PROBLEMS OF FRICTIONAL IGNITION IN TRANSPORT VEHICLES

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ABSTRACT

The article examines the problem of ignition ability of friction sparks when servicing rolling stock. It indicates the possibility of accidents associated with inflammation of gas-steam-air mixture. The mathematical analysis of sparking intensity was performed using basic equations. It is established that as a measure of intrinsic safety can serve a criterion that depends on intensity of sparking.

Keywords: transport, transportation of dangerous goods, flammable liquids, ignition source, friction sparks, sparking, intrinsic safety measure.

Background. *The growth of oil and oil products production, increasing their share in the fuel balance of the country, rapid development of the chemical industry, including the production of liquid products, have caused a significant increase in transportation of bulk cargoes. On transport hundreds of incidents involving dangerous goods occur annually: leakage of oil products, chemical, toxic and other hazardous substances posing a threat to human safety and the environment.*

Among emergency situations a special place is occupied by fires and explosions associated with transportation of flammable liquids. In recent years, 70% of fires occur in the transport sector on the rolling stock.

During loading and unloading of oil cargo at railway stations potentially dangerous situations emerge related to fumes of flammable liquids into the environment [1]. This is because the manhole of the tank, delivered to the pier for loading of light oil products in an open way, is in such a state for a long time [2], which leads to rapid formation of potentially explosive areas.

In order to avoid the scenario of an emergency [3] we have carried out research aimed at eliminating a source of ignition.

Objective. *The objective of the author is to consider frictional ignition in transport and problems accompanying this process.*

Methods. *The author uses general scientific and engineering methods, mathematical calculation, evaluation approach, analysis.*

Results. *One common source of ignition of flammable steam-gas mixtures are friction particles [4], which arise by friction or collision of working bodies of technological machines, mechanisms, as well as in the performance of technological and repair operations by service personnel.*

Friction sparks are sparks of impact and friction which are incandescent metal particle of about 100 microns in size [4], the temperature of which is between metal melting temperature.

Friction particles formed as a result of relative movement of two contacting surfaces depending on degree of dispersion, initial temperature, presence of an oxidant, and other factors may be heated to a visible glow temperature [5]. Friction metal sparks in certain circumstances are heated to a temperature at which particles ignite [6].

For some substances, the mechanism of particles heating to a temperature at which heat transfer to the combustible gas mixture becomes sufficient for ignition, is connected with catalytic properties of the particle surface. After warming up the critical volume of the mixture to the ignition temperature, the flame spreads throughout its volume, but it is a source of total risk.

As a result of long-term operation of bulk cars on the surface of metals and inside them cracks appear. The tanks are strengthened, repaired, however, despite this, strain aging processes occur, which inevitably leads to embrittlement of metal and increased sparking [7].

Ignition of the gas-air mixture is possible if the amount of heat given to the surrounding space by one or more sparks, satisfies the conditions of ignition of combustible mixture [8, 9]. The mechanism of ignition of flammable mixtures by frictional sparking remains understudied.

It is known that intensity and ignition ability of friction sparks depend on friction regime and collision of two bodies, physical and mechanical, chemical and physical properties of contacting surfaces, and other factors. However, not all friction sparks can ignite gas-air mixture.

The degree of dispersion of friction particles flying in space with a gas-air mixture, the number and power parameters are determined by load application speed and its value, as well as the physical and mechanical properties of materials of interacting bodies and surface coatings.

Intrinsic safety measure of work with tanks for transportation of flammable liquids may be some criterion that depends on intensity of sparking. This intensity for various materials is associated with the probability, which is determined experimentally. A similar problem of spark ignition of gas-air mixture is considered, for example, by D. V. Botvenko [9].

During simulation we used an analytical method of research using the following basic equations [8–12].

1. Newton-Richman law for convective heat transfer:

$$q = \alpha \Delta T. \quad (1)$$

Here, the density of the heat flow to the environment from the surface of a moving heated friction particle is proportional to the surface temperature difference of the friction particle and its surrounding gas environment (temperature drop).

The proportionality coefficient α is a coefficient of heat transfer, heat flow density at a temperature difference of 1 K, i.e. the amount of heat given off from the unit surface area per unit of time at a single temperature difference. The heat transfer coefficient depends on the type and temperature of a heating agent; temperature drop, type of convection and the flow regime (laminar or turbulent); surface condition and direction of flow; body geometry.

Equivalent record of Newton-Richman law (1) in the differential form:

$$\frac{d}{dt}\frac{\partial}{\partial S}Q = \alpha \Delta T. \quad (2)$$

We can derive an integral formula from the differential (2). The amount of heat given through the area at the interface of body area S for the time t, is proportional to the temperature difference between these bodies (assuming that it remains constant during this time):

$Q = \alpha t S \Delta T.$ (3)

2. Fourier law of heat dissipation intensity by heated bodies in the environment (thermal conductivity law): in steady-state energy flux density transmitted by thermal conductivity is proportional to the temperature gradient:

$$\vec{q} = -\kappa \cdot grad(T). \quad (4)$$

where $\vec{q}$ is a heat flow density vector (the amount of energy passing in unit time through unit area perpendicular to each axis);

κ is a thermal conductivity coefficient;

T is temperature.

Minus on the right shows that the heat flow is directed opposite to the temperature gradient vector (i.e., in the direction of the fastest temperature decrease).

In the integrated form the same expression takes a different view (if we talk about a steady heat flow from one edge of the parallelepiped to the other):

$$P = -\kappa \frac{S\Delta T}{l}, \quad (5)$$

where P is total power of heat losses;

S is area of the parallelepiped section;

ΔT is temperature difference of edges;

L is length, i.e. the distance between the edges of the conditional parallelepiped.

Fourier law does not take into account the inertia of the thermal conductivity process, that is, in this model temperature change at some point instantly spreads all over the body. It is not applicable to describe high-frequency processes (and, accordingly, processes which Fourier expansion has significant high-frequency harmonics). The inertia in the transfer equation (first introduced by Maxwell) is taken into account by the introduction of the relaxation term (proposed in 1948 by Cattaneo):

$$\tau \frac{\partial \vec{q}}{\partial t} = -(\vec{q} + \kappa \nabla T). \quad (6)$$

If relaxation time τ is negligible, then this equation becomes Fourier law (4).

Note that Newton-Richman law (2) is a type of boundary conditions (conditions of the third kind), which are placed in heat transfer problems. In this case, considering Fourier law it can be written as:

$$\frac{\partial T}{\partial n} = k(T_{out} - T_{in}). \quad (7)$$

And again: this law describes the situation only on the boundary of the body, inside the temperature is determined by its thermal conductivity. Heat flow inside the body is determined by Fourier law (4) that allows to find the distribution, solving thermal conductivity equation.

If internal thermal conductivity is much greater than the heat transfer coefficient (small Biot number), then inside the almost uniform temperature is set (if on the entire surface it is also the same), and then body cooling equation can be written as:

$$\frac{\partial T}{\partial t} = k(T_{out} - T). \quad (8)$$

Here coefficient

$k = \frac{\alpha S}{C}$, where C is heat capacity of the body.

From this equation it is easy to get that temperature of the body in such a situation would approximate the exponent to ambient temperature T_{out}:

$T(t) = T_{out} + e^{-kt}(T_0 - T_{out}).$ (9)

3. Criterial equation describing the process of dissipation of accumulated heat in the forced convection;

$Nu = 2 + 0{,}03\, Pr^{0{,}33} Re^{0{,}54} + 0{,}35\, Pr^{0{,}36} Re^{0{,}58},$ (10)

where Nu is Nusselt thermal criterion;

Pr is Prandtl thermal criterion;

Re is Reynolds criterion.

Criterion Re characterizes the motion of heated friction particle in gas-air medium and is given by:

$$\mathrm{Re} = \frac{\upsilon_f d_{eq}}{\nu_{gam}}, \quad (11)$$

where υ_f is speed of a heated friction particle relative to gas-air medium (m/s);

d_{eq} is characteristic size (equivalent diameter of a particle) (m);

ν_{gam} is kinematic viscosity of a gas-air mixture (m^2/s).

Speed of motion of a heated friction particle depends on the initial pulse obtained by a particle upon contact of two bodies.

Prandtl thermal criterion characterizes the ability of heat to spread in the environment and is determined by the formula:

$$\mathrm{Pr} = \frac{\nu_{gam}}{\chi}, \quad (12)$$

where χ is thermal conductivity coefficient:

$$\chi = \frac{\lambda}{\rho c_p}, \quad (13)$$

where λ is thermal conductivity;

ρ is density;

c_p is specific thermal capacity of a gas-air mixture.

4. Thermal conductivity equation with two sources (as a result of cracking of the surface layer and the work of friction forces) with appropriate boundary and initial conditions – to determine the temperature of friction sparks.

Preliminary for analysis of the energy to ignite a spark we estimate [10] possible heating temperature of friction particles. In this case, we assume that in case of impact the interaction of two bodies occurs, both in friction of a body, moving on the surface of another body with some known speed V_0 under the action of the pressure force F.

The friction force $F_{fr} = kF$, where k is friction coefficient.

If under the action of friction particle travels over the distance S, the work done by the friction force A (per time unit, i.e. power) will be:

$$A = \frac{1}{2} F_{fr} S = \frac{1}{2} kFV_0. \quad (14)$$

An important feature of the friction process is a discrete stochastic nature of frictional interaction in the contact zone between the contacting surfaces. This is due to the presence of the original micro-relief of surfaces in contact. During the initial contact the size of patches of actual contact patch (ACP) will be conditioned by the initial relief of rubbing surfaces. Depending on the applied load F and physico-mechanical characteristics of the contacting materials ACP varies in a wide range from fractions of a percent to tens of percent of the total (nominal) area and can be defined by the formula:

$S = F/\gamma^*,$ (15)

where γ^* is maximum stress limit.

The thin surface layer undergoes a noticeable and significant deformation and structural changes. In the plastic materials deformation varies from 10–15% up to 500–1000%. In brittle materials the surface layer will break. Thus, in friction input energy will be dissipated into heat only in contact patches. Therefore, the temperature calculation can be made for the contact area only.

If the value of the normal force F can be replaced by the value of material strength, meaning that the energy density is calculated at the contact patch, it is possible to get:

$A = N = k V_0 \gamma$ *. (16)

and one external parameter remains – speed V_0.

If we assume that the thickness of the active layer, in which deformation processes are developed as a result of friction, is significantly smaller than the size in longitudinal and transverse directions, the thermal conductivity problem can be considered as one-dimensional.

Based on the fact that two heat sources are considered, we write the thermal conductivity equation with two sources, namely:

1) w – as a result of cracking of the surface layer,
2) q – as a result of frictional forces,

and with the relevant boundary and initial conditions:

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} + \frac{w}{c\rho}, \quad 0 < x < \alpha,\ t > 0; \qquad (17)$$

$$-\lambda \frac{\partial T}{\partial x} = q\ ,\ T_{t=0} = 0; \qquad (18)$$

$$\kappa a = \frac{\lambda}{c\rho}. \qquad (19)$$

Heat source w should operate only in a thin layer (from10 to 100 microns). We represent it in the form of:

$$\frac{w}{c\rho} = Ae^{-\alpha x}. \qquad (20)$$

The calculations [10] found that at the dynamic contact speed in the range of 1 to 10 m / s theoretically established contact patch temperature reaches the melting point during 10^{-4}–10^{-6} seconds at a deformation thickness, reaching 500–1000%.

High thermal conductivity contributes to rapid removal of heat from the contacting surfaces and reduction of intensity of the contact temperature rise. If a solid alloy has a low thermal conductivity, the released heat is accumulated on the contact surfaces, resulting in rapid growth in contact temperature.

Friction sparking is associated with the conversion of a part of kinetic energy of mechanical interaction in warmth followed by exothermic oxidation and heating of particles. With increasing particle speed the contact temperature grows.

To determine the ignition ability of friction sparks and to assess their hazard in the analyzed combustible medium, we consider [12] thermal processes occurring during the motion of a single heated particle in gas-air medium.

The density of the heat flow q_f from the surface of a moving heated friction particle into the environment, according to Newton-Richman law (1) is proportional to the temperature difference between the surface of the friction particles t_f and the surrounding gas-air medium t_{gam}, i.e:

$q_f = \alpha(t_f - t_{gam})$, (21)

where α is heat transfer coefficient (W/(m²·°C));

t_f is surface temperature of a friction particle (°C);

t_{gam} is a temperature of surrounding gas-air medium (°C).

Equation (21) allows to determine the quantity of heat q_f which per unit of time is removed from the surface to the environment.

As follows from Fourier's law (4) from the surface of the particle friction the flow is removed

$$q_f = -\lambda_{gam} grad(t_f) = -\lambda_{gam} \frac{\partial t_f}{\partial n}, \qquad (22)$$

where n is a normal to the isothermal surface.

From (21) and (22) it follows:

$$\alpha(t_f - t_{gam}) = -\lambda_{gam} \frac{\partial t_f}{\partial n}, \qquad (23)$$

or $$\frac{\partial t_f}{\partial n} = -\frac{\alpha}{\lambda_{гвс}}(t_f - t_{gam}). \qquad (24)$$

Expression (24) is a mathematical description of the boundary conditions of the third kind.

To determine the heat losses Q of a moving friction particle over time τ_f, on the basis of (21), we obtain the expression:

$Q = \alpha(t_{fi} - t_{gam})S\tau_f$, (25)

where t_{fi} is initial temperature of surface of a friction particle;

S is a surface area of a heated particle.

The process of removal of the accumulated heat by a moving friction particle in the gas-air medium with forced convection is characterized by a criterial equation (10).

Speed of a heated friction particle υ_f depends on the initial pulse obtained by a particle upon contact of two bodies.

The value of heat transfer coefficient α, related to the surface of the heated friction particle can be determined on the basis of the dimensionless Nusselt criterion (10):

$$Nu = \frac{\alpha d_{eq}}{\lambda_{gam}}. \qquad (26)$$

From (26) the heat transfer coefficient is:

$$\alpha = \frac{Nu \lambda_{gam}}{d_{eq}}. \qquad (27)$$

Let's estimate the heat energy accumulated by a moving friction particle through the particle mass M and its specific heat capacity c_f:

$E = Mc_f t_f$. (28)

At the same time the mass of the particle is represented as:

$$M = \rho_f V = \rho_f \cdot \frac{\pi d_{eq}^3}{6}. \qquad (29)$$

In the expression (29): V is volume of the friction particle, ρ_f is its density.

Let's substitute (29) into (30):

$$E = \frac{\pi d_{eq}^3}{6} \cdot \rho_f c_f t_f. \qquad (30)$$

Conditions of ignition of a gas-air mixture by a cloud of sparks is:

$Q \geq Q_{ign}$. (31)

To assess the intrinsic safety of works we set the criterion K:

$$K = \frac{Q_{f\Sigma}}{Q_{ign}}. \qquad (32)$$

At K = 1 a gas-air mixture is in critical condition in relation to friction ignition, at K > 1 – in dangerous, and at K < 1 – in safe.

As a measure of intrinsic safety of work with tanks for transportation of flammable liquids may serve a criterion (34), which depends on intensity of sparking.

Conclusions. *The analysis suggests that more importance should be given to spark-producing ability of materials, because due to a number of breaches of processes safety the occurrence of sparks can lead to a crash.*

The urgency of the issue increases even more if we take into account the statistics of operation of freight fleet in circulation on the Russian railways. To date, tens of thousands of oil and gasoline tanks are in service with extended and double extended period of operation. The risk of an emergency related to inflammation of gas-steam-air mixtures during loading-unloading of oil products for such tanks is extremely high.

Apart from the existing arrangements to prevent a dangerous situation, it is necessary to pay particular attention to the need for additional technical measures to prevent the occurrence of potentially explosive area during technological operations with oil and petrol tanks.

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