

EXPLOSION HAZARD OF AEROSOL-VAPOUR MIXTURES APPEARING DUE TO EVAPORATION OF POOLS OF HEATED COMBUSTIBLE LIQUIDS

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ABSTRACT

Theoretical and experimental investigations of explosion parameters of aerosol-vapour mixtures, appearing due to evaporation of pools of heated combustible liquids with high boiling points (diphyl and some other oils) were executed. Experiments were performed in chambers, which had volumes 8 and 42 m³ (measuring of the rate of liquid pool evaporation and sizes of explosion zones) and 10 m³ (aerosol-vapour explosions). Semiempirical formulas were derived, which described the dependence of rate of evaporation W_{ev} and vertical size of explosion zone Z_{exp} from time and physico-chemical properties of combustible liquids. These formulas are in a good agreement with the experimental results and may be written in the following form:

$$W_{ev} = a \cdot P_e \cdot \exp(-b \cdot \tau),$$

$$Z_{exp} = C \cdot \frac{m_e}{M^{1/2}} \cdot \left(\frac{P_e}{P_f} - 1 \right) \cdot \left(\frac{F^{1.5}}{2 \cdot \nu_a} \cdot \frac{T_{in} - T_0^{1.5}}{T_0} \right)^n,$$

where a , b , c , n - constants; P_e - pressure of the liquid vapour at the initial temperature of the liquid T_{in} , kPa; τ - time from the beginning of liquid pool evaporation, s; m_e - mass of liquid in the pool, kg; M - molar mass of liquid, g·mole⁻¹; P_f - pressure of the liquid vapour at a flash point, kPa; F - area of the pool, m²; T_{in} - initial temperature of liquid in the pool, K; T_0 - the ambient air temperature, K; ν_a - kinematic viscosity of the air at the temperature of T_0 , m²·s⁻¹.

Some series of experiments of aerosol-vapour mixtures explosions in the closed chamber of volume 10 m³ were executed. The rate of pressure rise during the explosion was low in respect with gaseous mixtures explosions for such substances as methane and propane. The explosion pressure depends on pool area, initial temperature of liquid and time delay of combustion initiation. The effective mass coefficient of vapour participation in explosion which characterises the mass fraction of aerosol-vapour mixture between lower and upper flammability limits, was close to unity.

INTRODUCTION

Liquid high-temperature organic heat-carriers (HOH), such as mixture of

diephenyl and diephenyloxyde, AMT-300T oil, I-5A oil, mobilterm 600 and some other oils, are widely used in the modern chemical process industry. These technological processes are characterized by high temperatures (from 200 to 400 °C), exceeding flash points of HOH used. At the accidents the emergency relief into the industrial room can take place with further evaporation and formation of flammable mixtures of combustible vapour with air. Explosion hazard in this case will be characterized by a series of parameters, determined by emergency condition and HOH's temperature.¹⁻⁵ These parameters are: rate of evaporation, specific evaporating mass from 1 m², explosion zones sizes, effective mass coefficient Z of vapour participation in explosion and explosion pressure, realized at the ignition of flammable vapour-air mixture. The purpose of this article is the investigation of formation and combustion of local flammable mixtures of HOH vapour with air and the derivation of formulas for calculation of mentioned above parameters, characterized the explosion hazard of processes, in which the heated combustible liquids with high boiling points are used.

THEORY

Some results of theoretical and experimental investigations of evaporation of heated HOH are published elsewhere.^{6,7} The time dependence of specific evaporating mass from 1 m² during the cooling of liquid from its initial temperature T_{in} to room temperature T₀ can be determined from the expression:

$$m_s = a \cdot P_e [1 - \exp(-b \cdot \tau)], \quad (1)$$

where a, b are empirical coefficients; P_e - equilibrium vapour pressure of liquid at initial temperature T_{in}; τ is time from the beginning of evaporation.

From (1) we can obtain expression described the dependence of the evaporation rate W_{ev} on time:

$$W_{ev} = a' \cdot P_e \cdot \exp(-b \cdot \tau), \quad (2)$$

where a' = a · b. The values of constants a, b, a' are presented in literature.^{6,7}

The formation of flammable vapour - air mixtures at the evaporation of heated liquid is a non-stationary process, which proceeds at the cooling of liquid. Because large temperature difference between the liquid and ambient air takes place, it is obvious, that the natural convection is the main factor, controlled the mixing of vapour and air. In this case the horizontal sizes of explosion zone are close to the pool area. The vertical size of explosion zone Z_{exp} will be determined by the influence of natural convection and depends on the Grasshoff number Gr, which characterizes the buoyant force arising due to density difference between heated vapour-air mixture and ambient air. The dependence of height of explosion zone Z_{exp} from the Grasshoff number Gr will be described by the equation:

$$Z_{exp} = Z_0 \cdot A \cdot Gr^n, \quad (3)$$

where A, n are constants; Gr is Grasshoff number, given by the formula:

$$Gr = \frac{g \cdot l^3}{\nu_a^2} \cdot \frac{T_{in} - T_0}{T_0}; \quad (4)$$

$g=9,81 \text{ m} \cdot \text{s}^{-2}$ - earth gravity constant;
 $l=\sqrt{F}$ - characteristic size of evaporation pool;
 T_{in} - initial temperature of liquid in the pool;
 T_0 - temperature of ambient air;
 ν_a - kinematic viscosity of vapour-air mixture, which is close to the kinematic viscosity of air;
 Z_0 - the characteristic size constant of explosion zone, given by the formula:

$$Z_0 = m / \text{LFL}; \quad (5)$$

LFL - lower flammability limit of vapour in air.
 The formula (2) can be written in the following form:

$$Z_{exp} = B \cdot \frac{m_e}{M^{1/2}} \left(\frac{P_e}{P_f} - 1 \right) \left[\frac{F^{1,5}}{\nu_a^2} \cdot \frac{T_{in} - T_0}{T_0} \right], \quad (6)$$

where B - constant; m_e - specific mass of liquid in the pool on the area of 1 m^2 ; M - molar mass of the liquid; P_f - pressure of vapour, corresponding the lower flammability limit.
 The values of constants A , B , n were determined in the experiments, described in the next section.

EXPERIMENTAL

Experiments were executed with the most widely used HOH, such as mixture of diphenyl and diphenyloxide (diphenyl), AMT-300T oil and I-5A oil. The main characteristics of these liquids are presented in Table 1.

Table 1. The main characteristics of liquids investigated

Substance	Molar mass $\text{kg} \cdot \text{kmole}^{-1}$	Boiling point, $^{\circ}\text{C}$	Flash point, $^{\circ}\text{C}$	Autoignition temperature, $^{\circ}\text{C}$	Lower flammability limit % (vol.)
Diephyl	165,84	258	111	599	0,8
AMT-300T	260,3	390	172	332	0,4
I-5A	253,03	316	118	235	0,4

The influence of such parameters as initial liquid temperature, mass of liquid in the pool area and characteristics of substance was investigated.

The experiments for determination of explosion zone heights were performed in chambers with volumes of 8 and 42 m^3 . Liquids were placed in rectangular steel vessel, which had the upper moving cover, and heated till temperature from 170 to 300°C . The pool area was equal $0,25$, $0,5$, $2,0$ and $4,0 \text{ m}^2$ respectively. The liquid temperature was

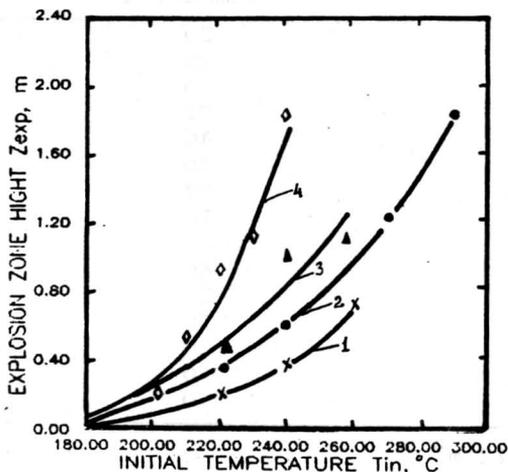
controlled by thermocouples. When the required liquid temperature was reached the upper cover was moved away, and the evaporation of liquid from free surface took place. The ignition spark sources at various heights from the liquid surface initiated the vapour-air mixtures. The flame registration was made by means of thermocouples placed near the liquid surface.

In order to determine the explosion pressure for non-uniform vapour-air mixtures ΔP_{exp} and effective coefficient Z of vapour participation in explosion the closed reaction chamber of volume 10 m^3 was used. Liquid was heated in the vessel of volume of $0,1 \text{ m}^3$ and moved through the heated tube into the chamber. After the time interval from 50 to 1800 s the formed vapour-air mixture was ignited by the spark source. Explosion pressure was measured by the pressure-transducer "Sapphire-22" with time constant of the order of $3 \cdot 10^{-3}$ s. Some experiments were performed when the liquid after the evaporation time interval before ignition was removed from the reaction chamber. Another group of experiments was executed when liquid was not removed before ignition, and combustion of liquid phase took place after ignition of vapour-air mixture. The evaporation area was $0,25$ and $0,72 \text{ m}^2$. Initial temperature of liquid was from 180 to 250°C for I-5A oil, from 230 to 400°C for AMT-300T oil and from 160 to 257°C for diephyl.

RESULTS AND DISCUSSIONS

It was found that the maximum value of explosion zone height was realised in the time interval—from 60 to 120 s after the evaporation beginning. The experimental and theoretical dependences of explosion zone height Z_{exp} from initial liquid temperature T_{in} were presented in the figure.

The theoretical curves satisfactorily coincide with the experimental data.



The experimental (points \diamond , Δ , \circ , \times) and theoretical (solid lines) dependences of explosion zone height Z_{exp} for initial liquid temperature T_{in} : 1- I-5A oil, area of evaporation $F=0.25 \text{ m}^2$; 2- I-5A oil, $F=0.5 \text{ m}^2$; 3- diephyl, $F=0.5 \text{ m}^2$; 4- diephyl, $F=4.0 \text{ m}^2$.

Some experimentally determined explosion pressures of non-uniform vapour-air mixtures formed during the evaporation of heated liquid pools were presented in Tables 2, 3.

Table 2. Explosion pressures of non-uniform vapour-air mixtures in the closed chamber of volume 10m^3 without combustion of liquid phase (for AMT-300T oil)

Evaporation area, m^2	Initial temperature of liquid phase, $^{\circ}\text{C}$	Ignition delay after the liquid entering into the chamber, s	Explosion pressure ΔP_{exp} , kPa	Effective coefficient Z of vapour participation in the explosion
0,25	233	270	59	0,5
0,25	270	180	205	1,0
0,25	275	165	234	1,0
0,25	310	160	140	0,8
0,25	280	180	250	1,0
0,72	344	50	159	1,0
0,72	354	97	162	0,7
0,72	343	1200	22	0,01
0,72	315	120	202	1,0
0,72	357	120	155	0,4

Table 3. Maximum pressures in closed chamber after ignition of vapour-air mixture with combustion of liquid phase (evaporation area $0,25\text{ m}^2$)

Substance	Initial temperature of liquid phase, $^{\circ}\text{C}$	Ignition delay after the liquid entering into the chamber, s	Maximum pressure ΔP , kPa
I-5A oil	242	20	53
I-5A oil	240	20	54
I-5A oil	230	30	51
AMT-300T oil	315	21	39
AMT-300T oil	345	40	54
AMT-300T oil	398	30	103
AMT-300T oil ^{a)}	354	97	162
AMT-300T oil ^{a)}	347	70	148
Diethyl	218	30	190
Diethyl	235	60	220
Diethyl	196	20	134
Diethyl ^{b)}	170	30	100
Diethyl ^{b)}	85	0	67
Diethyl ^{b)}	80	0	198
Diethyl ^{b)}	60	0	194

a) Evaporation area $F=0,72\text{ m}^2$.

b) Ignition of liquid surface by open fire.

During the combustion of liquid and vapour phases in the closed chamber the pressure increase ΔP was in the range from 40 to 220 kPa (table 3). This pressure is close to pressure realised during the combustion only liquid phase. But if a small venting area ($\sim 1\%$ of internal surface area of reaction chamber) took place then the pressure decreased to

values of the order of several kPa. This effect is caused by a low rate of combustion (the characteristic time for pressure rise in case of closed chamber is of the order of several tens of second). In the case of combustion only vapour phase (table 2) the pressure increase ΔP may reach the values from 22 to 250 kPa, which are very dangerous for the industrial buildings and several times exceed allowable value (5 kPa).² The effective coefficient Z was changed in a wide range (from 0,01 to 1,0). This effect was caused by turbulent mixing of vapour with air due to natural convection. For standards in the area of explosion and fire safety the value of $Z = 1,0$ must be accepted.

Here we may draw the following conclusions.

- A. The experimental investigations of evaporation, explosion zones formation and combustion of vapour-air mixtures for heated liquids with high boiling points were performed.
- B. The mathematical formulas were obtained, which describe the dependence of evaporation rate, specific evaporating mass, explosion zones sizes, effective mass coefficient Z of vapour participation in explosion from the initial temperature and physico-chemical properties of liquids.

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