BLEVE PREVENTION BY USING OF VENT DEVICES

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ABSTRACT

The main features of accidents with BLEVE's (Boiling Liquid Expanding Vapour Explosions), occuring in fires, are analyzed. Simple mathematical models, describing liquid or vapour discharge through perforations of vessels with superheated liquids and a liquid behaviour in heated by a fire vessel, are formulated. These models are verified on the basis of available in literature experimental data. The analysis of the well known accident with BLEVE on a railway tank in a fire and a fireball formation (Alma-Ata, 1989) is presented. It was shown, that this accident could be prevented by means of a vent device (safety valve or breaking diaphragm) with the cross-section area greater than 77 cm^2 and the operation pressure lower than 1.6 MPa. The using of such vent devices could prevent BLEVE's during fires with the presense of tanks with superheated liquids or liquefied gases.

INTRODUCTION

At a falling of a tank with a liquid or liquefied gas into a fire an explosion of this tanks is possible which is called BLEVE (Boiling Liquid Expanding Vapour Explosion) /1-3/. If this liquid or liquefied gas is combustible, a fireball (large scale diffusion flame with a strong thermal radiation) is formed. During the tank destruction shock waves with high amplitudes are produced. Accidents with BLEVE are characterised by serious destructions of a plant with people killed. Such accidents took place in Fazen (France, 1966), Mexico (Mexica, 1984), Alma-ata (Kazachstan, 1989) /14/. Severe consequences of BLEVE and its generic character for plants have stimulated attention of many investigators (see for example /5-12/). Some phenomenogical pecularlaties of accidents with BLEVE are revealed during these investigations.

Now some methods for the BLEVE prevention are known /13-15/:

- prevention of fire origin;
- cooling of tank walls in a fire by means of dispersed water;
- thermal isolation of tank walls;
- organization metal nets in side the tank in order to produce the more effective heat transfer;
- using of additions of substances preventing the homogeneous nucleation of liquid at a rapid pressure drop in the tank during the initial step of its destruction;
- using of corect projected vent devices.

The first three methods are widely used in practice, but according to the statistics they are not reliable enough. The application of metal nets inside the tanks is rather difficult, besides the effectiveness of such nets isn't proved neither theoretically nor experimentally. The same can be said about the additions preventing the homogeneous nucleation. The more perspective is the application of vent devices. This work is aimed on the investigation of this problem.

PRELIMINARY CONSIDERATION

Let us initially analyze the mechanism of BLEVE occurance. A

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heating of a closed vessel in a fire ieads to the liquid temperature elevation to values exceeding the normal boiling temperature. The vapour pressure is increased to values much greater than atmospheric pressure. A heating of dry tank walls causes a metal tensil strength reduction, leading to a tank destruction. A rapid pressure decrease causes the propagating into a liquid rarefaction wave, which is followed by a liquid boiling wave with the appropriate pressure elevation. The following accident scenario depends strong on a liquid temperature T_0 at the time moment of the tank destruction. If T_0 value exceeds so called superheating limit /13,14/, the homogeneous nucleation in the liquid occurs, and the liquid boiling takes place in an explosive regime with the fast pressure elevation and the tank explosion. If T_0 value is lower than mentioned above superheating limit, the liquid evaporates much more slowly. Because the boiling liquid wave is followed by a shock wave and ceases the liquid boiling /10/, the tank explosion doesn't occur.

The superheating limit at various pressures can be drawn on the p-T diagram of a liquid by a spinodal curve (Fig. 1), which is the geometric locus described by a formula

$$(\partial p/\partial \nu)_T = 0, \qquad (1)$$

where p is a pressure; T is a temperature and ν is a specific volume.

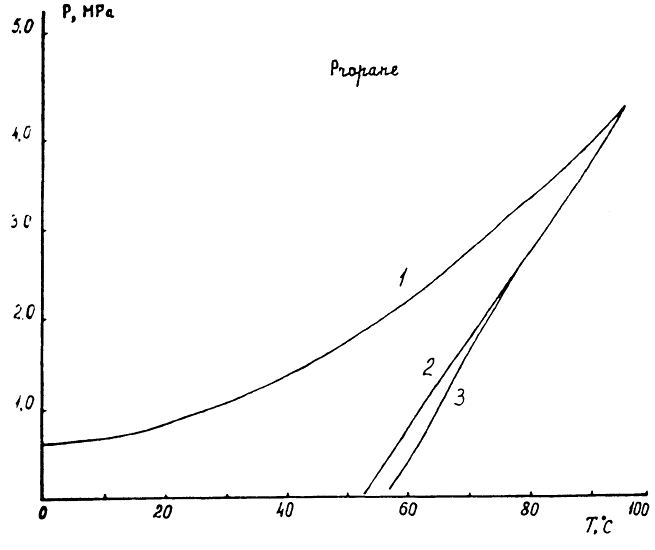

Fig. 1. State diagram "pressure P-temperature T" for propane. 1 - dependence of vapour pressure on temperature; 2 - spinodal curve (data [14]); 3 - spinodal curve (calculations results of this work).

From the diagram on Fig.1 it is easy to determine the minimum value of a superheating limit, at temperatures lower which BLEVE doesn't take place. This value corresponds to an intersection of a spinodal curve with an abscissa axis. For propane this minimum superheating limit is equal 53°C (the appropriate pressure is equal 1.6 MPa). At propane tempertures lower than 53°C (pressures lower than 1.6 MPa) BLEVE is impossible.

From this viewpoint the principle possibility of the BLEVE prevention can be seen by means of the application of vent devices (safety valves, breaking diaphragms) with operation pressures not greater than the pressure P_1, which corresponds to the minimum superheating limit, and having cross-sectional areas large enough in order to prevent a pressure elevation in a fire to values higher than P_1.

For the realization of the such method of BLEVE prevention [1] it is necessary to formulate at least a simple mathematical model for the tank with a liquid or liquefied gas in a fire. In our model we will not to consider in detail the tank walls heating and the loss of their strength, but we shall consider more accurate the processes in a liquid and vapour phases.

Let us initilly consider calculations of spinodal curves. We have decided the equation (1) for various temperatures using the liquid state Redlich-Quang equation /16/. Note that the application of a simple Van-der-Vaals equation gives wrong results, which differ sufficiently from literature data. Results of our calculation for propane are presented in Fig. 1. A good coincidence between calculated and literature data is observed (especially at high temperatures), that is an equation (1) with the state Redlich-Quang equation can be used for the evaluation superheating limiting temperatures.

Because of a possibility of a tank cracking in its lower part, where the liquid phase is stored, and an operation of vent devices it is nesessary to evaluate quantitavely the discharge processes for a liquid and vapour phases. Therefore let us consider models of mentioned above processes.

MODELING OF LIQUID PHASE DISCHARGE

During a discharge of a superheated liquid a two-phase medium is formed at exit of tube or perforation. The mass flux G is described in this case by a formula:

$$G= \frac{\mu\cdot F}{\nu_a} \sqrt{2\nu_a (W_o - W_a)}\ , \qquad (2)$$

where μ is a discharge coefficient; F - a perforation area; $\nu_a = 1/\rho_a$ - a specific two-phase medium volume at a perforation exit; W_o, W_a - specific enthalpies of a liquid phase and two-phase medium respectively; ρ_a - a density of a two-phase medium.

The values ρ_a, W_o, W_a can be determined from a reference literature (see for example /17/) taking into account that the W_o value is taken at the initial liquid temperature T_o, and the ρ_a, W^o_a at the normal boiling temperature T_b. It is proposed that a discharge occurs in adiabatic conditions, and the fraction η of a liquid phase, which evaporates instantaneosly, is described by a formula /1/:

$$\eta = C_{pl} (T_o - T_b)/L_{ev}, \qquad (3)$$

where C_{pl} is a specific liquid thermocapacity coefficient; L_{ev} specific heat of evaporation.

Let us at first consider the equation for a liquid discharge from a cold tank with the following propositions: liquid and vapour phase temperatures are equel to each other; temperatures are uniformly distributed in the tank volume; a heat exchange between a tank and an ambient air takes place.

The changes of liquid and vapour phase masses m_l and m_v with time t are described by the equations:

$$\frac{dm_l}{dt} = -G - \frac{dm_g}{dt} , \qquad (4)$$

$$\frac{dm_g}{dt} = V_g \cdot \frac{d\rho_g}{dt} + \frac{\rho_v G}{\rho_l} , \qquad (5)$$

where V_g is the vapour phase volume; ρ_g ρ_l - vapour and liquid phase densities at a temperature T.

The $d\rho_g/dt$ value is described by the equation:

$$\frac{d\rho_g}{dt} = - \frac{1}{\nu_g^{\,2}} \cdot \frac{d\nu_g}{dT} \frac{dT}{dt} , \qquad (6)$$

where ν_g - vapour specific volume. The $d\nu_g/dT$ value can be calculated by means of empirical relations from a reference literature (see for example /17/). For liquefied petroleum gases the dependence of ν_g on T is described by an empirical formula:

$$\nu_g = \nu_0 \exp(T_0/T), \qquad (7)$$

where ν_0, T_0 - constants for a given substance.

Substituting (5) and (6) in (4) and taking into account that $\rho_g/\rho_l = \nu_l/\nu_g$ (ν_l - specific volume of a liquid phase), we obtaine:

$$\frac{dm_l}{dt} = - G\left(1 + \frac{\nu_l}{\nu_g}\right) + \frac{V_g}{\nu_g^{\,2}} . \frac{d\nu_g}{dT} . \frac{dT}{dt} . \qquad (8)$$

The dependence of the V_g value on time can be described by an approximate equation

$$\frac{dV_g}{dt} = G\nu_l , \qquad (9)$$

which gives the satisfactory accuracy for the cold tank, when the dependence of the ν_l on temperature is rather slow /17/.

For the description of the dependence of the temperature T on time we have taken into account, that the liquid phase enthalpy changes by the evaporation and by the heat exchange with surrounding air, and obtaine:

$$C_{pl} \cdot m_l \frac{dT}{dt} = - L_{ev} \frac{dm_g}{dt} + \alpha F_t (T_a - T), \qquad (10)$$

where α - heat exchange coefficient; F_t - tank surface area; T_a surrounding air temperature.

Substituting (5) in (10), we find the equation describing the time dependence of the temperature:

$$\frac{dT}{dt} = \frac{1}{C_{pl} \cdot m_l - L_{ev} (V_g/\nu_g^{\,2}) \cdot (d\nu_g/dT)} \cdot \left[- \frac{\nu_l}{\nu_g} G \cdot L_{ev} + \alpha \cdot F_t (T_a - T)\right] . \qquad (11)$$

The proposed model was verified by means of experimental data /18/. In /18/ experiments were executed, where the mixture of propane and butane was discharged from a vessel with volume 50 dm^3, in which a perforation was in the lower part. The calculated and experimental results are presented in Fig.2. In Fig.2 for comparison the calculated by means of the well known Bernulli rofmula results are shown. It can be seen that results calculated by the proposed method are in a good agreement with experimental one in contrast to those obtained by the Bernulli formula.

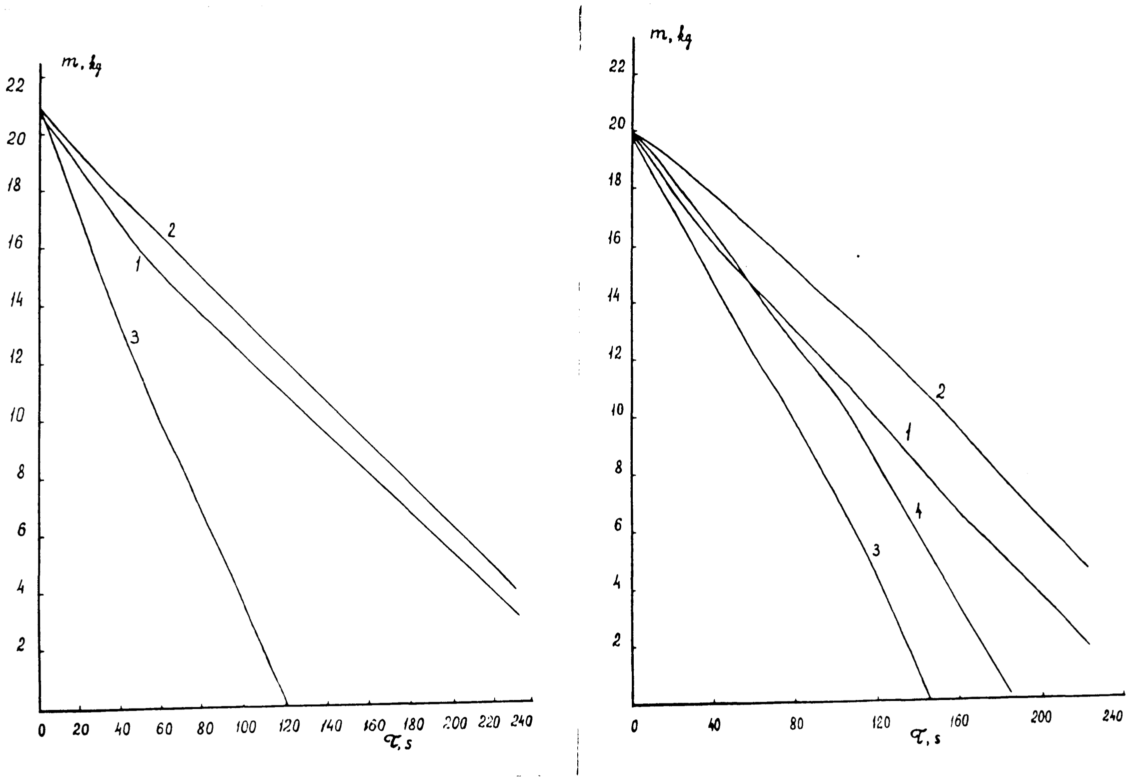

Fig. 2. Dependence of LPG mass m in a tank on time τ for LPG compositions: a - propane - 80,7% (mass.), butane - 19,3% (mass.); b - propane - 59,6% (mass.), butane - 40,4% (mass.).

1 - experiment [18]; 2 - calculations results of this work for perforation diameter d=4 mm; 3 - calculations by the Bernulli formula for d=4 mm; 4 - calculations results of this work for d=5 mm.

BEHAVIOUR OF THE TANK WITH SUPERHEATED LIQUID IN A FIRE

The model for the description of the behaviour of the tank with superheated liquid in a fire was created with using the same assumptions as in the previous section. Additionally a thermal flow from a fire to a tank was taken into account, which is uniformly distributed on the tank walls. Besides it is accepted that a mass liquid evaporation rate is equal to a mass vapour discharge rate through a safety valve, that is $dm_g/dt \approx 0$.

The time temperature dependence is described by the equation:

$$\frac{dT}{dt} = \frac{1}{C_{pl} m_l} (QF_t - GL_{ev}), \qquad (12)$$

where Q is the effective thermal flow intensity to the substance storaging in the tank.

The time dependence of the liquid mass is described by the equation:

$$\frac{dm_l}{dt} = - G. \qquad (13)$$

The dependence of the specific vapour phase volume with temperature is decribed by the formula (7), and for specific liquid phase volume - by the empirical expression:

$$\nu_l = \nu_{lo} + k(T - T_{lo}), \qquad (14)$$

where ν_{lo}, k, T_{lo} - constants for a given liquid, which can be taken from a reference literature.

The value of G can be described by the well know expressions:

- for subcritical discharge $\left(P_a/P > \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}\right)$

$$G = \mu F \cdot \sqrt{\frac{2\gamma}{\gamma-1} p\rho_g \left[\left(\frac{P_a}{P}\right)^{2/\gamma} - \left(\frac{P_a}{P}\right)^{(\gamma+1)/\gamma}\right]}, \qquad (15a)$$

- for critical discharge $\left(P_a/P < \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}\right)$

$$G = \mu F \cdot \sqrt{\gamma \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)} p\rho_g}, \qquad (15b)$$

where μ is dischage coefficient; F - perforation area; p - pressure; γ - adiabatic constant.

For the verification of the proposed model we have used the experimental data /19/. In /19/ the large-scale experiments were executed in which the behaviour of propane tanks with volume 10.25 m^3 in a fire was investigated. The operation of a safety valve was taken into account (the safety valve operation pressure was equal 1.43 MPa).

It was found that expressions (15) describe satisfactory a mass discharge rate at μ=1. The Q value was accepted 65 kW/m^2. The calculated results with experimental data /19/ are presented in Fig. 3. The agreement of theoretical and experimental results is rather satisfactory.

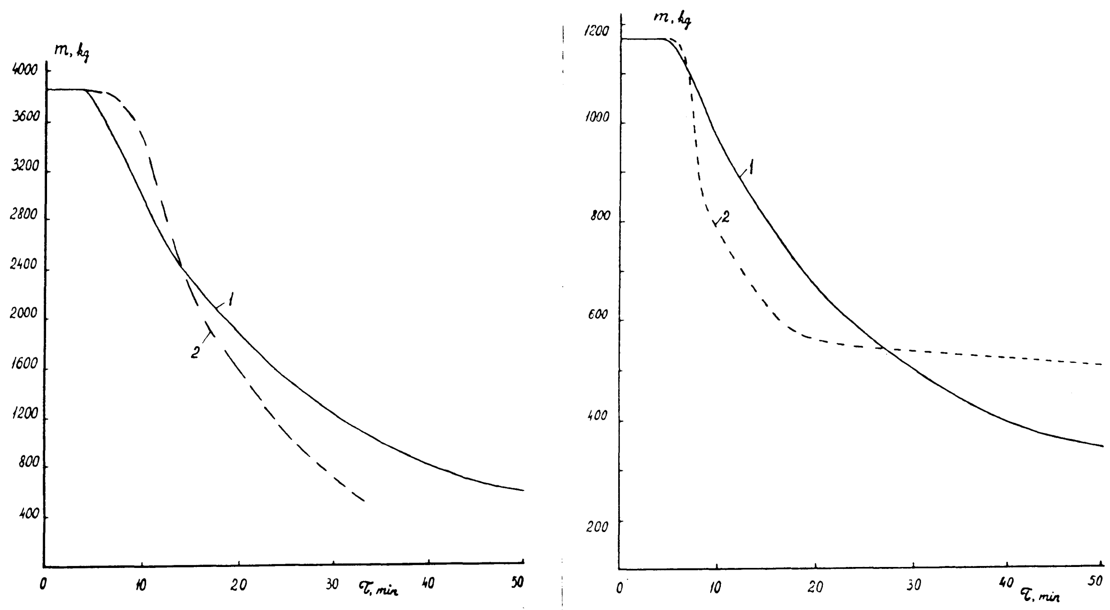

Fig. 3. Dependence of propane mass in a tank m on time τ for initial liquid phase volume fraction 72 (a) and 22 (b)%. 1 - calculations results of this work; 2 - experiment [19].

For the mass discharge rate G of a vapour phase the following empirical correlation from /20/ was also used:

$$G = F\cdot\sqrt{\left(\frac{p_c M}{RT_c}\right)\cdot p_c\cdot\left[0.167p_R{}^{5}+0.534p_R{}^{1.95}\right]}\ , \qquad (16)$$

where p_c is critical pressure; M - molar mass; R - gas constant; T_c - critical temperature; $p_R = p/p_c$ - non-dimensional pressure.

Results of calculations with using of the expression (16) are practically coincide with data obtained with the correlation (15) at μ=1.

APPLICATIONS OF PROPOSED MODELS FOR ANALISIS OF BLEVE ACCIDENT (ALMA-ATA, 1989) AND DETERMINATION OF REQIRED VENT DEVICES PARAMETERS

The proposed model was used for the analysis of the accident with BLEVE, which took place in Alma-Ata (Kazakhstan, 1989), and also for determination of required cross-sectional ares for vent devices in order to prevent BLEVE. Input data were the following /21/:

- tank volume - 54 m^3;
- initial liquefied petroleum gas (LPG) mass in the tank - 23 tonne;
- LPG composition - propane - 45% (mass.), butane - 55% (mass.);
- initial temperature - 30°C;
- cross-sectional area of the safety valve - 77 mm^2;
- operation pressure of the safety valve - 2,26 MPa;
- density of the thermal flow on the tank walls - 65 kW/m^2.

According to /21/, the accident had the follwing scenario. In the evening of 20 May 1989 because strong violation of railway rules the collision of two trains occured, as a result of which one railway tank with LPG was destroyed. The liquid phase flow from a perforation began. After 3-5 minutes after the discharge beginning the ignition of a vapour cloud occured, and a powerfull gaseous tourch formed, which almost entirely covered an adjacent tank with LPG. After 18-20 minutes from a fire begining a tank explosion (BLEVE) with a fire-ball formation took place, inspite of firemen began cooling of tank walls by means of water sprays. A fire-ball during its lifetime caused numerous fires at distances up to 180 m. As a result 200 people were injured, more than 20 people were killed, including 9 firemen.

Results of calculations of LPG parameters in the heated tank are presented in Fig. 4, where dependences of a mass of LPG in the tank, a volume fraction of a liquid phase and a pressure in the tank are presented up to the time moment of BLEVE begining. The LPG mass in the tank doesn't change noticeably, and the pressure reaches the value near 4.0 MPa, which is hazardous for the tank integrity even without tank walls heating. It can be noted that the liquid phase volume fraction increases that is liquid fills almost the whole tank volume. According to /21/, after the whole tank volume filling by a liquid phase a liquid boiling near internal tank walls is made difficult. A regime of the heat exchange between tank walls and a liquid phase in the form of the bubble boiling changes by a regime of a free convection in the closed vessel. In this case the heat exchange coefficient decreases with appropriate increase of tank walls temperature, and the tank destruction probablity increases.

We have analyzed the influence of vent device parameters (cross-sectional area F, operation pressure p_{op}) on a tank behaviour in a fire. A decrease of the safety valve operation pressure p_{op} from 2.26 to 1.6 MPa (the limiting pressure for a BLEVE initiation) at a fixed cross-sectional area F doesn't cause a noticeable change of LPG characteristics (curves 2 in Fig.4). At the same time the F value elevation to 770 mm^2 significantly changes the process hystory. The LPG mass in the tank after the safety valve operation beginning lowers noiceably both at an operation pressure 1.6 MPa and at 2.26 MPa. The liquid phase volume fraction begins to decrease, but a pressure increase in the tank doesn't stop, that is a safety valve with cross-sectional area 770 m^2 doesn't prevent BLEVE. The safety valve operation pressure also doesn't cause any significant influence on considered process parameters.

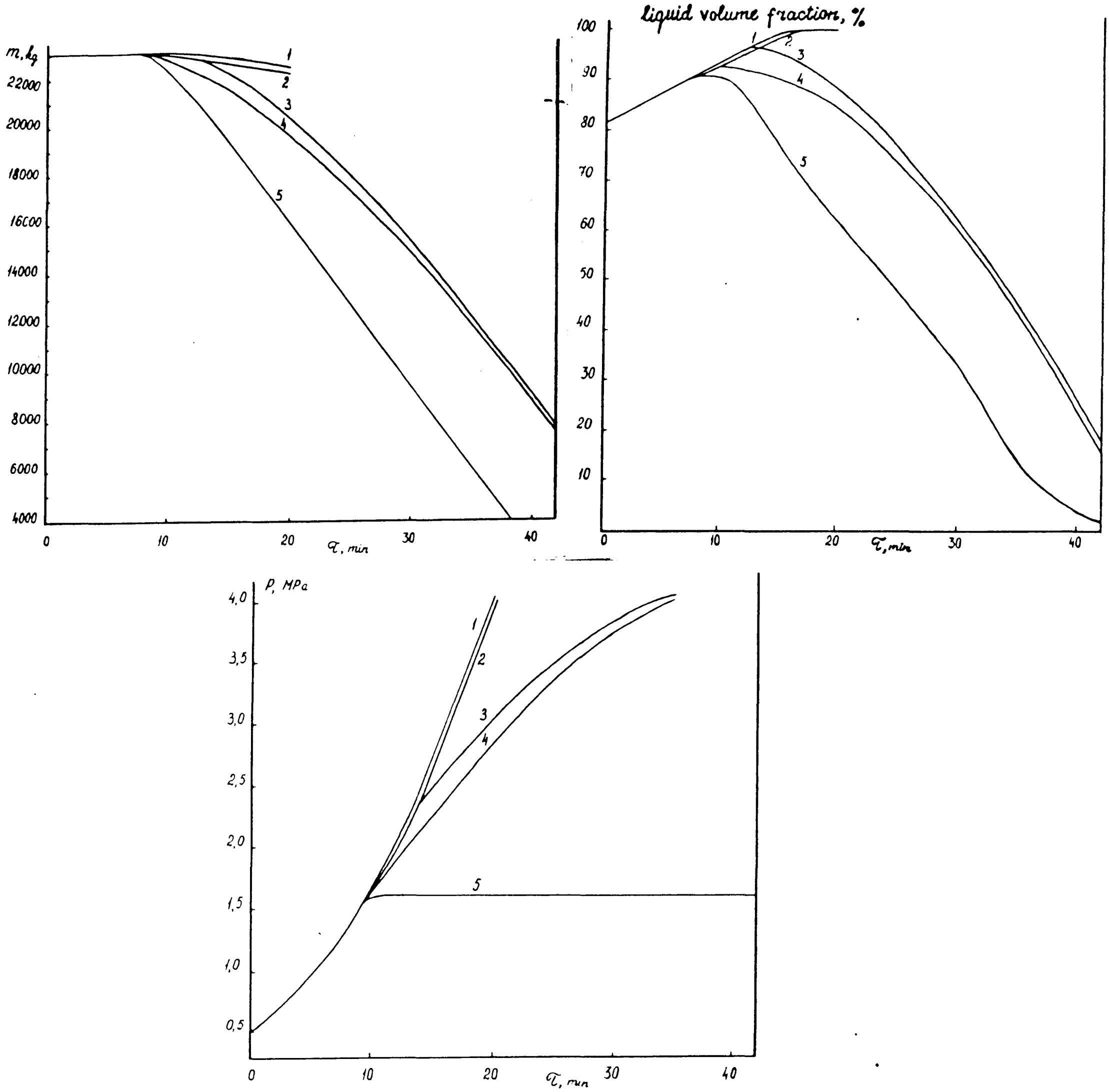

Fig. 4. Dependence of LPG mass in a tank m (a), liquid phase volume fraction (b) and pressure p (c) on time τ. 1 - safety valve cross-sectional area F=77 mm², operation pressure P_{op}=2,26 MPa; 2 - F=77 mm², P_{op}=1,6 MPa; 3 - F=770 mm², P_{op}=2,26 MPa; 4 - F=770 mm²,

At safety valve cross-sectional area 7700 m² after its operation beginning the LPG mass and the liquid phase volume fraction decrease rapidly, but the pressure remains near constant. The approximate constancy of a pressure after the safety valve operation bagining in the case of its sufficient cross-sectional area was experimentally shown in /5, 19/. If in the considered accident at the railway station Alma-Ata the LPG tank would be supplied by a safety valve with a large enough cross-sectional area (near 7700 mm²), BLEVE didn't take place, and the tank destruction caused by a thermal loading will be much less severe than in the case of a real accident.

CONCLUSIONS

1. The main pecularities of accidents with boiling liquid expanding vapour explosions (BLEVE) of tanks with superheated liquids or liquefied petroleum gases (LPG) are considered. The main methods of BLEVE prevention are analysed.

2. Simple mathematical models of such processes as discharge of a liquid or vapour phase from a tank with superheated liquid or LPG and a liquid behaviour in a tank subjected by a fire are proposed. These models are verified by means of available in literature experimental data.

3. The analysis of the accident with BLEVE and fire-ball formation on a railway tank with LPG subjected by a fire (Alma-Ata, 1989) is presented. It is shown that this accident can be prevented by a safety valve with cross-sectional area not less than 7700 mm^2 and operation pressure not greater than 1,6 MPa.

4. The conclusion can be made that accidents with BLEVE on tanks with superheated liquids or LPG in fires can be effectively prevented by means of vent devices (safety valves or breaking diaphragms) which have the the appropriate cross-sectional areas and operation pressures.

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