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# EVALUATION OF TWO-PHASE FLOW MODELS FOR ACCIDENTAL RELEASE AND COMPARISON WITH EXPERIMENTAL DATA

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## ABSTRACT

Understanding the dynamics of a two-phase flow (liquid and gas) has been studied quite extensively over the past. This problem is indeed of direct relevance for many areas such as transportation, chemical processes and for the area of industrial risk assessment.

For several years, INERIS has been conducting various experiments in order to understand the mechanisms of vaporisation during the release of products initially stored in the liquid phase, into the atmosphere. The purpose is to determine the gas fraction flowing not only in the pipeline but also in the released jet and the liquid fraction that could be trapped on the ground because of the presence of an obstacle.

The studied products were propane, butane and ammonia. Various regimes of flows were tested and a database was created.

Then, an evaluation of different models for calculating the two-phase flow and the droplet behaviour was based on flow regimes and experimental set-up. The first objective was to calculate the flow rate in the pipeline and predict the size of the droplets in the initial part of the jet. There was a wide scatter of the results and many difficulties arose during the determination of the flow evaporation rate.

This paper presents the experimental results and conclusions on the validity of the two-phase models depending on the products, experimental set-up, and pressure storage.

## 1 INTRODUCTION

In many chemical and process plants, gas are stored and transported in their liquid phase over their saturated pressure. In case of pipe rupture accident, the material contained in the tank is ejected through the aperture as a two phase jet which then disperse in the surrounding atmosphere. In order to estimate dispersion effects, we need to calculate the two-phase source term and in particular the mass flow rate. This paper presents a comparison between several models of two phase mass flow rates and measured data obtained during experimental tests performed by INERIS since the 90's.

The particularity of this experiments was not to have been designed for the understanding of the flow inside the pipe. The net of pipes linking the storage and the nozzle are composed of many kinds of ducts of different diameters and many types of valves and nozzles. Difficulty comes from the calculation of the pressure drop and to the understanding of the influence of

geometry changes. Furthermore, we do not know exactly the errors on each data measurement (temperature, pressure, flow rate ...).

The last difficulty comes from the composition of the fluid used in the experiments. For example, commercial butane has been used for the tests, and the composition of this fluid can be relatively variable from a delivery to another.

In those conditions, the use of simple models is delicate and leads us to ask our-self a lot of questions.

In the first part of this paper, the different experimental set-up are described. As part of the FLIE project (Flashing Liquids in Industrial Environment), INERIS carried out large-scale experiments with propane and butane releases at different over-pressures (Bonnet and Lacombe, 2004) from liquid phase. Then, several experimental projects of ammonia releases from saturated storage are presented.

The second part of the paper is a comparison between several models and a discussion about the use of each one. For the application to a break in a pipe, many authors have dealt with the two phase flow in nozzles, pipes and ducts. First of all, the results of the model of Bernoulli based on the calculation of a pure liquid flow rate, allow to well evaluate the liquid pressure drop of the different pipes used in the experimental set-ups.

We then compared models based:

- on the “strong cooling” (Lackmé, 1980), i.e. the pressure storage is wider than saturation pressure. This model is also called the “Bernoulli like” model,
- on the homogenous equilibrium hypotheses (Homogenous Equilibrium Model) called the Fauske model (Fauske and Epstein, 1988 ; Fauske, 1985),
- on the hypotheses of super-critical flow (Wheathley, 1987),
- the omega method (Leung, 1995 ; Boccardi et al., 2005) which is based on the Homogenous Equilibrium Model.

The omega method is the most recently developed, and is known to be the most relevant of the empirical methods near the saturation conditions (Boccardi et al., 2005).

We will see in this paper that the problem of friction loss calculations and pressure drop in general will give rise to lot of difficulties. This point has been already discussed by Leung, (2004); Boccardi et al. (2005), in particular for two phases (bubble , sluggy ...) flows.

The last point is the critical importance of thermodynamic parameters of products used. The difficulty comes from the evaluation of the saturation pressure and of the specific enthalpy in function of the temperature.

## **2 DESCRIPTION OF EXPERIMENTAL SET UP**

### *2.1 LPG release tests*

INERIS was involved in the European project named “FLIE” for “Flashing Liquids in Industrial Environment” which purpose was to improve knowledge of the interaction between a two-phase jet and an obstacle. The task of INERIS was to carry out large-scale experiments

to collect data useful for the improvement of the existing calculation modelling. In this paper we presented the device discharge only (see Bonnet and Lacombe, 2004, for a more complete description ). The layout of the elements constituting the device discharge is schematically represented in Figure 1.

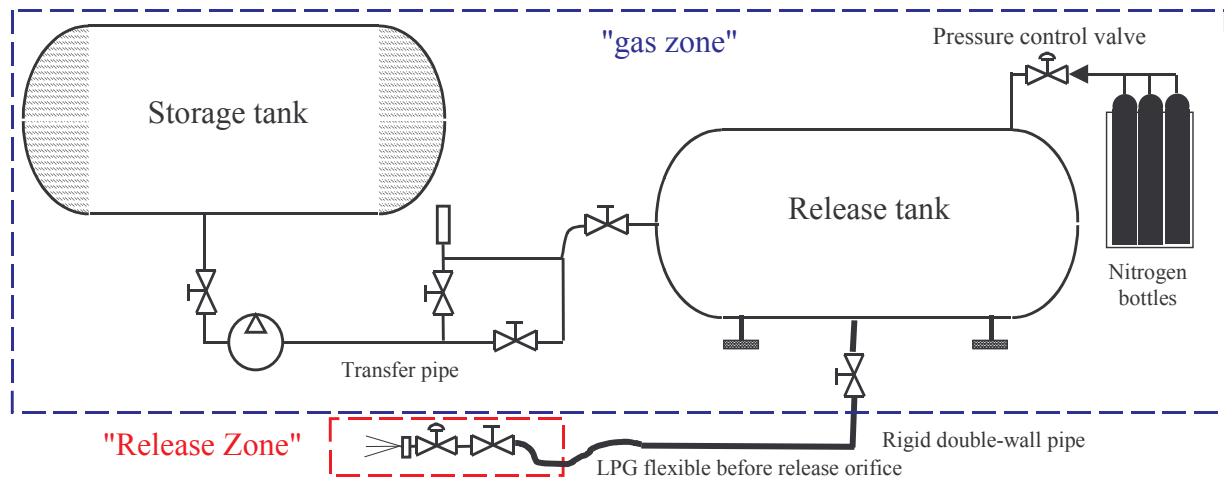


Figure 1 : schematic representation of the elements constituting the discharge device

The discharge device developed for the large-scale tests includes the following elements :

- a commercial LPG storage tank (buffer tank),
- a discharge tank (“5m<sup>3</sup> tank”),
- nitrogen frames; use of a nitrogen overpressure may be deemed necessary in certain cases to maintain an almost constant pressure during the test or to modify the discharge conditions,
- an LPG buffer tank,
- a point of discharge,
- a 5m<sup>3</sup> release tank that ensure the feeding of the point of discharge.

The link between the tank and the point of discharge is done in liquid phase (lower part of the tank) through a rigid pipeline (about 30m) then through a rubber pipe of a few metres in length. The section of this pipeline is 2 inches (50mm). The pipeline and the rubber pipe were insulated. Weight indicators were used to continuously measure the mass with an accuracy of about a hundred grams. These enabled the flow of the discharged product to be estimated. This measurement was completed by a level measurement and by measuring the temperatures in the tank. The discharge device allowed to perform propane and butane liquid releases at ambient temperature with a regulated pressure from the saturation pressure to 15 bar with an orifice (circular or rectangular shape) of an equivalent diameter from 10 mm to 25 mm.

## 2.1 Ammonia release tests

INERIS carried out an experimental program (undertaken with the financial support of the French Ministry of environment) in order to assess the time of answer of ammonia gas detectors and the effectiveness of the means of existing mitigation means (curtains of water, mist of water). The experiments were performed in a 80 m<sup>3</sup> chamber equipped with ventilation and washing of gases.

A bottle (B84) containing 40 kg of liquid ammonia under pressure of saturating steam (6,1 bars at 10 °C) was located in the chamber. It is linked up through a flexible with an implement of rejection which is schematically represented in Figure 2. It is constituted of a ¼ pneumatic gate, a right or bent rigid tube provided with a variable pipe. Diameters of the pipe were 0.5, 2 and 3 mm. The diameter passing through the level of the bottle is 4 mm. The flow rate of ammonia were governed by the pressure of saturating vapour of ammonia. The bottle of ammonia rests on a mass balance measurement which allowed to follow the loss of continuous mass.

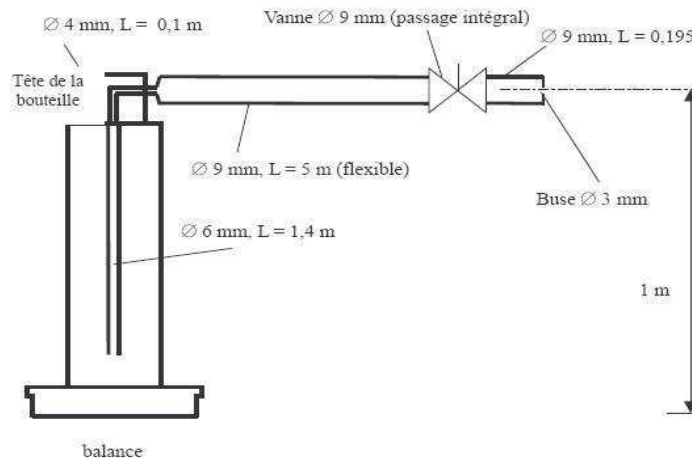


Figure 2 : schematic representation of the discharge device

### 3 THE MODELLING METHODS

Among all the models and calculation procedures available in the literature for studying two phase flow, we choose five models. The reader can find all the details of each one in the literature, so we do not give all the details of the procedures in this paper. The first one, called “Bernoulli”, is the simplest and the most known liquid flow rate calculation model. It allows us to over estimate the two-phase flow rate, and to check the liquid pressure drop value of the different experimental set-up.

Then, we choose the “Lackmé” model (Lackmé, 1980) developed in order to calculate two phase discharge of initially strongly sub-cooled water. The flow stays liquid in a big part of the pipe, and starts to evaporate when the value of the pressure is close to the saturation. The model of Lackmé, based upon subcooled water experiments, are to consider that the vaporisation starts at a pressure  $P_1$  lower than the saturation pressure. Lackmé proposed the following formulation :  $P_1 = k_1 \times P_{sat}(T_{int})$ ,  $k_1 = 0.95$ . This formulation is also called the “Bernoulli like” model.

When the fluid is stored between the strong sub-cooled conditions and the saturation, the Fauske model (Fauske, 1988) allows to calculate the mass flow rate. It is based on the Equilibrium Rate Model (ERM) which consider that the two phases have the same speed and the gas quantity is weak at the outlet of the pipe. Fauske introduce in the ERM model a new term to consider the non-equilibrium of the mix. Then, to consider the loss friction, Fauske involve a correction coefficient  $F$  depending on the fraction  $L/D$ , respectively the length and the diameter of the pipe.

For the choked flows near the saturation conditions, we use the Wheatley model (Wheatley, 1987) based upon the hypotheses :

- the expansion of the flow is isentropic and stationary,
- the two phase flow is homogenous and the liquid-gas mixing is in equilibrium state.

The last model used in this study is the so called omega method which is a commonly used homogeneous equilibrium model (HEM). This model is described in details in (Leung, 1995 ; Boccardi, 2005). Most of calculations were done with omega formulation for flow under high subcooling conditions (see equation (14) in Boccardi et al., 2005). In some case, we used the critical pressure (called omega 2 method) to estimate the maximum mass flow rate (see equation (8) in Boccardi et al., 2005).

#### 4 RESULTS AND DISCUSSION

The ratio R between the calculated mass flow rate and the experimental one has been chosen to evaluate the models prediction capabilities. It is presented as a function of the overpressure from the saturation  $\Delta P = P(T_{int}) - P_{sat}(T_{int})$  where  $T_{int}$  is the temperature inside the tank and  $P(T_{int})$  is the pressure inside the tank exposed at the ambient temperature  $T_{amb}$ . For several cases,  $T_{int} < T_{amb}$  because of the convection movements inside the tank.  $P_{sat}(T_{int})$  is the saturation pressure at the temperature  $T_{int}$ .

From Fig. 3, it can be seen propane, butane and ammonia experiments results compared with five models calculations. The diameter of the nozzles connected to the 50 mm diameter pipe varies from 5 to 25mm for propane and butane experiments and the diameter connected to the 9 mm diameter pipe varies from 0.5 to 3 mm for ammonia experiments.

We can firstly notice that models gives higher ratio values for butane than for propane and ammonia experiments. Butane experiments have been conducted with a mixture of propane and butane. The mixing characteristics are not very well known and an error on saturation pressure and enthalpy calculations is likely to exist. For a quantitative point of view, it is preferable to analyse propane and ammonia results. However, the same tendencies are observable for all data.

The Bernoulli method overestimates mass flow rate for all the data. It is an expected result. All the calculations have been conducted with constant discharge coefficients. We do not try to calibrate the pressure loss coefficient neither the contractions coefficient. Lenzing et al. (1998) shows that we need to take into account a discharge coefficient based upon a correlation for two phase flows. Following this approach the discharge coefficient is a function of the liquid alone and vapour alone discharge coefficients weighted by means of the void fraction of the mixture. Anyway, we do not have a measure of the gas fraction of the flow in our experimental data, so we can not evaluate the discharge two-phase coefficient and we only make a qualitative comparison between models.

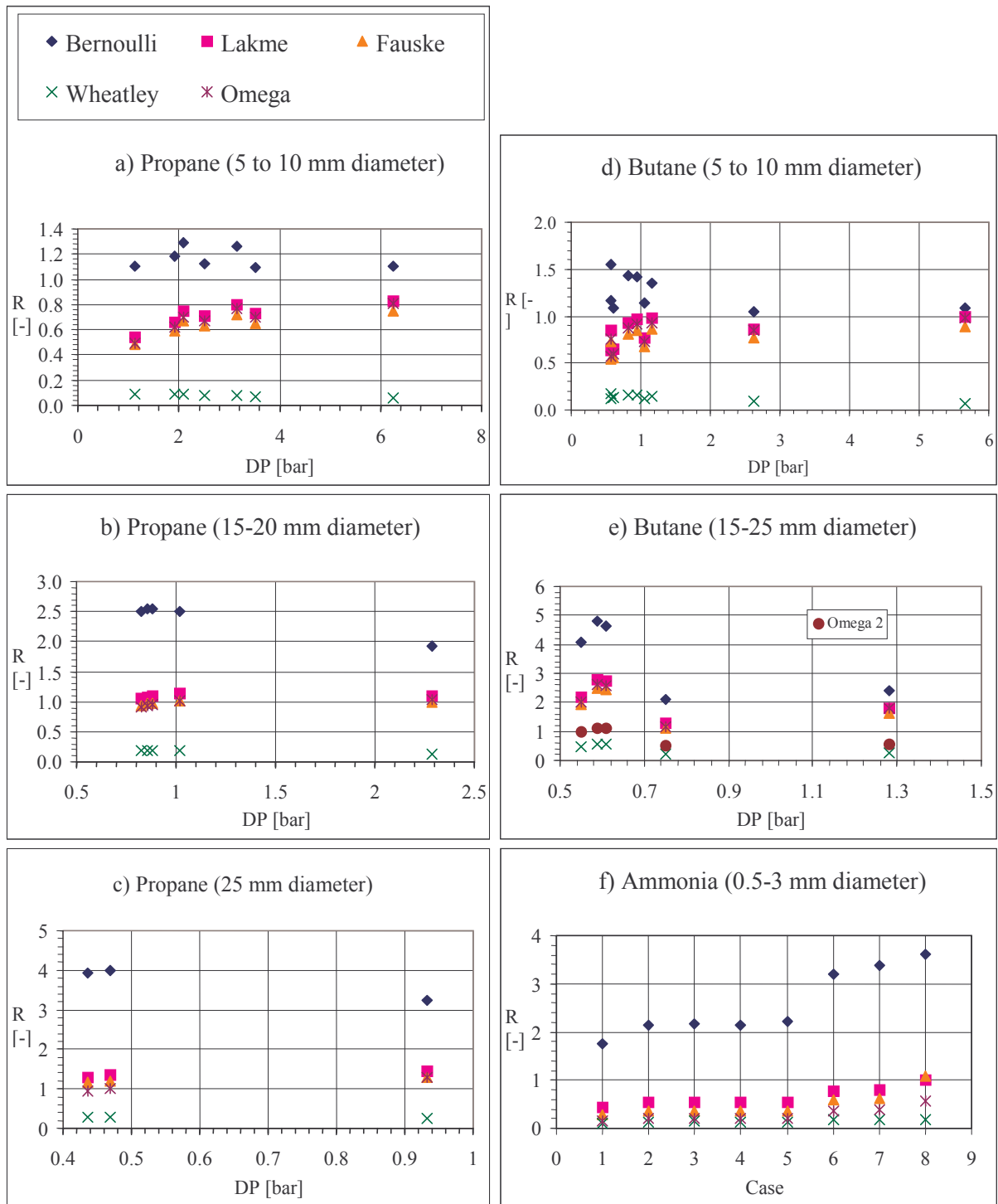


Figure 3 : Ratio between calculated and experiment mass flow rate as a function of the over pressure from the saturation. a) Propane and small diameters, b) Propane and medium diameters, c) Propane and big diameters, d) Butane and small diameters, e) Butane and big diameters, f) Ammonia.



On the figures 3a) and 3d), all the two phase models underestimate the flow rate when the nozzle diameters are smaller than 10mm. The Lackmé, Fauske and omega methods show similar results and seem to overestimate the gas part of the flow. The differences grow when the pressure decreases until  $P_{sat}$ . It seems that for small diameter, the gas part in the experimental flow rate is very weak for all pressures. The nozzle diameter is small in comparison to the pipe diameter. This big restriction reduces the speed of the flow inside the pipe, the friction loss are weak enough to produce a weak flash. The vapour production is then prevent when the pressure is under saturation conditions. The two phase models are then unable to correctly represent the physic. The error grows when the pressure is close to saturation pressure where all the models predict a grower part of vapour. We conclude that Bernoulli method could give a correct modelling for smaller diameter with a good choice of liquid discharge coefficient, i. e. considering a single phase flow without any vapour production in the pipe. The Wheatley method is adapted for choked flow. The large underestimation of the flow rate seems showing that the flow is not choked in all cases.

Results in figures 3b), c), e) and f) show that the vapour fraction of the low seems to enhance with the size of the nozzle. In cases of bigger diameter, all the models give a better concordance with experimental results. The homogenous hypothesis adopted in most of the models seems becoming pertinent. Models presents a better scoring with experimental data when ruptures of pipe are full section. In case of bigger diameter for butane experiment (see figure 3e) all the models drastically overestimate the mass flow rate when  $\Delta P < 0.7$ . An additional calculation (called omega 2 in figure 3e) with the omega approach (Boccardi et al., 2005) based upon the critical pressure for butane has bee done. This approach allows us to better estimate the mass flow rate.

The last part of this study is about ammonia experiments stored in saturation conditions. Fig 3f) shows comparisons between nozzles diameter of 0.5 mm ( case 1), 2 mm (cases 2 to 5) and 3 mm (cases 6 to 8). It can be seen that all two phases flow models underestimate the flow rate and the error decreases with the diameter growth. We can conclude once more that models are more pertinent for full section ruptures.

The comparison with the results of propane and butane experiments confirm how is complex to estimate two phase mass flow rates. We can observe two zones of application of the models when nozzles are big enough to allow an efficient vaporisation :

- the first zone is defined by  $\Delta P > 1$  bar, where the fluid is strongly subcooled. The Lackmé and omega models are better adapted, then Fauske model is quite good, and Wheatley approach is out of its validity domain.
- the second zone is defined by  $\Delta P < 1$  bar, called the slightly subcooled fluid zone. The Lackmé and Fauske models tends to overestimate the flow rate when  $\Delta P$  is decreasing, i.e. to under-estimate the gas part in the flow. This is not surprising because the Lackmé model was validated for strongly subcooled water. The omega method seems well appropriate in this zone. Data from pressure close to saturation pressure are missing to allows us to conclude on this point. Wheatley method starts to better estimate the mass flow rate, while remaining far below the values, but results data from  $\Delta P \approx 0$  bar are missing to complete this analysis.

For ammonia experiments, all models are strongly underestimating the mass flow rate. The reason seems to be the small size of the nozzles as we observe for butane and propane cases. We have to remind readers that all the aim of the experiments was not the mass flow rate calculation. There is unknown on the pressure drops, on the temperature and pressure measurements and on all the thermodynamic properties (saturation pressure and enthalpy).



## 5 CONCLUSIONS

INERIS has conducted several experimental set up to improve the better understanding of phenomena involved in a ejection of a gas stored in the liquid phase. The two phase mass flow rate calculation in pipes can be difficult following the size of the diameter nozzle in front of the pipe diameter. For full section ruptures, two phase flow models seems pertinent, and for small leaks the liquid model "Bernoulli" could match. On the other hand, for bigger leaks, calculations set problems. We can conclude that none of the models used in this study give good results for the whole set of data. In some cases, the good agreement can be challenged because those results do not seem to be reproducible.

INERIS is going to conduct new ammonia experiments exclusively dedicated to investigate the two phase mass flow rate. Those new results could allow us to have a better use of the models.

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