GPEX: a Generalized Program for Extinguishing Systems

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ABSTRACT

Extinguishing systems may be roughly described as a network of pipes connecting ending nozzles to the main storage of the extinguishing gas. Installations often contain a restrictor plate, most of the times directly behind the manifold. Restrictor plates reduce the pressure of the flowing gas to a certain value so that the pipe system downstream the restrictor may be designed for a reduced pressure. Due to the necessary strong reduction of the pressure (say from 200 bars to 50-60 bars) a so called overcritical flow near the restrictor plate appears. For this overcritical flow the usual relation between the pressure drop and the mass flow are not any more correct. A similar situation of overcritical flow appears at the nozzles discharge where sonic velocity is reached. Specific momentum balance equations should be adopted for those situations.

European Community regulations constrain both the discharge time of the extinguishing gas to an upper limit value and the maximum concentration of the extinguishing gas on the flooding zones. As a consequence the governing equations of the phenomena (momentum, energy and mass) should be solved in the time domain, but, by means of the basic assumptions later reported, the integration of the dynamic system may be simplified with a quasi-steady-state approximation; the whole system is then turned into an algebraic non linear system of equations.

The paper presents a generalized program which offers several advantages compared with the existing commercial ones: flexibility of adopting different extinguishing mixtures from a property data bank, accuracy in the extinguishing performances and possibility to switch from design case studies to simulation predictions.

1. INTRODUCTION

Fire suppression (extinguishing) systems are commonly distinguished by means of the adopted extinguishing agent: compressed gases (inert gases), allowing for single phase compressible fluid flow, or chemical agents (halogenated or not) allowing for two phases flow.

Aim of this paper is to present a generalized code describing the discharge dynamics in the case of compressed gases adoption as fire suppressant agent.

A fire extinguishing system may be roughly described as a network of pipes connecting ending nozzles to the storage of the extinguishing agent. The connection between pipes and storage is made by valves which, in case of fire, automatically release the extinguishing agent into the pipes. The discharge of the gas from pipes into the ambient passes through nozzles located at the end of the pipes.

Due to the high pressure level of the gas container (150-200 bar) a drastic pressure reduction is obtained behind the manifold by means of a restrictor plate (a convergent-divergent orifice) where both a supersonic flow and a depressurization below the critical pressure are produced (Liepmann and Roshko, 1967). As a consequence the downstream pipe network, after the pressure reduction, can be designed for a meaningfully lower pressure level (55-60 bar).

A fire extinguishing system may be, therefore, simply sketched as in fig. 1, in terms of a sequence of sections, at two pressure levels, passed by the gas during the extinguishing phase.

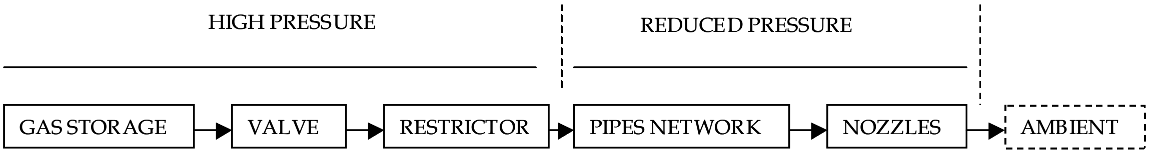

Fig.1 : *Sketch of an extinguishing system*

The pressure reduction at the restrictor substantially determines the pressure level over the whole pipe network: only the losses at the nozzles exit, where sonic conditions are reached at the beginning of the discharge, become significant.

European Community regulations constraint both the discharge time of the extinguishing agent to an upper limit value and its maximum concentration within the flooding zone.

As a consequence, the governing equations of the phenomena (momentum, energy and mass balances) should be solved in the time domain.

Two simplifying assumptions have been adopted for developing the model (Elliot et al., 1984):

a) Temperature, pressure and composition in the bottle storing the gas are only dependent on the initial conditions and on the outage fraction (fraction of the charge mass leaving the bottle). As a consequence the impact of the increased kinetic energy of the fluid leaving the bottle on the bottle energy balance is neglected.
b) The average flowrate exiting the network over a small time step is equal to the flowrate that would exit from the bottle, if the bottle conditions were held steady during that time step. Such an assumption holds if the pipe network volume is not greatly larger than the bottle volume and it allows to simulate the system dynamics by means of a cascade of steady-state conditions described by a set of non linear, algebraic equations.

The code developed and described in this paper offers several advantages if compared with the existing commercial ones: flexibility of adopting different extinguishing agents mixtures from a thermodynamic data bank, accuracy in extinguishing performances and possibility to switch from dynamic simulation predictions to design case studies performed automatically as a series of simulations.

2. DYNAMIC SIMULATION MODEL

The dynamic simulation model is the kernel of the whole code being used as such for stand alone simulation predictions and as a 'tool' for the design cases.
With the assumptions a) and b) described in the previous chapter, the model approach has been assumed as a sequential modular one, so that the calculations proceed from the storage and end at the nozzles, solving sequentially all the intermediate items encountered inside the pipe network. The calculation intrinsically needs the definition of initial conditions which are guessed and iteratively changed to match an equal number of calculated boundary conditions.
The system may be simply summarized as:

$$\bar{x} - z(\bar{x}) = 0 \tag{1}$$

where:

x array of size N which stands for the initial conditions,

z array of size N which stands for the calculated boundary conditions,

Provided the above mathematical formulation, the dynamic simulation model requires:

- a non linear algebraic system solver
- a library of component models pertaining momentum, energy and mass balance for all the possible items forming the extinguishing system: pipe, elbow, t distributor, nozzle, restrictor, valve and bottle
- a library of physico chemical properties describing the mixture used as extinguishing agent.

2.1 Non-Linear algebraic system solver

A generalized multi-algorithm procedure (Buzzi and Tronconi, 1986) involving Newthon-Raphson, Broyden and Gradient methods has been adopted to solve the system of equations 1).

2.2 Library of component models

The pipe model is described by the following equations representing respectively momentum, mass and energy balances for an adiabatic, compressible fluid flow in ducts(Hougen et al., 1964):

$$P_2 = P_1 - \frac{1}{2} f\, \overline{\rho} \overline{V} \frac{L}{D} + (\rho_1 H_1 - \rho_2 H_2) g \tag{2}$$

$$\rho_1 V_1 - \rho_2 V_2 = 0 \tag{3}$$

$$E_1 - E_2 = 0 \tag{4}$$

where:

P	pressure
ρ	density
g	gravitational acceleration
f	friction factor
H	height
D	pipe diameter
L	pipe length
V	velocity
E	total energy content

Subscripts 1 and 2 refer to pipe inlet and outlet conditions respectively, upper lined variables are averaged between input and output values.

The pipe network components such as valve, elbow and tees are modeled in terms of equivalent pipe length. For tees the pipe equations are slightly modified for taking into account the two outlet streams; in particular the mass balance equation 3) is conveniently replaced by:

$$\lambda M_1 - M_2 = 0 \qquad \text{and} \qquad (1-\lambda) M_1 - M_3 = 0 \tag{5}$$

where:

M	mass flowrate
λ	splitting factor

Subscripts 1 refers to pipe inlet and 2,3 refer to pipe outlets.

Although the restrictor and the nozzles work in different ways (the nozzle allows the sound velocity as an upper limit at the throat, while the restrictor plate, due to the diverging section, permits both to exceed the sound velocity and to obtain an overcritical expansion) they are modeled by the unique following form:

$$M = k_1 . P_0^{K_2} D^{K_3} A \rho_c V_c \tag{6}$$

$$\rho_1 V_1 - \rho_2 V_2 = 0 \tag{7}$$

$$E_1 - E_2 = 0 \tag{8}$$

where:

M	mass flowrate
K_1, K_2 and K_3	coefficients experimentally determined
A	throat area
P_0	pressure upstream the throat
V_c	sound velocity
ρ_c	critical density evaluated at $P_c = P_0\left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}$ where γ is the expansion coefficient

Equation 6) requires that the pressure behind the opening is less or equal the critical pressure, otherwise it is replaced by ordinary gas-dynamic correlations for subcritical flows (Liepmann and Roshko, 1967). It is worth to point out that the initial discharge phase, involving sonic flow at the nozzles, strongly affects the whole phenomenon dynamic.

The bottle model is represented by and adiabatic expansion at constant volume through either a proper equation of state or equivalent experimental regressions:

$$P(v,m,T)_{t+dt} - P(v,m,T)_t = 0 \tag{9}$$

$$E_{t+dt} - E_t = 0 \tag{10}$$

Where:

v	constant volume of the bottle
m	mass hold up inside the bottle
T	average temperature
E	total energy content
t, dt	time and time interval

2.3 Library of physico chemical properties

At the moment the physico chemical properties Library contains data referring to the following extinguishing agents:

- Nitrogen
- Argon
- IG55 (Nitrogen-Argon (50/50))
- CO_2
- Nitrogen-Argon- CO_2 (50/45/5)

For each agent experimental regressions on T and P have been stored for evaluating density, viscosity, expansion coefficient and heat capacity at constant pressure.

2.4 Dynamics simulation procedure

Provided the following hypothesis:

- A consistent sequence of the network components, from the bottle to the nozzles, is used.
- All the network variables are known at time t.
- Assigned as initial values 'x' of system 1) the bottle holdup and the splitting factors (if any) of each tee at time t+dt

it easily demonstrated that

- the number of nozzles is equal to the number of tees + 1
- the whole network may be sequentially solved and the values 'x' are matched by the equal number of equations 3) in which the outlet mass fluxes ρV are the calculated boundary condition 'z'.

In practice the algebraic system 1) has a size N equal to the number of nozzles. Each equation of the system may be reduced to the form:

$$\mathrm{Gupstream}_i(x) - \mathrm{Gcalculated}_i(x) = 0 \qquad \text{for } i=1,N \qquad (11)$$

where:

- Gupstream	flowrate reaching the inlet of each nozzle after the sequential solution of the network
-Gcalculated	flowrate calculated at the nozzle exit at assigned nozzle upstream conditions

The procedure starts at time t=0 where all the network variables are known.

3. NETWORK DESIGN

The network design aims to provide the throat diameters of the restrictor and of the nozzles. It is commonly accepted as more convenient to exclude from this phase the calculation of the sizes of all the remaining components, such as pipe, elbow and tees diameters. Also the bottle volume and the initial bottle holdup are normally assumed as known values. The bottle charge pressure is, by definition, an assigned data. In addition if the flooding ambient is divided into separated 'zones', it is commonly assumed that all the nozzles flooding the same zone have the same throat diameter.

The design problem is therefore reduced in size to the calculation of the restrictor throat diameter and of the diameters of the nozzles in different zones, provided that all the remaining geometric data are known.

As a consequence the design problem size is ND equal to the number of zones +1.

The design has to satisfy some constraints given by the current EU regulation:

- Discharge time assigned (60 s)
- Maximum pipe network pressure (55 bar)
- Minimum oxigen concentration (13.9 %) in each flooding zone at the discharge time

(It is worth to point out, although it is evident, that the maximum pipe network pressure occurs, in any case, during the initial time step at the exit of the restrictor plate.)

The design phase is seen as the solution of an algebraic system of equations:

$$C_{O2,i}(\overline{d}) - C_{O2,ass} = 0 \qquad i=1, ND-1 \tag{12}$$
$$P\max(\overline{d}) - Pass = 0$$

where:

d	Unknown design throat diameters
$C_{O2,i}$	Oxigen concentration in the i^{th} flooded zone at the discharge time assigned by regulations (60 s)
$C_{O2,ass}$	Oxigen concentration assigned by regulations (13,9%)
Pmax	Maximum pipe network pressure
Pass	Maximum pipe network pressure assigned by regulations (55 bar)

The system of the above equations is solved by the same solver used for the dynamic simulation problem. Each function evaluation requires, however, a complete dynamic simulation at assigned throat diameters and discharge time. This makes indeed the calculation slow and time consuming: this disadvantages are returned by the benefit of having an exact solution of the proposed problem.

4. CASE STUDY

Figure 2 sketches a simple network involving the following components:
-2 bottles of 0.14 m^3 and 38.37 kg of agent IG55 each, at 293 K and 2E+7 Pa.
-1 restrictor
-10 pipe sections
-2 elbows
-3 tees (90° branch)
-4 nozzles
-1 flooding zone (volume=100 m^3)

The scheme was designed and the following throat diameters have been calculated:
Restrictor: 0.00866 m ,Nozzles: 0.00668 m

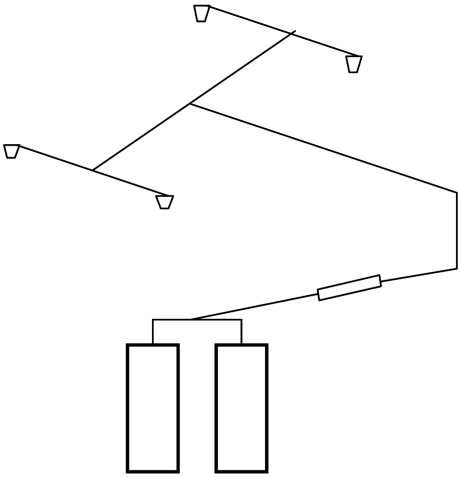

Fig.2 *Schematic of an extinguishing system*

Fig 3 report the bottle holdup and pressure profiles vs the discharge time at the design conditions.

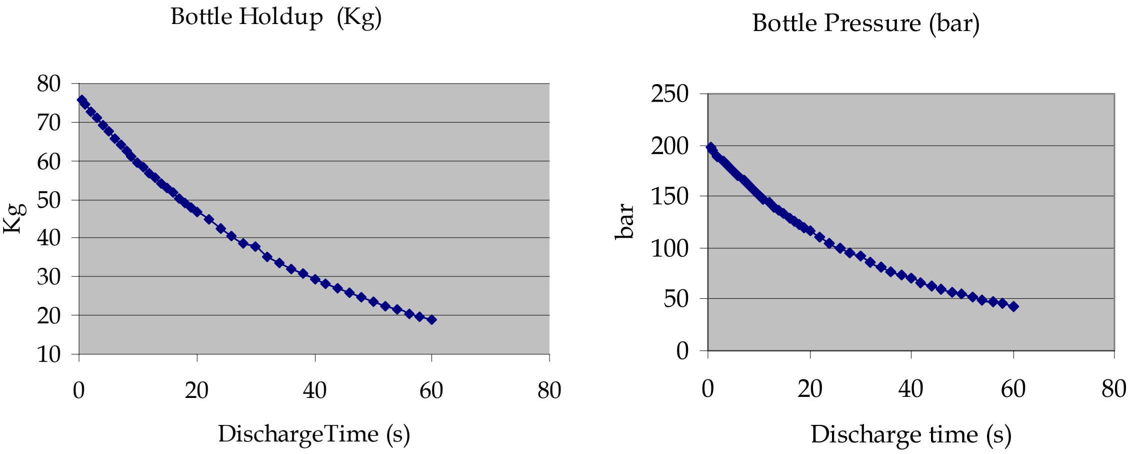

Fig.3 *Hold up and Pressure profiles*

5. Conclusions

The description of a program for the dynamic simulation and design of extinguishing systems has been reported. The program shows intrinsic flexibility to different extinguishing agents and a solidity in solving both simulation and design problems. The approach renders the problem equivalent to a successive steady state solution on the time domain of algebraic equations for both the simulation and for the design cases.

6. REFERENCES

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