© Strojniški vestnik 49(2003)5,254-266
ISSN 0039-2480
UDK 614.84:614.86:004.94:519.87
Izvirni znanstveni članek (1.01)
© Journal of Mechanical Engineering 49(2003)5,254-266
ISSN 0039-2480
UDC 614.84:614.86:004.94:519.87
Original scientific paper (1.01)

Analiza požara pri prometni nezgodi

An Analysis of a Fire Resulting from a Traffic Accident

Peter Vidmar - Stojan Petelin

Prispevek temelji na zamisli, kako opisati obnašanje požara. Delo je zasnovano na analitičnem proučevanju nastanka, razvijanja in širjenja požara in obsega področja termodinamike, prenosa toplote, hidrodinamike ter zgorevanja, ki pomenijo osnovo modeliranja dinamike požarov. Delo prikazuje primer iztekanja nevarne gorljive kemikalije iz cisterne, kar lahko privede do požara. Skušali smo izdelati model širjenja požara v okolici skladišča z gorljivim plinom in prikazati, kolikšen del okolice bi bil pri tem prizadet. Model upošteva vremenske vplive, predvsem hitrost in smer vetra. Uporabili smo računalniški področni ali predelni model ***Safer Trace****. V predelnem modelu so pojavi opisani s fizikalnimi in empiričnimi enačbami. Pomanjkljivost modela je, da ni mogoče upoštevati topologije področja.*

Predstavljeni so matematični modeli, ki prikazujejo disperzijo nevarne tekočine v okolico z upoštevanjem vremenskih vplivov.

(Ključne besede: nezgode prometne, analize požarov, modeli matematični, oblaki plinski)

This paper is an attempt to define fire behaviour. The work is based on an analytical study of a fire's origin, its development and spread. The study is based on thermodynamics, heat transfer and a study of hydrodynamics and combustion, which represent the basis of fire dynamics. The article describes a practical example of a leak of hazardous chemicals from a tank truck. Because of the flammability of the fluid, a fire may start. We have tried to model the fire propagation around a flammable-gas warehouse and show how the surrounding area could be affected. The model also considers weather conditions, in particular the wind speed and direction. The computer code ***Safer Trace,*** *which is based on zone models, was used to do this. This means that the phenomena are described with simplified physical and empirical equations, and one of the disadvantages of this computer code is its inability to consider the ground topology.*

Mathematical models are presented, and they show the propagation of a hazardous fluid in the environment, while considering the meteorological data.

(Keywords: traffic accident, fire modelling, mathematical models, vapour clouds)

0 UVOD

Govoriti o nevarnosti požarov, pomeni govoriti o požarni varnosti. Od začetka industrializacije je požarna varnost pridobivala na pomenu zaradi potrebe po varstvu človeških življenj in materialnega premoženja. Področje varnosti zajema predpise in zakone, ki obravnavajo preventivo in postopke pri protipožarni obrambi. Običajno vemo, kje so kritična mesta za nastanek požara, tako v zaprtih prostorih kakor na odprtih površinah. Mesto nastanka požara je naš prvi vstopni parameter v modelu.

Delo obravnava model požara na odprtem ter način, kako sproščeni plini vplivajo na okolico in sam požar. Modelirali smo plinsko skladišče v Srminu pri Kopru v Sloveniji.

Simulacijo smo izvedli s predelnim modelom **Trace 8.4,** ki ga razvija **Safer-EMS**, in omogoča simuliranje kemijskih reakcij, ki potekajo pri

0 INTRODUCTION

Talking about a fire hazard means talking about fire safety. From the early days of industrialisation, fire safety has developed a great deal because of the need to protect human life and property. The field of safety includes regulations and acts that deal with fire prevention and the procedures involved in fire fighting. in most cases we know the most probable starting point of fire in the case of both open and closed spaces. The starting point of the fire is then considered as the first input parameter in the model.

This paper describes fire modelling in open spaces and how the released cloud of gas affects the surroundings and the fire itself. The place we have modelled is a gas warehouse in Srmin, near the city of Koper in Slovenia.

The simulation was run using the zone model called **Trace 8.4**, developed by **Safer-EMS**, which is able to calculate the chemical reactions that lead to zgorevanju. Empirični modeli, zasnovani na fizikalnih zakonitostih, obsegajo različne vrste izpustov, meteoroloških pogojev, gostoto ovir v prostoru itn. Pri predelnem ali področnem modeliranju razdelimo prostor v dele, znotraj katerih se s fizikalnimi in empiričnimi enačbami izračunava vrednost posameznih veličin.

Rezultati modela so lahko: smer in hitrost požara, temperaturni vpliv na okolico, nevarnost eksplozije in izpusti nevarnih plinov. Uporabljena modelska tehnika je poznana tudi kot metoda zgoščenih parametrov.

Po svetu je znanih več računalniških programov za modeliranje požarov. Med njimi smo se srečali predvsem z naslednjimi: FDS (Fire Dynamics Simulator) [5], CFX 4,5 [15], Jasmine 3.12a [14], Smart Fire [16]. Predelni modeli: Safer **Trace** [1], CFAST (Consolidated Fire and Smoke Transport Model) [17].

1 OZADJE MODELA

Program **Trace** je konzervativni program zasnovan na fizikalnih in empiričnih modelih, s katerimi modeliramo vir in širjenje požara. Glavni modeli in pod-modeli v programu **Trace** so: model izpusta skozi razpoko; model dinamike vira (dinamika izbruha plamena, nastanek aerosolov, mešanje z zrakom); model izhlapevanja luže; model disperzije dimnega oblaka v atmosfero in model disperzije curka; model toplotnega sevanja za različne vrste požarov ter model za računanje tlačnega vala pri eksploziji oblaka z gorljivim plinom.

Predpostavka modela se začne s poškodbo hrama in iztekanjem tekočine. Začetne razmere narekuje hitrost in način iztekanja tekočine iz hrama. Zaporedje dogodkov in uporabljeni modeli so prikazani v nadaljevanju.

1.1 Model iztekanja skozi razpoko

Model iztekanja skozi razpoko je navidez ustaljen in izračunava iztekanje plina in/ali kapljevine skozi razpoko ali priključeno cev. Iztekanje lahko povzroči nastala razpoka na hramu ali zlom pritrjene cevi. Model upošteva lastnosti kemikalije, vremenske vplive (zunanji tlak in temperaturo), geometrijsko obliko razpoke (okrogla, pravokotna z gladkimi ali ostrimi robovi) in stanje v hramu (tlak, temperatura). V nasprotju z modelom puščanja na cevi, ki je ustaljen, se pri navidez ustaljenih parametrih, kakor so tlak in temperatura deloma spreminjajo, kar je odvisno od prehodnega pojava med iztekanjem.

Trace zajema tri modele izpustov: prvi opisuje izpust kapljevine skozi luknjo (z upoštevanjem dvofaznega toka), drugi popisuje iztekanje nasičene pare skozi razpoko. Tretji opisuje izpust stisnjenega

combustion. Empirical equations derived from physical equations consider different release scenarios, meteorological conditions, obstacle densities, etc. A zone-modelling technique divides the physical space into zones. Within each zone the uniform physical phenomena are computed using physical and empirical equations. This computational technique is also called the lumped-parameter modelling technique.

The direction in which the fire spreads, the speed of fire propagation, the influence of temperature on the environment, the risk of explosion and the release of hazardous gases are the results of this analysis.

Many fire-propagation models exist. Some of the models we found are CFD (Computational Fluid Dynamics) models: FDS (Fire Dynamics Simulator) [5], CFX 4,5 [15], Jasmine 3.12a [14], Smart Fire [16]; and zone models: Safer **Trace** [1] and CFAST (Consolidated Fire and Smoke Transport Model) [17].

1 MODEL BACKGROUND

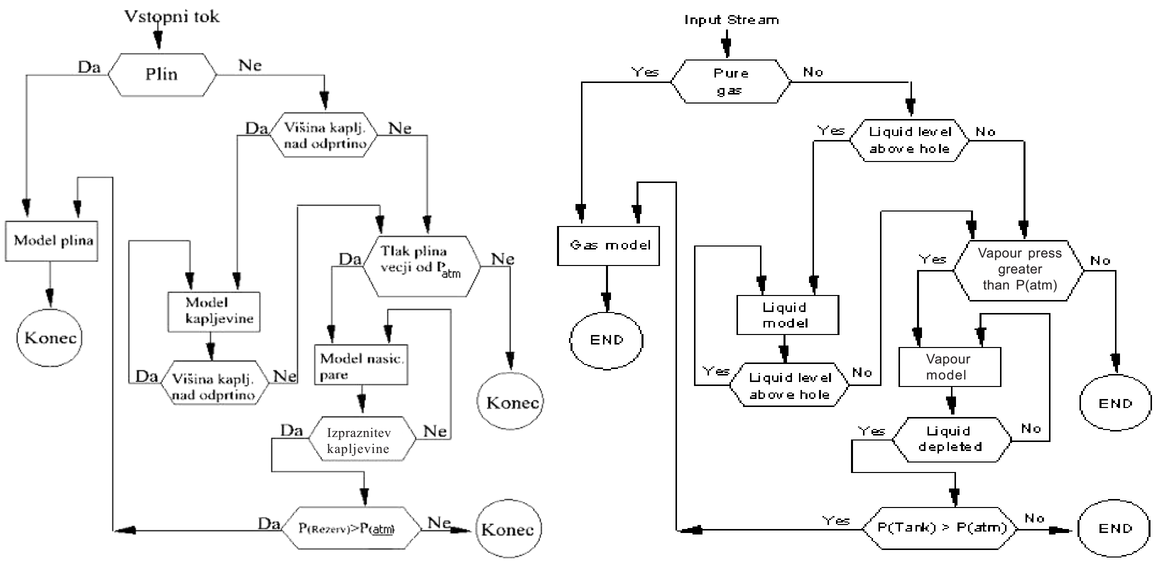
The zone conservative model Trace is based on physical and empirical equations essential for computing the fire's source and its spread. The main submodels in Trace are as follows a model of release rates from the rupture; a source dynamics model (dynamics of flashing, aerosol formation and initial air entrainment); a pool evaporation model; models of the atmospheric dispersion of a vapour cloud and jet dispersion; a thermal radiation model for different fire sources; and a blast overpressure model for vapour cloud explosion.

The assumption of the model begins with a tank break and a leak of fluid. The fluid leak rate and the release type from the tank dictate the initial conditions. The following sequence of events is explained in more detail in the text and the corresponding models that are used are described.

1.1 Tank-rupture model

The **Trace** tank model is a quasi-steady-state model that calculates the discharge rate of gases and/or liquids from a tank or pipe system caused by a rupture in the tank or shearing of the attached pipe. It takes into account chemical properties, environmental variables (atmospheric pressure and ambient temperature), rupture geometry (circular, rectangular, smooth or jagged edges) and the containment variables (pressure, temperature). In contrast to a pipe-leak model, which is steady state, the quasi-steady-state model means that variables like pressure and temperature change slightly with time depending on the leak release rate.

Three discharge models exist: one to describe the release of liquid from a hole (including two-phase flow), one to describe the release of vapour from a rupture above a boiling liquid, and one to describe the release of a com-



Sl. 1. *Logična povezava med modeli za model iztekanja skozi razpoko pri programu **Trace***
Fig. 1. *Logic for algorithms within the tank-rupture model in **Trace** code*

plina. Logična povezava med modeli je prikazana na sliki 1 [1].

1.2 Dinamika vira izpusta

Algoritmi, omenjeni v poglavju iztekanja skozi razpoko, definirajo stanje sproščanja iz hrama. Iztekajoča kemikalija ima lahko v osnovi tri oblike toka (izpusta): (1) iztekajoči plin, (2) hlapljiva kapljevina (kapljevina, ki bo izhlapela in tvorila vnetljivo mešanico plina in aerosola) ali (3) kapljevina, ki se izlije na zunanjo površino ter ustvari lužo (mlako) in za tem izhlapi. Različni tokovi (izpusti) in začetna dinamika izvora so osnova za nastanek plinskega oblaka.

Vžigalno razmerje hlapljivosti lahko ocenimo z razmerjem ([10] in [1]):

pressed gas. The logic for passing parameters between these models is illustrated in Figure 1 [1].

1.2 Source Dynamics

The algorithms mentioned in the tank-rupture section determine the state of the released stream from containment due to a failure/rupture. This released chemical should, in general, consist of three release "streams": (1) escaping gas, (2) liquid that remains airborne (which will itself break up into a flashing fraction of gas and an aerosol fraction) and (3) liquid that falls to the ground to form a pool, which then evaporates. The various "streams" and the initial source dynamics are involved in the formation of a vapour cloud.

The estimation of the flash and aerosol fraction is defined as ([10] and [1]):

$$x = c_L (T_o - T_B) / \Delta h_V \qquad (1).$$

Ovrednotenje nastanka aerosola je bistveno bolj zapleteno. Obseg nastanka aerosola je odvisen od lastnosti v hramu (tlak, temperatura itn.) ter lastnosti razpoke (smer izpusta, geometrijska oblika razpoke).

Zato mora omenjeni postopek omogočiti pravilno ovrednotenje aerosolnega deleža. Delež aerosola v toku izpusta je funkcija vžigalnega razmerja iz enačbe (1).

Dinamika aerosola je zasnovana po modelu s slike 2.

Entalpijsko ravnotežje sistema je podano z naslednjo enačbo:

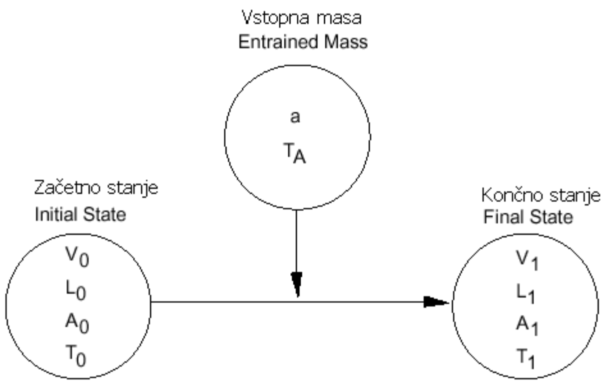
The estimation of the airborne liquid (or aerosol) stream is much more difficult to formulate. The magnitude of the aerosol stream depends upon the containment variables (pressure, temperature, etc.) and is also affected by the rupture characteristics (orientation, geometry of the hole).

Hence, the present approach consists of achieving the capability to define the aerosol fraction. The aerosol content of the stream is assumed to be a function of the flashing fraction, defined above, Eq. 1.

The aerosol dynamics considers the model presented in Figure 2.

An enthalpy balance for the system produces:

$$\left(m_{V1} - m_{V0}\right) L_a + m_{V1} \int_{T_0}^{T_1} c_V dT + m_{L_1} \int_{T_0}^{T_1} c_L dT + m_A \int_{T_A}^{T_1} c_A dT + m_{A_0} \int_{T_0}^{T_1} c_A dT = 0 \qquad (2)$$



Sl. 2. *Vstopanje zraka v začetni plinski oblak*
Fig. 2. *Air entrainment into the initial vapour cloud*

Enačbo za idealni plin uporabljamo za plinasto stanje:

The ideal-gas law is assumed in the vapour phase:

$$p_{V_1} = \frac{p \cdot \frac{m_{V_1}}{MW}}{\frac{m_{V_1}}{MW} + \frac{\left(m_{A_0} + m_A\right)}{MW_A}} \qquad (3).$$

Za delni tlak uporabljamo Antoinovo enačbo [10]:

And an Antoine vapour-pressure equation is used [10]:

$$\ln p_{V_1} = C_8 + \frac{C_9}{C_{10} + T} \qquad (4).$$

V končnem stanju obsega plinski oblak začetno maso kemikalije in vstopno maso zraka. Končno energijsko stanje sistema je izračunano iz entalpijske bilance (2), plinske enačbe (3) in Antoinove enačbe za delni tlak pare (4) [8].

In the final state, the vapour cloud contains the initial mass of chemical vapour and the entrained mass of air. The final state of the system is derived from the enthalpy-balance equation (2), the ideal-gas equation (3) and the Antoine vapour-pressure equation (4) [8].

$$\frac{C_1 + C_2 T}{C_6 + C_7 T} - Exp\left\{C_7 + \frac{C_8}{C_9 + T}\right\} = 0 \qquad (5).$$

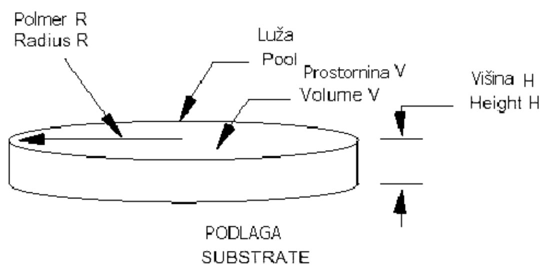
$$C_1 = (m_{V0}+m_L)\, c_L\, T_0 + m_A\, c_A\, T_A + m_{A0}\, c_A\, T_0$$
$$C_2 = -(m_{L0} + m_{V0})\, c_L - m_A\, c_A - m_{A0}\, c_A$$
$$C_3 = \Delta h_V - (c_v - c_L)\, T_0$$
$$C_4 = c_v - c_L$$
$$C_5 = (MW / MW_A) * m_{A1}$$
$$C_6 = C_1 + C_3\, C_5$$
$$C_7 = C_2 + C_4\, C_5$$

1.3 Hlapenje luže

Luža je modelirana kot pokončni valj prostornine V, polmera R in višine H.

1.3 Pool evaporation

The pool is modelled as an upright cylinder of volume V, radius R and height H, as shown in Figure 3.



Sl. 3. *Luža, modelirana kot pokončni valj*
Fig. 3. *Liquid pool modelled as an upright cylinder*

V vsakem časovnem koraku t lahko prostornino luže opišemo kot:

$$V_P(t) = V_0 + \int_{t=0}^{t} \left(\dot{V}_{IN}\right) dt - \frac{m}{\rho_L} \quad (6),$$

m - masa uparjene tekočine iz luže od časa t=0 do časa t

$\dot{V}_{IN}$ - prostorninski tok kapljevine v lužo

Enačba (6) predstavlja prostorninsko bilanco luže.

Model izhlapevanja luže zajema tudi model prenosa toplote. Glavni namen je izračunavanje uparjanja, ki se pojavi zaradi toplotnega sevanja, prevoda toplote in naravne ali prisilne konvekcije.

1.4 Disperzija plinskega oblaka v atmosfero

V prvem koraku izračunamo iztekanje kapljevine iz hrama ter delež nastale pare in aerosola. Aerosol je oblak majhnih kapljic tekočine ali delcev trde snovi, ki lebdijo v zraku. Po izračunu uparjenih kapljic aerosola vzdolž poti oblaka, lahko določimo skupno količino uparjene tekočine. V tem poglavju opisujemo model disperzije plinskega oblaka. Program **Trace** omogoča izbiro med različnimi tipi izpustov; trenutni izpust, ustaljen stalni izpust za pline z večjo ali manjšo gostoto.

V obravnavanem primeru upoštevamo trenutni izpust iz hrama na ravni tal. Tak primer privede do hitrega nastanka plinastega oblaka nad ravnjo tal z visoko koncentracijo vsebnosti plina.

Zaradi zelo hitrega prehodnega pojava je težko spremljati spreminjanje parametrov, predvsem v bližini vira izpusta.

Plinski oblak modeliramo kot pokončni valj. Ko je ta oblikovan, začnejo nanj delovati sile težnosti, ki vplivajo na obliko oblaka. Hitrost na robu opišemo z enačbo [1]:

$$\frac{dR}{dt} = k_1 \left[\left(\frac{\rho_{CLOUD} - \rho_A}{\rho_{CLOUD}} \right) \cdot g \cdot h \right]^{1/2} \quad (7),$$

k_1 je stalnica usedanja oblaka, ki je odvisna od vrste izpusta plina in vremenskih vplivov, med katerimi je najpomembnejša hitrost vetra. Pomembno je opozoriti, da model disperzije ne upošteva turbulentnega toka.

1.4.1 Potovanje oblaka

Premik oblaka zaradi vetra je modeliran kot [1]:

$$\frac{dx}{dt} = U_{CLOUD} \quad \text{pri } z = 0,4\ h_{CLOUD} \quad (8),$$

x - spremenljivka razdalje v smeri vetra,

U_{CLOUD} - hitrost oblaka (upoštevana kot hitrost vetra na višini 0,4 krat višina oblaka).

At any time t the volume of the pool can be written as:

m - mass of liquid vapourized from pool starting at t = 0 to time t

$\dot{V}_{IN}$ - volumetric flow of liquid into the pool

The above equation (6) represents a volumetric balance of the liquid pool.

A heat-transfer model is also included in the pool-evaporation model. The main purpose is to compute the evaporation rate due to radiation, conduction and natural or forced convection heat transfer.

1.4 Atmospheric dispersion of a vapour cloud

Leak rates from a tank rupture were calculated; initial gas, "flashing" and an aerosol are formed. An aerosol is a cloud of tiny liquid droplets or fine solid droplets suspended in the air. Calculating the droplet evaporation along the cloud trajectory, the overall vapour generation rate is obtained. In this section the dispersion model of the vapour cloud is described. The **Trace** computer code can consider different types of release: instantaneous, steady continuous and transient for dense (active) and lean (passive) gases.

Our application case considers a ground-level instantaneous release from the tank rupture. This is the most catastrophic scenario, which can lead to the rapid formation of a vapour cloud near ground level resulting in a high concentration of gas.

Because of a very fast transient and changes of the variables, it is difficult to predict the course of events, especially close to the source of dispersion.

Once the cloud, which is modelled as a cylinder, is formed, it begins to slump under the effect of gravity. The velocity of the edge of the cloud can be described as [1]:

where k_1 is a slumping constant that depends on the characteristic of the released gases and the weather conditions. The most important of these is the wind speed. It is important to note that the dispersion model does not assume turbulent flow.

1.4.1 Cloud transport

The cloud transport due to wind is modelled as [1]:

x - downwind distance variable,

U_{CLOUD} - cloud speed (is assumed to be equal to the wind speed at 0.4 times the cloud height).

0,4 krat višina oblaka je vzeta kot primerjalna višina oziroma prijemališče sile vetra v smeri gibanja oblaka.

0.4 times the cloud height is assumed to be a reference height or the centre of gravity of wind force in the direction of cloud movement.

1.4.2 Porazdelitev koncentracije plina znotraj oblaka

1.4.2 Concentration distribution within the cloud

V primeru izpusta gostejšega plina je pričakovati, da se bo oblikoval homogen sredinski predel, vzdolž katerega pa se proti robovom oblaka koncentracija zmanjšuje. Razlika koncentracij na robu oblaka je pri izvoru največja, medtem ko se pri disperziji oblaka v smeri vetra zmanjšuje. Porazdelitev koncentracije je ponazorjena z Gaussovo porazdelitvijo, kar pomeni, da imajo črte enakih koncentracij obliko tipične Gaussove porazdelitve. Gaussove odvisnosti za disperzijo oblaka niso povsem pravilne za vse vrste začetnih pogojev in tipov izpustov, vendar jih zaradi konzervativnosti modela vseeno uporabljamo [7].

In most dense gas releases, it is expected that there will be a central core region of uniform concentration along with edges at which the concentration decreases. It is expected that close to the source the edges will be sharp and as the cloud disperses downwind the edges will become less steep. The concentration field is calculated considering a Gaussian distribution. This means that the isopleth limits, or the edge of observed concentration limits, takes a typical Gaussian distribution. Gaussian correlations for the atmospheric cloud dispersion are not proper for any initial conditions and release type, but are used as a conservative model [7].

1.5 Toplotno sevanje

1.5 Thermal radiation

Osnovna enačba prenosa toplote s sevanjem je [11]:

The basic equation for heat transfer by thermal radiation is [11]:

$$q = e \cdot k \cdot \tau \qquad (9).$$

Program **Trace** zajema različne modele virov, to so ognjena krogla, ki obravnava ekspanzijo ob eksploziji pare, požar mlake, požar curka, požar iznad tal, gorenje plinskega oblaka in navaden požar.

V našem modelu smo uporabili naslednje: model požara mlake, model ognjene krogle ter v skrajnem primeru model gorenja plinskega oblaka.

The **Trace** code includes different fire-source models, such as Fireball, taken from boiling-liquid expanding-vapour explosions, liquid-pool fires, jet fires, flares and stacks, flash fires and generic fire sources.

The following models could be used: the liquid-pool fire model, the Fireball model and extreme conditions such as the flash fire model.

1.5.1 Model gorenja mlake

1.5.1 Liquid-pool fires

Glavni parameter, ki ga model empirično izračuna, je masni delež izgorele kemikalije ([1] in [10]):

The basic parameters computed empirically by the model are the mass-burning rates from the pool ([1] and [10]):

$$\frac{dm}{dt} = \dot{m}_v = \frac{0,001 \cdot \Delta h_C}{\Delta h_V}, \quad \dot{m}_v \doteq \dot{m}_c \quad \text{pri / when } T_{BP} \le T_{AMB} \quad [\mathrm{kg/(s \cdot m^2)}] \qquad (10)$$

$$\frac{dm}{dt} = \frac{0,001 \cdot \Delta h_C}{\Delta h_V + c_P (T_{BP} - T_{AMB})} \quad \text{pri / when } T_{BP} > T_{AMB} \quad [\mathrm{kg/(s \cdot m^2)}] \qquad (11).$$

Sevalno energijo pri požaru luže določimo z naslednjo empirično enačbo ([1] in [5]):

The radiation emissive power from liquid-pool fires is calculated using an empirial relation ([1] and [5]):

$$e = E_M \cdot \exp(-0,12 D_P) + E_S \left[1,0 - \exp(-0,12 D_P)\right] \quad [\mathrm{W/m^2}] \qquad (12),$$

E_S - sevani toplotni tok dima = 20.000 W/m²
E_M - največji sevani toplotni tok blišča = 140.000 W/m²

E_S - emissive power of smoke = 20,000 W/m²
E_M - maximum emissive power of luminous spots = 140,000 W/m²

1.5.2 Gorenje plinskega oblaka

1.5.2 Flash fires

Metodologijo modela gorenja plinskega oblaka predstavljajo naslednji koraki:

The overall methodology can be described in the following steps:

- Razberemo porazdelitev parametrov v prerezu plinskega oblaka iz modela disperzije.
- Na izbranih mestih znotraj oblaka izračunamo povprečene koncentracije v prečnih prerezih in višine oblaka.
- Z izračunanimi povprečnimi koncentracijami v prečnih prerezih in višinami oblaka izračunamo čela plamena.
- Iz čel plamena izračunamo toplotno sevanje na izbranih mestih.
- Z iteracijo po vseh čelih plamenov izračunamo izpostavljenost toplotnemu sevanju po času.

Hitrost plamena računamo kot funkcijo hitrosti vetra z uporabo naslednje empirične enačbe [1]:

- Obtain snapshot of the cloud from the atmospheric dispersion model.
- At discrete locations within this snapshot, create crosswind-averaged concentrations and cloud heights
- Using the crosswind-averaged concentrations and cloud heights, create flame fronts.
- Calculate the thermal radiation at a receptor location from the flame front.
- Iterate over all flame fronts to obtain the profile of thermal radiation versus exposure time.

The flame speed is calculated as a function of the ambient wind speed using an empirical equation [1]:

$$S_{flame} = 2,3 \cdot U_W \qquad (13),$$

S_{flame} - hitrost plamena
U_W - hitrost vetra

S_{flame} - flame speed
U_W - wind speed

1.5.3 Ognjena krogla

Model ognjene krogle se uporablja za modeliranje hitrih izpustov z ekspanzijo, posebej iz hramov. Algoritem izračunava velikost, mesto in trajanje ognjene krogle po empiričnih enačbah ([1] in [11]):

1.5.3 Fireball

The Fireball model is used to model rapid liquid-expanding releases, especially from tanks. The empirical algorithm estimates the size, location and duration of the fireball, Figure 4 ([1] and [11]):

$$D_c = 5,8\, m_f^{1/3} \qquad (14)$$

$$t_c = \begin{cases} 0,45\, m_f^{1/3} & \text{pri/when} \quad m_f < 30.000\ kg \\ 2,6\, m_f^{1/6} & \text{pri/when} \quad m_f \geq 30.000\ kg \end{cases} \qquad (15),$$

$$h_c = D_c / 2$$

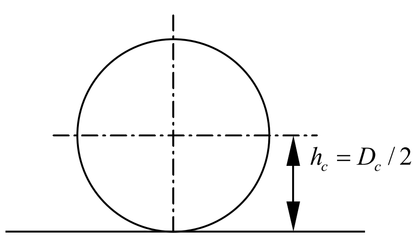
m_f - masa goriva znotraj ognjene krogle
D_c - največji premer ognjene krogle po koncu izgorevalne faze
t_c - trajanje izgorevalne faze
h_c - višina središča ognjene krogle nad tlemi

Sevani toplotni tok iz površine ognjene krogle lahko določimo na dva načina. V prvem primeru vrednost lahko absolutno definiramo v enoti W/m^2, v drugem primeru pa definiramo delež zgorevalne toplote, spremenjene v sevalno energijo. Običajna vrednost koeficienta je 0,35 [1].

m_f - mass of fuel within the fireball
D_c - maximum diameter of the fireball at the end of the combustion phase
t_c - duration of the combustion phase
h_c - height of the fireball centre above ground level

The surface emissive power of the fireball can be specified using two options. The first is when the value is specified directly [W/m^2], the second case is when the fraction of the total combustion heat converted to thermal radiation is specified. The commonly used value is 0.35 [1].

$$e = \frac{f \cdot m_f \cdot \Delta H_c}{4\pi \cdot \left(D_c / 2\right)^2 \cdot t_c} \qquad (16),$$



Sl. 4. *Navpični prečni prerez ognjene krogle*
Fig. 4. *Vertical cross-section of the fireball*

f - delež zgorevalne toplote, spremenjene v sevalno energijo

2 MODEL POŽARA IN REZULTATI SIMULACIJE

Prvi model obravnava najmanj verjetni in katastrofalni scenarij. Predpostavimo, da se zaradi prometne nezgode med dvema cisternama sprosti v atmosfero v zelo kratkem času (v trenutku) skupno 40.000 kg mešanice propan/butana, se vžge in izgori v zelo kratkem času (manj kot ena minuta). To je model ognjene krogle.

Drugi model predpostavi hiter izpust iz cisterne z vsebnostjo 40.000 kg mešanice propan/butana. Predpostavljena hitrost puščanja je zelo velika, tako da je izpust skoraj trenuten. Površina pravokotne razpoke je 900 cm^2. Model predpostavlja, da plin izhlapi na viru in naredi plinski oblak. Plinski oblak se vžge 30 sekund po izpustu. Program **Trace** simulira disperzijo plinskega oblaka in izriše črte enakih koncentracij plina in črte enakega toplotnega sevanja.

Dovoljene koncentracije so približno ocenjene z upoštevanjem strupenosti posamezne komponente v mešanici. Vrednosti so: nizka (500 ppm), srednja (5000), visoka (100.000 ppm).

Mesto nastanka požara je izbrano naključno na področju plinskega skladišča v Srminu pri mestu Koper. Vsi modeli nam dajo zanimive in uporabne rezultate.

2.1 Model ognjene krogle

Scenarij ognjene krogle je zelo podoben eksploziji, vendar brez upoštevanja tlačnega čela. Primerjava z eksplozijo je mogoča zaradi zelo kratkega izgorevalnega časa.

Izračunani čas trajanja ognjene krogle je 20 sekund. Model izračuna zelo veliko toplotno obremenitev, ki prizadene obsežno zunanje področje. Slika 5 prikazuje območje obremenjeno s toplotnim

f - fraction of the total combustion heat converted to thermal radiation

2 FIRE MODEL AND SIMULATION RESULTS

The first fire-model scenario assumes the most improbable and catastrophic event. In a traffic accident between two road tankers, it is assumed that the complete inventory – 40,000 kg of propane/butane mixture – is instantaneously released into the atmosphere, catches fire and combusts in a very short time, less than one minute. Such a model is called a fireball model.

The second model scenario assumes a fast leak from a road tanker containing 40,000 kg of propane/butane mixture. The tank leak rate is assumed to be very high so that the release is quasi-instantaneous. The rectangular area of the orifice is 900 cm^2. The model assumes that gas evaporates at the source and forms a vapour cloud. The gas cloud is ignited 30 seconds after release. The **Trace** computer code simulates the cloud dispersion and evaluates the dispersion isopleths and the thermal radiation isopleths.

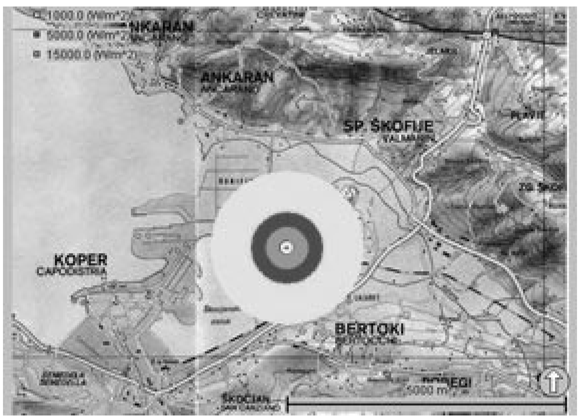
The concentration limit was approximately defined, considering the toxicity and concentration of each mixture compound. The values are as follows: low (500 ppm), medium (5000 ppm), high (100,000 ppm).

The dispersion and fire source were coincidentally chosen inside the area of a gas warehouse in Srmin, in the vicinity of the city of Koper. All models give us interesting and useful results.

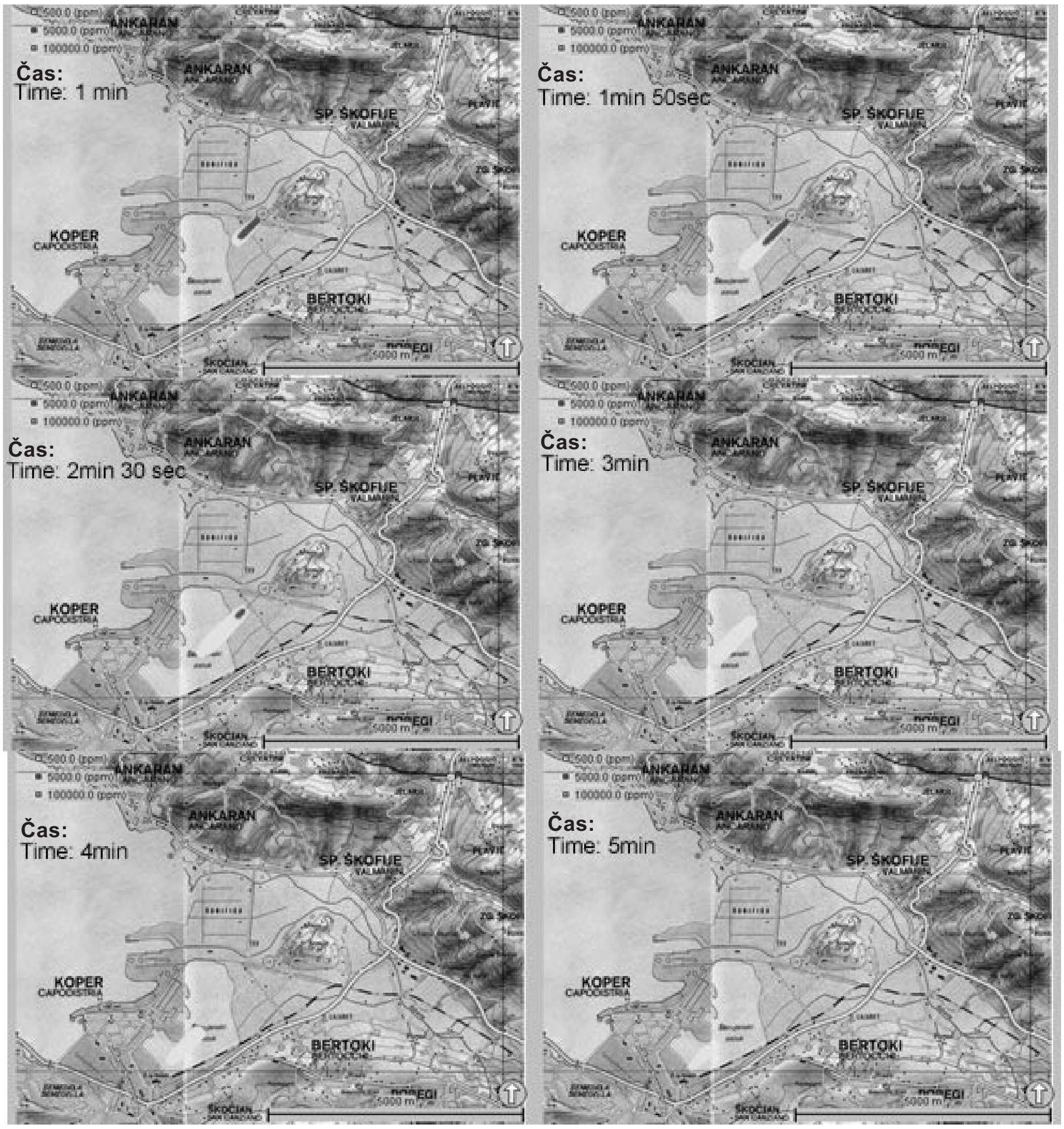
2.1 Fireball model

The fireball scenario is assumed to be very similar to an explosion without an overpressure impact. Such a comparison should be reasonable because of the very short time of the combustion process.

The duration of the fireball is 20 seconds. The model computes an enormous thermal impact that affects a wide surrounding area. Figure 5 shows that the most affected area, with a thermal radiation of 15



Sl. 5. *Toplotno sevanje kot posledica vžiga ognjene krogle*
Fig. 5. *Thermal radiation isopleths as a consequence of the 'Fireball' ignition*



Sl. 6. *Disperzija plinskega oblaka po iztoku iz hrama pri hitrosti vetra 15 m/s*
Fig. 6. *Dispersion of vapour cloud after tank dispersion at a wind speed of 15 m/s*

tokom 15 kW/m^2 premera 740 m. Emitirano toplotno sevanje ognjene krogle je 342,768 kW/m^2 na površini ognjene krogle.

2.2 Model iztekanja iz hrama

Dovoljene koncentracije nevarnih snovi ter meje strupenosti smo povzeli po Podatkovni banki nevarnih snovi Narodne medicinske knjižnice ZDA (US National Library of medicine – Hazardous Substances Data Bank) [9]. Koncentracija propan/butana 5000 ppm nima nobenega posebnega vpliva na človeka po enourni izpostavljenosti. Pri koncentraciji nad 10 % (100.000 ppm) propan/butan ne povzroča vidnega draženja oči, nosu ali dihalnih poti.

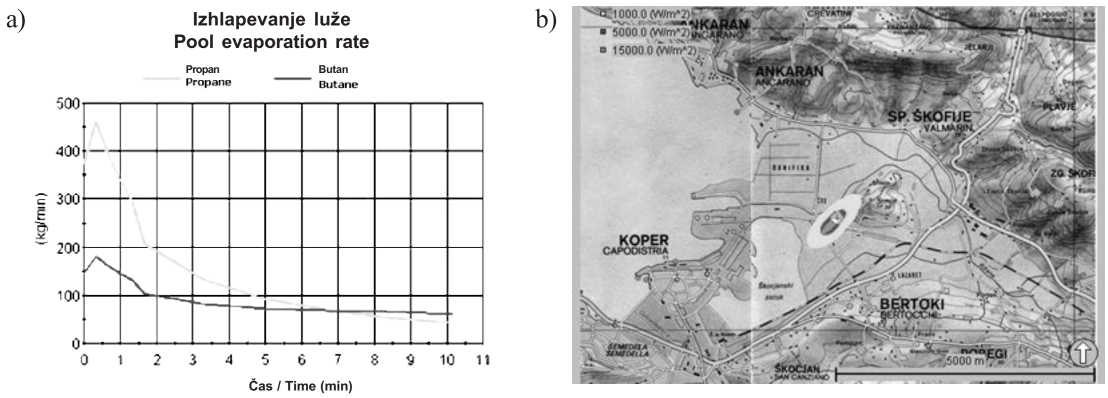
Zaradi zelo velike odprtine na rezervoarju je trajanje izpusta samo 100 sekund. Smer vetra je 45^o (jugovzhod) ter hitrost vetra 15 m/s. Velika hitrost vetra pomeni večje vstopanje (mešanje) zraka v plinski

kW/m^2, has a diameter of 740 m, and the emissive power of the fireball is 342.768 kW/m^2 on the fireball surface.

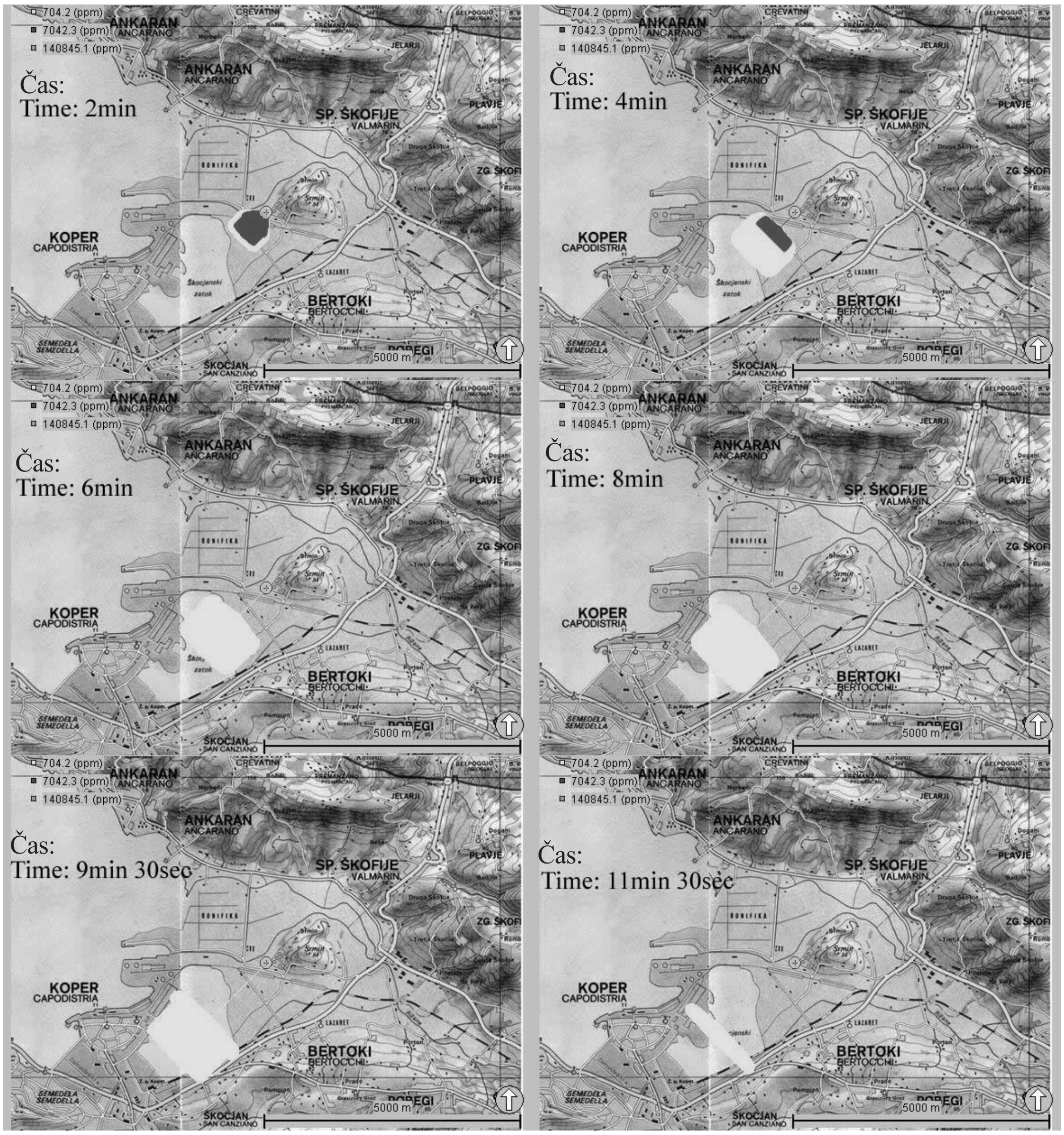
2.2 The tank-leak model

Concentration isopleths were obtained from the US National Library of medicine – Hazardous Substances Data Bank [9]. The concentration of propane/butane 5000 ppm has no particular effect on the human body after an exposure of one hour. At concentrations up to 10% (100,000 ppm) propane/butane caused no noticeable irritation to the eyes, nose or respiration tract.

Because of a very large hole in a tank, the duration of the release was calculated to be only 100 seconds. The wind direction was assumed to be 45^o (south-west) and the wind speed 15m/s. Such a wind speed means a very fast air entrainment in the cloud



Sl. 7. *Izhlapevanje luže in toplotno sevanje po vžigu plinskega oblaka*
Fig. 7. *Pool evaporation rate and the thermal radiation after the cloud ignition*



Sl. 8. *Disperzija plinskega oblaka po iztoku iz hrama pri hitrosti vetra 2 m/s*
Fig. 8. *Dispersion of vapour cloud after the tank dispersion at a wind speed of 2 m/s*

oblak, kar pomeni hitrejšo disperzijo. Pomembno je izpostaviti, da mešanica propan/butan sama po sebi ni strupena.

Čas vžiga plinskega oblaka je v modelu definiran 30 s po izpustu. Vrh funkcije pri 30 s na diagramu izhlapevanja luže na sliki 7 pomeni vžig oblaka. Slika 7 prikazuje toplotno obremenitev, ki pa je po pričakovanju prizadela manjše območje kot v primeru modela z ognjeno kroglo. Po vžigu plinskega oblaka se izhlapevanje zmanjša zaradi začetka izgorevalnega pojava. Dejansko diagram na sliki 7 prikazuje neto delež izhlapevanja oziroma razliko med izhlapelim in izgorelim deležem plina. Celoten čas izhlapevanja je izračunan na 23 minut.

Pri manjši hitrosti vetra so dinamika disperzije bistveno spremeni. Glavni razlog je manjše vstopanje zraka v plinski oblak. Rezultat tega je bolj gost oblak, ki potuje v smeri vetra in ohranja visoko koncentracijo plina dlje časa.

Smer vetra je ponovno 45^o (jugozahod) ter hitrost vetra 2m/s, slika 8. Lepo je vidno, da je plinski oblak obstojen dlje časa ter obsega večjo površino.

Čas vžiga oblaka je določen na modelu, vžge se 30 s po izpustu. Vrh pri 30 s v diagramu izhlapevanja luže na sliki 9a pomeni vžig oblaka. Slika 9b prikazuje toplotno obremenitev, ki pa je po pričakovanju prizadela manjše območje kakor v primeru modela z ognjeno kroglo, vendar večje kakor pri hitrosti vetra 15 m/s. To pomeni, da se toplotna obremenitev povečuje z manjšanjem hitrosti vetra. Sliki 9c in 9d

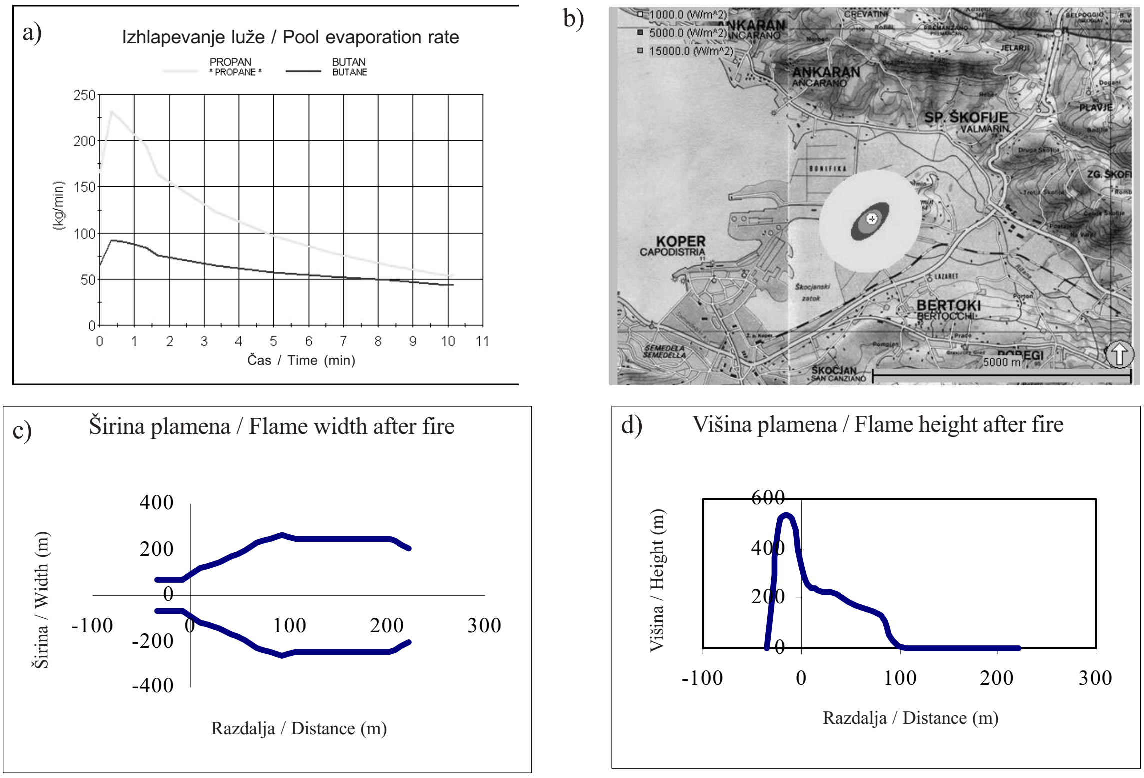
and its faster dispersion. It is important to note, as mentioned above, that the propane/butane mixture is itself not toxic.

The ignition of the cloud was prescribed 30 seconds after the beginning of dispersion. Such an ignition occurs in a very short time. The peak at about 30 seconds in the diagram of Figure 7 shows the flash fire ignition. As expected, the thermal-impact affected area is smaller than in the case of a Fireball. After the cloud ignition the evaporation rate decreases because of combustion initiation. In fact Figure 7a represents the net rate of evaporation, or better, the difference between the evaporation and combustion rates. The total time of evaporation is calculated to be 23 minutes.

The dispersion dynamics becomes very different at low wind speeds. The main reason is the lower air entrainment in a vapour cloud. The expected result is a more homogeneous cloud that moves in the wind's direction, conserving the high gas concentration for a longer time.

The wind direction was assumed to be 45^o (south-west) and the wind speed was 2m/s, Figure 8. It is clear that the cloud is present for a longer time and its surface is larger than for higher wind speeds.

The ignition of the cloud was prescribed 30 seconds after the beginning of dispersion. The peak at time 30 seconds on Figure 9a shows the flash fire ignition. As expected, the thermal impact affected area is lower than in the case of the fireball, but larger than in the case of the wind speed of 15 m/s. This means that the thermal dispersion increases with a



Sl. 9. *Izhlapevanje luže in toplotno sevanje po vžigu plinskega oblaka pri hitrosti vetra 2 m/s*
Fig. 9. *Pool evaporation rate and the thermal radiation after a cloud ignition at a wind speed of 2 m/s*

prikazujeta širino in višino plamena, ki sta izračunani z modelom gorenja plinskega oblaka 30 sekund po začetku iztekanja.

3 SKLEP

Ob upoštevanju zunanjih razmer, ki smo jih našteli, so dobljeni rezultati dokaj obetavni. V primeru majhne hitrosti vetra in smeri 45° (jugozahod) iz določenega vira, plinski oblak z veliko koncentracijo plina ne doseže mesta Koper. Slika 7 prikazuje premik oblaka in njegove koncentracije.

Drugi pomemben rezultat je čas, v katerem oblak doseže poseljeno območje. Pri hitrosti vetra 15 m/s se to zgodi v 3 minutah. Nikoli pa ne doseže maksimalne koncentracije (5000 do 10.000 ppm). Pri hitrosti vetra 2 m/s, pa plinski oblak doseže poseljeno območje v 8 minutah in se razredči (koncentracija pod 500 ppm) po 12 minutah. Slika 9 prikazuje karakteristiko plamena (toplotno sevanje), ki se razvije po modelu gorenja plinskega oblaka. Toplotna obremenitev je zelo velika in prizadene območje v premeru 400 metrov od vira.

Pomembno je omeniti, da opisane Gaussove odvisnosti za disperzijo oblaka niso povsem pravilne za vse vrste začetnih pogojev in tipov izpustov [7]. Ker pa so modeli programa **Trace** konservativni, lahko verjamemo, da so dobljeni rezultati dovolj dobri in na varni strani.

Globalni rezultat naše analize je pokazal, da zunanji požar 3 km severovzhodno od Kopra, s predpisanimi karakteristikami (40.000 kg propan-butana) in vremenskimi razmerami, ne bi ogrožal varnosti mesta.

lower wind speed. Figures 9c and 9d show the flame width and the flame height, calculated with a flash fire model 30 seconds after the release initiation.

3 CONCLUSIONS

For a traffic-induced external fire, the results are positive. In the case of a low wind velocity of 2m/s in a direction of 45° (south-west) from the prescribed source, the cloud at high concentration should not reach the city of Koper. This can be seen in Figure 8, which represens the transport and the concentration of the gas cloud.

Another important result is the time when the vapour cloud reaches the populated area. At a high wind speed of 15 m/s it occurs after 3 minutes, where the maximum concentration (5000 to 10,000 ppm) is never attained. At a low wind speed of 2 m/s the gas cloud reaches the populated area after 8 minutes and vanishes (concentration lower than 500 ppm) after the 12 minutes. Figure 9 shows the characteristic of the flame (thermal radiation) produced after flash fire model. The thermal impact is very wide, and affects the surrounding area over a radius of more than 400 meters from the source.

It is also necessary to note that the described Gaussian correlations for the atmospheric cloud dispersion are not correct for any initial conditions and release type [7]. Because the computer program **Trace** model is a conservative one, we should know that the obtained affected area limits are good enough to confirm the credibility of the results.

The global result of our analysis shows that the external fire, 3 kilometres north-east of Koper, with the described characteristics (40,000 kg of propane-butane mixture) and environmental conditions, would not threaten the safety of the city.

4 SIMBOLI
4 SYMBOLS

gostota	ρ	kg/m^3	density
prenosnost	τ	-	atmospheric transmissivity
specifična toplota	c	J/kgK	specific heat
Antoinove konstante	C_8, C_9, C_{10}	-	antoine constants
premer	D	m]	diameter
sevalna energija	*e*	W/m^2	emissive power
težnostni pospešek	g	m/s^2	acceleration due to gravity
višina	h	m	height
zgorevalna toplota	Δh_c	J/kg	heat of combustion
toplota uparjanja	Δh_V	J/kg	heat of vaporization
konstanta širjenja oblaka	k_1	m	slumping constant
masni pretok	$\dot{m}$	kg/s	mass flux
masa	m	kg	mass
molekularna masa	MW	kg/mol	molecular weight
tlak	p	Pa	pressure
toplotni tok sevanja	q	W/m^2	thermal radiation at a receptor
polmer	R	m	radius
temperatura	T	K	temperature
faktor pogleda	*k*	-	view factor of the flame
vžigalno razmerje	x	-	flashing fraction

Indeksi		Indices
zunanji, začetno stanje	0	ambient, initial state
uparjalni	B	boiling
tekočina, zrak, plin, para	L, A, G, V	liquid, air, gas, vapour
končno stanje	1	final state
luža, produkti	P	pool, product
vstopni tok	IN	inflow
oblak	C	cloud
uparjalna točka	BP	boiling point
zunanji	AMB	ambient

5 LITERATURA
5 REFERENCES

[1] Safer System LLC, User's guide trace 8-description of modelling algorithms, *Westlake Village*, California, USA-1996
[2] Vidmar, P., S. Petelin (2001) Model of fire spread around Krško power plant, Nuclear Energy in Central Europe 2001-International Conference, Portorož.
[3] Vidmar, P., S. Petelin, D. Lovinčič (2000) Basis of fire spread modelling, International Conference on Traffic Science 2000, Portorož.
[4] Chedaille J., Y. Braud (1972) Measurements in flames, *Edward Arnold*.
[5] Dougal, D. (1998) An introduction to fire dynamics, *John Wiley & Sons Ltd*.
[6] Vidmar, P., S. Petelin (2001) Fire models for enclosed and open spaces in transport systems, International Conference on Traffic Science 2001, Portorož.
[7] Mc Grattan, K. B., H. R. Baum (1997) Smoke plume trajectory from in suit burning of crude oil in Alaska, NIST-USA-1997.
[8] http://antoine.fsu.umd.edu/chem/senese/101/liquids/faq/antoine-vapor-pressure.shtml
[9] http://toxnet.nlm.nih.gov
[10] SFPE Handbook (1995) Fire protection engineering, 2nd edition, *National Fire Protection Association.*
[11] Baulak, C.E. (2000) Heat transfer in industrial combustion, *CRC Press LCC*, USA.
[12] Cote, A.E. (2000) Fire protection handbook, Eighteenth edition, *NFPA-USA*.
[13] Baulak, C.E. (2001) Combustion handbook, *CRC Press*, USA.
[14] Kumar, S., S. Miles, M. Chitty (1994) Jasmine user's guide, *Building Research Establishment*, USA.
[15] AEA Technology, CFX 4 User's manual, *AEA Technology, Harwell,* UK 2000.
[16] Galea, E., M. Petel (1998) Smartfire technical manual, FSEG, *University of Greenwich*, UK.
[17] Jones, W., G. Forney, R. Peacock, P. Reneke (2000) A technical reference for CFAST, *National Institute of Standards and Technology*, USA.

Naslov avtorjev: Peter Vidmar
prof.dr. Stojan Petelin
Fakulteta za pomorstvo in promet
Univerza v Ljubljani
Pot pomorščakov 4
6320 Portorož
peter.vidmar@fpp.uni-lj.si

Authors' address: Peter Vidmar
Prof.Dr. Stojan Petelin
Faculty of maritime studies and transport
University of Ljubljana
Pot pomorščakov 4
6320 Portorož, Slovenia
peter.vidmar@fpp.uni-lj.si

Prejeto:
Received: 10.4.2002

Sprejeto:
Accepted: 12.9.2003

Odprto za diskusijo: 1 leto
Open for discussion: 1 year