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Experimental investigation of the effect orifice shape and fluid pressure has on high aspect ratio cross-sectional jet behaviour

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Abstract

Prevention of major disasters such as Piper Alpha is a concern of oil and gas companies when commissioning a new offshore superstructure. Safety studies are undertaken to identify potential major hazards, risks to personnel and that sufficient precautions have been employed to minimise these. Such an assessment will also include the consideration of the protection from gas leaks such as the optimum positions of gas leak detectors and startup safety procedures after a leak. This requires a comprehensive knowledge of the behaviour of the leaking hydrocarbons as they emerge from the leak into the area of concern. Such leaks are most likely to emanate from a high aspect ratio cross-sectional curved slot in a pipeline. This paper challenges the conventional view that it is sufficient to model such leaks as axisymmetric jets. This paper is therefore concerned with an experimental study carried out on a series of more realistic high aspect ratio cross-sectional jets issuing from a flange orifice. Both high quality photographs in both planes of the jets and some quantitative pressure data is examined for a high aspect ratio cross-sectional jet of air at pressures up to 4.136 bar. The effect of changing aspect ratio, fluid pressure and orifice shape will be discussed and put into context with regard to how this relates to offshore analysis studies.

Keywords: Jets; Visualisation; Offshore safety

1. Introduction

Safety has paramount importance within the oil and gas industry. There are many potential hazardous situations within the drilling, production and processing areas both on

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Nomenclature

D diameter of axisymmetric jet
N exponent of velocity decay
$\bar{z}$ dimensionless distance from orifice

Greek letters
α first angle for jet classification
β second angle for jet classification
δ width of gasket

and offshore. Several of these come about because there are highly volatile, flammable and toxic liquids and gases being transported significant distances through pipelines often at high working pressures of up to 500 bar [1].

Three major hazards that can occur with toxic and flammable materials are fire, explosion and toxic release. A knowledge of these hazards in order to minimise the risk to personnel, the environment and equipment is necessary for good engineering design of an offshore structure. Flammable materials only present a danger of combustion when they are mixed with air between certain defined concentration levels. Therefore, if a released vapour cloud is allowed to disperse and mix with air there becomes a danger of combustion. Consequently ventilation needs to ensure that the cloud is dispersed sufficiently so that the mixture falls below the lower flammability limit. There are two factors that will affect the concentration of the flammable material; jet controlled mixing due to entrainment, and further away the prevailing weather conditions or ventilation system will determine atmospheric mixing. For low velocity releases the latter is the predominate influence, whereas for the majority of offshore pipelines it is more usual for jet mixing to dominate the behaviour of the gas concentration and velocity fields.

Safety studies are an essential part of the design and commissioning of offshore superstructures. After the Piper Alpha disaster [2] emphasis has been on the better and faster detection of leaking hydrocarbons from pipelines within modules. It was found, Davenport [3], in a survey of incidents on offshore installations that one of the primary causes of explosion risk is due to the failure of a pipeline containing high temperature and pressure hydrocarbons. This could be due to a flange failure, crack in the pipe due to corrosion [4] or an accident rupturing the pipe's structural integrity. The cross-section of the leak geometry is unlikely to be circular and in the case of a flange it is likely to be a rectangular cross-section, of up to a 1000:1 aspect ratio in some cases.

Predicting the behaviour of gas leaks within a safety study for an offshore module is increasingly being undertaken using computational methods. This has the advantage that full-scale scenarios can be modelled and a multiple number of possibilities can be investigated. The accuracy and reliability of the data does therefore depend upon the assumptions made when modelling [5]. One of the problems when modelling such cases is to generate sufficient local grid refinement in the vicinity of the jet as well as a large enough global computational domain. However, work on local grid refinement is presently helping to make it possible to achieve good enough simulation meshes [6]. Currently [7] safety studies are based on axisymmetric jets issuing from leaks in the assumption that there is little difference between the behaviour of axisymmetric jets and high aspect ratio cross-sectional rectangular jets. If such a leak is considered to be axisymmetric with no preferred direction or mixing characteristics modelled as is current practice then this could have a profound effect on safety analysis [5]. Within an offshore production module for example there is a variety of equipment around many of the pipelines. Escaping hydrocarbons from a leak will be therefore likely to encounter obstacles within a few jet widths of the jet source. The spreading rate of the jet and the degree of mixing within that short distance could significantly affect the dispersion within the module. In Carissimo et al. [8] there is little emphasis on the nature of the leak and there is a need for more work to be done on near field congested releases.

In the past there have been a prevalence of studies on axisymmetric jets [9] due to their wide range of applications in the aerospace and mechanical industries. Unfortunately this sometimes precludes more general engineering uses, but it is still considered sufficient to use an axisymmetric assumption to give the characteristics of the fluid jet in such safety studies. This is largely based upon the fact that a square cross-sectional jet consists of a potential core region that blends, at approximately eight slot widths downstream into axisymmetric decay. As the aspect ratio increases a characteristic decay region connects the two that increases in length as the aspect ratio increases. It is still assumed that even at an aspect ratio of 100:1 that axisymmetric decay will occur at some point; it is not clear if this is true for higher aspect ratios or is even a valid assumption to make whenever a slot jet is modelled.

The study of high aspect ratio cross-sectional jets is crucial to advancing the understanding of their behaviour and how this relates to offshore safety analysis. In offshore pipelines the working fluid is a highly flammable hydrocarbon mix at high pressures (up to 500 bar) and temperatures. It was unfeasible to work in a laboratory at such extremes of pressure and with dangerous fluids but useful information could be gained from lower pressure (up to 4.136 bar) isothermal air jets as a first step towards more realistic modelling within a safety analysis. These assumptions mean that the experimental jets do not take into account the two or three phase nature of the jets and what effect this may have upon the behaviour of the jets. It is unlikely though that any safety analysis will account for these [5]. This work will give the computational modeller a better understanding of jet behaviour and its effect on safety studies.

2. Background

In order to fully understand the nature of jets issuing from high aspect ratio cross-sectional orifices it is necessary to comprehend all aspects of jet behaviour from planar to axisymmetric jets. All the work reviewed and carried out in this paper is on those that are free turbulent shear flow jets. There is no direct effect of any fixed boundary on the turbulence within the flow field. In this study an air jet spreading into air at rest that then creates a surface of separation with the still surrounding air was investigated. The shear occurring at this surface generates eddies that move both along and across the mixing layer. The motion of the eddies results in an exchange of fluid from either side of the mixing layer and the surrounding medium being carried downstream with the jet and leading to an overall increase in the size of the jet.

There have been three main sub-categories of jet flow that have been studied. These are defined by the shape of the nozzle creating the jet under the premise that nozzle geometry determines the characteristics of the jet flow [10,11]. These are the two-dimensional (planar) jet, circular cross-sectional (axisymmetric) jet and the three-dimensional free jets.

2.1. Axisymmetric jet behaviour

There exists much work on axisymmetric jet flow, it is considered to be one of the most prevalent in engineering and other applications. As the axisymmetric jet assumption is commonly used for simplicity in many modelling situations a brief overview will be given here of the salient features of such flows. This will also give the industry standard base case for comparison with the high aspect ratio cross-sectional jets studied.

An axisymmetric jet has some features in common with other jets such as a potential core and a decay region. Of particular interest is the region far from the orifice as it is this behaviour that it is said that two- and three-dimensional jets approximate to in the far field. The potential core length is said to be 6.9 D [12] from the jet exit. The centreline velocity decay is well established as proportional to $1/\bar{z}$ [13] and the spreading angle from the centreline is approximately 10–15° [14]. Simpson and Holdø [15] investigated a plane jet numerically and found that the inlet condition for the jet can have an effect upon the near field flow.

2.2. Planar jet behaviour

A two-dimensional jet is the ultimate high aspect ratio cross-sectional jet. In reality two dimensionality is not possible to achieve, but some experimental attempts have been made [16–18]. These experiments covered aspect ratios up to 128:1 and give a starting point for the present work.

A high aspect ratio cross-sectional jet was used by Van der Hegge Zijnen [16] to form an approximately planar jet. In the study it was observed that velocity peaks were present at ±80% of the distance from the central slot. This is referred to as the saddleback velocity distribution. High intensities are present within the shear layers at the edges of the jet and this causes considerable difficulty in pressure measurements for such jets. There is a substantial velocity component in the transverse direction due to the process of entrainment of the surrounding fluid into the jet.

For self-preservation of two-dimensional jets the properties are independent of orifice shape and size and depend only on the momentum of the jet. This requires the structure of the jet to be similar at all streamwise locations. It is believed that if self-preservation is achieved then a two-dimensional jet has been attained. Self-preservation for an orifice of aspect ratio 48:1 was observed to take place at distances greater than 30 slot widths from the jet exit [17]. However, aspect ratios of up to 128:1 were studied in [20] and showed that the point of self-preservation was attained at a distance dependent on the nozzle aspect ratio. The larger aspect ratios achieved self-preservation much further downstream than the smaller ones. There is no further confirmation for larger aspect ratio jets but it is evident that high aspect ratio cross-sectional jets are likely to behave in a unique way and different to those of jets with axisymmetric cross-sections.

So-called jet flapping is the spatial movement of the complete jet in an oscillatory manner, which is associated with the generation of large-scale, eddies at the jet/ambient interface. An investigation [19] found no correlation between velocity measurements taken simultaneously on either side of the jet but Goldschmidt and Bradshaw [20] found that it did indeed exist in planar jets. However, later experimental measurements [21] clearly showed that the large-scale eddies are heavily negatively correlated, indicating a link between the eddy motion and that of the jet oscillation. It has not yet been established which of these phenomena is the cause and which is the effect. Using a spaced-averaged transient numerical techniques to model a 10:1 aspect ratio jet, Simpson [22], demonstrated both the saddleback velocity distribution and the jet flapping. It also indicates that better visualisation techniques should be used to observe these phenomena.

2.3. Three-dimensional jet behaviour

Three-dimensional jets are those where the flow properties vary in all three dimensions. These are not necessarily rectangular cross-sectional jets, other orifice shapes such as elliptical and triangular have been studied [23]. This study was an extensive study of such three-dimensional jets with aspect ratios of 10:1, 20:1 and 40:1 as well as axisymmetric. It was concluded that at low speeds, initiated from non-symmetrical orifices, jets decay to axisymmetric form far downstream. There were three distinct regions of axial velocity decay as shown in Fig. 1: the potential core region where the centreline velocity is constant; the characteristic decay region where the centreline velocity decays at a rate proportional to the distance downstream raised to an exponent of a value between 0.5 (that for a two-dimensional jet) and 1 (implying an axisymmetric decay); and the axisymmetric decay region where the flow is similar to that of an axisymmetric jet.

It has been found [24], in agreement with others that there is a decrease in the major axis of the jet width and an increase in the minor axis jet width. Eventually these axes switch and the jet becomes more axisymmetric in nature. A 2:1 aspect ratio turbulent jet was studied numerically [25], using a third-order Runge–Kutta scheme for temporal integration and a

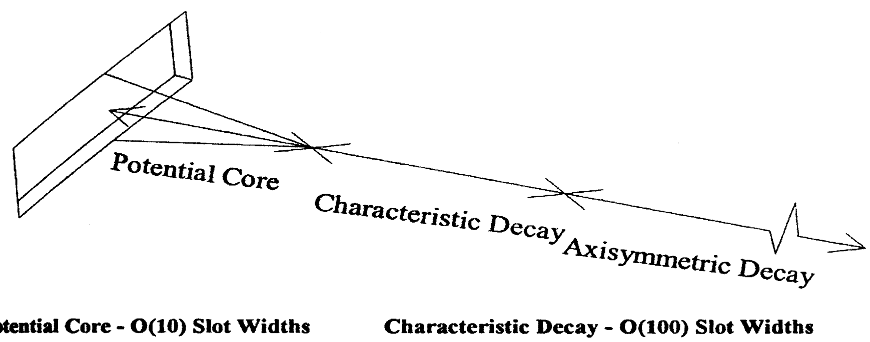


Fig. 1. Schematic of the flow field of a rectangular jet showing the different decay zones.

fourth-order compact scheme for spatial discretisation. The low Reynolds number cases were direct simulations and large eddy simulations for those at high Reynolds numbers. It was found that axis switching was dependent on instability waves present in the inlet boundary layers and could be induced in both laminar and turbulent jets by single-mode forcing.

The jet flow characteristics for all broad categories of jet shapes are summarised as a background to the experimental work done here on high aspect cross-sectional jets emanating from a curved surface such as a tube flange. From this paper it will become apparent that there is not only interesting different behaviour from such jets but that this can have a severe impact on other aspects of fluid modelling within a safety analysis.

It has been seen from studying the three categories of jets that there are certain key features that will help determine the behaviour of the high aspect ratio cross-sectional jet. In its early stages the jet is expected to have a potential core region that will be of a decreasing length as the aspect ratio increases that will be Reynolds number independent. The characteristic decay region behaviour will be indicative of whether the flow is more like a two-dimensional or axisymmetric jet and finally whether an axisymmetric decay region exists within the frame that the jet is studied.

The aspect ratios in this work range from 26:1 to 239:1 with a preliminary study of the effect of curvature upon the jet behaviour also being undertaken. Three pressure ratios are used to give a range of Reynolds numbers for the flow. The experimental work is in two stages:

- high quality visualisation of a number of different orifice geometries;
- detailed measurement data from four of these cases.

3. Experimental method

3.1. Apparatus

The basic experimental rig is shown in Fig. 2. This was used for both the visualisation and velocity measurement stages of the experimental work.

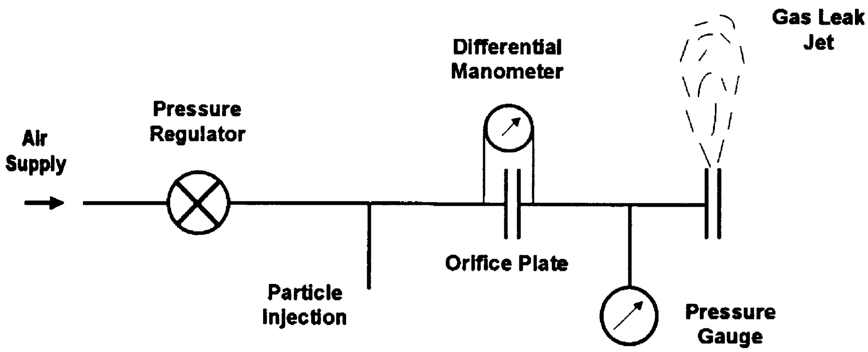


Fig. 2. Schematic of the experimental rig.

3.2. Flow visualisation

The flow visualisation method used followed that proposed by Borean et al. [26]. By using a thin laser light sheet, a quasi two-dimensional plane can be illuminated within a three-dimensional flow. The laser then allows sufficient light for photographs to be taken of the complex flow field. In order to obtain images that can provide the required information and that are an improvement upon previous work a number of factors have to be considered. Firstly the selection of laser is important; the light concentration must be sufficient to illuminate the particles within the flow adequately, a large light sheet is required so a high laser output is needed and has to be delivered within a short illumination period. Due to the high velocities encountered within gas jets no mechanical method of shuttering the illumination is possible. Instead a pulsed copper vapour laser, electronically switched at repetition rates of up to 30 kHz is used producing 15 W of visible light. A beam of 25 mm in diameter is produced and theoretically a single pulse of the laser could capture an individual turbulent eddy rotating at a frequency of 10 MHz. The laser pulsing is controlled by a microprocessor device that is synchronised with the opening and shutting of the camera shutter. It was possible with this system that the number of pulses on each exposure could be selected. This ensured that single frozen shots in time (1 pulse) and *time averaged* images (100 pulses) could both be taken. The light sheet was achieved by use of an optical system, further explained in [27].

The jet needs to be seeded with particles that the light sheet can reflect in order to give an indication of the motion within the jet. Care has to be taken to ensure these particles do follow the true motion of the fluid. A smoke pellet producing spherical particles of zinc chloride with a mean diameter of 0.5 μm was introduced into the air system. Further details of the method can be found in Meares et al. [28].

3.3. Pressure measurements

Pressure probes were positioned within the jet by a complex three-dimensional traversing mechanism. A three-hole yaw probe was used to survey the flow velocity field monitored by a series of calibrated and amplified pressure transducers. The output from the pressure transducers was logged by a 486 PC via a 12-bit data translation analogue to digital converter board. The computer moved automatically between data points and then data taken as required. A sampling frequency of 200 readings per second for a duration of 4 s was used for this work. Calibration of the pressure probes was done and corrections to recorded values from the probe was done via software specifically written for the purpose.

4. Methodology

4.1. Gas leak geometry

The experimental study was to investigate the physical principles that affect high aspect ratio cross-sectional jets in particular relation to gas leak jets. A series of realistic flange failures in gaskets were used as shown in Fig. 3. The gasket thickness was 2 mm and the classification system is summarised in Fig. 4. This allows easy extension for other angles

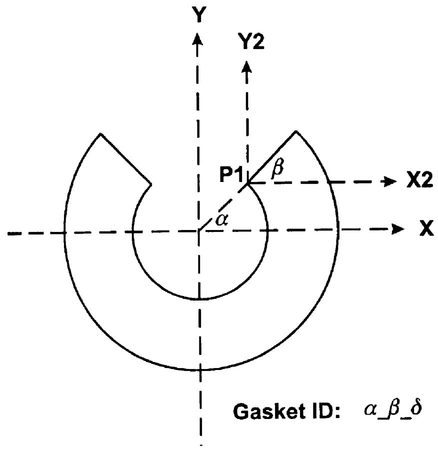


Fig. 3. Schematic of the geometries of flange leaks.

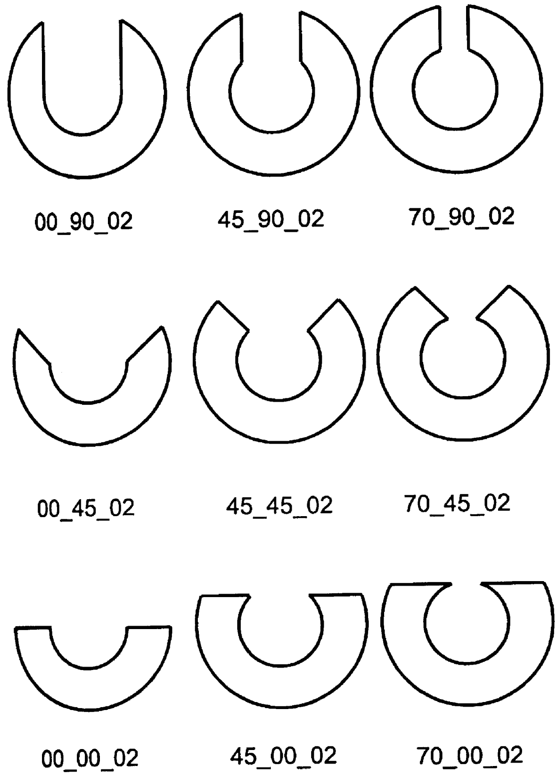


Fig. 4. Gasket classification system.

Table 1
Inner and outer aspect ratios of gasket studied

Gasket	Aspect ratio (outer)	Aspect ratio (inner)	Outer:inner ratio
00_90_02[a]	119.7:1	119.7:1	1:1
00_45_02[a]	174.9:1	119.7:1	1.5:1
00_00_02	239.5:1	119.7:1	2:1
45_90_02	59.8:1	59.8:1	1:1
45_45_02	119.7:1	59.8:1	2:1
45_00_02[a]	184.5:1	59.8:1	3:1
70_90_02	26.6:1	26.6:1	1:1
70_45_02[a]	85.7:1	26.6:1	3.2:1
70_00_02	165:1	26.6:1	6.2:1

[a] Indicates some quantitative data available.

although the range studied here is $0 \leq \alpha \leq 70^\circ$ and $0 \leq \beta \leq 90^\circ$. These gasket geometries were chosen because they were felt to be representative of the range of gasket failures that could occur. The choice gave a balanced but wide range of shapes and aspect ratios.

A series of flow visualisation tests with all nine geometries was carried out to give a clear indication of the main physical properties influencing the flow structure. Further investigations for a more limited number of geometries involved time mean velocity measurements using a three-axis pressure probe. Results were obtained along the line of symmetry aligned with the largest length of the jet nozzle cross-section and at stations up to 500 mm from the jet exit. The pressure ratios (ratio of the pressure in the pipeline and the atmospheric pressure) used were 5.08, 3.72, 2.36 and 1.68. This gave actual pressures of 413.6 kPa (40 psi), 137.9 kPa (20 psi), 68.9 kPa (10 psi) and 34.5 kPa (5 psi), respectively. Table 1 gives the equivalent aspect ratios for the gaskets studied; these are divided up into inner and outer pipe aspect ratios.

4.2. Images

The jets were frozen in time by using just a single pulse of the laser. This means that oscillations up to 3 kHz could be observed provided that the spatial resolution of the film media was sufficiently high. In the present case this was 1600 ASA FUJI which provides approximately 100 lines/mm; for a standard negative size this provides a resolution grid of 3800×2200 which gives a spatial resolution of approximately $0.15\,\text{mm} \times 0.15\,\text{mm}$. Time averaged properties were studied using integrated photographs of 100 pulses with an integration time of 1/30 s (the laser's pulsing frequency was set at 3 kHz). Two perpendicular planes of the downstream development of the jet were studied with a distance of 100–150 slot widths photographed. This was felt to be sufficient to measure the average spreading angle of the jets.

4.3. Pressure measurements

Four representative leak geometries were chosen to allow a more detailed investigation of the velocity field at the four pressures. These were as follows:

1. parallel sided leak with channel type nozzle geometry, 00_90_02;
2. wide nozzle angle producing a large exit area geometry, 00_45_02;
3. plate separation type geometry with a straight edge perpendicular to the jet exit direction, 45_00_02;
4. rapidly contracting then diverging exit geometry, 70_45_02.

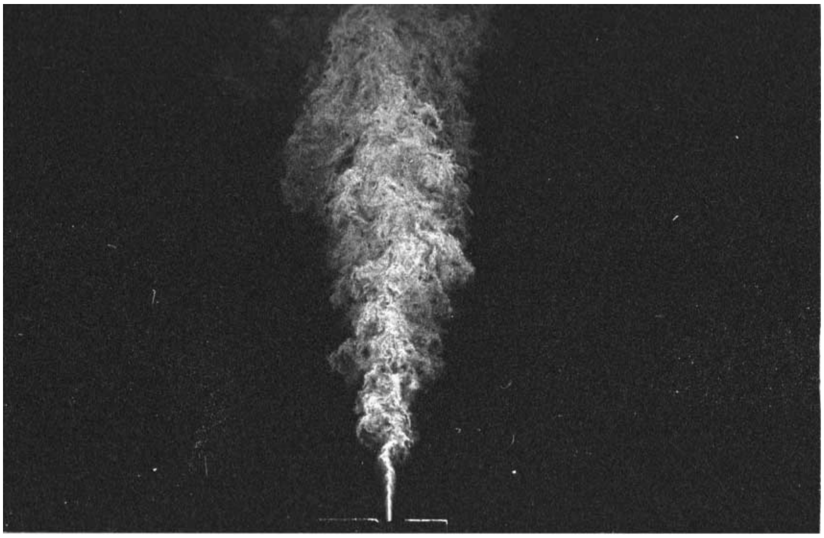
5. Results

The results were analysed by studying the differing Reynolds numbers, inner and outer aspect ratios and orifice shape using both the visualisation data and the pressure measurements. There are also some general observations that can be made. Fig. 5(a) shows a moment of the jet frozen in time with a one-pulse shot. The large turbulent structure can be seen and the entrainment of unseeded air by these large vortices which contributes to the spreading angle as seen in Fig. 5(b). It was also seen through a number of instantaneous images that the phenomena known as jet flapping takes place in the plane parallel to the flange. It appears that the initial core breaking down coincides with the commencement of entrainment caused by large-scale eddies. This motion oscillates between front and back of the jet in what appears to be a low frequency, oscillatory manner and continues through the downstream development of the jet. This correlates with previous experimental studies [20,21] for planar jets and also with computational studies [22], for a 10:1 aspect ratio rectangular cross-sectional jet.

Visible in many of the photographs are possible shock waves in the initial zone of the jet (Fig. 6). These appear at the higher pressures but not in all jets at the same pressure. It is the orifices with the smallest exit geometries such as 70_90_02, 00_90_02 and 45_90_02. These are possible weak oblique shock waves increase in dimension as the pressure is increased which eventually combine only in 70_90_02 with normal shock waves at the highest pressure. Shocks could possibly occur in the parallel sided gaskets because the jet cannot expand until after leaving the flange, whereas other geometries allow the expansion between the flange plates. It is well known that the presence of shock waves will affect the concentration levels of leaking gas within the jet.

5.1. Outer aspect ratio

Out of the nine gasket configurations studied there are only two that have the same outer aspect ratio, 00_90_02 and 45_45_02. Fig. 7 shows the spreading angles both perpendicular and parallel to the flange. The shape of the jet is very different, with the 45_45_02 spreading faster than the 00_90_02 in spite of having a smaller inner aspect ratio. This may well be due to parallel sides in the 00_90_02 within the gasket restricting the spreading of the jet. For 90_00_02 as the pressure increases there is very little effect on the jet and the spreading angle remains approximately that of an axisymmetric jet, whereas for 45_45_02 as the pressure increases the spreading angle alters considerably and becomes significantly greater than that for an axisymmetric jet. This appears to indicate that the orifice shape has a significant effect on the spreading of the jet.



(a)

(b)

Fig. 5. Gasket 70_00_02 at 20 psi parallel to the flange for (a) 1 pulse and (b) 100 pulses.

5.2. Inner aspect ratio

For the inner aspect ratio there is more choice of orifice shapes to compare. For the 70_**_02 series of gaskets, Fig. 7(b) indicates that as the pressure and the outer aspect ratio increases the shape of the jet remains much the same. For the 00_**_02 and 45_**_02

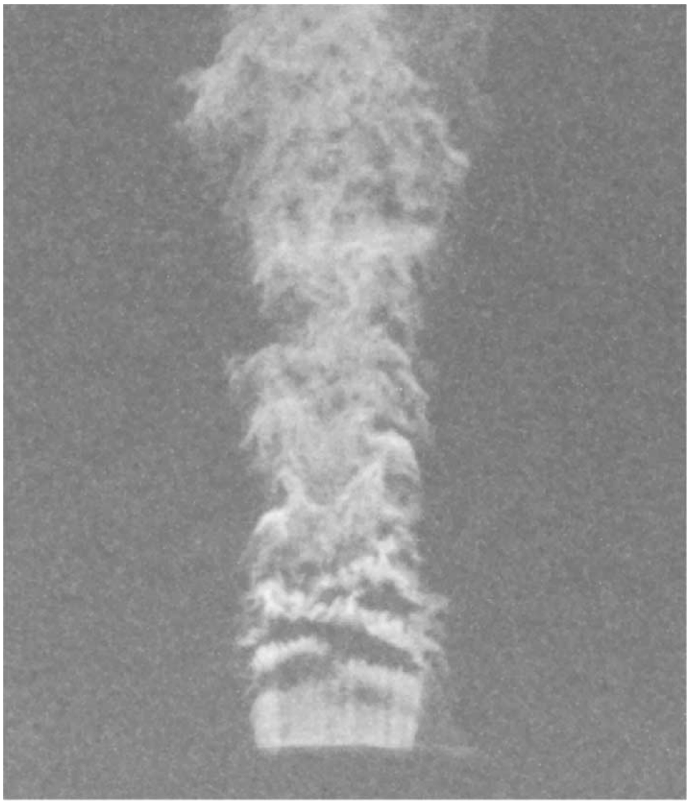


Fig. 6. Gasket 70_90_02 at 60 psi for one pulse perpendicular to the flange showing possible shockwaves.

categories, respectively, the spreading angles increase as both the pressure and outer aspect ratio increases. This indicates that for the 70_**_02 class the inner ratio is so small this is the possible defining factor in the behaviour of the jet. For the other jet ratios it is possibly the orifice shape and the outer aspect ratio that dominates the behaviour.

It can be seen that the spreading angles for the 00_90_02 geometry perpendicular to the flange has a spreading angle that is fairly constant and around 12°, that of a round jet. For 00_45_02 the spreading angle increases significantly to between 35 and 40° with the angle increasing as the pressure increases. For 00_00_02 the range is approximately 40–70° at the highest pressure. The general increase in the spreading angle increases with the amount of gasket removed has increased. For the two other groups of inner aspect ratios, 45_**_02 and 70_**_02 the differences are not so dramatic. This could be because there is less in general of the gasket removed. For the 70_**_02 class of gaskets the spreading angles are much more in keeping with those for a round jet throughout the pressure range. For the spreading angle parallel to the flange the range is much smaller, between 9 and 15°. There is much less of a clear pattern for each of the groups of gaskets. For the majority as the pressure increases to 40 psi and above the spreading angle increases.

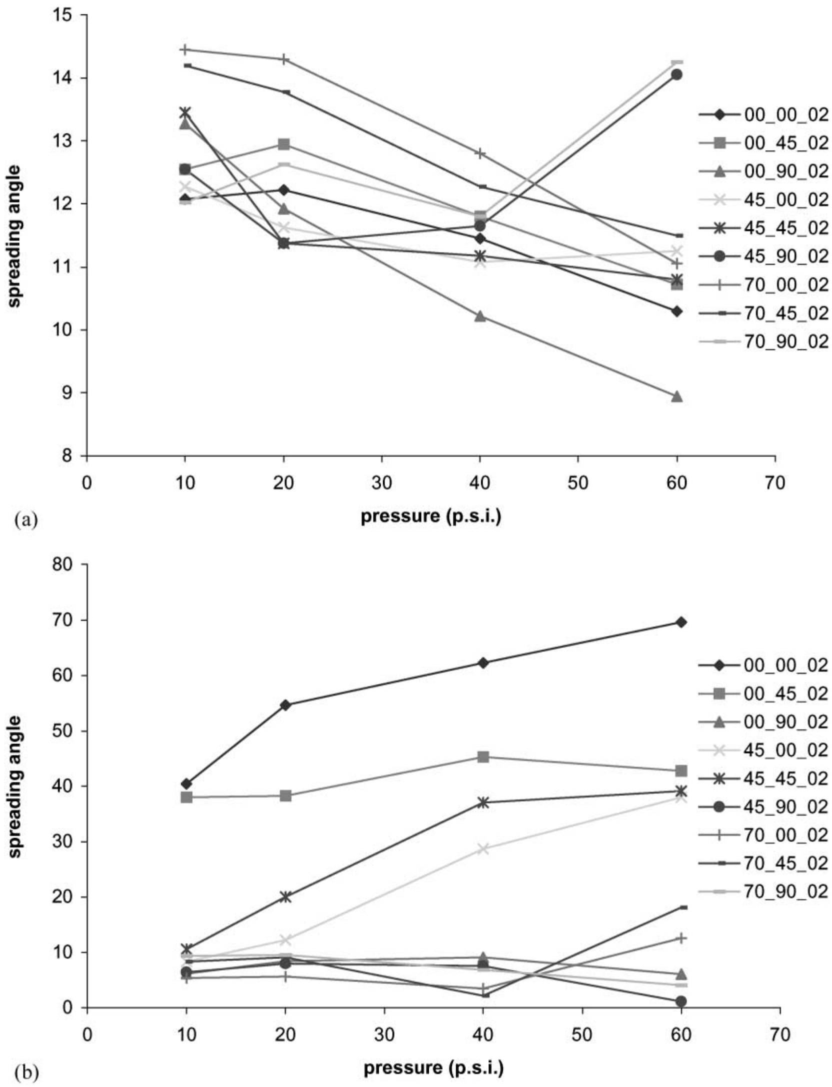


Fig. 7. Spreading angles (a) parallel and (b) perpendicular to the flange.

There are only three possible inner aspect ratios, 26.6:1, 59.8:1 and 119.7:1. In terms of pressure data then 00_90_02 and 00_45_02 can be compared. The difference in the gasket geometry between these is that 00_90_02 has parallel sides, whereas 00_45_02 has diverging sides from inner to outer slot. Fig. 8 shows the centreline velocity decay for three pressure differences. It can be seen that the flow from gasket 00_90_02 follows a very similar path with a defined potential core length. The total rate of pressure decay then increases as the jet enters the characteristic decay region. Again there are no significant changes in the

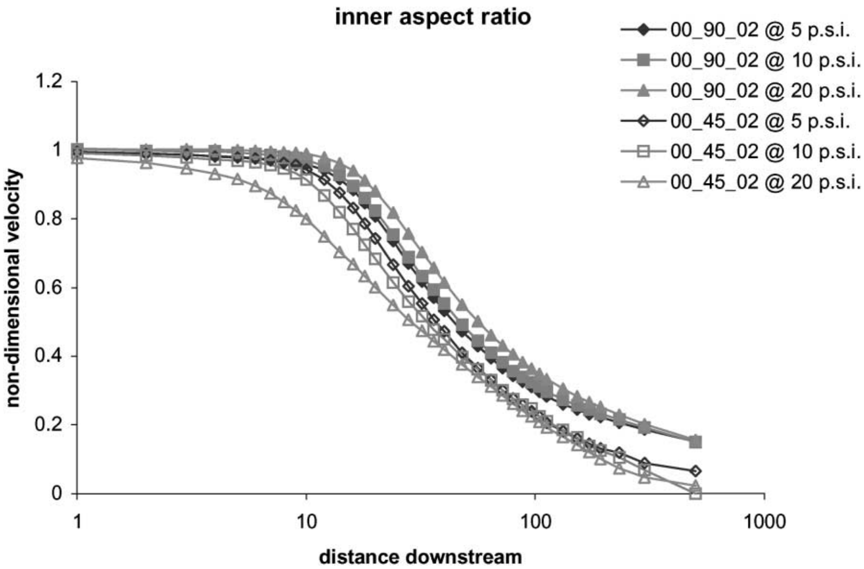


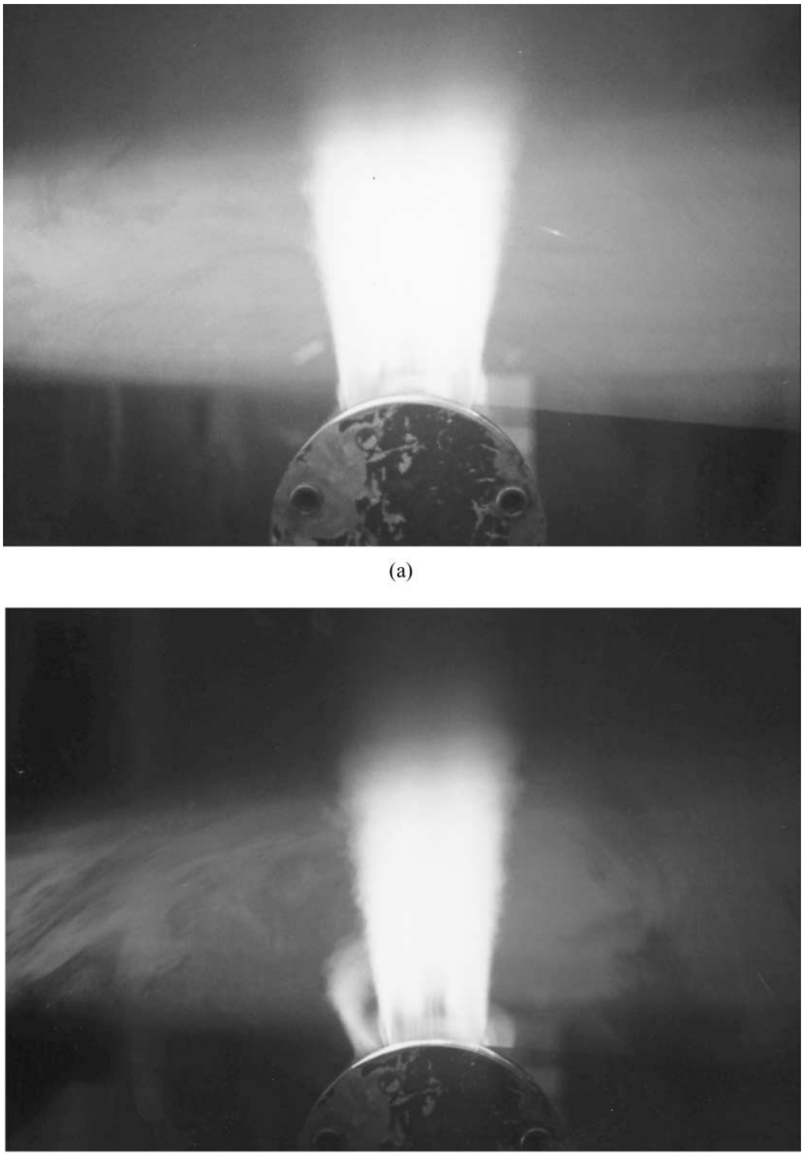
Fig. 8. Centreline velocity decay for three pressure differences.

jet as the nozzle pressure ratio is increased indicating some independence from Reynolds number. For gasket 00_45_02 there is a difference in behaviour. As the pressure increases the potential core region length decreases and the rate of velocity decay does not remain constant. This could indicate that the difference in the geometry from inner to outer slot is causing a decrease in potential core length and decrease in the velocity decay rate. As the pressure increases the decrease in the potential core length could be indicating that the jet is starting within the orifice itself for the 00_45_02 gasket. Therefore, the entrainment of air starts earlier than for the 00_90_02 geometry. In terms of comparison with an axisymmetric jet in general as the pressure increases the potential length is different and the characteristic decay rate shallower.

5.3. Outer:inner aspect ratio

Looking at the ratio between the aspect ratios it can be seen (Fig. 9 (a)–(c)) by comparing the 1:1 ratios (the ** _90_02 class) that again there is little change in shape or behaviour. As this ratio increases to 2:1 (Fig. 10(a) and (b)) there is a vast difference in the look of the jets. For 3:1 ratio, as the pressure increases so does the spreading angle (Figs. 11(a) and (b), and 7(a) and (b)).

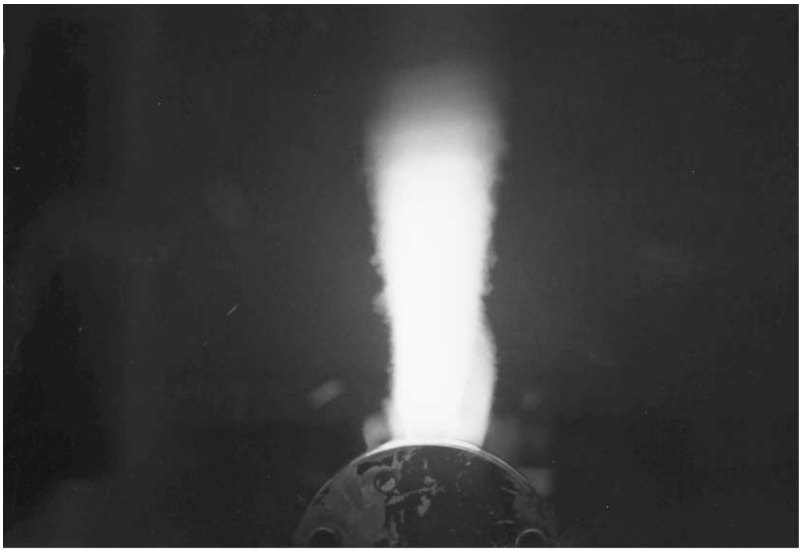
Fig. 12 shows the non-dimensional velocity profiles for an outer:inner aspect ratio of 3:1. It can be seen that as the pressure increases the profiles start diverging in terms of the potential core length. As the distance from the jet increases so there are more distinct differences between the profiles with those at lower pressure and then from the 45_00_02 gasket having a shallower slope.



(a)

(b)

Fig. 9. Time averaged images taken perpendicular to the flange at 40 psi for (a) 00_90_02, (b) 45_90_02 and (c) 70_45_02.



(c)

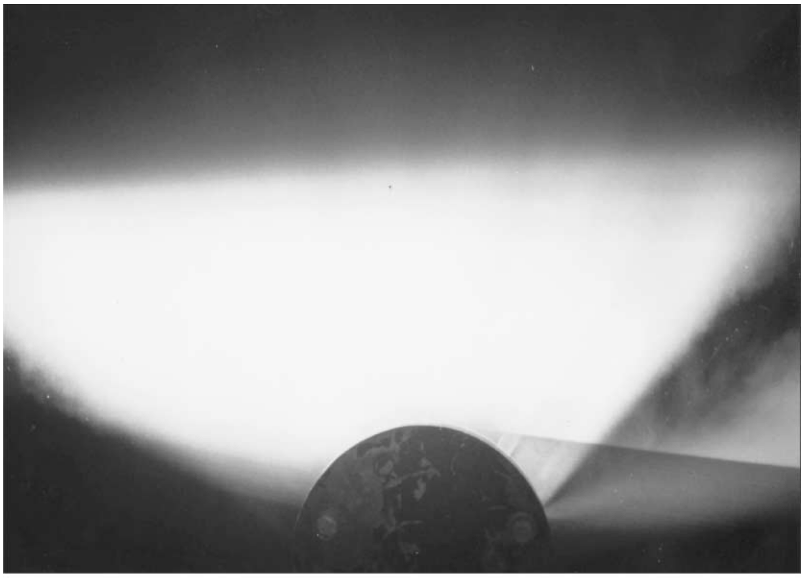
Fig. 9. (*Continued*)

Fig. 13(a) and (b) show velocity decay for two pressures for three gaskets with increasing outer:inner aspect ratios. Gasket 00_90_02 has a 1:1 ratio, 00_45_02 has 1.5:1 and 45_00_02 has a 3:1 ratio. It can be seen that as the pressure and the outer:inner ratio increases the length of the potential core decreases and moves further away from that of an axisymmetric jet. The slope of the decay region also gets shallower.

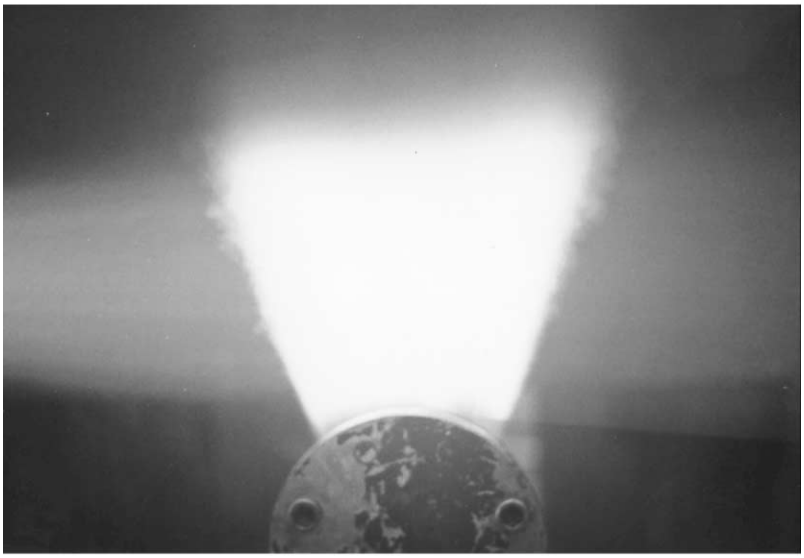
5.4. Orifice shape

Within this investigation there are three different shapes of gaskets; the **_00_02, **_45_02 and **_90_02 families. Looking at the parallel exit gaskets there is little change up to 137.9 kPa for the spreading angle (Fig. 7(a)). Above this exit pressure the flow becomes choked and therefore sonic. The spreading angle then decreases which is suggested to be to allow the static pressure to rise to counteract the overexpansion of the jet. The overexpansion of these jets maybe a result of the geometry restricting all entrainment motion whilst within the flange plates. Interestingly perpendicular to the flange (Fig. 7(b)) although the behaviour is fairly similar up to 137.9 kPa for 00_90_02 with the largest exit the angle decreases but for the other two it increases. For 45_90_02 and 70_90_02 up to 137.9 kPa the behaviour is very different but after choking the behaviour is the same.

The **_45_02 and **_00_02 families follow a similar pattern for both the perpendicular and parallel spreading angles. The spreading angle increases as the pressure increases for the parallel plane with the 70_00_02 and 70_45_02 configurations having the smallest angles and the 00_45_02 and 70_00_02 the largest. This corresponds to the smallest and largest openings in the gasket, respectively. The range is between 5 and 70° in the perpen-

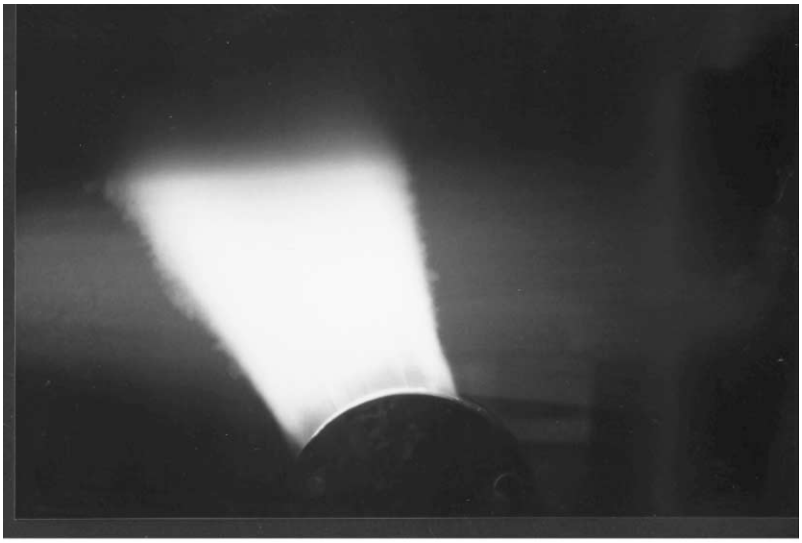


(a)

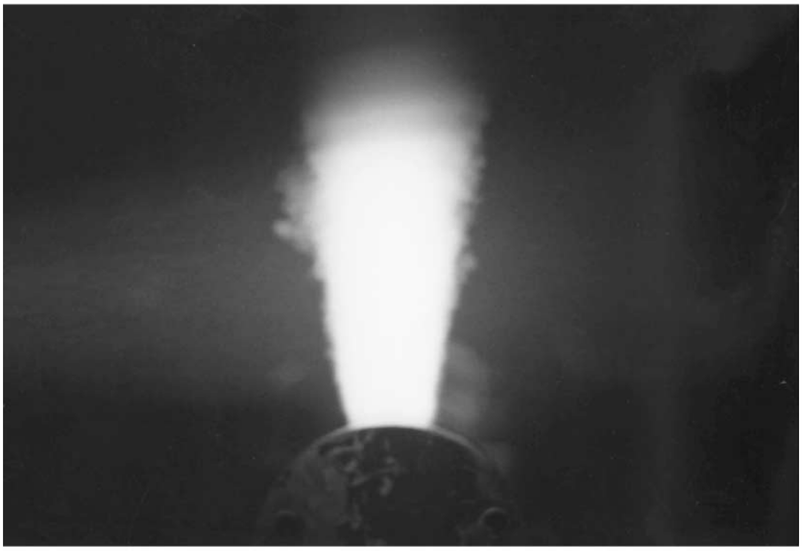


(b)

Fig. 10. Time averaged images taken perpendicular to the flange at 20 psi for (a) 00_00_02 and (b) 45_45_02.



(a)



(b)

Fig. 11. Time averaged images taken perpendicular to the flange at 20 psi for (a) 45_00_02 and (b) 70_45_02.

dicular plane as the pressure increases the spreading angle decreases in these two families of shapes. Here the smallest opening gaskets (70_00_02 and 70_45_02) have the largest angles on the whole. The range of angles is much smaller, between 10 and 15°, that of an axisymmetric jet.

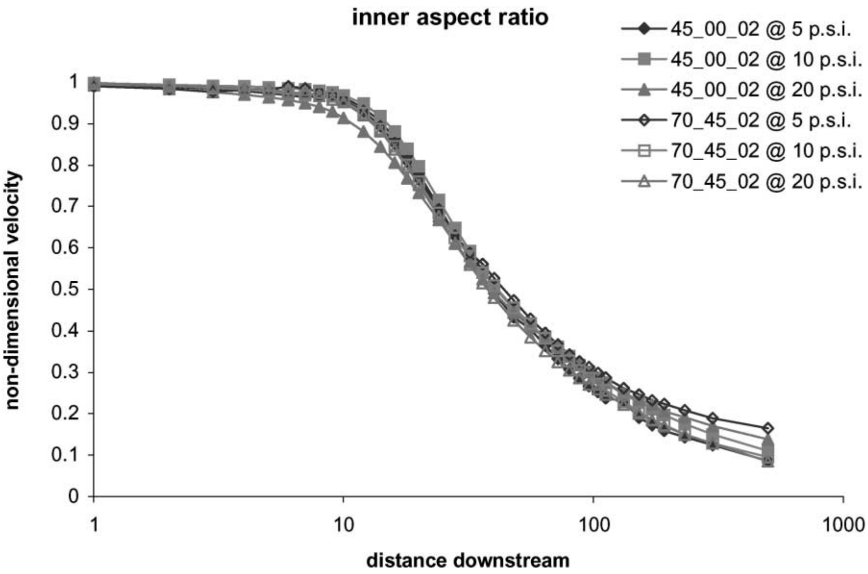


Fig. 12. Non-dimensional velocity data for outer:inner aspect ratio of 3:1.

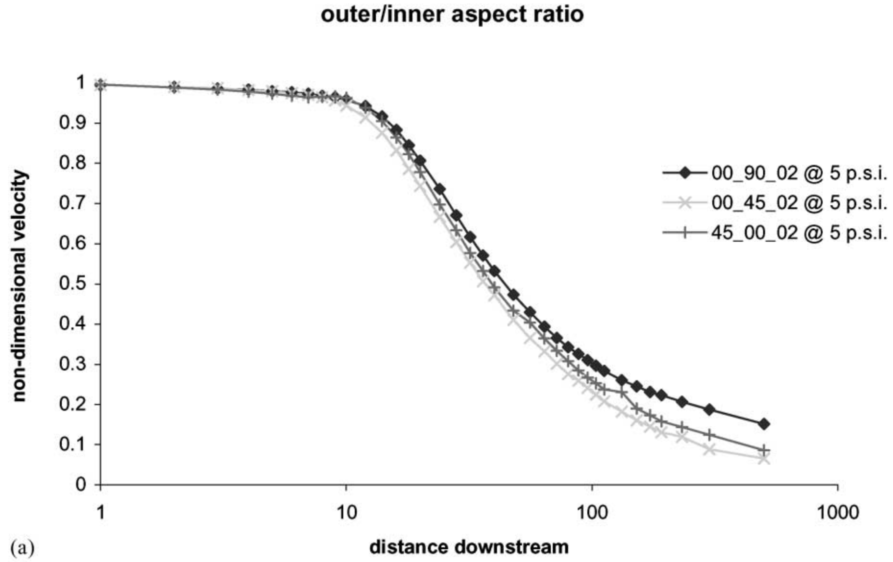
Comparing pressure data for 00_45_02 and 70_45_02 (Fig. 14) the length of the potential core with pressure behaves very differently. For 70_45_02, with a small opening it increases as pressure increases whilst for 00_45_02 it decreases. This indicates that the potential core in these cases cannot be completely independent of the flow Reynolds number. This implication is that as the pressure increases further the profiles will get further away from that of an axisymmetric jet.

5.5. *Reynolds number*

Table 2 shows the cases of approximately the same Reynolds numbers. Looking at the length of the potential core as Reynolds number increases it can be seen that the differences between the lengths reduce (Fig. 15). It can be seen that as the Reynolds number increases differences in the profiles are beginning to be evident. For the spreading angle in the parallel plane the 00_90_02 and 70_45_02 gaskets have very similar angles within the range of a round jet (Fig. 7(b)) but the 45_00_02 at 137.9 kPa is much different. In the perpen-

Table 2
Reynolds numbers of the jets used in the pressure investigations

Approximate Reynolds number		
30,000	40,000	50,000
00_90_02 (34.5 kPa)	00_90_02 (68.9 kPa)	00_90_02 (137.9 kPa)
70_45_02 (34.5 kPa)	70_45_02 (68.9 kPa)	70_45_02 (137.9 kPa)
	45_00_02 (137.9 kPa)	



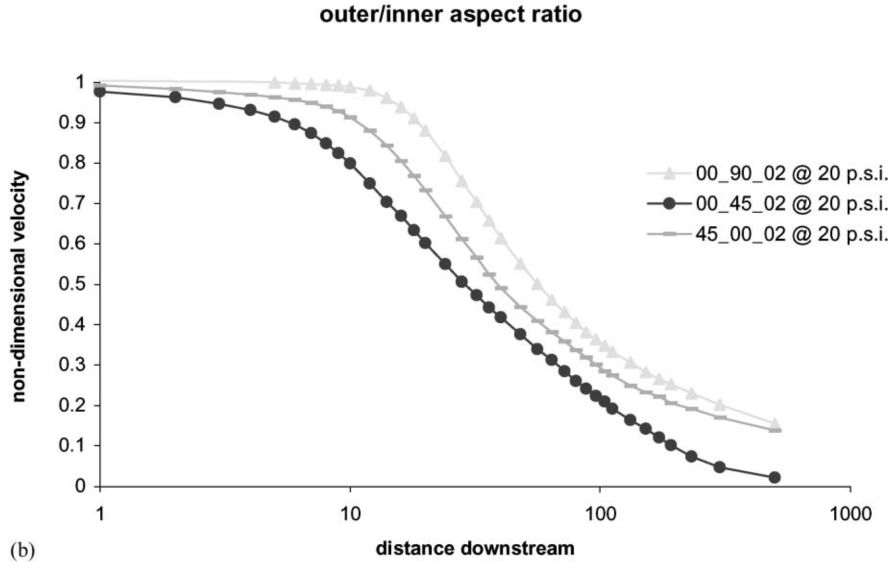
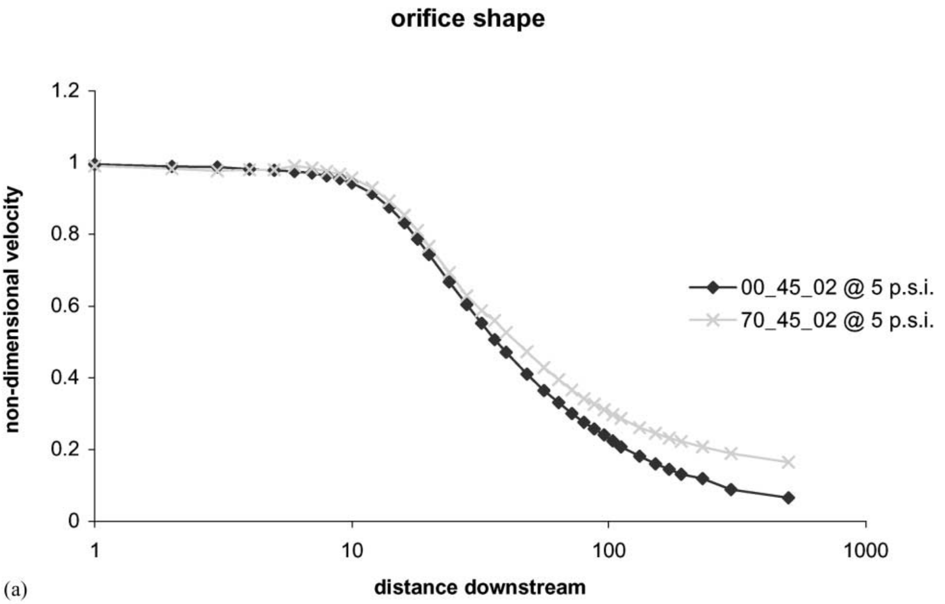
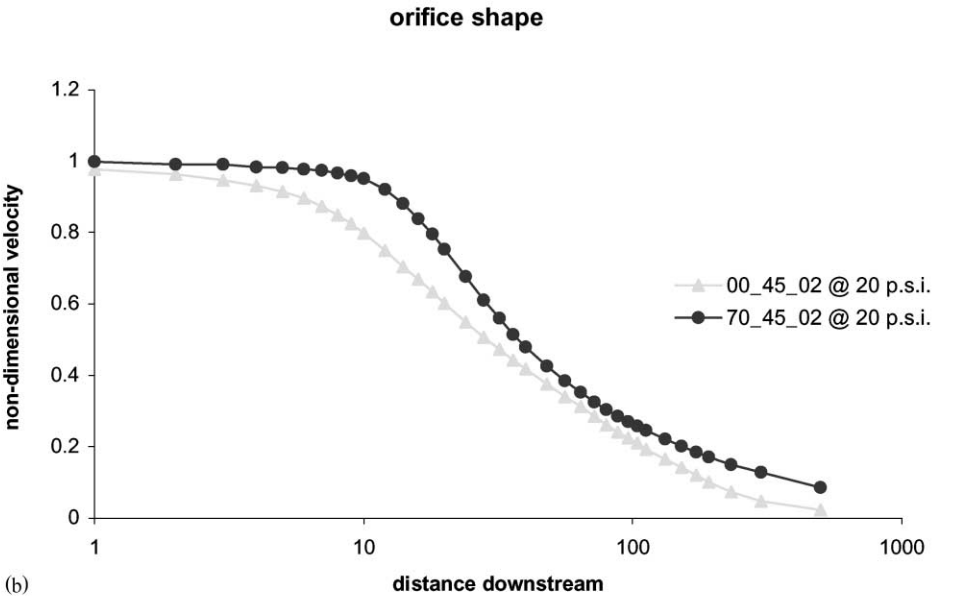


Fig. 13. Non-dimensional velocity for (a) 5 psi and (b) 20 psi for increasing outer:inner ratios of 1:1 (00_90_02), 1.5:1 (00_45_02) and 3:1 (45_00_02).

dicular plane the angles reduce as the Reynolds number increases (Fig. 7(a)). Fig. 16(a) and (b) show mean velocity profiles at 34.5 and 68.9 kPa exit pressure for 00_90_02 and 70_45_02. Only two distances from the jet are taken and it can be seen that the profiles are vastly different. 00_90_02 shows the classic saddleback velocity profile, whereas 70_45_02 does not.



(a)



(b)

Fig. 14. Non-dimensional velocity for (a) 5 psi and (b) 20 psi for the same shape but different aspect ratio orifice shapes.

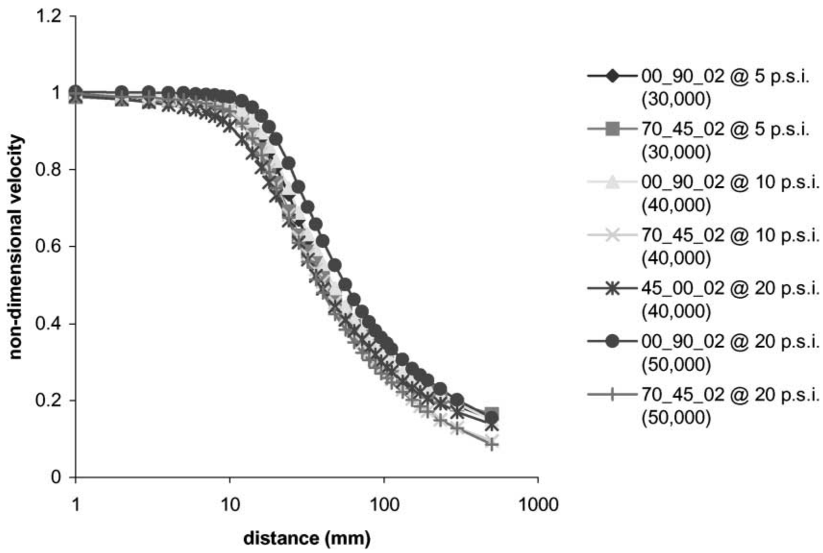


Fig. 15. Non-dimensional velocity distributions for Reynolds number of 30,000, 40,000 and 50,000.

5.6. Mass flow rate

An important consideration in any safety study is the mass flow rate of the leak. Fig. 17 shows the non-dimensional velocity profiles for profiles of approximately different mass flow rates. It can be seen very clearly that for similar mass flow rates the profiles are very different for each profile. The lowest mass flow rate (0.13 kg/s) exhibits the most similar profile and as the mass flow rate increases so does the divergence of the profiles. For 0.23 kg/s mass flow rate the velocity profile span the extremes with different potential core lengths, characteristic decay rates and certainly nothing like an axisymmetric jet. It is recognised that the mass flow rates are much smaller that those that would be found in an offshore pipeline leak but the implication from this work is that as mass flow rate increases the shape of the orifice and aspect ratio has an increasingly profound effect on the jet behaviour.

6. Discussion

It can be seen from the previous section that there are many effects to be considered when assessing the effect of a realistic orifice shape and jet profile on the distribution of hydrocarbons after a leak. The main aim of the paper has been to demonstrate that a high aspect ratio jet behaves very differently from that of an axisymmetric one. This is evident from various measures of a jet such as the spreading angle and centreline velocity decay. It cannot be emphasised enough the importance of getting the behaviour of the jet correct for assessing the levels and distribution of hydrocarbons after a high pressure gas leak onboard an offshore superstructure. Concentration levels are all important, as it is these

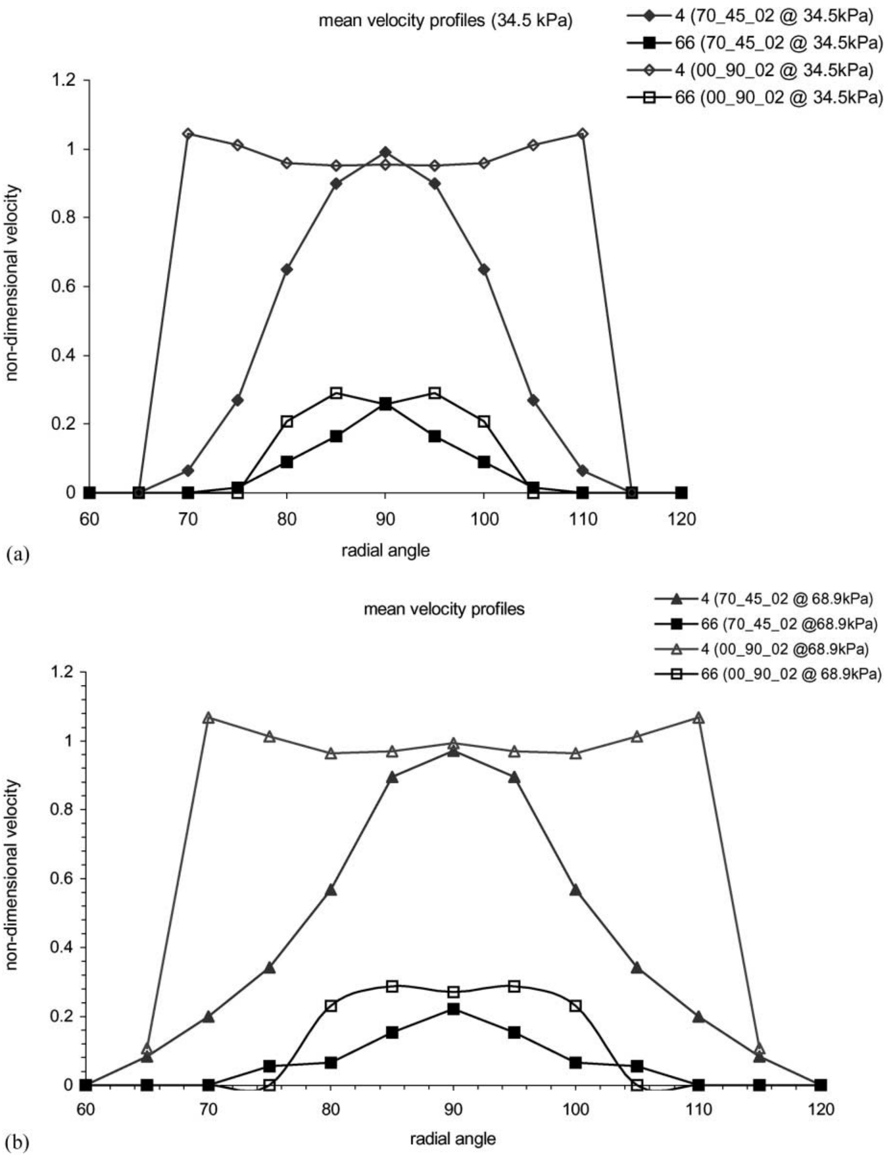


Fig. 16. Mean velocity profile at (a) 34.5 kPa and (b) 68.9 kPa exit pressure.

that determine whether an area is within the upper and lower explosion limits and therefore whether it is at risk of explosion if contact with an ignition source such as hot equipment is likely. It is well known that concentration levels are related to both the Reynolds number and mass flow rates of the leak.

It is not known how a gasket will rupture when a leak occurs; this means that there is no single gasket shape that is a best case. The concern is the levels of concentration that could

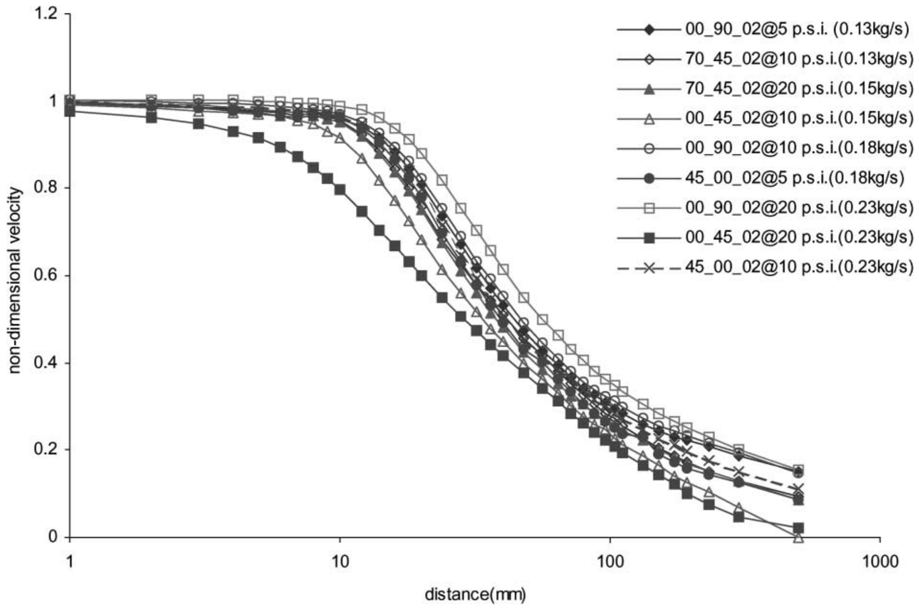


Fig. 17. Non-dimensional velocity distributions for mass flow rates of 0.13, 0.15, 0.18 and 0.23 kg/s.

escape into the atmosphere. Fig. 18 shows the centreline velocity decay comparison for the four gaskets at three pressures with an axisymmetric jet at a Reynolds number of 100,000.

It can be seen that the form of the centreline velocity decay is very different for the axisymmetric jet (Fig. 18). The potential core lengths of some of the gaskets are similar to that of the axisymmetric jet but for the higher pressures the potential core length decreases, significantly in some cases. The other noticeable difference is in the slope of the velocity decay region. This implies that the axisymmetric jet is not entraining as much air as the high aspect ratio jets. This could have a profound effect upon the concentration of hydrocarbons within the jet. The high aspect ratio jets could reach a concentration within the explosion limit much sooner that an axisymmetric jet. It is likely that this trend for the axisymmetric jet will continue as the distance increases from the jet nozzle, beyond where experimental data exists, and there will continue to be a big difference between the velocity decay values. It is therefore unlikely that the rectangular cross-sectional jets will attain the velocity decay of an axisymmetric jet as assumed. It has already been seen that in many cases the spreading angle of the jets is much greater than for that of a classic axisymmetric jet and also tends to increase with pressure. This reinforces the idea that it is more probable that such jets will encounter objects within the area of the leak that could cause ignition of the cloud of hydrocarbons. This comparison between the standard shape jet used for many safety studies and a more realistic orifice shape highlights the significance of using a more correct model, as the consequences could be dire.

It has been seen that there are many factors that influence the spreading and decay rate of the jet. These include the shape and size of the orifice and the relation between the size of the inner and outer slots within the gasket. In many of these cases the Reynolds number and

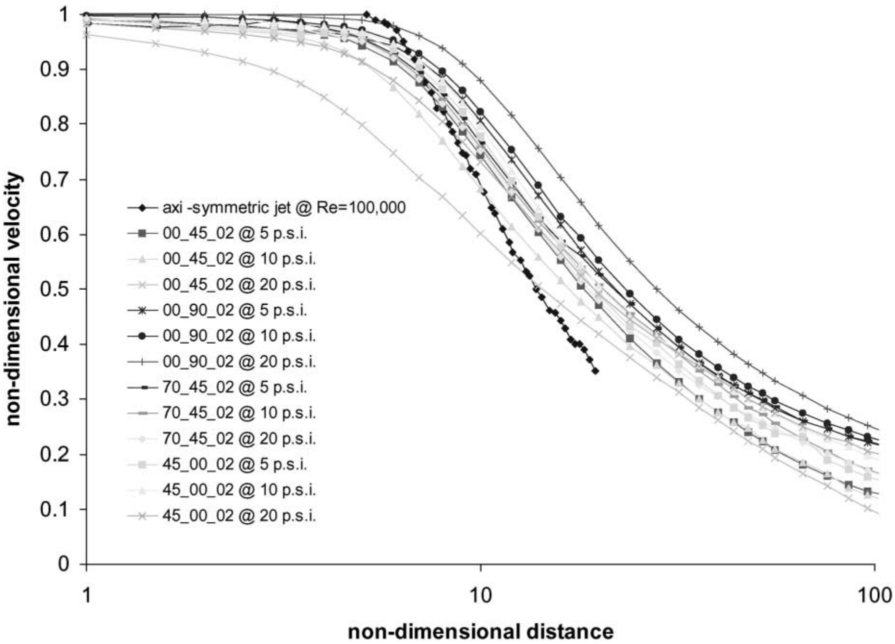


Fig. 18. Centreline velocity decay for all four gaskets and an axisymmetric jet [29].

mass flow rate also affect the behaviour of the flow. In determining concentration factors such as the entrainment process and whether shock waves are present can also be a factor.

Concentration decay is known to be a direct function of the velocity decay in a jet. When comparing the centreline decays of the present study with those of axisymmetric jets it is seen that from Fig. 18 that all of the cases studied have lower velocity decay rates. The implication of the use of axisymmetric jets for safety studies may not be a conservative measure. The present results suggest that realistic leak geometries are necessary in order to ensure conservatism in estimating LEL locations.

7. Conclusions

Current offshore safety models have an inherent weakness in that they do not take proper account of the nature of the gas leaks. This work addresses one of the many aspects of modelling of gas leaks that has been neglected, that of the effect of the aspect ratio and shape of the jet orifice. Computational modellers should beware of treating all gas leaks as axisymmetric jets as this is likely to predict concentration levels that could underestimate the time to LELs within an offshore safety analysis.

The following specific conclusions can be drawn from this work:

- A high aspect ratio jet behaves in a very different way to that of an axisymmetric jet even far downstream.

- There is a range of spreading angles for the geometries studied that in many cases do not correspond to that for an axisymmetric jet.
- The classic saddleback velocity profile has been found but only for certain geometries.
- The orifice geometry in the streamwise direction was found to have an effect. Even for the same mass flow rate, the velocity decay behaviour was affected by streamwise orifice changes. This was found to be more significant at higher mass flow rates.
- There is a minor Reynolds number only effect upon the centreline velocity decay profile.
- In the plane parallel to the flange low frequency oscillations were observed in many of the jets.
- In the parallel plane to the flange the gulping of entrained air could be observed, causing uneven concentration levels of leaked gas within the jet, especially at the edges.
- At higher pressure and with parallel-sided gaskets possible shock waves were observed within the jet. These can cause uneven concentrations of leaked gas within the jet.
- The gasket shape is an important factor in the behaviour of the jet.

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