Technical Rationale for Protective Equipment Propane Tanks in a Model Fire

Vladimir Popov, Eugene Asmankin, Philipp Sukhov, and Julia Bolandova

Abstract Railway transportation of liquefied petroleum gases in special tank wagons requires special attention to safety on the railway. A new method for analyzing the scenario of tank cars of liquefied hydrocarbon gases is proposed. It is based on the methodology for calculating the behavior of a rail tank car with liquefied gas in a fire. This method simulates processes using the «Fobot» software package. This mathematical model considers a metal tank with LPG, the outer surface of which contains a heat-insulating layer consisting of a layer of a porous non-combustible material (mineral wool) and a foaming fire-retardant paint. With the help of "Fobot", calculations of an emergency situation were made using various methods of fire protection. Certain patterns were deduced, conclusions were drawn to assess the degree of elaboration of this topic. The possibilities for improving this complex have become known, as well as the ability to design various emergency situations using all kinds of fire-fighting materials and technically improved devices.

Keywords Emergency situations on the railway · Railway tanks · Thermal risk · Simulation of emergency situations

1 Introduction

A large amount of liquefied petroleum gases (LPG) is transported by rail in special tank cars. A number of accidents with fires and explosions that occurred with railway tank cars for the transportation of LPG indicate a high fire and explosion hazard of the processes of transportation of these substances. Often accidents of LPG tank cars proceed according to the scenario when the tank with LPG is exposed to the fire source, as a result of which an explosion of the tank is possible, with consequences that can be catastrophic. One of the methods of fire protection of LPG tank cars is to choose a safety valve of such a passage section, which, on the one hand, prevents the explosion of the tank car for a given period of time under various accident scenarios, on the other hand, provides a minimum discharge of LPG into the environment.

V. Popov · E. Asmankin (✉) · P. Sukhov · J. Bolandova
Russian University of Transport (MIIT), Moscow, Russia 127994

A. Beskopylny and M. Shamtsyan (eds.), *XIV International Scientific Conference "INTERAGROMASH 2021"*, Lecture Notes in Networks and Systems 247,
https://doi.org/10.1007/978-3-030-80946-1_17

There are few studies of such emergency scenarios. Therefore, the purpose of this work is to develop a more accurate mathematical model of the behavior of LPG tank car located in the fire center and the calculated state of the LPG tank car in a model fire center during a full-scale experiment.

Often, accidents in LPG tank cars proceed according to the scenario when a tank with LPG is exposed to a fire source, as a result of which an explosion of the tank is possible, with consequences that are sometimes catastrophic. To prevent such accidents, various methods of fire protection of LPG tank cars are proposed:

- Increasing the thickness of the bottom of the tanks;
- Equipping tanks with protective screens to protect them from impacts;
- Arrangement of safety arches on tank hatches;
- Use of thermal insulation;
- Application of a fire retardant coating on the outer surface of tanks;
- Increase in flow area of safety devices.

These and other measures for fire protection of LPG tank cars can be developed on the basis of experimental and theoretical research.

In the process of calculating the critical parameters for the operation of the safety valves of tanks, it is necessary to obtain positive or negative results of the selected methods of fire protection of LPG tank cars.

2 Materials and Methods

In this mathematical model, a metal tank with LPG is considered, on the outer surface of which there can be a heat-insulating layer, consisting partly of a layer of porous non-combustible material (such as mineral wool), and the remaining part of the outer surface of the tank can be covered with foaming fire-retardant paint. It is assumed that at the moment of time $\tau = 0$ the temperature of LPG and the temperature of the layers of the two-layer tank wall are equal to the temperature of the ambient air TV and on a certain part of the outer surface of the tank F_0 (heat-insulating layer, if any), an external surface heat source with power q. If there is a fire-retardant coating on the walls of the tank, the heat flux causes its quasi-instant swelling with the formation of a heat-insulating layer with a thickness of L_{frc}, which depends on the initial thickness of the coating layer and its properties. It is assumed that the temperatures of the tank walls, as well as the temperature and pressure of the LPG, do not depend on the coordinates; the ambient temperature is considered constant. The thermophysical properties of the metal of the tank walls, the heat-insulating layer and the layer of the intumescent fire-retardant coating are assumed constant. The convective and radiative heat exchange on the outer surface of the tank with the ambient air temperature TB is taken into account. In the tank boiler, depending on the combination of LPG operating parameters, the following heat transfer modes are possible: surface, bubble or film boiling of liquid; natural convection of a liquid or gas in a large volume. When the safety valve is opened, a critical outflow of the two-phase LPG medium into the surrounding space occurs.

Two-phase region:

$$P < P_{cr}; T < T_{cr}; \quad (1)$$

Continuity equation

$$V\frac{d\left[\rho'(1-\beta)+\rho''\beta\right]}{d\tau} = -G, \quad (2)$$

where, V—tank volume; ρ', ρ''—density of the liquid and gas phases at the saturation line, respectively;

β—volumetric gas content; G—critical flow rate of a gas–liquid mixture flowing out of a safety valve

$$G/S = \left[\frac{(1-\beta)\rho'}{k} + \beta\rho''\right]\sqrt{\gamma RT_S\left(1+\frac{1-\beta}{\beta}\cdot\frac{\rho''}{\rho'}k^2\right)}; \quad (3)$$

$k = w''/w'$—slip coefficient;

$$k = 0.17x^{0.18}\left(\frac{\rho'}{\rho''}\right)^{(1/2)} - \text{Fauske model} \quad (4)$$

$$k = \left(\frac{\rho'}{\rho''}\right)^{(1/3)} - \text{Moody model}; \quad (5)$$

$$\gamma = c'_P/c''_P; \quad (6)$$

R—universal gas constant; S—safety valve flow area.

Energy equation

$$V\frac{d[\rho' i'(1-\beta)+\rho'' i''\beta]}{d\tau} = -Gi_k + V\frac{dP}{d\tau} + \alpha_в F_в(T_W - T_S), \quad (7)$$

where i', i''—enthalpy of liquid and gas phases on the saturation line, respectively; i_k—enthalpy of outflowing gas–liquid mixture; P—pressure in the tank boiler; $\alpha_в$—heat transfer coefficient on the inner surface of the boiler tank; $F_в$—internal surface area of the boiler tank; T_w—temperature of the inner surface of the tank boiler; T_S—LPG temperature at saturation line.

$$P = f(T_S) - \text{saturation line} \quad (8)$$

$$\begin{aligned}&\text{Single phase} - P > P_S;\, T < T_{cr};\quad \text{and}\\&\text{supercritical region} - P > P_{cr};\, T > T_{cr};\end{aligned} \tag{9}$$

Continuity equation

$$V\frac{d\rho}{d\tau} = -G, \tag{10}$$

where V—tank volume; $\rho = f(P, T)$—density of single-phase LPG; G—critical flow rate of boiling single-phase liquefied gas flowing out of the safety valve.

Energy equation:

$$V\rho\frac{di}{d\tau} = -G(i_k - i) + V\frac{dP}{d\tau} + \alpha_в F_в (T_W - T_S), \tag{11}$$

where $i = f(P, T)$—enthalpy of LPG; T_W—temperature of the inner surface of the tank boiler.

To calculate the critical pressure in the tank, I took the following parameters:

- model of 4-axle LPG tank 15-1200-02;
- safety valve SV(32–2.25);
- LPG—propane;
- design temperature 20 °C.

3 Results

To calculate (simulate) the development of the accident according to the BLEVE scenario, the «Fobot» software package was used.

The use of technical means of protecting LPG tanks in the fire site should at least prevent the development of an accident according to the BLEVE scenario within the time (4 h) required for the deployment of the fire department [1–11].

The following methods of fire protection are supposed to be applied in the fire center:

- Equipping the tank with safety valves:

  Standard valve—(SV(32–2.25)).
  Response pressure—2.25 MPa.
  Nominal diameter of the flow area $d_y = 32$ mm;

- Covering 95% of the outer surface of the tank with thermal insulation thickness $\boldsymbol{\delta_{in}} = 20$ mm.

  Thermal properties of insulation (identical to mineral wool):

- density—$\rho = 150$ kg/m^3,
- heat capacity - $c = 1000$ J/(kg K),
- coefficient of thermal conductivity—$\lambda = 0.047$ W/(m K);
  - Application of a foaming fire retardant coating SGK-1 in thickness $\boldsymbol{\delta_{foa}} =$ 20 mm on the remaining outer surface of the tank. Thermophysical properties of SGK-1:
- density—$\rho = 10$ kg/m^3,
- heat capacity—$c = 1000$ J/(kg K),
- coefficient of thermal conductivity—$\lambda = 0.07$ W/(m K).

Enter data into «Fobot», start modeling the situation.

Detailed results are structured, summarized and presented calculations are presented in Tables 1 and 2.

4 Conclusion and Discussion

The four-axle tank car for LPG 15–1200-02 is equipped with an SV(32–2.25) safety valve with an opening pressure of 2.25 MPa and a closing pressure of 1.95 MPa. Figure 1 shows that the pressure graph in the tank is limited to 2.25 MPa. After the pressure (Fig. 1) and temperature (Fig. 2) in the tank have dropped, the safety valve SV(32–2.25) closes [12–14].

The «Fobot» program is a complex of databases that can contain the data necessary for the calculation for any types of railway tanks, liquefied gases, safety valves, heat-insulating materials and fire-protective coatings, as well as software interpolation and other auxiliary modules, modules for calculating heat transfer characteristics and numerical solution of a system of differential equations.

Calculations using the «Fobot» software package show that the selected fire protection means:

- equipment of a propane tank (model 15-1200-02) with a safety valve (actuation pressure 2.25 MPa, nominal bore diameter $d_y = 32$ mm);
- covering 90% of the outer surface of the tank with thermal insulation $\delta_{is} = 20$ mm;
- foaming fire retardant coating thickness $\delta_{is} \approx 20$ mm on the remaining outer surface of the tank, ensure that the tank remains in the model fire source for 4 h without the development of an accident according to the BLEVE scenario [15].

Table 1 Results of calculating LPG—Propane. Tank 15-1200-02

№	View Accidents, Duration (4 h)	Remedies			Start WorkValve (min)	Condition of the tank at the end of the accident					
		Valve type	SGK-1δ_c (mm)	Thermal insulation (mm)		LPG parameters			LPG pressure change law		Outcome of the accident, boiler state
						state of LPG	P (MPa)	T (°C)	Valve adjustment	Unregulated growth	
1	3 degrees (T_a = 20 °C)	valve standard d_y = 32 mm	20	20	96.5	Gas	2.07	58.7	+	–	Not deformed

Table 2 Results of calculating LPG - Propane. Tank 15–1200-02

Event №	Event/process	Time (min)	Temperature (°C)	Pressure (MPa)
1	The beginning of the process. Two phases	0	20.15	0.8403
2	One phase-liquid	95.84	59.74	2.12
3	SV(32–2.25) opened	99.00	60.09	2.25
4	Two phases	99.00	59.63	2.11
5	SV(32–2.25) closed	99.06	55.56	1.95
6	One phase-liquid	101.93	60.67	2.16
7	SV(32–2.25) opened	104.15	60.91	2.25
8	Two phases	104.18	60.46	2.15
9	SV(32–2.25) closed	104.21	55.61	1.95
10	One phase-liquid	107.99	61.63	2.20
11	SV(32–2.25) opened	109.32	6175	2.25
12	Two phases	109.33	61.29	2.19
13	SV(32–2.25) closed	109.37	55.61	1.95
14	SV(32–2.25) opened	114.32	62.56	2.25
15	SV(32–2.25) closed	114.36	55.64	1.95
16	SV(32–2.25) opened	119.11	62.57	2.25
17	SV(32–2.25) closed	119.17	55.62	1.95
18	SV(32–2.25) opened	124.10	62.57	2.25
19	SV(32–2.25) closed	124.16	55.61	1.95
20	SV(32–2.25) opened	129.28	62.57	2.25
21	SV(32–2.25) closed	129.35	55.66	1.95
22	SV(32–2.25) opened	146.76	62.57	2.25
23	SV(32–2.25) closed	134.76	55.62	1.95
24	SV(32–2.25) opened	140.27	62.57	2.25
25	SV(32–2.25) closed	140.36	55.65	1.95
26	SV(32–2.25) opened	146.04	62.56	2.25
27	SV(32–2.25) closed	146.14	55.66	1.95
28	SV(32–2.25) opened	151.98	62.56	2.25
29	SV(32–2.25) closed	152.08	55.63	1.95
30	SV(32–2.25) opened	158.18	62.57	2.25
31	SV(32–2.25) closed	158.29	55.65	1.95
32	SV(32–2.25) opened	164.59	62.56	2.25
33	SV(32–2.25) closed	164.72	55.66	1.95
34	SV(32–2.25) opened	171.25	62.57	2.25
35	SV(32–2.25) closed	171.38	55.66	1.95

(continued)

Table 2 (continued)

Event №	Event/process	Time (min)	Temperature (°C)	Pressure (MPa)
36	SV(32–2.25) opened	178.10	62.57	2.25
37	SV(32–2.25) closed	178.25	55.64	1.95
38	SV(32–2.25) opened	185.19	62.57	2.25
39	SV(32–2.25) closed	185.35	55.66	1.95
40	SV(32–2.25) opened	192.56	62.57	2.25
41	SV(32–2.25) closed	192.73	55.66	1.95
42	SV(32–2.25) opened	200.19	62.57	2.25
43	SV(32–2.25) closed	203.76	55.67	1.95
44	SV(32–2.25) opened	208.09	62.57	2.25
45	SV(32–2.25) closed	208.29	55.67	1.95
46	SV(32–2.25) opened	216.24	62.56	2.25
47	SV(32–2.25) closed	216.45	55.66	1.95
48	SV(32–2.25) opened	224.67	62.56	2.25
49	SV(32–2.25) closed	224.92	55.68	1.95
50	SV(32–2.25) opened	233.48	62.56	2.25
51	SV(32–2.25) closed	233.72	55.67	1.95
52	Process completed	240	58.66	2.2

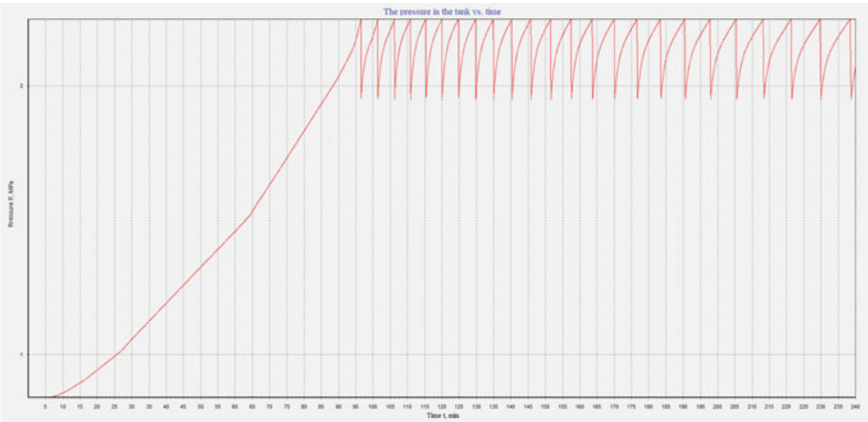

Fig. 1 The pressure in the tank vs. time

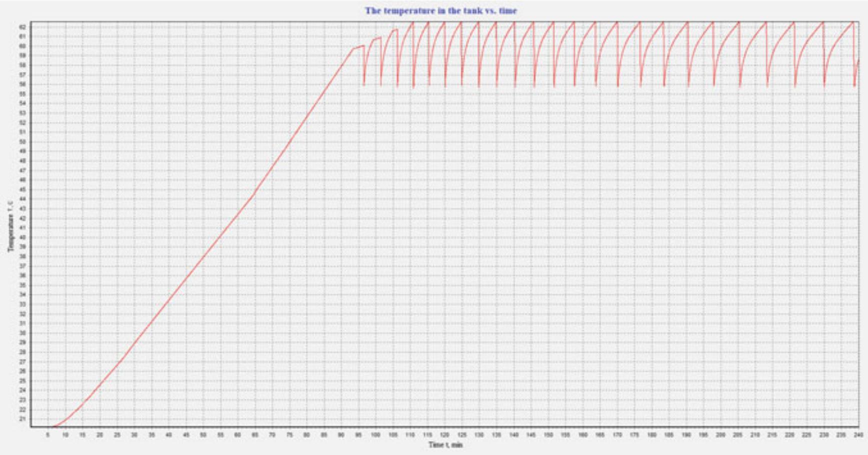

Fig. 2 The temperature in the tank vs. time

References

1. Jingde L, Hong H (2021) Process Saf Environ Prot 145:94–109. https://doi.org/10.1016/j.psep.2020.07.038
2. Yuanyuan WX, Gu LX, Yong PY, Ni SW, Wei Z (2020) J Loss Prev Process Ind 68. https://doi.org/10.1016/j.jlp.2020.104319
3. Jingde L, Hong H (2020) J Loss Prev Process Ind 65. https://doi.org/10.1016/j.jlp.2020.104107
4. Sellami I, Manescau B, Chetehouna K, de Izarra C, Nait-Said R, Zidani F (2018) J Loss Prev Process Ind 54:69–84. https://doi.org/10.1016/j.jlp.2018.02.010
5. Mingzhi L, Zhenyi L, Yi Z, Yao Z, Xuan LDZ (2018) J Hazard Mater 342:634–642. https://doi.org/10.1016/j.jhazmat.2017.09.002
6. Hemmatian B, Planas E, Casal J (2017) Process Saf Environ Prot 106:138–149. https://doi.org/10.1016/j.psep.2017.01.007
7. Bhushan KM (2016) J Loss Prev Process Ind 41:60–67. https://doi.org/10.1016/j.jlp.2016.03.003
8. Qian-xi Z, Dong L (2013) Procedia Eng 52:602–606. https://doi.org/10.1016/j.proeng.2013.02.192
9. Hemmatian B, Planas E, Casal J (2016) J Loss Prev Process Ind 40:81. https://doi.org/10.1016/j.jlp.2015.12.001
10. Zhao Y, Zhenyi L, Xiaohui S, Xinming Q, Yi Z, Deping Z, Qing L (2015) Energy Procedia 75:880–885. https://doi.org/10.1016/j.egypro.2015.07.204
11. Abo-Elkhier M, Muhammad K (2020) Eng Failure Anal 110. https://doi.org/10.1016/j.engfailanal.2020.104401
12. Li YZ, Ingason H (2018) Tunn Undergr Space Technol 81:568–589. https://doi.org/10.1016/j.jhazmat.2011.01.136
13. Brambilla S, Manca D (2010) J Hazard Mater 182:346–357. https://doi.org/10.1016/j.jhazmat.2010.06.039
14. Pasman H (2015) Risk analysis and control for industrial processes—gas, oil and chemicals, 1–31. https://doi.org/10.1016/j.matpr.2020.08.524
15. Liu L, Ni L, Jiang J-C, Zhang W-X (2018) Procedia Eng 211:479–487. https://doi.org/10.1016/j.proeng.2017.12.039