Pipeline Release Rate Model (PiRRaM) for Pressure Liquefied Gases

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As part of a programme of continuous development and improvement of HSE's land use planning models, the Health and Safety Executive (HSE) has identified the need for a new independent model for predicting release rates from major accident hazard pipelines transporting pressure liquefied fluids at or above the saturated vapour pressure. HSE requires a model that can predict the characteristics of pipeline releases from full-bore ruptures down to small holes. This paper introduces the Pipeline Release Rate Model (PiRRaM) which has been developed to satisfy HSE's requirements.

PiRRaM models the flow in the pipe as consisting of three zones: a stationary zone, an expanding pressurised liquid zone and a saturated two-phase zone. The saturated flow model closely resembles the PipeBreak model described by Webber et al. (1999), with the pressurised liquid zone being a logical extension of the saturated model to a compressible liquid. The key difference between PiRRaM and previous models is the treatment of pressurised initial conditions, for which a new rarefaction-wave balancing mechanism has been developed. This enables PiRRaM to transition smoothly from conditions where the liquid compressibility effect is unimportant (full guillotine ruptures) to scenarios where the liquid compressibility effect is important (small holes).

PiRRaM has been developed to model the full range of hole sizes, from full bore ruptures to small punctures, and has been extensively validated using data from propane pipeline experiments in the 1980's (the Isle of Grain Trials) and newer data from recent carbon dioxide pipeline experiments. The validation dataset contains 17 experiments in addition to the Isle of Grain Trials and covers a wide range of conditions: from small-scale laboratory experiments releasing tens of kilograms of fluid to full-industrial scale experiments storing nearly 10,000 tons. The experiments also cover a range of operating conditions with hole sizes varying from less than 1% of the pipeline cross-sectional area through to full-bore ruptures.

Verification of PiRRaM is established through extensive sensitivity studies to identify behaviour that may indicate software problems, and comparisons to other pipeline models. Specifically, PiRRaM is compared to predictions from BLOWDOWN, OLGA, PipeBreak, PipeTech, PROFES and SLURP, for predictions published in the academic literature using propane, ethylene and carbon dioxide.

PiRRaM is found to perform well, without need for calibration, for the full range of hole sizes where experimental data is available and to make predictions that are comparable to other models. Previously, it has been believed that pipeline models are not applicable to hole sizes less than 20% of the pipeline area. This is shown to no longer be an issue. Comparisons between PiRRaM predictions and the extended dataset indicate that small holes may now be modelled with acceptable accuracy.

Keywords: PiRRaM, MISHAP, HSE, pipeline modelling, holes, pressure liquefied gas, carbon dioxide, MAH pipelines

Introduction

The Health and Safety Executive (HSE) uses a computer model, MISHAP (**M**odel for the estimation of **I**ndividual and **S**ocietal risk from **HA**zards of **P**ipelines), to calculate the risks to people, and ultimately the land-use planning (LUP) zones from Major Accident Hazard (MAH) pipelines carrying flammable substances.

MISHAP contains several sub-models to calculate the release rates, failure rates and consequences should a pipeline fail. As part of a programme of continuous development and improvement, a need was identified for a new independent model that would be suitable and adaptable to HSE's future needs and changing IT environments.

This paper describes the development of the new model PiRRaM (**Pi**peline **R**elease **Ra**te **M**odel) for calculating the release rates from pipelines transporting pressure liquefied substances (such as propane, butane and ethylene) for pipelines running at or above the saturated vapour pressure. PiRRaM is applicable to a wide range of failure scenarios from full-bore ruptures all the way down to small holes that have an area of just a few percent of the pipe cross sectional area, over the initial 30 s of a release

Experimental data

Pipeline experiments are useful to help inform the design of models as well as serving as a validation dataset. The earliest experiments considering the decompression of pipelines containing pressure-liquefied gases is the Isle of Grain Trials (Cowley and Tam 1988; Tam and Higgins 1990; Richardson and Saville, 1996a+b). These experiments utilised a shock-tube configuration, whereby the fluid is initially stationary at uniform pressure before being discharged through a single end. The apparatus is then monitored to measure the inventory mass, with pressure and temperatures measured at different locations along the pipe during the resulting decompression.

Recent interest in using pipelines for Carbon Capture and Storage (CCS) (see Gant *et al.*, 2017) has led to more experiments looking into the technical challenges associated with safely transporting CO_2. This has motivated joint industry projects: CO_2QUEST (Gou *et al.*, 2016; Gou *et al.*, 2017), CO_2PipeTrans (Witlox *et al.*, 2015; and Armstrong and Allason 2014), CoolTrans (Cooper and Barnett, 2014); and other experiments (Clausen *et al.*, 2012; and Vree *et al*., 2015). CO_2 experiments serve as a valuable source of validation evidence provided that the temperature of the working fluid through the apparatus remains above the triple point, where freezing may occur.

A validation dataset has been developed which contains a wide range of experiments: from small-scale laboratory experiments releasing tens of kilograms of fluid to full-industrial scale experiments storing nearly 10,000 tons ($\approx 10^7$ kg). The experiments also cover a range of operating conditions with hole sizes varying from less than 1% of the pipeline cross-sectional area to full-bore rupture. Experiments are typically run until the pipe is at a uniform atmospheric pressure with the remaining contents stationary.

Review of existing release rate models

A thorough review of the background literature and other available models has been undertaken. There is significant cross-over into pure gas releases, and the first paper identified is Fanneløp and Rhyming (1982). Here, an integral-type model for full guillotine breaks to pipelines transporting gases is derived analytically from the one-dimensional conservation equations for mass, momentum and energy, corresponding to compressible pipe flow. Fanneløp and Rhyming (1982) split the depressurisation process into three separate regimes: an early time regime, at the instant the pipe is broken; an intermediate time regime, where some of the fluid in the pipe has started to accelerate towards the fracture location and some of the fluid remains unaffected by the break; and a late time regime where the entire contents of the pipe is in motion. This conceptual discretisation of different flow regimes establishes important modelling concepts that form the foundation for later integral models, a brief summary of which now follows.

Morrow *et al.* (1983) derived a phenomenological model for pressure-liquefied fluids which later became SLURP. Tam and Higgins (1990) used the Isle of Grain dataset to develop an empirical model of pipeline decompression. This model was developed assuming exponential decay of the mass flow rate and is broadly analogous to the empirical relationship proposed in Bell (1978) for gas pipeline decompression.

The BLOWDOWN pipeline model was developed by Richardson and Saville (1992, 1996a) using principles that are a logical extension of the Fanneløp and Rhyming model for pressure-liquefied gases, with the inclusion of choked flow at the fracture location. A series of models were then developed in relatively quick succession. The PipeTech model described by Mahgerefteh et al., (1999) and Oke et al., (2003) used the method of characteristics to calculate fully transient solutions of pipeline failures.

Webber *et al.* (1999, 2003) developed the PipeBreak model following on from the work of Fanneløp and Rhyming (1982), which was subsequently incorporated into DNV's Phast consequence model. Chamberlain (2000) described the development of a pipeline model for use in Shell's consequence model FRED.

Pipeline modelling discussion

There are two categories of pipeline release models: those assuming homogeneous equilibrium between phases, and those that don't. Homogeneous equilibrium is the assumption that the two-phase fluid is sufficiently well mixed for there to be thermodynamic equilibrium between phases (i.e. the vapour and liquid phases have the same temperature). A key experiment that informed the understanding of pipeline modelling was the Isle of Grain P47 trial. This was a transient release of propane from a horizontal slot with an area reported to be equivalent to a 50 mm hole (Richardson and Saville, 1996a+b), which was the smallest hole-size experiment of that type at the time. Webber *et al.* (2010) suggested that the poor performance of the homogeneous equilibrium (HEM) type models (specifically, PipeBreak and PipeTech) for the Isle of Grain P47 trial was evidence that HEM-type pipeline models may be missing key physics that enables them to make accurate predictions for the case of partial ruptures in pipelines. The result of this is that DNV's Phast model restricts the application of PipeBreak to holes greater than 20% of the pipe cross sectional area.

The models and software from the literature have been reviewed in light of HSE's requirements for a model that is capable of working across a range of hole sizes and operating conditions, including pressures exceeding saturation vapour pressure. Although there are several existing release rate models that can be applied to pipelines, none of them fully meet HSE's requirements. HSE needs to model holes that range in size from less than 1% of the pipeline cross-sectional area to full-bore rupture. The uncertainty regarding the applicability of some models to the smaller hole sizes means that they are unsuitable for HSE's use. Additional validation data was found in the smaller hole-size range that was not available at the time of the development of the models from the literature. This data can be used to determine whether or not pipeline models can be used to predict release rates for these small hole sizes.

Several different types of pipeline models were identified in the literature, ranging from integral models (i.e. PipeBreak, FRED) which mathematically simplify the conservation equations into a computationally more amenable form, to full CFD - type simulations (i.e. OLGA). One of the key limitations of the current generation of integral pipeline models is the lack of a consistent method to model the effect of liquid compressibility. Pressure-liquefied gases, when escaping confinement through a sharp-edged orifice, behave in a manner that is consistent with incompressible flow and are accurately described using Bernoulli's equation for incompressible flow (Richardson *et al.*, 2006). This can lead to initial mass flow rates that are an order of magnitude higher than the value corresponding to a choked two-phase flow.

The integral pipeline models typically assume an immediate decompression to the saturated vapour pressure. This is a problem because there are circumstances where the pressurised flow will last for a significant period (beyond 30 s), and there is a risk of significantly underestimating the early mass flow rate if the pressurised flow is ignored.

Our research into the dynamics of pressurised liquid flow in relation to pipeline decompression has identified four novel properties of rarefaction waves propagating through pipes containing pressure liquefied gases. These are highlighted in **Figure 1**, which plots the transient pressure evolution at a location 250 mm upstream of the orifice plane, in the moments immediately after the pipe is opened. Examination of **Figure 1** (top) highlights the following observations: 1) the pressure immediately upstream of the orifice can significantly exceed the saturated vapour pressure; and 2) the pressure immediately upstream of the orifice plane depends on the hole size, with smaller holes correlating with higher pressures and vice versa. The small-hole observations provide strong evidence to the occurrence of pressurised liquid flow at the orifice, which requires Bernoulli's equation for incompressible flow to be modelled accurately (Richardson *et al.*, 2006). However, pressures below the initial saturated vapour pressure for the full-bore rupture releases indicate that choked saturated two-phase flow is also likely.

Figure 1 (lower left and right) shows the transient evolution of the measured pipeline pressure at locations 40 m, 100 m and 160 m upstream of the orifice plate for the case of the CO_2PipeTransP3T6 experiment (hole corresponding to 3.7% of the pipe cross-sectional area). **Figure 1** (lower left) plots the measured pressure against time at the different locations, this demonstrates that the flow immediately behind the rarefaction wave may be considered to have a uniform pressure which is indicative of flow that can be modelled as frictionless for small holes. **Figure 1** (lower right) plots the measured pressure against the similarity variable proposed by Landau and Lifschitz (1987). The collapsing of the experimental data provides strong support to adapting the Landau and Lifschitz (1987) solution for ideal gas flow to a compressed equation of state. Recently, Hammer *et al.* (2022), have used an analogous approach to estimate the initial mass flow rate from experiments releasing CO_2 from pipelines through sharp-edged orifices and nozzles.

As HSE is primarily interested in the first 30 s of flow, it is clear that the effects of rarefaction waves are important to enable an accurate representation of the initial moments of a release of fluid. A review of the literature indicates that the coupling between the hole size and the pressure immediately upstream of the hole has until now received little attention. A conceptually simple explanation for this behaviour is that the pressure drop across the rarefaction wave determines the rate at which material is flowing into the frictionless zone downstream of the rarefaction wave. Conservation of mass requires that material leaves this zone at an equal rate. For the case of small hole releases, the mass release dynamics of pressure-liquefied gases at pressures exceeding saturation are required. However, for full bore ruptures, choked flow may also be required.

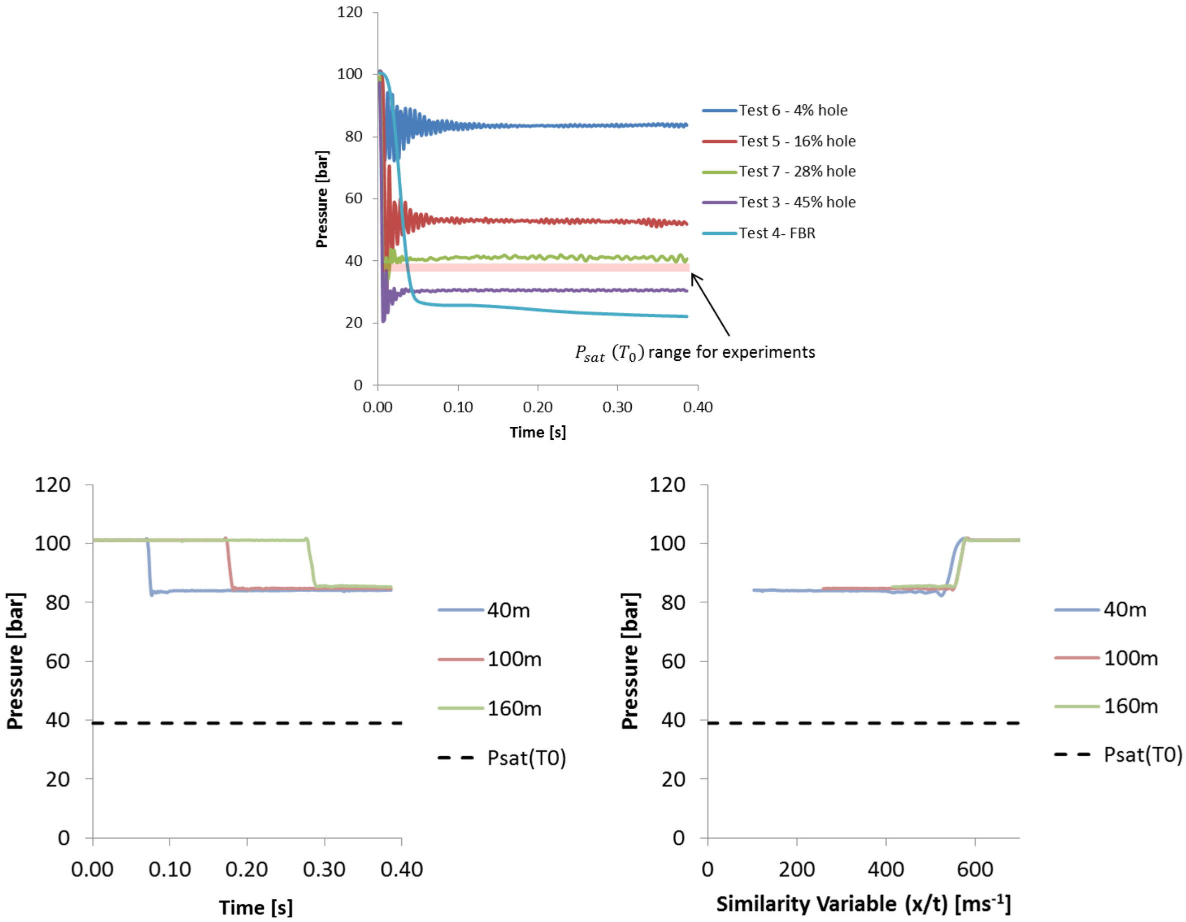

Figure 1 Pressure versus time at a position 250 mm upstream of the orifice plane for 5 of the CO_2PipeTrans Phase 3 experiments (top), pressure profiles in the pipe for a 10 mm diameter hole (CO_2PipeTrans-P3T6) at various locations upstream of the orifice against time (lower left), and the corresponding profiles shown using the Landau and Lifschitz (1987) similarity theory (lower right).

HSE's requirements present a significant challenge to pipeline models for three key reasons:

1. HEM modelling is believed to be inappropriate for modelling holes in liquefied gas pipelines
2. The dynamics of rarefaction wave propagation immediately after a failure are coupled to hole size

3. Pressurised liquid releases should be considered for small holes

Given that a suitable model has not been identified in the literature, there is now a requirement to develop a new model which meets HSE's on-going modelling requirements. A review of the different modelling techniques employed in existing pipeline models has been performed and has been used to develop a framework for a new model.

PiRRaM was developed following the PipeBreak model (Webber *et al.*, 1999), with additional features that are necessary to meet the HSE specification. Specifically, PiRRaM is a homogeneous equilibrium pipeline model, using a slowly evolving solution method. PiRRaM models the flow in the pipe as consisting of three zones: a stationary zone, an expanding liquid zone and a saturated two-phase zone. The saturated flow model closely resembles the PipeBreak model as described by Webber *et al.* (1999), and the pressurised liquid zone is a logical extension of the saturated flow model to a compressible liquid. In all cases, heat transfer between the pipe walls and the transported fluid is ignored. The key difference between PiRRaM and previous models is the treatment of pressurised initial conditions. Specifically, on the basis of the new insights into the CO_2PipeTrans experimental data, PiRRaM uses Bernoulli's equation for incompressible flow for cases when the flow is pressurised above the saturated vapour pressure, alongside a rarefaction-wave balancing mechanism. This enables the new model to transition smoothly from conditions where the liquid compressibility effect is unimportant (full guillotine ruptures) to scenarios where the liquid compressibility effect is important (small holes).

PiRRaM models up to three zones representing different flow regimes within a pipeline during a release as the pipeline depressurises. Not all of the zones are present all of the time. The model solves the conservation equations for mass, momentum and energy using equations of state specific to the fluid in each zone and outputs the mass flow rate and other flow characteristics at atmospheric pressure for use in subsequent consequence models. These are output at regular time intervals until a user specified time is reached.

HSE uses PiRRaM to model accidental pipeline failure scenarios to inform land use planning decisions. The methodology that HSE adopts needs to account for the limited amount of information that is known when the modelling is carried out. It is therefore necessary to simplify the scenario into an analytically tractable form by making assumptions about the pipe and its contents. Specifically, immediately prior to an accidental release, the contents of the pipe are assumed to be stationary at uniform pressure and temperature. The pipe is also assumed to extend infinitely in each direction either side of a release, with each side contributing half of the release. This approximation is necessary due to the inherent uncertainty regarding an accidental release scenario and is consistent with HSE's approach of considering a cautious best estimate. Comparisons to experiments use a finite pipe length (and inventory) corresponding to the apparatus in question.

Model Overview

PiRRaM is an integral model consisting of several sub-models, each of which is an analytical solution to the conservation equations for mass, momentum and energy, that are reproduced below for the case of a compressible flow along a pipe (Massey, 1989):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho U) = 0 \qquad \text{Mass conservation} \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho U) + \frac{\partial}{\partial x}(\rho U^2) = -\frac{\partial P}{\partial x} - 2f\frac{\rho U|U|}{D} \qquad \text{Momentum conservation} \qquad (2)$$

$$\frac{\partial}{\partial t}\left[\rho\left(h + \frac{1}{2}U^2\right)\right] + \frac{\partial}{\partial x}\left[\rho U\left(h + \frac{1}{2}U^2\right)\right] = 0 \qquad \text{Energy conservation} \qquad (3)$$

These equations describe the evolution of a fluid of density ρ, velocity U, enthalpy h, at time t, and position x in a pipe with internal diameter D and fanning friction factor f. The derivation of these equations assumes that the flow is well mixed across the pipe cross-section, and the properties at a given location in the pipe depend only on upstream distance from the pipe outlet (i.e. the problem has only a single spatial dimension, x (m), the distance along the pipe).

PiRRaM is the unification of three different solutions to the conservation equations, each valid for a particular stage of the depressurisation. For example, the first solution describes the frictionless flow at the earliest stages of the release. The second and third solutions consider pure liquid and two-phase pipe flow with friction respectively. The three solutions are assembled depending on the nature of the flow that is present in the pipe. For example, if a zone of pressurised liquid and a two-phase flow are simultaneously present in the pipe, PiRRaM matches the liquid flow solution to the two-phase solution and calculates the result.

The pipe decompression is assumed to evolve through 4 stages, independent of the three solutions already identified. These stages differ depending on whether the initial conditions are pressurised or saturated and are defined as follows:

Stage 1: Rarefaction balancing model – following Landau and Lifschitz (1987)

Stage 2: Choked saturated liquid flow – the flow in the pipe consists of an expanding liquid, with a stationary flow zone if the pipe is sufficiently long.

Stage 3: Choked saturated two-phase flow - the exit conditions from the pipe are saturated and choked. This extends the solution of Webber et al. (1999) to include a pressurised liquid flow zone

Stage 4: Unchoked saturated two-phase flow - the exit conditions from the pipe are saturated and unchoked. This is essentially a special case of stage 3.

If the pipe is initially assumed to be saturated, the solution method has three stages, corresponding to stages 2 to 4 of the pressurised solution (above), omitting the pressurised liquid flow zone (stage 1). In this case, the PiRRaM model should precisely reproduce DNV's PipeBreak model. Stages 1 and 2 correspond to frictionless flow and pure liquid pressurised frictional flow solutions respectively, and stages 3 and 4 refer to two-phase flow solutions where the mass flux density is iteratively reduced by a factor γ at each timestep. That is, at each timestep, PiRRaM calculates the mass in the pipe and other parameters (pressures etc...) for the given mass flow rate, and then calculates the time corresponding to the step using mass conservation.

The principal assumption utilised in the later stages of PiRRaM (i.e. between stages 2, 3 and 4) is that the flow is slowly evolving. This follows previous pipeline models: PipeBreak, BLOWDOWN and SLURP, that demonstrate how the slowly varying flow approach allows rapid calculation of a given scenario and is relatively simple to implement. It appears that this method does not have a negative impact on the predictive capability of the models for large holes and full-bore ruptures (Webber et al., 2010).

As such, the time derivative in both the momentum and energy equations is negligible (i.e. both $d(\rho U)/dt$ & $d\left(\rho\left(h + {}^{1}\!/_{2}\ U^2\right)\right)/dt \rightarrow 0$), thereby enabling the transient solution to be "assembled" using mass conservation from a series of quasi-steady state solutions to the momentum and energy equations. This requires the calculation of the quasi-steady pressure profile in the pipe, which enables the inventory mass corresponding to a given mass flow rate to be calculated. These quasi-steady solutions also assume that the mass flux density profile along the pipe is uniform ($dG/dx \rightarrow 0$).

Model Intercomparison

The implementation of PiRRaM has been subject to extensive testing and consistency checks to ensure that the software is correctly implementing the model equations. There has also been wide-ranging model input sensitivity testing to ensure that the model predictions are reliable across the expected range of input values. The literature review identified a range of predictions for scenarios using other models: namely SLURP, PROFES, BLOWDOWN and PipeTech for published cases using propane, ethylene and carbon dioxide. These predictions have been digitised and are used to form a model intercomparison dataset, enabling comparisons between PiRRaM predictions and other models.

In the case of saturated liquid initial conditions, PiRRaM should precisely reproduce the predictions made by DNV's PipeBreak model in Phast. Figure 2 shows an example of one such comparison for the Isle of Grain P40 Trial, which was a rupture test on a propane pipeline. The predictions from both models are almost identical and vary only due to the marginally different material properties predicting slightly different inventory masses. These differences cause an inconsequential small delay in the PipeBreak prediction in comparison to the PiRRaM prediction. Overall, the agreement between PiRRaM and PipeBreak indicates that the two-phase flow solutions work as intended in PiRRaM.

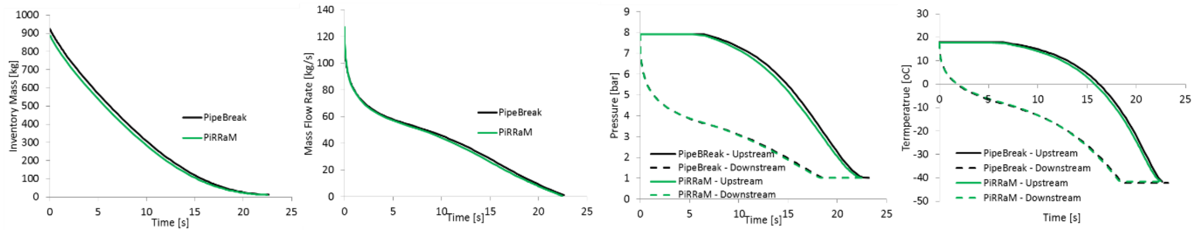

Figure 2 Comparison between PiRRaM (green lines) and DNV's PipeBreak model in Phast (black lines) for the Isle of Grain P40 trial assuming a saturated initial condition showing inventory mass (far left), mass flow rate (middle left), upstream and downstream pressure (middle right) and temperature (far right) respectively.

Cleaver *et al.* (2003) describe several comparison cases between SLURP and PROFES using propane. The three releases all correspond to full-bore ruptures, assuming a pipe diameter of 250 mm, and varying the pressure between 20 and 70 barg at a fixed temperature of 15˚C. Figure 3 presents the transient mass flow rate predictions from PROFES, SLURP and PiRRaM for the three cases. The predictions from all three models are very similar. The only notable difference is the initial mass flow rate in case 3, where PiRRaM and SLURP make slightly different predictions. PiRRaM initially makes a larger prediction in comparison to SLURP before falling to a slightly lower value, however, the agreement between the models is acceptable in all cases.

The reason for the difference between the models for the prediction of the initial mass flow in case 3 is unclear. PiRRaM predicts that the initial release rates in cases 1 and 3 are choked saturated liquid releases, with case 2 modelled as a transitional release with a mass flow rate determined by the rarefaction wave propagating upstream. This interim classification release is a pragmatic method necessary to bridge the gap between a choked two-phase flow release and an incompressible liquid release. In such a case, the mass flow rate through the orifice is taken to equal the maximum mass flow rate the rarefaction wave can deliver which occurs when the downstream pressure is saturated.

It is unknown why the SLURP prediction changes significantly between case 1 and case 3. Notably, Cleaver *et al.* (2003) does not include the initial mass flow rate values for the PROFES calculations, which might resolve the issue. However, case

1 is also shown in Cumber (2007), where PROFES predicts the initial mass flow rate to be approximately 450 kg/s, which exceeds the PiRRaM value by approximately 30%.

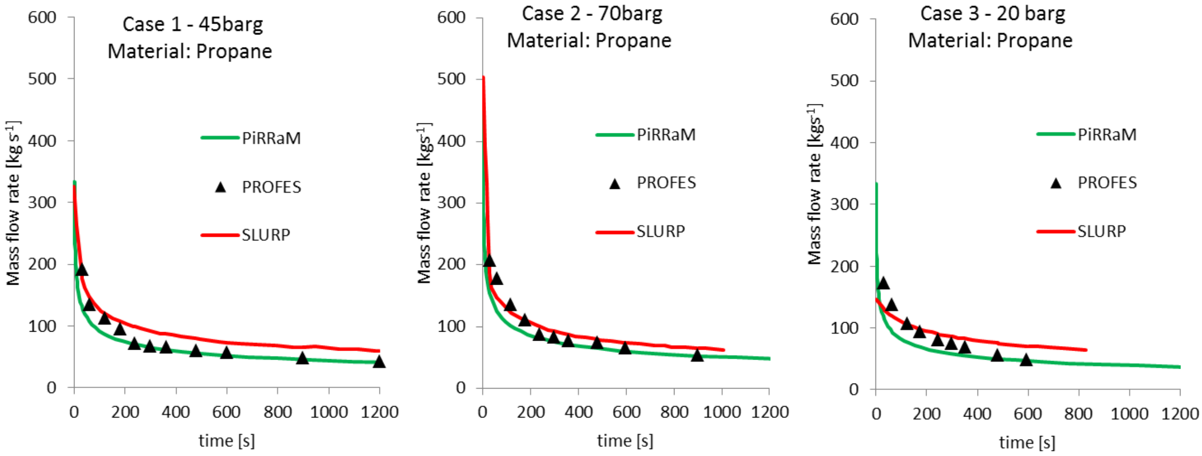

Figure 3 Comparison of the transient mass flow rate for the predictions described in Clever et al. (2003) (SLURP and PROFES) and PiRRaM, for releases of propane from a 25 cm diameter pipe at 45 barg (left), 70 barg (middle) and 20 barg (right).

OLGA is a model that solves the full transient conservation equations using a much more complex method than PiRRaM and is capable of including additional physical effects that are not included in PiRRaM. A comparison against OLGA is essentially a test of the assumptions regarding quasi-steadiness, homogeneous equilibrium, frozen flow[1] and the exclusion of heat transfer in the model. Unfortunately, only a single OLGA case corresponding to the Clausen *et al.* (2012) experiment, a 9000 tonne industrial scale CO_2 release, is available for comparison. Figure 4 shows a comparison of PiRRaM and manually digitised predictions from OLGA for the Clausen *et al.* (2012) experiment. The agreement between the models for the mass flow rate and the inventory mass is good, despite PiRRaM using a compressed liquid density corresponding to $0.95T_{crit}$ (the upper limit of validity of the pressurised liquid density correlation used in PiRRaM). This causes an overestimation of the inventory mass, which is appreciable at later times, although does not significantly affect the mass flow rate calculation. However, there are appreciable differences in the upstream and downstream temperature predictions (Figure 5), and it is important to note that OLGA made better predictions than PiRRaM for the orifice temperature in comparison to the experimental data in this case. Further differences between OLGA and PiRRaM are attributed to the fact that PiRRaM ignores heat transfer between the fluid in the pipe and its surroundings (the pipe wall, earth / air).

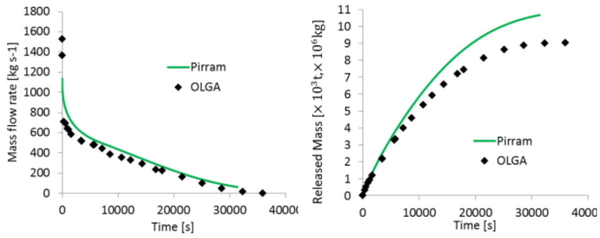

Figure 4 Comparison of PiRRaM and OLGA predictions for the mass flow rate and released mass.

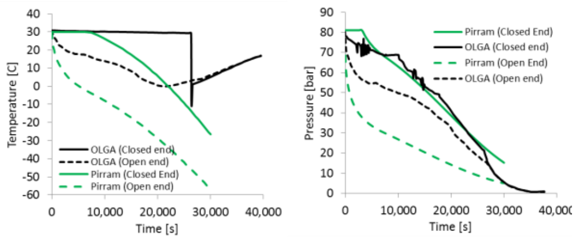

Figure 5 Comparison of PiRRaM and OLGA predictions for the temperature and pressure at the open and closed ends of the pipe.

Cooper and Barnett (2014) report predictions made by PipeTech and SLURP corresponding to a full-bore rupture of a 600 mm diameter, 96 km long pipeline transporting CO_2 at 30˚C and 150 barg. In this scenario, valves located 8 km either side of the release are closed 900 s after the release begins. Figure 6 shows the mass flow rate versus time predicted by PiRRaM, PipeTech, and SLURP. The PiRRaM prediction finishes at 900 s as PiRRaM is unable to model the valve closing event. The only notable feature is that PiRRaM makes a considerably larger prediction (factor of 2) for the initial mass flow rate in comparison to the other models, which rapidly decays. The reason for this could be due to the highly transient, rapidly decaying behaviour of the mass flow rate that could not be accurately digitised from the plots in Cooper and Barnett (2014). The agreement at times after 10s between the different models is good.

[1] The liquid and vapour phases are well mixed, do not separate and travel with the same velocity along the pipe.

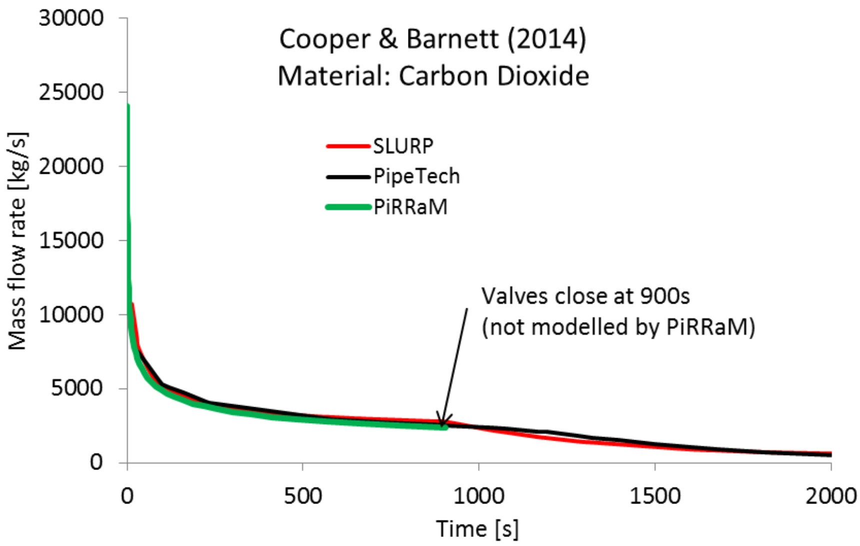

Figure 6 Predictions of the mass flow rate versus time from PiRRaM, PipeTech and SLURP for a full-bore breach to a 96 km long pipeline transporting carbon dioxide.

Model Validation

The final assurance process is a wide-ranging model validation exercise comparing PiRRaM to the complete experimental dataset identified in the literature review. The complete experimental dataset contains 27 experiments, and it is not possible to provide comparisons across the entire dataset here. Instead, the results of a comparison of PiRRaM to six representative experiments are detailed, ranging from full bore ruptures to small holes, small scale experiments to industrial scale releases, and for propane and CO_2. The intention is to highlight both the strengths and weaknesses of the model. Table 1 provides an overview of the experiments, with the PiRRaM input parameters presented for each case, which match the description of the experimental apparatus as closely as possible.

Table 1 Model input parameters for the validation cases considered here.

Experiment	*Pipe Length m*	*Pipe Diameter mm*	*Aperture mm*	**% of pipe area**	*Temp. ^oC*	*Pres. bar*
Isle of Grain P40	100	150	150	100	17.8	21.6
Isle of Grain P47	100	150	50	11.1	14.6	21.3
CO_2PipeTrans P3T4	200	52.4	50	91.0	4.9	100.5
CO_2PipeTrans P3T5	200	52.4	20	14.6	6.4	100.9
Vree *et al.* (2015)	30	50	3	0.36	20.9	120
Clausen *et al.* (2012)	50,000	581	200	11.8	30	81

The reduced experimental dataset used here contains one full bore rupture using propane (Isle of Grain P40). There are three intermediate hole experiments where the hole area is approximately 11-15% of the pipe area; using propane (Isle of Grain P40) and CO_2 (CO_2PipeTransP3T5 and Clausen *et al.*, 2012), at experimental and industrial scales. Finally, a single experiment releasing CO_2 through a 0.36%hole is chosen. In evaluating the performance of PiRRaM, it is important to note that the model has not been tuned or calibrated to the experimental dataset in any way. Nor has the description of the experiment dimensions been chosen in a manner to improve the accuracy of the model prediction. The experimental dataset was either digitised from the literature or, where possible, the raw data is used.

Full Bore Ruptures

Models assuming homogeneous equilibrium between phases and frozen flow are known to be capable of making accurate predictions for full bore ruptures (Webber *et al.*, 2010). PiRRaM is no different in this regard, making acceptable predictions for experimental data without the need for calibration or tuning parameters. Across the eight full bore rupture experiments included in the complete dataset, the performance of PiRRaM is comparable with other models. Figure 7 shows comparisons of the transient PiRRaM predictions (in green) and the experimental data (in black) for inventory mass (left), upstream and downstream pressure (middle) and upstream and downstream temperature (right) for the Isle of Grain P40 test. The overall quantitative agreement between the PiRRaM model predictions and the experimental data is good. There is a slight under-prediction of temperature and pressure downstream, which could be due to the temperature sensors being placed slightly upstream of the orifice. The saturated flow model, i.e. Stage 3 of PiRRaM, predicts an infinite pressure gradient at the end of the pipe, so it is expected that the pressure at this point might seem poorly predicted.

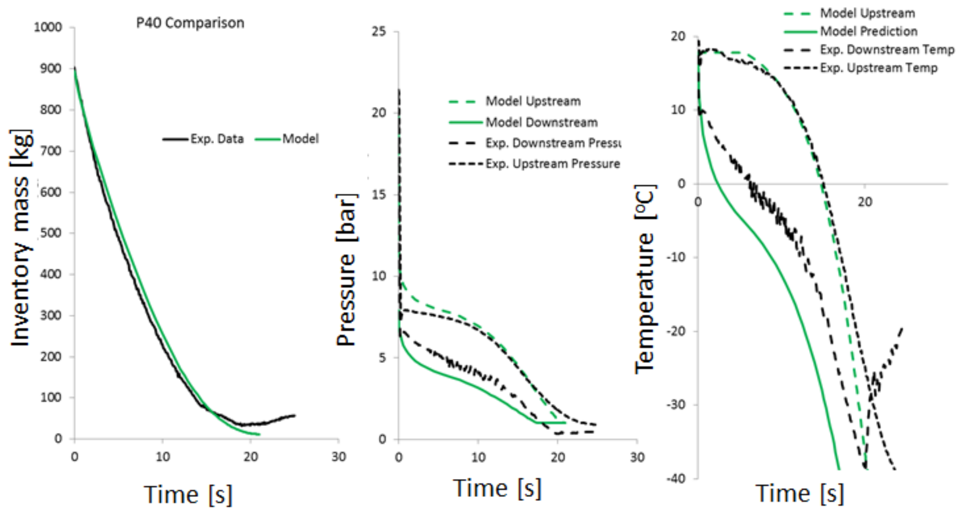

Figure 7 Comparison of PiRRaM to Isle of Grain experiment P40, from left to right, Inventory mass, Pressure and Temperature

Large Holes (11%-15% of the pipeline area)

Historically, models assuming homogeneous equilibrium between phases and frozen flow were believed to lose predictive accuracy as the hole size decreased towards 10% (Webber et al., 2010). This is based upon the poor performance of models that were available at the time in predicting the Isle of Grain P47 experiment, which used a slot shaped orifice with an area equivalent to a 50 mm diameter hole (Richardson *et al.*, 1996a & b). The poor comparison to the experimental data eventually led to PipeBreak in DNV's Phast consequence model restricting the model to holes exceeding 20% of the pipeline area.

Given there are now new experiments using CO_2 for similar sized holes, it is instructive to see if the additional evidence supports or challenges the restriction of the application of HEM type models. Figure 8, Figure 9 and Figure 10 show comparisons of the transient PiRRaM predictions (in green) and the experimental data (in black) for inventory mass (left), upstream and downstream pressure (middle) and upstream and downstream temperature (right), for the Isle of Grain P47 experiment, the CO_2PipeTrans Phase 3 Test 5 experiment and the Clausen *et al.* (2015) industrial scale release respectively.

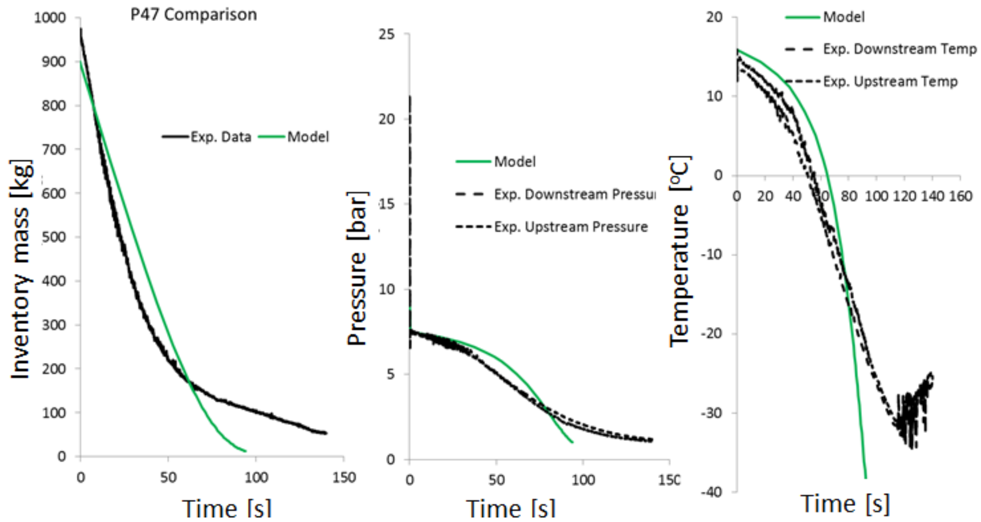

Figure 8 Comparison of PiRRaM to Isle of Grain experiment P47. The model predictions for the upstream and downstream temperature and pressure are indistinguishable, and the model line therefore represents both.

The comparison to the Isle of Grain P47 experiment (Figure 8) follows the long-established tradition of HEM type models underpredicting the experimentally measured mass flow rate, although the PiRRaM predictions for the upstream and downstream temperature are quantitively very reasonable over the initial 50 s (corresponding to 80% of the inventory mass being expelled).

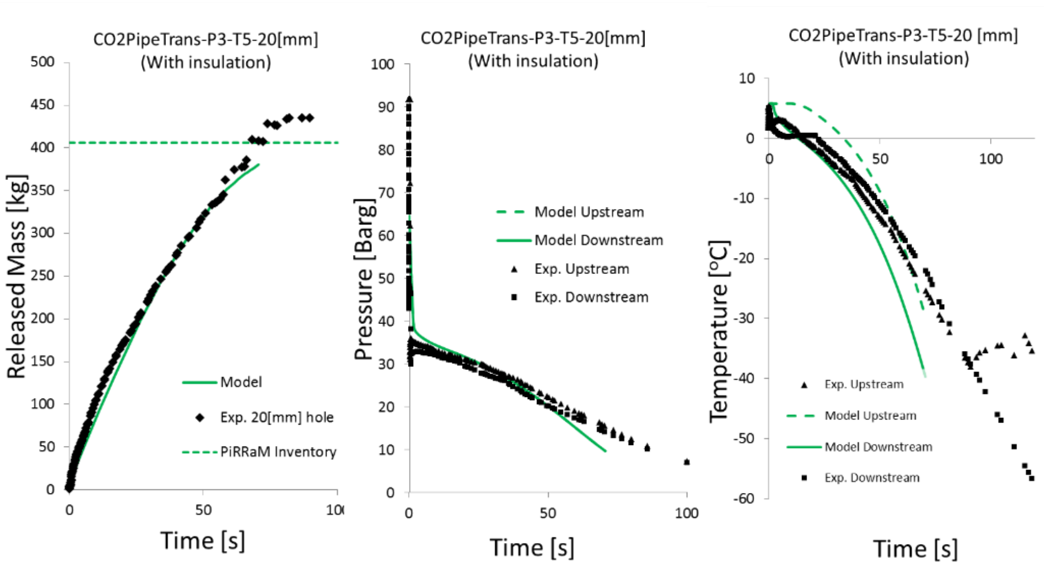

Figure 9 Comparison of PiRRaM to the CO_2PipeTrans Phase 3 Test 5 experiment (20 mm hole)

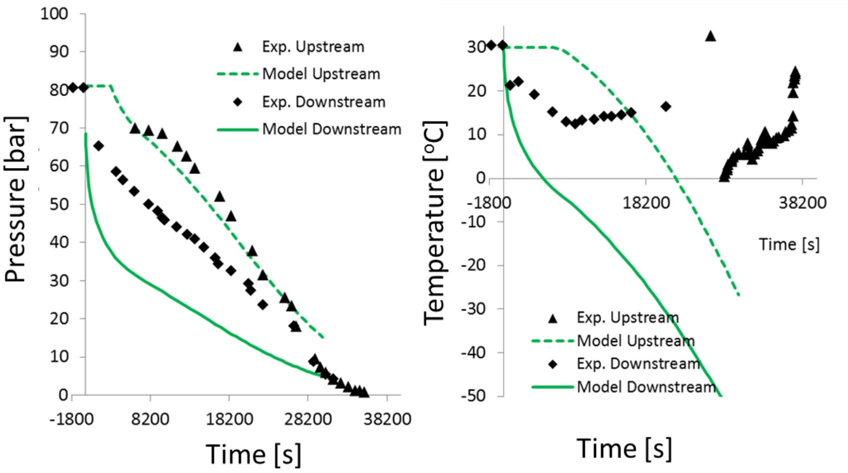

Figure 10 Comparison of PiRRaM to the Clausen *et al.* (2012) experiment

Comparison between PiRRaM and the CO_2PipeTrans P3T5 experimental data are much more encouraging (Figure 9). The inventory prediction from PiRRaM (left) appears to closely follow the experimental measurements, although there appears to be considerable uncertainty in these measurements as the measured mass released eventually exceeds the known inventory (indicated by the horizontal dashed line). Similar comparisons between PiRRaM predictions and the experimental pressure and temperature measurements show that PiRRaM is quantitively capturing the behaviour, again with acceptable accuracy. Notably, the particularly good agreement in this experiment may be aided by the pipe in the experiment being insulated, therein restricting the flow of heat from the air into the pipe. PiRRaM does not model heat transfer effects, which makes it particularly suited to this case up to 60 s. After 60 s, the predicted temperature falls significantly below the measured values. This is consistent with heat transfer being neglected in PiRRaM.

The final intermediate hole experiment relates to measurements on an industrial scale pipeline containing 9300 tonnes CO_2 from a 50 km long, 58.1cm internal diameter[2] pipeline discharged in a shock-tube configuration for the majority of the release. The authors measured the upstream and downstream temperature and pressure throughout the release. The pipe surface roughness is assumed to be 0.05 mm which represents a typical value. PiRRaM produces results until the thermodynamic triple point is met (around 5 bar), at which point the calculation is stopped. Due to the proximity of this case to the critical point, the equation of state used in PiRRaM for the liquid is not valid. Therefore, PiRRaM is run using liquid compressibility properties at 0.95 of the critical temperature which corresponds to the upper limit of validity for the pressurised liquid equation of state used.

Due to the scale of the experiment, inventory measurements were not possible, however, it is still useful to compare PiRRaM predictions to the pressure and temperature, measured at the release point, and at the farthest point upstream (see Figure 10).

[2] Clausen *et al.* (2012) report the pipeline as having a diameter 60.9cm. However, this is inconsistent with the inventory reported to be 9300 tonnes using an accurate equation of state. In which case, the internal diameter is assumed to be 58.1 cm as this corresponds to the correct inventory.

PiRRaM has already been shown to make comparable inventory predictions to the far more sophisticated OLGA model for this case (see Figure 4. The lack of heat transfer modelling in PiRRaM leads to PiRRaM making very poor predictions for the transient upstream and downstream temperature measurement (Figure 10, right), however the pressure prediction is qualitatively very reasonable, particularly at the upstream end and beyond 287,200 s at the downstream end.

PiRRaM has been shown to make reasonable predictions for CO_2 pipelines for intermediate scale holes. This could imply that the poor performance for the Isle of Grain P47 experiment may be interpreted as outlying behaviour. The literature relating to the Isle of Grain trials acknowledges that the P47 trial may have been subject to a higher level of experimental uncertainty, due to the load cell data not being accurately corroborated by the neutron beam scattering (NBS) measurements (Richardson and Saville, 1996 a & b). Notably, the other Isle of Grain experiments generally had excellent agreement between load cell data and the NBS measurement. Tam and Higgins (1990) also acknowledge that there is a delay due to “valve actuation”, followed by a period of “flow establishment”, which is followed by established flow. Exactly how the data was processed though the initial period of the release is very important in quantifying any remaining uncertainty.

Small holes (<1% of the pipe area)

Figure 11 compares the PiRRaM predictions to the experimental data corresponding to the smallest hole size present in the validation dataset, at 0.33% of the internal pipe area (i.e. a 3 mm hole at the end of a 50 mm external diameter pipe). Specifically, Figure 11 shows comparisons of the transient PiRRaM predictions (in green) and the experimental data from Vree *et al.* (2015) (in black) for mass flow rate (left), upstream and downstream pressure (middle) and upstream and downstream temperature (right).

PiRRaM appears to do a reasonable job of capturing the earliest stage of the decompression and predicts an initial mass flow rate that is 3% lower than the initial experimental value. The decay to saturated conditions ($t = 0$ s $\rightarrow t = 10$ s) appears to be modelled with satisfactory accuracy. Over the subsequent period ($t = 10$ s $\rightarrow t = 150$ s), the mass flow rate, temperature and pressure are also predicted well. After this period, the model predicts significantly lower temperatures, in line with the lack of heat transfer modelling as has been discussed previously.

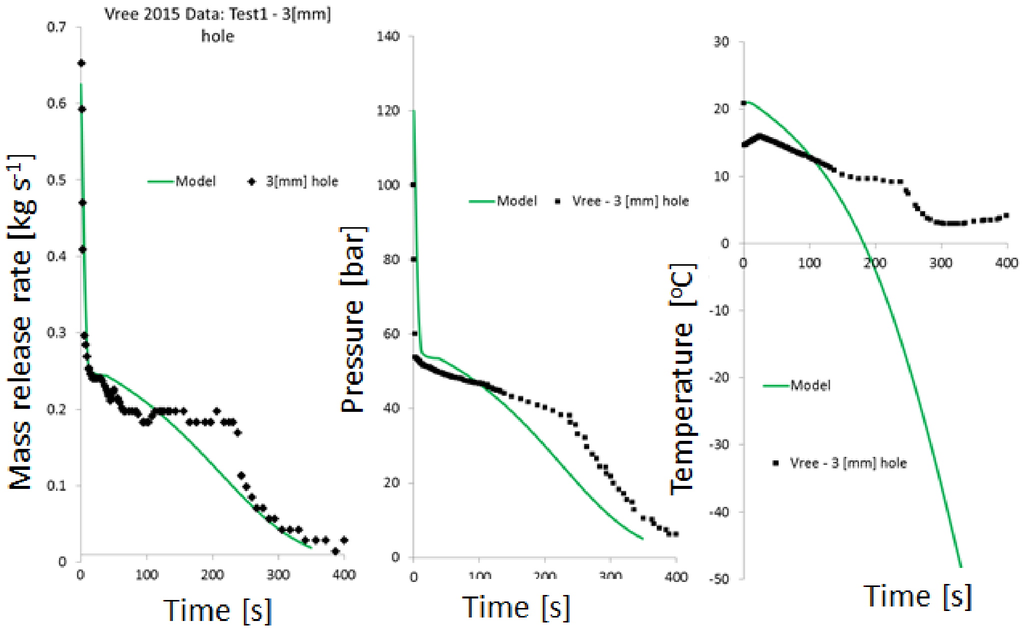

Figure 11 Comparison of PiRRaM to the Vree *et al.* (2015) Test 1 experiment (3 mm hole)

Summary

This paper describes the development of HSE’s new pipeline release rate model, PiRRaM, which is now used to model failures of MAH pipelines carrying pressure liquefied gases. PiRRaM has been subject to extensive sensitivity testing, thorough verification comparisons to industry models, and a wide-ranging validation exercise. PiRRaM has been shown to produce acceptable results across the range of physical parameters that HSE needs to model. Areas where the model performance is weaker have been highlighted and explained. The key limitation of the new model is the lack of a model for heat transfer from the ground into the fluid. Remarkably, the transient behaviour of the inventory mass and mass flow rate seems to be unaffected by this choice, however, it results in a release that is cooler and with a tendency towards predicting a higher liquid content than might be observed in practice. This is only an issue over very long timescales for the small-hole scenario and is not of concern for HSE where only the first 30 s of the release are currently considered.

The key innovation in PiRRaM has been developing a method to incorporate the effect of liquid compressibility on the initial mass flow rate prediction. Using new insights obtained by analysing CO_2PipeTrans data, a method has been developed that uses the pressure drop across the rarefaction wave to determine the likely outflow dynamics. For small holes, the rarefaction wave balancing technique predicts the flow is governed by Bernoulli’s equation for incompressible flow, whereas large holes and full bore ruptures are likely to lead to saturated choked flow releases. The rarefaction balancing approach provides a material specific method which uses the physical properties of the fluid in question to provide a smooth transition between saturated choked flows and pressurised liquid flows.

A key finding which emerged during the PiRRaM development process is that the poor performance of PiRRaM for the Isle of Grain P47 experiment appears to be an outlier in comparison to other comparable experiments. Specifically, PiRRaM is shown to make acceptable predictions for the CO_2PipeTransP3T5, and Clausen *et al.* (2015) experiments, which have a comparable relative hole size. Comparisons between PiRRaM predictions and the complete experimental dataset, which is not possible to include here, reveal that there are several additional small hole experiments for which PiRRaM makes acceptable predictions. Moreover, the comparison between PiRRaM and the Isle of Grain P47 represents the worst performance of PiRRaM. Notably, load cell and the neutron beam measurements for the Isle of Grain P47 experiment shown in Richardson and Saville 1996(a & b) are significantly different for the P47 experiment.

In summary, there are now several additional experimental datasets pertaining to small hole releases from pipelines for which PiRRaM makes acceptable predictions. It is plausible that the Isle of Grain P47 experiment may have had an experimental uncertainty that is larger than previously acknowledged. Therefore, given the good performance of PiRRaM for several independent small-hole pipeline release experiments reported by different authors, it is reasonable to infer that the inventory measurements in the Isle of Grain P47 experiment may be unreliable and that the model is suitable for all sizes of holes.

Authorship

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Disclaimer

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