mass of the shield, kg; Δt is the difference in temperature between the internal and external surfaces of the shield.

The high thermal resistance of the test samples of the heat insulation structure shielded via ion-plasma spraying (see $R_{ion-plasma}$ in Figure 3), is due to low metal content and higher quality of the shield, whose surface is smooth and brilliant as aluminum, if deposited in vacuum, does not become dull and has a high reflection coefficient [9]. The reflection coefficient of high purity (99.99%) aluminum equals 93% [10]. If the temperature is above 130°C we also observe stabilization of thermal resistance of the shielded test sample of the heat insulation structure due to the fact that $R_s \gg R_{ins}$.

The test samples of the heat insulation structure that were shielded via ion-plasma spraying are the most efficient in terms of reduction of the radiation heat transfer. The use of this method of metallization allows to increase the thermal resistance of the heat insulation structure by 35% or even more if compared with an unshielded sample.

5   Conclusions

We have studied a number of shielding methods (foil winding, ion-plasma spraying and electric arc wire spraying) for reduction of the radiation heat transfer.

The efficiency of various methods of shielding heat insulation structures in terms of reduction of radiation heat transfer is determined by thermal resistance.

The thermal resistance of test samples of the heat insulation structure that were shielded via electric arc wire spraying at the temperatures in the range from 110°C to 150°C was somewhat lower than in case of other shielding methods because of the high degree of roughness of the surface. If the temperature is above 130°C there is a trend toward stabilization of the thermal resistance of the heat insulation structure that has been shielded via electric arc wire spraying because the specific thermal resistance of the external surface of the heat insulation structure R_s becomes more significant than the other component of the total thermal resistance R.

At temperatures above 150°C the thermal resistance of test samples that were shielded via electric arc wire spraying is higher than the thermal resistance of the samples shielded via aluminum foil winding due to low metal content.

The high thermal resistance of test samples of the heat insulation structure that were shielded via ion-plasma spraying (higher by 35% or more than the thermal resistance of unshielded samples) is due to both, the high value of the reflection coefficient of the aluminum layer that has been deposited in vacuum and the low content of metal.

The experimental data provide evidence of the efficiency of the shields produced via ion-plasma spraying and electric arc wire spraying in terms of

reduction of the radiation heat transfer at temperatures above 150°C that are typical for operation of power equipment. The ease of manufacture and low consumption of metal are the advantages that allow to regard these shielding methods as having good prospects for their use in heat insulation structures of power equipment in the future.

Acknowledgement

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