HSE

Health and Safety
Executive

An investigation into the performance of the PipeTech computer code in calculating Isle of Grain pipeline blowdown tests

Prepared by the **Health and Safety Laboratory**
for the Health and Safety Executive 2010

RR774
Research Report

HSE
Health and Safety
Executive

An investigation into the performance of the PipeTech computer code in calculating Isle of Grain pipeline blowdown tests

David Webber
Mike Wardman
Health and Safety Laboratory
Harpur Hill
Buxton
Derbyshire
SK17 9JN

Ian Hirst (HSE)

The computer code PipeTech, developed in the Department of Chemical Engineering at University College London, predicts the outflow following rupture or puncture of a long pipeline containing one or more pressurised hydrocarbons. It is currently used by the Health and Safety Executive (HSE) in determining its advice to local planning authorities on control of land-use in the vicinity of major accident hazard pipelines. The underlying theory is described by its authors in numerous articles in archival scientific journals (notably Oke, Mahgerefteh, Economou and Rykov, 2003). The modelling involves solution of the transient conservation equations for 1-D flow using the Method of Characteristics, with a 3-D representation in the vicinity of a puncture. Heat flows between the fluid and the walls of the pipeline, and through the walls of the pipeline, are included. Satisfactory comparisons of PipeTech calculations and measurements from the Piper Alpha accident and from two of the Isle of Grain experiments on release of LPG from a damaged pipeline have been shown in published documents. In addition, HSE has obtained a good comparison of PipeTech calculations with measurements from a ruptured pipeline carrying natural gas.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

HSE Books

First published 2010

CONTENTS

EXECUTIVE SUMMARY

Objectives

The computer code PipeTech is currently used by the Health and Safety Executive to predict the release rate of flashing, pressurised liquids from a ruptured pipeline. Comparison with Isle of Grain experimental data reveals that whilst it works well for full guillotine breaks (termed ruptures) it does less well for smaller breaches (termed punctures). An objective of the work described in this paper is to find out why this is so, and to determine what can be done to improve the situation.

Main Findings

The theory behind PipeTech appears to be reasonable but is too complicated to permit much in the way of pencil-and-paper analysis. However, another code, PipeBreak, (part of DNV's PHAST suite), is rather simpler, whilst being based on essentially the same physical principles, and it experiences similar successes and failures when compared with the same experimental data. Furthermore PipeBreak is already very familiar to the principal author of this report and has already been the subject of considerable analytic effort. Our first conclusion is that whatever assumption is causing a poor fit to the experimental data on puncture is present in both these models, and the cure, if found, may rectify both. PipeBreak's amenability to pencil-and-paper analysis may therefore provide a key to the solution.

An examination of the nature of 3-dimensional flow near a puncture (one of the main differences between full guillotine breaks and smaller breaches) indicates that this in itself does not provide the answer, unless it is also accompanied by a different set of thermodynamic assumptions.

We examine the assumption of a flashing flow, in homogeneous equilibrium and choked in the breach. This leads to a reasonable analytic prediction for full guillotine breaks, but too small a release rate (by a factor of 2 or more) for a breach whose area is about 10% of that of the pipe cross-section. It is this discrepancy which is the problem in the code PipeBreak and, we conclude, also in PipeTech.

We argue that a pipe with a small breach is essentially the same as a vessel with a small hole, as the essential one-dimensional nature of the flow for a full guillotine break does not apply in this case. The length of the reservoir behind the orifice becomes unimportant. Releases from vessels have been analysed in the past with quite different assumptions from those prevalent in PipeBreak and PipeTech. However, reasons for the difference are hard to come by, and while they predict the initial flow rate from punctured vessels, a model for its evolution on a par with what PipeBreak and PipeTech do for pipe breaches seems, as far as we have found, to be absent.

The experimental evidence for pipes with a small breach points strongly to equilibrium two-phase flow, though not necessarily *homogeneous* equilibrium. We argue that *homogeneous* equilibrium flow may be associated with 1-D flow along the pipe, but in a more complicated converging flow zone near the orifice, the equilibrium may become *inhomogeneous*.

Recommendations

This work points to a gap in understanding of the relationship between two-phase flows from pipes and vessels. Full bore pipe ruptures are well modelled by both the computer codes considered here, but how that transforms into a release from a vessel as the breach becomes smaller is apparently not understood, and nor indeed are the details of two-phase releases from vessels. Further review, modelling, and experimental effort are recommended if this is to be better understood. Understanding the Isle of Grain experiments better may also aid an improved understanding of release from vessels.

1 INTRODUCTION

The computer code PipeTech, developed in the Department of Chemical Engineering at University College London, predicts the outflow following rupture or puncture of a long pipeline containing one or more pressurised hydrocarbons. It is currently used by the Health and Safety Executive (HSE) in determining its advice to local planning authorities on control of land-use in the vicinity of major accident hazard pipelines. The underlying theory is described by its authors in numerous articles in archival scientific journals (notably Oke, Mahgerefteh, Economou and Rykov, 2003). The modelling involves solution of the transient conservation equations for 1-D flow using the Method of Characteristics, with a 3-D representation in the vicinity of a puncture. Heat flows between the fluid and the walls of the pipeline, and through the walls of the pipeline, are included. Satisfactory comparisons of PipeTech calculations and measurements from the Piper Alpha accident and from two of the Isle of Grain experiments on release of LPG from a damaged pipeline have been shown in published documents. In addition, HSE has obtained a good comparison of PipeTech calculations with measurements from a ruptured pipeline carrying natural gas.

For a description of the Isle of Grain tests see, for example, Richardson and Saville 1996 or Tam and Cowley 1988. As we shall illustrate in Section 2 below, comparisons of our own PipeTech results[1] with the results of these tests show a reasonable agreement for full bore rupture, but progressively poorer agreement for smaller breaches. It is the objective of this study to try to understand what is going on in the small breach cases, to review relevant aspects of the PipeTech model, to find out why it performs less well, and finally to suggest how improvements might be made.

Working through the description of the underlying theory given by Oke et al 2003 in some detail revealed nothing obviously wrong. We do not have access to the internal coding of PipeTech, so we could not investigate there. Hence the one avenue left to us was to investigate PipeTech's performance against other experimental data and/or against the predictions of other computer codes.

The features of PipeTech under investigation – a good representation of a spectrum of data but a less good representation of the Isle of Grain partial breach data - are shared by another model known to HSL and HSE, "PipeBreak" (Webber, Fannelop and Witlox, 2001), which underlies part of DNV's Phast/Safeti suite of risk assessment codes[2]. Much of the main development of that model is given in the open literature by Webber, Fannelop and Witlox, 1999 (although the name PipeBreak was not used at that time). Specific development objectives included that the code should comprehend the behaviour of ethylene at pressures approaching 100 bar, at temperatures close to its critical temperature, and in very long (many km) pipelines; and that it should comprehend the behaviour of propane at modest pressures and in short (100 m) pipes. It was also required to run sufficiently quickly to be used in a risk assessment framework. The fuller description is contained in the PipeBreak Theory Manual, but this is confidential to Phast/Safeti licensees (of whom HSL and HSE are two).

The physical principles underlying PipeTech and PipeBreak are similar (though not identical) but the numerical procedures adopted to solve the equations are very different. PipeTech uses a numerical technique, the method of characteristics, to solve the partial differential equations. PipeBreak makes carefully thought-out approximations of profiles to reduce the numerics to a

---

[1] *Obtained with PipeTech V24, sent to HSE on 1 August 2007.*

[2] *The problem with the partial breach Isle of Grain data was discovered and partly analysed in DNV's validation of PipeBreak. This resulted in the imposition of limits in PHAST so that this (PipeBreak) module is not used outside its considered scope of applicability.*

problem involving only ordinary differential equations. In view both of the similarities and of the differences of the models, the similarity of the results from PipeTech and PipeBreak, both for full guillotine breaks and for smaller breaches, provides a very useful line of enquiry for this report.

The general agreement of the two codes is extremely encouraging. It indicates on the one hand that the complicated method of characteristics of PipeTech has been implemented without apparent errors, and on the other that the carefully thought-out approximations of PipeBreak (needed to make it run so quickly) were indeed sufficiently carefully thought-out!

The question then remains of why the agreement with experiment is poor for smaller breaches. Neither of the codes has much in the way of free parameters (as such) which can be tweaked to give significantly different results. The agreement for full-bore ruptures therefore constitutes a great predictive success. But the reasons for the failure for smaller breaches must be buried fairly deeply in the models.

Both codes are essentially one-dimensional pipe flow models. In the development of PipeBreak, the absence of a model for 3-D flow close to a small (less than full bore) breach was noted, and conjectured as a possible cause of the discrepancy with data. However the rather more complex PipeTech model includes a sub-model for 3-D flow near a small breach and, as we have noted, empirically it seems to make next to no difference.

PipeTech is too complex to be amenable to pencil-and-paper analysis, and so further direct investigation by that route is prevented. However, the simpler code PipeBreak *is* amenable to such analysis and, given the similarity of both their underlying physics and their results, it makes sense to attempt to explain the failure of PipeBreak for small breaches, on the basis that it is almost certainly the same mechanism at work in PipeTech.

The one major assumption underlying both models, and which is absolutely crucial for obtaining the results, is that of homogeneous equilibrium flow, and so our attention will therefore fall naturally on that. In particular, the homogeneous equilibrium model has specific predictions for choked flow at the orifice, and is an important factor in determining the outflow rate.

The remainder of this work is therefore organised as follows:

- examine some Isle of Grain trial data in the context of the models' predictions;
- review the nature of choked flow in a pipe;
- review the explicit analytic model used in PipeBreak in view of the similar results of PipeBreak and PipeTech;
- discuss models of discharge from vessels and apparent difference between vessels and pipes; and
- draw conclusions for PipeBreak and PipeTech.

2 THE ISLE OF GRAIN DATA

Here we show some of the Isle of Grain experimental data. Details of the tests are given in Richardson and Saville (1996). For the purposes of this study, electronic records of the data at 0.1 second intervals were obtained by private communication with Richardson (Hirst, 2005). The trials involved a 100 metre long and 154 mm (6-inch) internal diameter pipe containing LPG (recorded as 95% propane and 5% butane) held at pressure in the liquid state. The pipe was blocked at one end, and opened rapidly at the other, either to full bore or with an aperture which was some fraction of the pipe cross-section. Throughout the depressurisation measurements were taken of the pipe inventory and of the pressure and temperature of the fluid near to each end of the pipe. Sensors were located along the pipe, and particularly 10 cm from the open end and 1.5 cm from the closed end. Richardson and Saville's judged uncertainties in the measured quantities are +/- 5% in the inventory, +/- 50000Pa in the pressures and +/- 2K in the temperatures.

The following figures show measured data and our calculations with PipeBreak and with PipeTech for three of the trials. For the PipeTech calculations the LPG was modelled as 95% propane and 5% butane. For PipeBreak, it was considered a good approximation to model it as pure propane (especially in view of the experimental pressure-temperature curves given below). We shall use the comparisons shown here together with the known analytic properties of PipeBreak to present an understanding of the flow (or highlight the lack of one).

2.1 TRIAL P40 – FULL BORE RUPTURE

First let us look at a full bore rupture experiment, trial P40, for which the initial pressure and temperature of the LPG were 21.6 bar absolute and 17.8°C respectively. The inventory and the pressure and temperature near to each end of the pipe, measured and predicted, were:

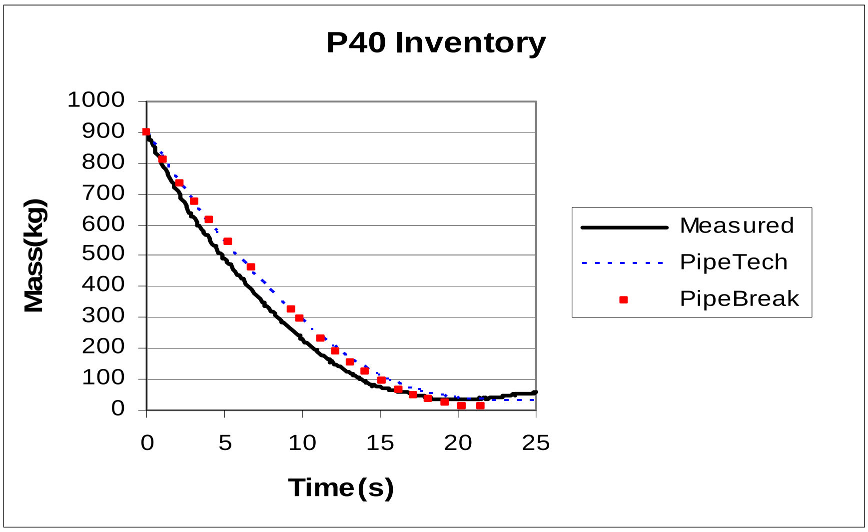

Figure 1a – P40 Inventory

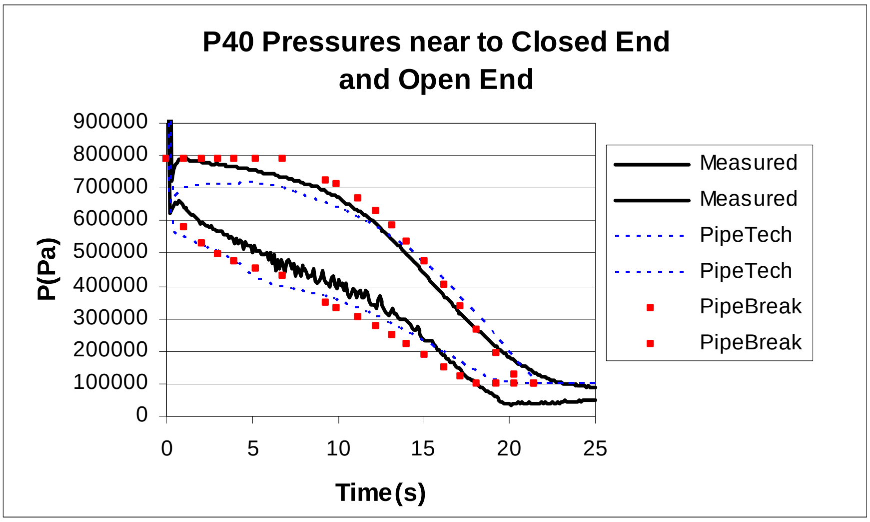

Figure 1b – P40 Pressures near to closed end and open end

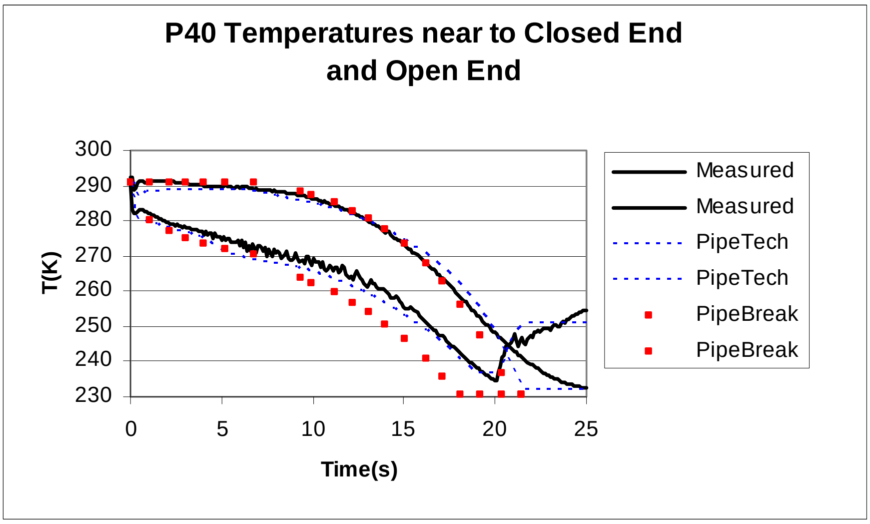

Figure 1c – P40 Temperatures near to closed end and open end

The overall comparison is favourable at both ends of the pipe. The later points, where the outlet temperature rises correspond to the last remains being expelled from the depressurised pipe, are not significant for our purposes.

2.2 TRIAL P42 – FULL BORE RUPTURE

The same graphs for trial 42, a full bore rupture from different initial conditions (11.3 bar absolute, 20°C) are:

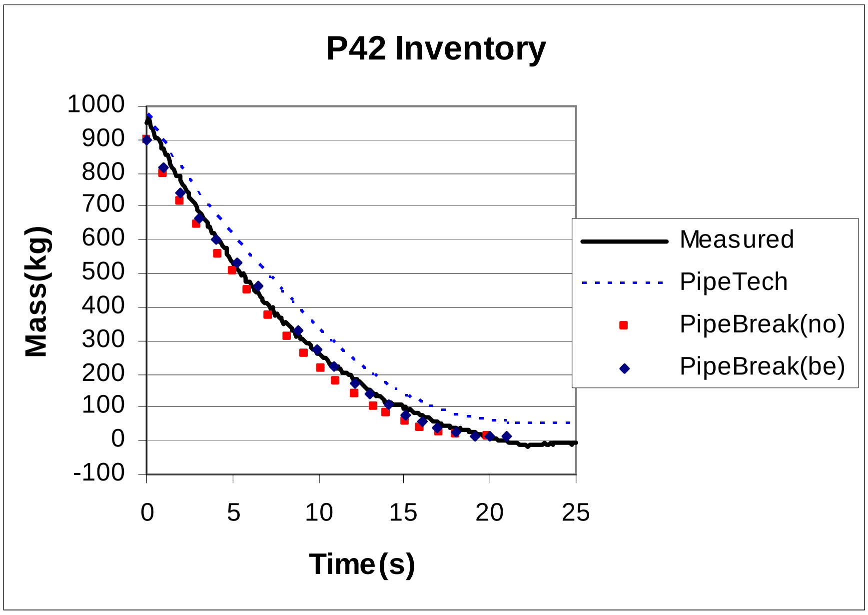

Figure 2a – P42 Inventory

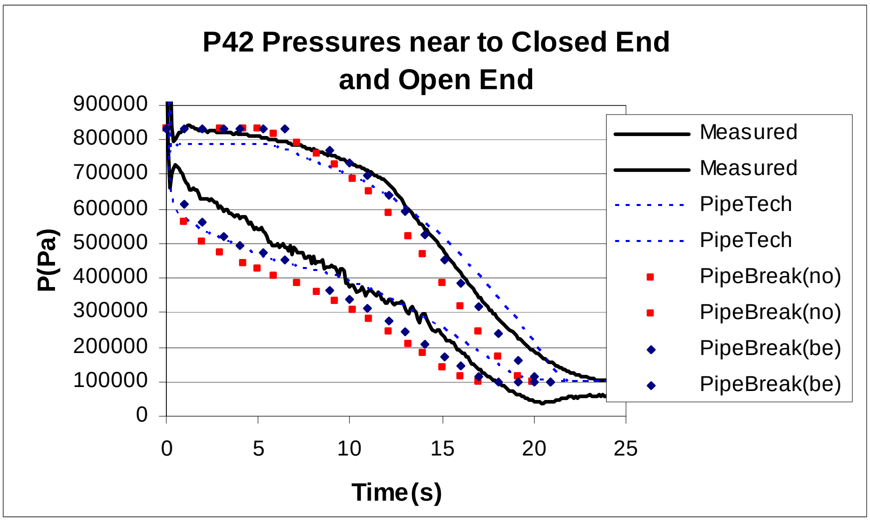

Figure 2b – P42 Pressures near to closed end and open end

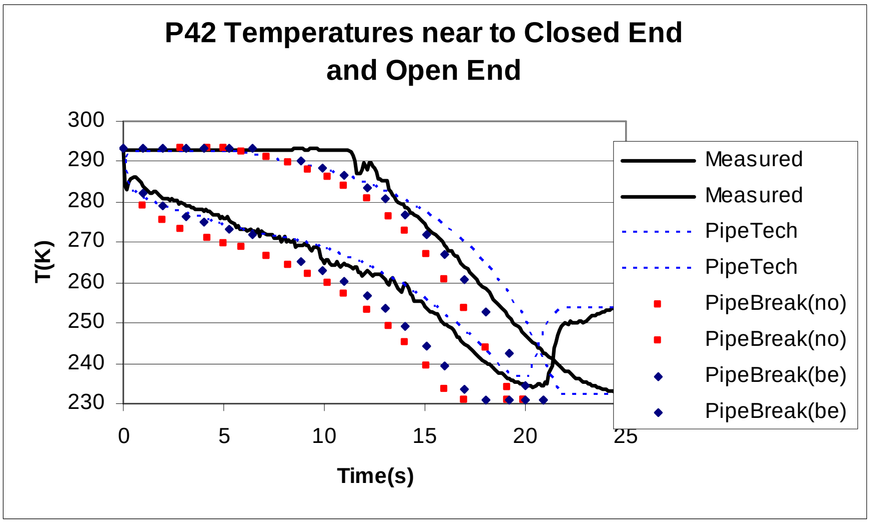

Figure 2c – P42 Temperatures near to closed end and open end

In this case two sets of results are given from PipeBreak. Those labelled PipeBreak(no) had no representation of heat transfer through the walls of the pipe; those labelled PipeBreak(be) had best-estimate heat transfer. It can be seen that inclusion of heat transfer gives only a slightly closer fit to the measured data, and so, for the sake of simplicity, heat transfer was not included in the other PipeBreak calculations presented here; it is automatically included in the PipeTech model.

2.3 TRIAL P47 – A SMALLER BREACH

Trial 47 had initial conditions (21.3 bar absolute, 14.6°C) similar to P40, but the release was through a small circular aperture in the end of the pipe, with area only about 10% that of the pipe cross-section. The measured data and the results from the calculations are:

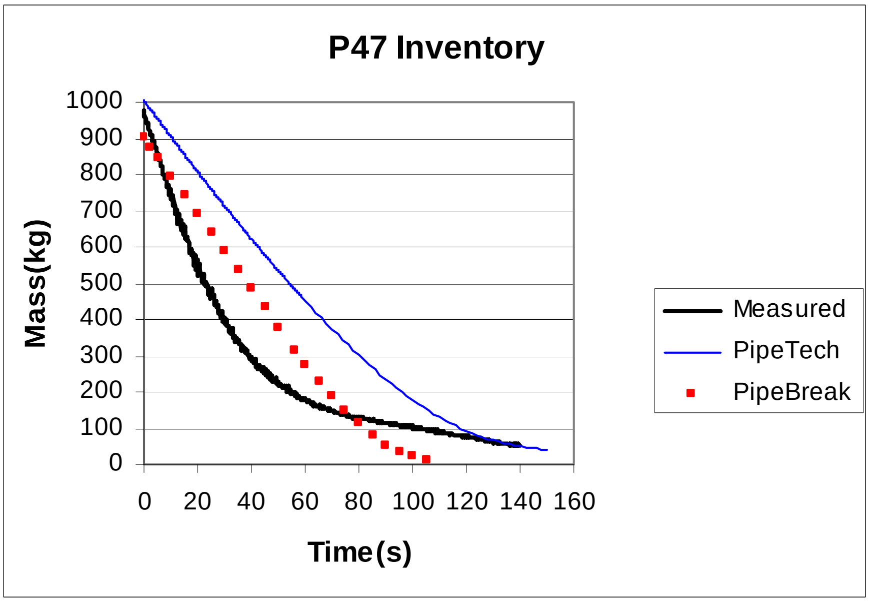

Figure 3a – P47 Inventory

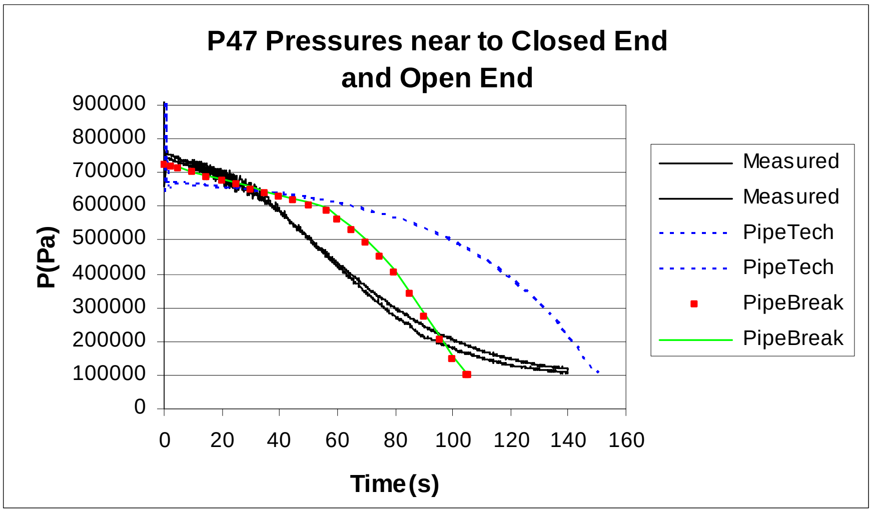

Figure 3b – P47 Pressures near to closed end and open end

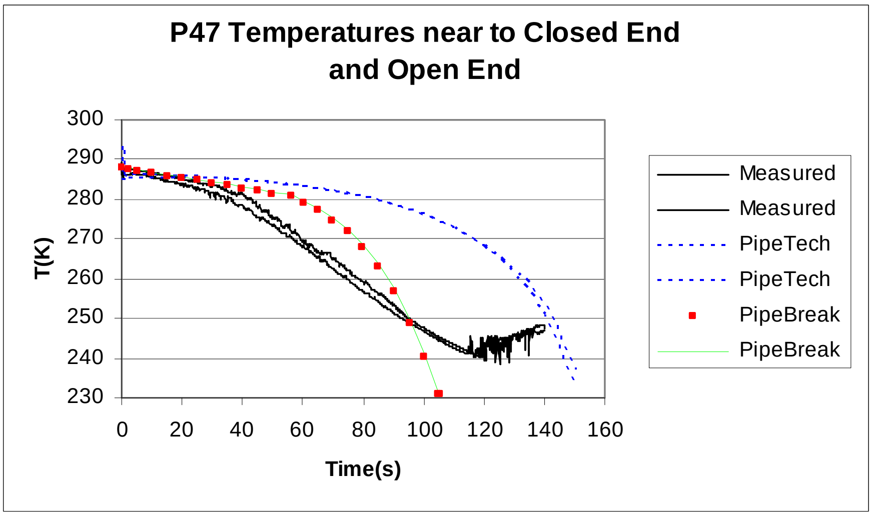

Figure 3c – P47 Temperatures near to closed end and open end

The results of PipeBreak are closest to the measured data, but neither program performs well, and qualitatively both programs have the same characteristics. Initially the pressure, temperature, and inventory predictions all fall too slowly. Later they all fall too rapidly. The fact that PipeBreak does slightly better is hardly a ringing endorsement, but it *is* interesting in view of the fact that it is PipeTech which allows for 3-D flow near the orifice. Physically something seems to be happening which is rather different from what is embodied in either of the models[3].

---

[3] *As mentioned in the introduction, the inapplicability of PipeBreak to smaller apertures was first noted during its original validation process, before its incorporation into the PHAST suite of codes. Because of this the PHAST suite prevents users from launching PipeBreak for a breach whose area is smaller than 20% of the pipe area. So the 11% breach in Test P47 is well outside the range where PipeBreak may be used in PHAST.*

2.4 PRESSURE VS TEMPERATURE

Before going on to discuss the above results in more detail, it is worth plotting pressure against temperature for the measurements closest to the ends of the pipe. The interval between plotted points is 0.1 seconds. The results for the three trials are:

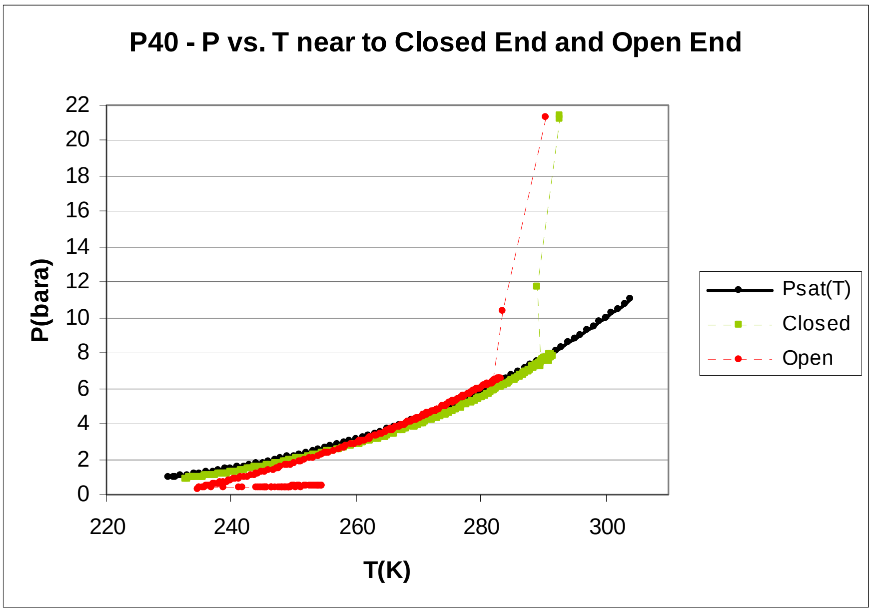

Figure 4a – P40 - P vs T near to closed end and open end

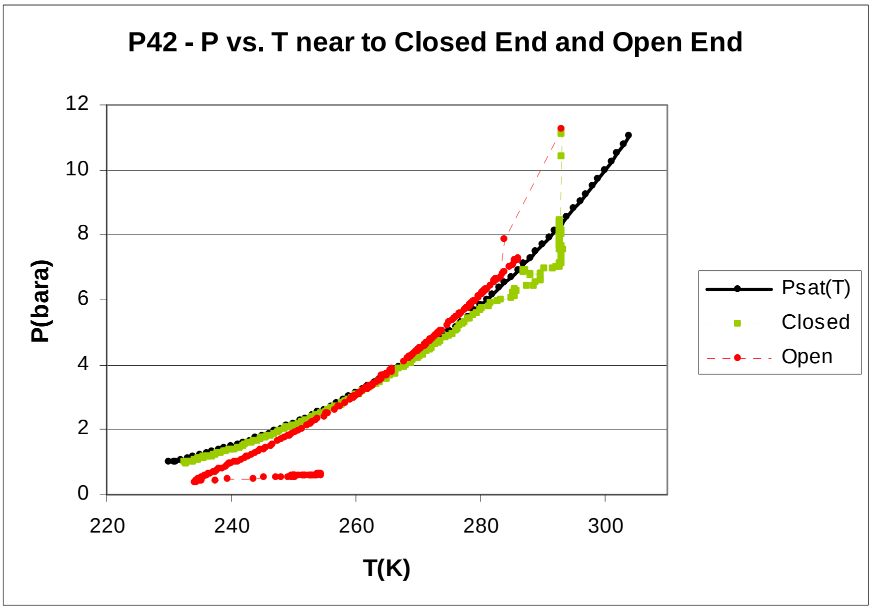

Figure 4b – P42 - P vs T near to closed end and open end

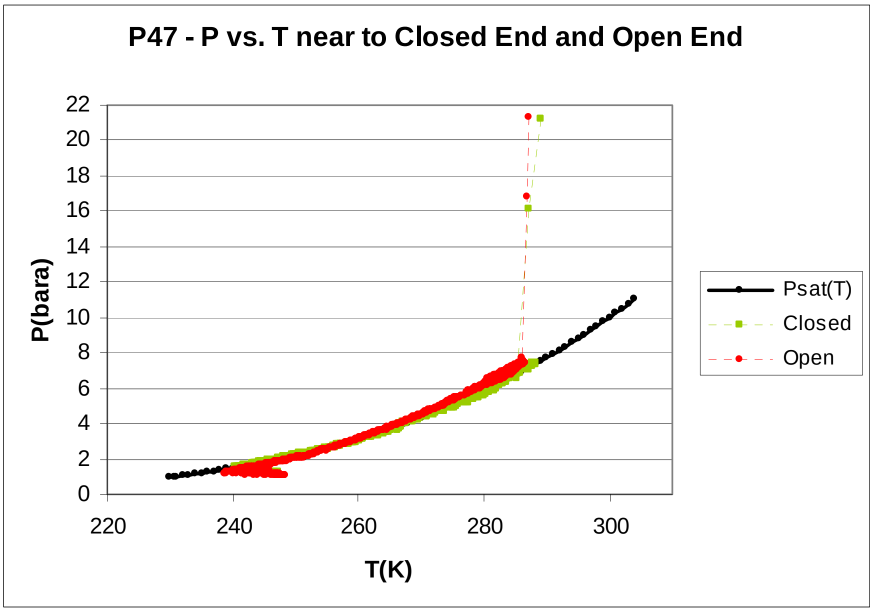

Figure 4c – P47 - P vs T near to closed end and open end

The solid black curve (Psat(T) is the saturated vapour pressure curve of propane. In all three trials the measured pressure/temperatures curves close to both ends of the pipe follow it closely, after a very rapid initial drop and until the pipe is essentially empty. On the face of it, this is excellent support for the Homogeneous Equilibrium Model.

2.5 DISCUSSION

In the full-bore guillotine break experiments P40 and P42 the overall comparison is favourable, but what is not completely clear from the graphs is the rapid evolution of the discharge predicted over a very short period of time.

For example PipeBreak predicts (for Trial P40) that the liquid mass fraction of the ejected material drops from 1 to 0.9 over the first second, while the pressure and temperature values change rather less.

Thus the time-variation of the process is crucial to understanding the physical processes. This contrasts sharply with much of the work done on release from vessels (to which we return below) where the process is often modelled as steady-state.

The feature of the comparison which alerts us most is the under-prediction of the initial discharge rate in trial P47 – the small breach. Furthermore this is accompanied by other features which are worth noting.

PipeBreak models the discharge as starting to vaporise from an initial uniform saturated liquid state at the breach. The vaporisation front works its way upstream towards the closed end, and only when it reaches the closed end does the pressure start to drop there. This is clear in the model of the full bore ruptures, and (in the graphs of temperature and pressure against time) the data seem to be in accord. This is particularly clear in the data from trial P42. It is far less clear in the case of the small breach P47. All the while, the pressure difference driving the flow is assumed to be balanced by friction forces, resulting in a quasi-steady flow. The pressure at the orifice is determined by a choke, appropriate to the discharge rate. Thus PipeBreak manages to fit the data well for P40 and P42 and much less well for P47 with essentially no free parameters.

In trials P40 and P42 there is a significant pressure difference between the ends; in the small breach case P47, the pressure difference is very small (both as measured and as predicted).

PipeTech, with a broadly similar model but a completely different solution method, gives qualitatively similar results. The main feature of PipeTech which might have made a difference is the inclusion of a 3-D flow model near the orifice for a small breach. It doesn't improve the predictions over those of PipeBreak and we shall discuss below why we do not now think that this *should* make any difference. But first let us give an intuitive understanding of why small breaches may behave differently from guillotine breaks.

2.6 "CECI N'EST PAS UNE PIPE!" [*]

The small pressure drop along the pipe in trial P47 raises the question of "When is a pipe not a pipe?" and in fact we shall argue that trial P47 may be behaving more like a vessel.

If we consider a very small hole in the otherwise blanked off end of a pipe (see below) it is intuitively apparent that the flow through it at any time may be responding to conditions in the near neighbourhood of the puncture. It may be completely oblivious to the difference between a hole in (say) a large spherical reservoir and a long pipeline. In that case, even the latter situation may be better described by a model for flow from a punctured vessel. The flow along the pipe would not be the prime determinant factor of the release rate (at least not for a long time after the breach is initiated) and a model based on pipe flow may be barely relevant. In that sense, what looks like a pipe may not *be* a pipe, exactly as Magritte pointed out (albeit somewhat differently).

---

[*] *René Magritte. The artistic allusion is far too tempting for this poor anglophone author, even though the pipe in question, if it were in France, would more likely be "un gazoduc". But let's not allow that to spoil a good pun.*

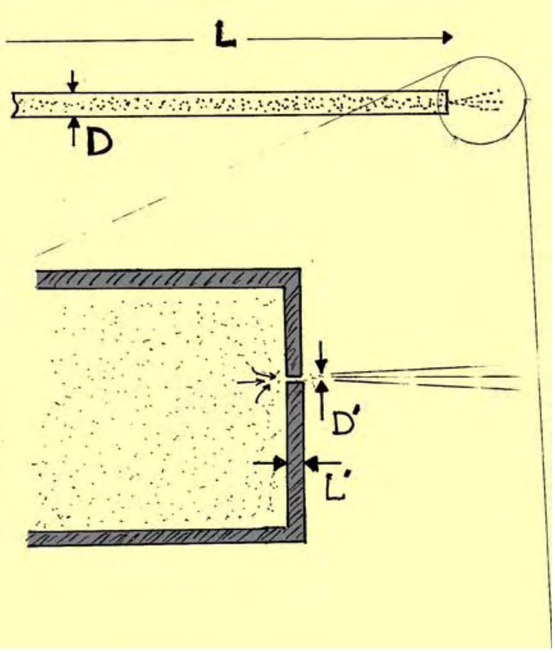

Fig 5: A puncture in the end of a long pipe: *the upper figure shows a portion of a pipe of total length L and diameter D. The lower figure magnifies the region around the puncture, showing fluid escaping through a small orifice of length L' and diameter D'. For a full guillotine break (D'→ D) then L' becomes irrelevant and L may be important (if not immediately, then later). For D'<<D it is difficult to imagine that the pipe is any different from a vessel and L, D may be completely unimportant.*

Some of the Isle of Grain trials (eg P47) used pipes with a puncture area down to around 10% of the total pipe area. Empirically this seems small enough that the ideas which lead to convincing models of the flow in the case of guillotine breaks become rather less than convincing.

3 CHOKED FLOW IN A PIPE

In this section we review the theory of choked flow in a pipe (as is appropriate for a full guillotine break) and how it leads to a discharge at the speed of sound in the fluid. We shall show by example how this may be independent of the existence of a 3-D flow zone near the orifice. We shall postpone discussion of what exactly is meant by the speed of sound in a saturated liquid, but that too is important.

3.1 GENERAL CONSIDERATIONS

The general mass and momentum equations of flow are taken as

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla_i(\rho u_i) &= 0 \\ \frac{\partial \rho u_j}{\partial t} + \nabla_i(\rho u_i u_j) + \nabla_j p &= -F_j \end{aligned} \tag{3.1}$$

where ρ is density[*], p is pressure, u is velocity, and F is a friction term which we can consider in more detail if necessary. Let us see what assumptions lead to classic choked flow, and what they tell us about it. (A sum is implied over repeated indices)

Now focus on a cylindrical pipe with a guillotine break, so that flow is directed along the pipe towards the break with velocity u. In this case, the above equations become

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} &= 0 \\ \frac{\partial \rho u}{\partial t} + \frac{\partial(\rho u^2 + p)}{\partial x} &= -F \end{aligned} \tag{3.2}$$

where x is the distance along the pipe.

For the moment let us assume that the flow is essentially steady and that we may neglect friction. In these circumstances

$$\begin{aligned} \frac{d\rho u}{dx} &= 0 \\ \frac{d(\rho u^2 + p)}{dx} &= 0 \end{aligned} \tag{3.3}$$

which are the equations of classic steady choked flow. The first of these equations gives a constant mass flux, and thence the second may be written

$$\left[(\rho u)^2 \frac{d(1/\rho)}{dp} + 1\right]\frac{dp}{dx} = 0 \tag{3.4}$$

---

[*] *We shall use both density ρ and specific volume v=1/ρ throughout according to which is more convenient. The importance of both fluid dynamic and thermodynamic processes make this the most reasonable course.*

or

$$\left[1-\frac{u^2}{c^2}\right]\frac{dp}{dx} = 0 \tag{3.5}$$

where

$$c^2 = \frac{dp}{d\rho} \tag{3.6}$$

with the derivative being taken along the flow. If pressure and density vary along the flow with no heat transfer to the flow, then this is the thermodynamic derivative at constant entropy, and c is by definition the speed of sound in the fluid.

Steady flow in long pipelines arises through a balance of driving pressure gradient and friction. Putting the friction back in gives the steady flow momentum equation

$$\left[1-\frac{u^2}{c^2}\right]\frac{dp}{dx} = -F \tag{3.7}$$

Now picture steady two-phase flow. As one moves downstream towards the orifice, fluid vaporises, the density decreases, and the velocity increases to preserve the mass flux. As the velocity approaches c, then a choke is set up with small ($1-u^2/c^2$) and large dp/dx. A valid approximation is that u tends to c and dp/dx tends to minus infinity (though at finite p).

3.2 THE CODES PIPEBREAK AND PIPETECH

The above leads us to expect a release at the speed of sound (in the two-phase medium). The codes PipeBreak and PipeTech both appear to get this about right when compared with the full guillotine break examples (eg trial P40) of the Isle of Grain trials.

It is clear that they both do worse for releases through smaller orifices (eg trial P47), significantly underpredicting the initial release rate[*]. In the validation of PipeBreak it was observed that, in this case, the predicted pressure gradient along the pipe was very small – casting doubt on the idea of a balance of pressure gradient and friction along the pipe. But if the governing factors are the speed of sound in the fluid and the area of the orifice, should that be important?

PipeTech has a model of the flow near the small orifice which is better, on the face of it, than PipeBreak's 1-D flow assumption. But its predictions for this case are no better.

In order to understand how it is that a converging 3-D flow near an orifice might *not* make a difference, in the appendix we look at flow along a converging conical pipe.

---

[*] *Both PipeBreak and PipeTech make allowance for a breach which is smaller than full bore and so the situation is more complicated than these simple considerations imply. We shall return to this later.*

In this case the convergence in the flow is seen to change the way the choke is approached, but not the choke condition itself, and so the converging flow does *not* change predictions of the discharge rate significantly.

On the positive side, this allows to understand why PipeBreak and PipeTech do not produce very different results, but it still leaves us the problem of understanding why both have predictive problems for small orifices.

Having made this demonstration, let us now return to essentially cylindrical pipes.

4 THE DISCHARGE VELOCITY

As noted earlier, the PipeTech model does not offer an explicit understanding of the discharge velocity. However PipeBreak does, and we reproduce the derivation here. We have noted that the discharge velocity is the speed of sound, but the question is how one actually estimates the speed of sound in two-phase flow or a saturated liquid.

4.1 DISCHARGE VELOCITY AS A FUNCTION OF PRESSURE

In general, a small pressure change dp along the pipe is accompanied by a specific volume change dv, a temperature change dT, a specific enthalpy change dh, a change in liquid mass fraction dη, but no specific entropy change (ds=0).

We need to estimate

$$c^2 = \frac{dp}{d\rho} \equiv -v^2 \frac{dp}{dv} \tag{4.1}$$

The enthalpy change is

$$dh = Tds + vdp = vdp \tag{4.2}$$

If the two-phase fluid remains in homogeneous equilibrium then

$$dp = \psi \, dT \tag{4.3}$$

where ψ(T) is the slope of the saturated vapour pressure curve, which we shall take as given. The specific enthalpy and specific volume may be expressed in terms of those of the liquid (L) and gas (v) phases by

$$h = \eta h_L + (1-\eta) h_v \tag{4.4}$$

$$v = \eta v_L + (1-\eta) v_v \tag{4.5}$$

where η is the mass fraction of the liquid component at the point in question.

In fact the liquid and vapour specific enthalpy and volume are quite generally related by the Clapeyron equation

$$\frac{h_v - h_L}{v - v_L} = T\psi \tag{4.6}$$

so that the liquid mass fraction can be eliminated to give

$$h = h_L + (v - v_L) T\psi \tag{4.7}$$

Differentiating gives

$$dh \quad = \quad dh_L \quad + \quad (dv - dv_L)T\psi \;+ (v - v_L)d(T\psi) \tag{4.8}$$

or

$$vdp \quad = \quad dh_L \quad + \quad (dv - dv_L)T\psi \;+ (v - v_L)d(T\psi) \tag{4.9}$$

or

$$vdp \quad = \quad \frac{dh_L}{dT}\frac{dp}{\psi} \quad + \quad (dv - \frac{dv_L}{dT}\frac{dp}{\psi})T\psi \;+ (v - v_L)(\psi + \frac{d\psi}{dT})\frac{dp}{\psi} \tag{4.10}$$

and hence

$$\left[-\frac{1}{\psi}\frac{dh_L}{dT} \;+ T\frac{dv_L}{dT} \;- v\frac{1}{\psi}\frac{d\psi}{dT} + v_L(1 + \frac{1}{\psi}\frac{d\psi}{dT}) \right] dp \quad = \quad T\psi\, dv \tag{4.11}$$

so that

$$c \quad = \quad v\sqrt{\frac{T\psi}{\left[\;\frac{1}{\psi}\frac{dh_L}{dT} \;- T\frac{dv_L}{dT} \;+ (v - v_L)\frac{1}{\psi}\frac{d\psi}{dT} - v_L \right]}} \tag{4.12}$$

In these equations the derivatives are all along the vapour pressure curve (ie with dp = ψdT). Knowledge of the liquid properties and the vapour pressure curve now allow us to evaluate this estimate, as a function of outlet pressure or temperature (which are related by p = p_{sat}(T)). This is done in PipeBreak.

Almost immediately after the break occurs, we may assume that the contents of the pipe are in a saturated liquid state, in which case the initial discharge velocity is

$$c_0 \quad = \quad v_L\sqrt{\frac{T\psi}{\left[\;\frac{1}{\psi}\frac{dh_L}{dT} \;- T\frac{dv_L}{dT} \;- v_L \right]}} \tag{4.13}$$

And now the problem is clearer. PipeBreak (and empirically, we believe, also PipeTech) predicts this discharge velocity initially. It also predicts an initial discharge density of

$$\rho_L \quad = \quad 1/v_L \tag{4.14}$$

The initial temperature and pressure are given by the storage conditions and so, at this level, there is no difference in flow velocity (or flow rate per unit orifice area) whether there is a full guillotine break or a smaller breach.

It is useful also to write equations (4.12) and (4.13) as expressions for the mass flux density G=ρu at the choke:

$$G \quad = \quad \sqrt{\frac{T\psi}{\left[\frac{1}{\psi}\frac{dh_L}{dT} \quad - T\frac{dv_L}{dT} \quad + (v - v_L)\frac{1}{\psi}\frac{d\psi}{dT} - v_L\right]}} \tag{4.12a}$$

$$G_0 \quad = \quad \sqrt{\frac{T\psi}{\left[\frac{1}{\psi}\frac{dh_L}{dT} \quad - T\frac{dv_L}{dT} \quad - v_L\right]}} \tag{4.13a}$$

One point needs careful consideration. In the case of a less-than-full-bore breach, PipeBreak demands continuity of the total mass flux ρuA and of density ρ through the orifice, and so $A_{orifice} < A_{pipe}$ implies $u_{orifice} > u_{pipe}$. And in trial P47 we are considering a factor of about 8.8. It is therefore important to be clear which of these velocities the above considerations apply to. In fact PipeBreak assumes that the choke is **in** the orifice, so the discharge from the orifice is as described above and the flow in the pipe behind is correspondingly slower for a partial breach.

Why this appears to be essentially true also in the model PipeTech is less clear, but we can conjecture that something similar is going on.

4.2 THE SPECIFIC VOLUME

As a measure of how vaporisation proceeds, let us write down the specific volume. For simplicity we shall assume no heat transfer from the pipe wall to the fluid, though Webber et al (2001) did in fact allow for it.

We note then that there are two conserved fluxes in the model. The mass flux density (ie mass flux per unit pipe area)

$$G \equiv \rho u \tag{4.15}$$

and

$$E \equiv h \quad + \quad u^2/2 \tag{4.16}$$

To find v(p) we take the two expressions for enthalpy from (4.7) and (4.16):

$$\begin{aligned} h \quad &= \quad h_L \quad + \quad (v - v_L)T\psi \\ h \quad &= \quad E \quad - \quad (Gv)^2/2 \end{aligned} \tag{4.18}$$

eliminate h, and solve the resultant quadratic equation for the specific volume v (anywhere in the pipe) to get

$$v \;=\; \frac{-T\psi + \sqrt{(T\psi)^2 + 2G^2(E - h_L + v_L T\psi)}}{G^2} \tag{4.19}$$

where, as ever, $p = p_{sat}(T)$ and $\psi = dp/dT$.

4.3 DISCUSSION

Equation (4.13a) provides an absolute prediction of the initial discharge flux. There are no free parameters. This analytic result from PipeBreak makes the point explicitly, but the (less analytically tractable) model PipeTech is so similar in essence that the same must surely apply. The initial flux depends only on the temperature, the properties of the liquid, and the shape of the saturation curve $p_{sat}(T)$.

After time zero, there is cooling at the orifice and the discharge gradually acquires a larger vapour component with $(v-v_L)$ increasing from zero. The large difference between vapour and liquid specific volumes means that this latter variation may have the largest effect on the discharge rate. Importantly, the curvature of the vapour pressure line (see fig 4) implies $d\psi/dT>0$ and so increasing specific volume in equ (4.12a) tends to decrease the discharged mass flux density. By contrast, the discharge velocity (see equ 4.12) tends to increase with specific volume (but not as fast as the specific volume itself resulting in a decreasing mass flux density).

This is seen qualitatively in both the data and the predictions for all trials. But in the partial breach case (P47) the predicted flux is initially too low, and whereas the data show the flux dropping somewhat later, this flux change happens much more slowly in the models.

Let us focus first on the initial discharge rate in trial P47 – the slope of the lines in Fig3a at time zero. The models under-predict the discharge rate very significantly. If we consider it reasonable to suppose that this *is* a pure liquid release at time zero, then the velocity of the discharge must be much higher than the models are predicting.

The choke velocity calculated analytically here (following the method of PipeBreak) was fine for full bore ruptures, and we need an explanation of why it is good in that case (a triumph for the parameter-free theory) but inadequate for smaller breaches. Furthermore the initial velocity is predicted to be the speed of sound in the saturated liquid, whereas experiments are telling us it is in fact faster.

Clearly something different must be happening in the case of the smaller breach, and we need to consider what that might be.

5 TWO-PHASE DISCHARGE FROM VESSELS

5.1 INTRODUCTION

We have suggested that in the case of the small breaches, the pipe may effectively be behaving as a vessel. It is therefore pertinent to review some of the literature on two-phase discharges from punctured vessels.

Fauske and Epstein (1988) discuss two-phase releases both from vessels and from pipes, and therefore provide a useful point of reference. Prominent in their work is the idea that discharge velocities from holed vessels should be significantly larger than from long pipes. May this provide the answer to why the discharge velocity (after time zero) in trial P47 above is larger than predicted by the pipe model? Let us examine their work and find out.

5.2 HEM CHOKED FLOW IN THE MODEL OF FAUSKE AND EPSTEIN

Fauske and Epstein assume that in releases from a short pipe, where the vessel pressure is supplied by the vapour pressure of the liquid, the initial release will be of saturated liquid, exactly as does PipeBreak. They estimate the release velocity to be

$$c_{0(FE)} \quad = \quad v_L \sqrt{\frac{T\psi^2}{\left[\dfrac{dh_L}{dT}\right]}} \tag{5.1}$$

This can be obtained from our expression (4.13) by neglecting the two negative terms in the denominator, and is therefore clearly always greater than the estimate made by PipeBreak. The validity of this may not be immediately apparent, but the following observation may be relevant.

If we take (4.4-3.6) and assume *isenthalpic* flow instead of *isentropic* flow, then we find as the liquid fraction tends to 1, and approximating the liquid specific volume as unchanging, that:

$$\begin{aligned} & dh_L \sim (h_v - h_L)d\eta \\ & dv \sim -(v_v - v_L)d\eta \\ & \frac{dv}{dp} = \frac{dv}{dh_L}\cdot\frac{dh_L}{dT}\cdot\frac{dT}{dp} \sim -\left(\frac{1}{T\psi^2}\right)\frac{dh_L}{dT} \end{aligned} \tag{5.2}$$

giving precisely the Fauske-Epstein estimate of the discharge velocity. For propane at 298K Fauske and Epstein calculate a discharge rate, based on this, of 8500 kg/m^2/s. This is somewhat larger (as we have shown it must be) than the rate predicted by PipeBreak, which was around 5750 and 6040 kg/m^2/s for the full bore ruptures of trials P40 and P42 respectively.

Now Fauske and Epstein do not make any specific consideration of pipe flow, but state that the discharge from a long pipe will be less, owing to frictional losses, by some empirical factor F(L/D) where L/D is the length to diameter ratio of the pipe. They gave F(0) = 1 by definition with F decreasing with L/D. They quote F(400) = 0.55. (The Isle of Grain full bore rupture trials have L/D ~ 660.) Fauske and Epstein compare their model with some data on a runaway ethylbenzene-styrene reaction in a geometry with L/D ~ 430 and get a reasonable estimate of the initial discharge rate by including their F-factor.

The model PipeBreak, based as it is on a quasi-steady balance of pressure drop and choked flow at the orifice, has a lot to say about this. Introducing an arbitrary friction factor is not justifiable as the model is already largely based on friction. But nor is it needed, as the predicted initial flow rate is smaller, entirely owing to what we would argue is a better estimate of the speed of sound in the two-phase flashing fluid.

In fact, going further, friction is completely unimportant at time = zero in PipeBreak as (at this singular moment) essentially nothing is flowing within the pipe. Friction *does* however control the change in discharge rate as time increases and is absolutely crucial in this respect. More specifically, PipeBreak starts with stagnant saturated liquid in the pipe, and then a region of non-zero two-phase flow grows from the orifice. This flow region eats its way upstream into the stagnant liquid, and it is only within the two-phase zone that friction has any effect. (The point where the flash front reaches the upstream end of the Isle of Grain pipe is particularly clear on the Isle of Grain illustrations shown earlier – it is at that moment when the upstream pressure and temperature start to drop.)

We therefore conclude that Fauske and Epstein’s friction factor has little to do with friction and much more to do with improving their estimate of the speed of sound.

We also observe that Fauske and Epstein, in common apparently with most work on two-phase releases from vessels, are interested in finding the release rate in what is generally considered a steady process. The Isle of Grain trial P47, however, tells us a lot about the time-variation of the discharge, and any successful explanation of the release rate must also be extended to its evolution over time.

5.3 DISCHARGE FROM VESSELS

Fauske and Epstein also discuss the limit of *very* short pipes and, in the extreme, discharge from vessels. They do this very differently. We note that pure liquid discharges are commonly estimated by noting that Bernoulli’s theorem for incompressible flow results in constancy of $u^2/2 + p/\rho$ along stream lines. Thus with a conserved mass flux density ρu the changes Δu and Δp in velocity along the stream line are related by

$$\frac{1}{2}(\rho u)\Delta u + \Delta p = 0 \tag{5.2}$$

If a liquid accelerates though a pressure drop $|\Delta p|$ at an orifice, from rest to velocity u, then one therefore expects the mass flux density to be given by

$$(\rho_L u) = c_D \sqrt{2\,|\,\Delta p\,|\,\rho_L} \tag{5.3}$$

where c_D is a discharge coefficient, 1 in the idealised case but often around 0.6 for incompressible flow in real orifices. The above derivation is summarised here to emphasise that this oft-quoted formula applies to incompressible flow (ie liquids) and has no consideration of anything like a choke; u for two phase flow must be smaller than the speed of sound *in the single phase liquid*.

Fauske and Epstein assert that this is the appropriate model of discharge of a saturated liquid from a vessel through an orifice. The assumption is that there is no vaporisation, and that the saturated liquid behaves as an incompressible liquid in the orifice. The speed of sound in a pure liquid is much greater than the speed of sound in the homogeneous equilibrium two-phase fluid, and so this can result in much larger discharge velocities.

In fact it is important to emphasis this. The speed of sound in a fluid is expressed thermodynamically as

$$c = \sqrt{\left(\frac{dp}{d\rho}\right)_s} \tag{5.4}$$

- the square root of the derivative of pressure with density at fixed entropy. In idealised incompressible fluids, where no amount of pressure will change the density, this becomes infinite. In gases the speed of sound is lower than in liquids, because of this relation. In two phase fluids on the saturation curve, a small decrease in pressure can result in a large decrease in density by causing some liquid to vaporise. Two-phase fluids can therefore be very compressible and have a correspondingly slower speed of sound than either the liquid or the gas.

But this begs a big question. In two-phase fluids there is an extra thermodynamic variable – which we can take to be the liquid mass fraction. Thus in order to determine the velocity (5.4), one constraint (s = constant) is not enough. Something else must be constrained too.

The analytic PipeBreak model makes it clear what it is, and the answer is provided by the homogeneous equilibrium model. In that case the extra constraint relates pressure and temperature by $p - \psi(T) = 0$. This means that the liquid mass fraction η will change under the derivative, and the same is true of PipeTech.

Fauske and Epstein's model of discharge from vessels posits that $d\eta = 0$ in the discharge resulting in the speed of sound corresponding with that in a pure liquid. This is so large that choked flow does not enter their consideration in this case, and the actual discharge velocity is much smaller than this value.

This idea also begs some questions (to which we shall return below), but, on the face of it, the discharge velocity from the smaller breaches at the Isle of Grain *does* appear to be larger than the homogeneous equilibrium speed of sound and this may therefore require us to abandon the strict homogeneous equilibrium model of PipeBreak and PipeTech in dealing with smaller breaches.

It is interesting to ask how well the liquid discharge model (5.3) does for the Isle of Grain trials discussed above.

Trial	Orifice (%)	Orifice [m^2]	Est. ρ_L [kg/m^3]	Est $\|\Delta p\|$ [Pa]	Liq. model velocity: [m/s]	Liq. model discharge [kg/s]	Experiment [kg/s]
P40	100%	0.0186	483	520000	27.8	250	90
P42	100%	0.0186	483	560000	28.9	260	140
P47	11.4%	0.00212	483	650000	31.1	32	26

To obtain these figures we have estimated the outlet pressure difference by taking the experimentally measured pressure close to the orifice and subtracting an atmospheric pressure estimated as 1bar. We have used a discharge coefficient of 0.6. The measured velocities are those deduced from the data as above.

In the case of the full bore pipe ruptures (where no-one is proposing to use this model), it overestimates the discharge rate by a factor of 2 or more. In the case of the smaller orifice (where one might propose to use it), it is quite close to the largest discharge rate observed between 5 and 10s after the start of the flow.

We should also note that Fauske and Epstein define a criterion for when to use their pipe model and when to use the orifice (liquid discharge) model. Considering a vessel with a short pipe attached then the pipe model is considered appropriate if the pipe is longer than a critical length scale L_C and the orifice model is considered appropriate if the pipe is of zero length. For an intermediate length L they use a model which interpolates between the two:

$$\begin{aligned} G &= G_{pipe} && ;\, L \geq L_C \\ \frac{1}{G^2} &= \frac{L}{L_c}\frac{1}{G_{pipe}^2} + \left(1 - \frac{L}{L_c}\right)\frac{1}{G_{vessel}^2} && ;\, L < L_C \end{aligned} \tag{5.5}$$

except that they apparently forgot to include the $(1\text{-}L/L_c)$ factor in the second term of the bottom formula and thus end up with an interpolation which is unnecessarily discontinuous at $L=L_C$. However, in the case they present, the effect is largely cosmetic.

They take L_C to be 10 cm. The justification for this is entirely empirical and there is no hint of what group of parameters multiplying to a dimension of length might produce this critical parameter. This leaves us with a very unsatisfactory situation in which discharge from vessels is thought to be entirely different from pipes, but in which there is no understanding of the physical basis of this assertion.

For our purposes, though, we probably want L=0 for the Isle of Grain trials.

However, as we noted, quite apart from the absence of any understanding of why this release should be completely different thermodynamically from the full bore breach, there are problems with such an interpretation. Figures 4a and 4b show a temperature drop (measured at the discharge end at about 10 cm behind the breach) in the small breach experiment following the $p_{sat}(T)$ curve as the system depressurises – just as in the full bore breach (though the time scale is different). How is it cooling? In the PipeBreak model the cooling corresponds with heat being used to cause vaporisation. But if that is happening 10 cm behind the breach in the small bore breach, how can it be an unchoked liquid discharge *at the orifice*? If that is not happening, then where is the heat going? And if the pressure were to drop (as it must) with no significant temperature drop, there would be superheated liquid in the pipe – of which there is no sign experimentally.

In fact PipeBreak does give very good predictions of the pressure and temperature (figs 3b, 3c) for the first 40 seconds or so (where it underestimates the discharge rate) after which it overestimates the discharge rate and underestimates the drop in temperature and pressure. The vessel liquid discharge model may give a better discharge rate in the early stages but it is difficult to see that it can explain the temperature drop.

It may therefore be that the Fauske-Epstein liquid discharge model is of only very limited help in understanding these experiments.

6 OBSERVATIONS

The models PipeBreak and PipeTech are both based on the homogeneous equilibrium model. The assumption is made that at any point along the pipe, liquid and vapour are at the same temperature and pressure (in equilibrium) and distributed identically (homogeneously) across it.

We cited the P vs T graphs of Sect. 2.4 as the best experimental evidence for the (very popular) homogeneous equilibrium model. However, technically speaking, it only indicates *equilibrium* and homogeneous is a further assumption on the part of the models.

This assumption goes hand in hand with modelling the flow as one-dimensional. For example, even if temperature and pressure were uniform across the pipe cross-section, if the liquid mass-fraction were not then the density would not be, and the velocity field would surely find it impossible to adjust itself so that both the ρu and ρu^2 terms in the flow equations (3.1) could be uniform across the pipe. *Inhomogeneous* equilibrium would therefore surely be enough to preclude one-dimensional flow.

Returning now to the idea of 3-D flow very close to the orifice, it appears we may have been too hasty in ruling it out as a governing factor in trial P47. If the flow is in homogeneous equilibrium up to the point of measurement (which is 10cm upstream of the orifice), but becomes *inhomogeneous* close to the orifice, then we might end up with a scenario where liquid is preferentially in the centre of the pipe, and gas preferentially near the walls. In this case there would be more liquid in the release than we have predicted. (Tentatively, we observe that this cross-sectional distribution might be supported by the idea of preferential vaporisation near the walls which provide nucleation sites and a source of external heat.)

A priori there are two ways in which a larger mass release rate can occur than is predicted by the homogeneous equilibrium choke: a higher density (by having a larger liquid fraction) or a higher velocity. It would be nice, from the point of view of simplicity, to assume that the discharge velocity *is* close to the homogeneous equilibrium choke velocity, and that the enhanced mass discharge rate is provided by the fact that there is a greater liquid mass fraction. But in fact this would not work at time zero, where the initial discharge is anyway predicted to be pure liquid (at least by PipeBreak). Thus a model is required in which a higher velocity is achieved, and we expect both the density and the velocity to be higher than currently predicted.

7 SUMMARY AND CONCLUSIONS

The code PipeTech has been shown to fit the full guillotine break data from the Isle of Grain Trials (Richardson and Saville 1996, Tam and Cowley 1988) in which LPG (95% propane, 5% butane) was released from a 100m long pipe. However, the fit is nowhere near as good in those experiments where the aperture at the end of the pipe is significantly smaller than the full cross-section.

Our objective has been to find out why there is this predictive failure for the latter cases. Our investigations have revealed quite a lot, but fall short of producing a model which improves the fit. The following is a summary of the results presented here.

a) Examination of the PipeTech theory (Oke et al 2003) revealed no obvious flaw, but the model is complicated, and much is buried in the numerics of the computer program.

b) The model is very similar in its basic physical assumptions to another model called PipeBreak (Webber et al 1999, 2001), but its numerical solution procedure is entirely different. PipeTech uses a numerical technique, the method of characteristics, to solve the partial differential equations. PipeBreak makes greater use of simplifying assumptions, allowing it to go further analytically before a numerical procedure is invoked (to solve a set of ordinary differential equations). This gives a more complete understanding of what is going on (if we accept the validity of the assumptions) and admits a simpler numerical procedure.

c) For the three Isle of Grain tests studied here, the codes PipeTech and PipeBreak give very similar results for both the full bore ruptures (where they both fit the data well) and qualitatively similar results for the partial breach experiments (where they both fit less well).

d) This agreement between models indicates that PipeBreak's assumptions are sound, and that PipeTech's more complicated numerics have been correctly implemented. The reasons for the poorer fit in the case of a partial breach must lie in the physical assumptions common to these models. An analytic examination of those assumptions can be carried much further looking at the more tractable model PipeBreak.

e) One of the things which PipeTech considers which PipeBreak does not, is the 3-dimensional nature of the flow near the orifice. When PipeBreak was derived, it was thought that this might be an important reason for the poorer fit to the partial breach. Conclusion (d) above seems to indicate that this is not the most important factor. As one possible check we have performed here an analytic study of a converging flow down an open-ended conical pipe – a 3-D flow, albeit a very particular one. The results corroborate the idea that 3-D flow is not *per se* at the root of the problem.

f) One of the common assumptions is that the flow is above all one in which pressure drop along the pipe is balanced by friction. This is very explicit in PipeBreak but present also in PipeTech. We observe that in the case of a very small hole in the end of a pipe the flow should be dominated initially by what is happening close to the orifice; the large reservoir which is the pipe is essentially irrelevant (Fig.5). This may invalidate the physical assumptions and make a model of a release from a vessel more appropriate. (Ceci n'est pas une pipe!)

g) The small bore breaches in the Isle of Grain Experiments may be small enough that we are seeing such an effect. We believe that the very small pressure drop seen along the pipe, both in the experiments (eg P47 Fig 3b) and in PipeBreak's predictions, is alerting us to this.

h) It is therefore expedient to look also at models of releases from vessels. We have looked in some detail at a prominent one – that of Fauske and Epstein (1988).

i) Fauske and Epstein observe that releases from vessels tend (the aperture being equal) to be a greater rate than those from full guillotine breaks in pipes. This is exactly what we need to understand.

j) Unfortunately, in the light of the PipeBreak model (produced long after Fauske and Epstein's) we do not believe their explanation to be correct. Fauske and Epstein start with the idea of a short pipe and estimate the release velocity of a two-phase fluid as the speed of sound in the two-phase fluid. They do not analyse the flow in the pipe but argue that in longer pipes the velocity will be less due to friction, and introduce a phenomenological factor by which they reduce their result to make a prediction for longer pipes. We have shown that their original velocity estimate is an over-estimate (due either to neglect of important terms or use of an isenthalpic assumption instead of isentropic) and that in fact no friction factor is needed. Indeed initially there can be none because only fluid very near the orifice is in motion. The model PipeBreak is based entirely on friction along the pipe, and gives a much more complete understanding of what is going on in pipes with full bore ruptures.

k) Fauske and Epstein also present the argument that a very short pipe is like a vessel and argue that releases from vessels are very different. In fact in this case they work with the velocity of sound in a liquid as the limiting one (which is much larger than the two-phase homogeneous equilibrium sound velocity). They model the release as a liquid release which is not choked. In this case we must concur to some extent. The partial breach Isle of Grain experiments *do* indicate a higher release velocity, and if homogeneous equilibrium were the whole story it couldn't happen; the flow would choke at the lower velocity seen in the full bore ruptures.

l) We have noted that what Webber et al (1999, 2001) took as experimental support for the homogeneous equilibrium model is, strictly speaking, only evidence for equilibrium (a local equilibrium which changes along the length of the pipe, of course).

m) Furthermore it appears that an inhomogeneous equilibrium flow (with liquid fraction but not temperature and pressure varying across the pipe cross-section) could not be purely one-dimensional along the pipe. We have therefore conjectured that there may be an inhomogeneous zone, for example between the open end measurement 10cm upstream and the orifice itself, which may be associated with a converging flow in the centre of the pipe, leading to the discharge. Modelling two-phase flow in such a zone may also have a lot to say about discharge from vessels.

All in all it seems very probable that something different is happening in the flow in the case of the Isle of Grain partial breaches from what is going on in the full bore ruptures, that it is happening close to the orifice, and that it is not being modelled either by PipeTech or PipeBreak.

We believe that a resolution of this needs a better understanding of the two-phase flow from a punctured vessel, and in particular the nature of the flow near a small orifice. A wider ranging review of the literature on two-phase releases from vessels, as well as modelling and experimental effort may be needed in order to obtain such a resolution. But the time evolution of the narrow bore Isle of Grain trials is well measured and very significant, and may in turn help give a better understanding of two-phase releases from vessels.

8 POSTSCRIPT

As the current study was nearing completion, a report was received (Richardson et al, 2006) describing a series of experiments and theoretical analyses exploring the limitations of the Homogeneous Equilibrium Model (HEM) for predicting the outflow of pressurised hydrocarbons (mixtures of natural gas, propane and condensate) through a small orifice. The study found that for a liquid mass fraction in the orifice below 0.8 the HEM was a good approximation, but that for a higher liquid mass fraction it was not. In these latter circumstances the assumption of incompressible flow with a discharge coefficient of about 0.6 gave excellent agreement with the measurements. Possible reasons suggested for the breakdown include the influence of slip or thermodynamic non-equilibrium.

We have since learned from the PipeTech team that they have applied PipeTech to the Richardson measurements and have reached the same conclusions. Accordingly, they are producing an extended version of PipeTech which allows the user the option to use a Modified HEM, which replicates the standard HEM for liquid fractions below 0.8 and uses the liquid flow model otherwise. This is an interesting and potentially useful development, but at the time of writing we do not have full details of the work, nor do we have the extended PipeTech code.

14 November 2007

9 APPENDICES

9.1 FLOW DOWN A CONVERGING OPEN CONICAL PIPE

When PipeBreak was developed, its authors considered absence of a model for 3-D flow near the orifice to be a possible cause of the poorer fit to partial breach data. PipeTech does model this, but fares no better against the data.

To try to understand why, let us do another idealised flow calculation, but this time not 1-D parallel flow. In fact we can model the constricting flow (very simplistically) as that down a converging conical tube. We can use the same flow equations but in (r, θ, φ) spherical polar coordinates centred on the imaginary apex of the cone. The wall of the pipe is the surface θ=ξ where ξ is the half angle of the cone, and $r>r_0$ where $r_0 \tan \xi$ is the radius of the aperture. We shall consider spherically symmetric flow in negative r direction.

In spherical coordinates the gradient of a scalar S and divergence of a vector A are of the form

$$\nabla S = \left(\frac{\partial S}{\partial r}, \quad \frac{1}{r}\frac{\partial S}{\partial \vartheta}, \quad \frac{1}{r\sin\theta}\frac{\partial S}{\partial \varphi} \right) \tag{8.1.1}$$

$$\nabla . A = \frac{1}{r^2}\frac{\partial (r^2 A_r)}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial (A_\theta \sin\theta)}{\partial \theta} + \frac{1}{r\sin\theta}\frac{\partial (A_\phi)}{\partial \phi} \tag{8.1.2}$$

Accordingly when the steady flow, the friction along the wall and the pressure gradient are in the radial direction, then

$$\begin{aligned} \frac{d\rho u r^2}{dr} &= 0 \\ \frac{1}{r^2}\frac{d(\rho u^2 r^2)}{dr} + \frac{dp}{dr} &= -F \end{aligned} \tag{8.1.3}$$

Where u (< 0) is now the radial velocity, dp/dr>0 as r points in the upstream direction and F< 0 so that friction acts in the +ve r against the effect of the pressure gradient. To compare with the previous choked flow analysis, let us see recast the momentum equation as follows:

$$\left[(\rho u r^2)^2 \frac{1}{r^2}\frac{d(1/(\rho r^2))}{dp} + 1 \right]\frac{dp}{dr} = -F \tag{8.1.4}$$

Now

$$\frac{d}{dp}\left(\frac{1}{\rho r^2}\right) = -\frac{1}{\rho^2 r^2}\frac{d\rho}{dp} - \frac{2}{\rho r^3}\frac{dr}{dp} \quad = -\left[\frac{1}{\rho^2 r^2 c^2} + \frac{2}{\rho r^3}\left(\frac{dp}{dr}\right)^{-1} \right] \tag{8.1.5}$$

Thus

$$\left[1 - \frac{u^2}{c^2} - \frac{2\rho u^2}{r}\left(\frac{dp}{dr}\right)^{-1}\right]\frac{dp}{dr} = -F \tag{8.1.6}$$

or

$$\left[1 - \frac{u^2}{c^2}\right]\frac{dp}{dr} = \frac{2\rho u^2}{r} + |F| \tag{8.1.7}$$

Note that the friction is typically modelled with a Fanning term of the form

$$|F| = \frac{2f\rho u^2}{D} \tag{8.1.8}$$

where f is a Fanning coefficient and D is the diameter of the pipe – in this case D = r tanξ. Interestingly the effect of the converging pipe can be expressed by the transformation

$$f \rightarrow f + \tan\xi \tag{8.1.9}$$

If the choke condition is again defined by the vanishing of the coefficient of dp/dr then it is the same: u=c. The difference in the flow is a modified friction factor, which will change the way the choke is approached, but not the choke condition itself. We thus conclude that moving away from the assumption of parallel flow near the orifice is *not* going to change predictions of the discharge rate significantly.

10 REFERENCES

H K Fauske and M Epstein (1988) “Source term considerations in vapour cloud modelling”, *J Loss Prev Process Ind* **1** (1988) 75-83

A Oke, H Mahgerefteh, I Economou, Y Rykov (2003) “A transient outflow model for pipeline puncture”, *Chem. Eng. Sci.* **58** (2003) 4591-4604

S M Richardson and G Saville (1996) “Isle of Grain Pipeline Depressurisation Tests” HSE Offshore Technology Report OTH 94 441 ISBN0-7176-1228-7

S M Richardson, G Saville, S A Fisher, A J Meredith and M J Dix (2006) “Experimental determination of two-phase flow rates of hydrocarbons through restrictions” *Trans.IChemE, Part B, Process Safety and Environmental Protection*, January 2006 **84**, pp.40-53.

V H Y Tam and L T Cowley (1988) "Consequences of pressurised LPG releases: the Isle of Grain full scale experiments", GASTECH 88, 13th International LNG/LPG Conference, Kuala Lumpur

D M Webber, T K Fanneløp and H W M Witlox (1999) "Source Terms from Two-Phase Flow in Long Pipelines following an Accidental Breach", in "International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials" AIChE (1999) ISBN 0-8169-0781-1 pp 145-167

D M Webber, T K Fanneløp and H W M Witlox (2001) “The ‘PIPEBREAK’ model for two-phase discharge from long pipelines: theory manual” [Distributed with the PHAST suite of codes by Det Norske Veritas.]

11 NOMENCLATURE

ξ	Half angle of the cone
$\psi(T)$	Slope of the saturated vapour pressure curve
ρ	Density
A	Area
c	Speed of sound
$d\eta$	Change in liquid mass fraction
dv	Specific volume change
dT	Temperature change
ds	Specific entropy change
dp	A small pressure change along the pipe
dh	Specific enthalpy change
D	Diameter
E	Energy flux
F	Friction term
G	Mass flux
h	Enthalpy
p	Pressure
T	Temperature
u	Velocity
v	Specific volume
x	Distance along the pipe

Published by the Health and Safety Executive 04/10

HSE

Health and Safety
Executive

An investigation into the performance of the PipeTech computer code in calculating Isle of Grain pipeline blowdown tests

The computer code PipeTech, developed in the Department of Chemical Engineering at University College London, predicts the outflow following rupture or puncture of a long pipeline containing one or more pressurised hydrocarbons. It is currently used by the Health and Safety Executive (HSE) in determining its advice to local planning authorities on control of land-use in the vicinity of major accident hazard pipelines. The underlying theory is described by its authors in numerous articles in archival scientific journals (notably Oke, Mahgerefteh, Economou and Rykov, 2003). The modelling involves solution of the transient conservation equations for 1-D flow using the Method of Characteristics, with a 3-D representation in the vicinity of a puncture. Heat flows between the fluid and the walls of the pipeline, and through the walls of the pipeline, are included. Satisfactory comparisons of PipeTech calculations and measurements from the Piper Alpha accident and from two of the Isle of Grain experiments on release of LPG from a damaged pipeline have been shown in published documents. In addition, HSE has obtained a good comparison of PipeTech calculations with measurements from a ruptured pipeline carrying natural gas.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

RR774

www.hse.gov.uk