DISPLACEMENT OF GAS FROM A RUPTURED CONTAINER AND ITS DISPERSAL IN THE ATMOSPHERE

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SYNOPSIS

Many industrial processes involve the storing of large quantities of gases, sometimes at high pressures. These gases may be toxic or may be flammable when mixed with air and their accidental release may produce a considerable hazard.

The paper considers the discharge from a high-pressure container when a break occurs in the pipe system attached to the container. The mixing of the gas with the atmosphere during this discharge is considered.

When the pressure in the container reaches the atmospheric pressure (or when a container is already at atmospheric pressure), gas displacement may take place under the action of buoyancy. The paper considers these buoyancy-driven flows which lead to gas being displaced from the container with ingress of air into the container. The difficulties of estimating the dispersion of the released gases around the plant site are discussed.

Introduction

Many industrial processes involve the storage of large quantities of gases, sometimes at high pressure. The gases may be toxic or may be flammable when mixed with air and their accidental release may produce a considerable hazard. When designing a plant in which gases will be stored, consideration will naturally be given to the possibility of accidental release of this kind and to the consequences of it.

If a gas is stored at high pressure and some breach of the container occurs, the gas will be discharged through the breach until the pressure reaches atmospheric pressure; it may be useful to be able to estimate the time taken to discharge the gas. If there is a valve between the breach and the container, it is possible to estimate the amount of gas that would be discharged in the time taken to close the valve. It may be necessary for men to approach the breach and hence some estimate of the concentrations likely to be found around the plant would be useful. This, however, is a very difficult problem to consider in general terms.

If the gas in a container is not at high pressure (or has reached atmospheric pressure), further displacement of gas may take place if the density of the gas differs from that of the surrounding atmosphere. It is possible for buoyancy-driven flows to be set up which will cause gas to be displaced from the container with ingress of air. This can lead to hazards outside the container and can produce dangerous conditions inside the container.

Discharge of Gas from a High-pressure Container

Basic results

If a vessel containing gas under high pressure should rupture over a large area of the vessel, the discharge would be extremely rapid. Techniques similar to those used by Woods and Thornton[1] would have to be used to describe the resulting flow and it would be necessary to consider three-dimensional flows. Here we are concerned with a container with pipes connecting it to other parts of the plant; we consider what would happen if one of the pipes was breached. The flows described by Woods and Thornton[1] correspond to the starting flow in our system. However, the flows we are considering in this section take place over times that are long in comparison with the duration of the initial unsteady flow, and we regard the flows as quasi-steady, that is, the steady-flow equations hold at any time.

We shall also restrict consideration to pressures in the plant greater than about two atmospheres (that is, pressures for which the flow through the breach will be sonic. The exact pressure at which flow ceases to be sonic will depend on the ratio of specific heats of the gas concerned). To calculate the flow for any breach would require a knowledge of the shape and size of the hole which, of course, are unknown. We have, therefore, assumed that the pipe is severed completely and that the pipe cross-sectional area is the smallest cross-section of the system being considered; this is likely to give the most rapid discharge of gas from the container.

In deriving the equations it has been assumed that the perfect-gas laws are obeyed and that the flow is isentropic and quasi-steady. The system considered is that of a container of volume, V, discharging through a minimum area, A_1 (the throat of the system). As long as the pressure in the container is above some critical value, the flow speed at the throat will be sonic and the mass flow will be determined by the sonic speed (Shapiro[2]).

The mass flow, q, through the nozzle is given by:

$$q = \rho_1 u_1 A_1 \qquad (1)$$

where u is the flow velocity, ρ the density and the subscript "1" refers to conditions at the throat. But the flow speed at the throat is sonic, and equation (1) may be written:

$$q = K_1 A_1 \rho a \qquad (2)$$

where:

$$K_1 = \frac{\rho_1}{\rho} \frac{a_1}{a}$$

and a is the speed of sound. Variables without subscripts refer to conditions in the container at any time, t.

Now:

$$a^2 = \gamma \frac{p}{\rho}$$

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where p is the pressure and γ the ratio of specific heats, and by making use of the equation of state:

$$p = \rho R T \quad . \quad . \quad . \quad (3)$$

equation (2) may be written:

$$q = K_2 A_1 \frac{p}{T^{\frac{1}{2}}} \quad . \quad . \quad . \quad (4)$$

where:

$$K_2 = K_1 \left(\frac{\gamma}{R}\right)^{\frac{1}{2}}$$

and R is the gas constant.

If conditions are governed by an adiabatic process, then:

$$p = B\rho^{\gamma} \quad . \quad . \quad . \quad (5)$$

where B is a constant.

Differentiating with respect to time and making use of equation (3) yields:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \gamma R T \frac{\mathrm{d}\rho}{\mathrm{d}t} \quad . \quad . \quad (6)$$

The mass of gas in the cylinder is ρV and hence the rate of discharge is:

$$-\frac{\mathrm{d}(\rho V)}{\mathrm{d}t}\,.$$

Thus:

$$q = -V\frac{\mathrm{d}\rho}{\mathrm{d}t} \quad . \quad . \quad . \quad (7)$$

Hence equation (6) may be written:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = -\frac{\gamma R T}{V} q \quad . \quad . \quad (8)$$

Using equations (3), (4), and (7) it can be shown that:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{p}{T}\frac{\mathrm{d}T}{\mathrm{d}t} - RK_2 \frac{A_1}{V} pT^{\frac{1}{2}} \quad . \quad . \quad (9)$$

Combining equations (9) and (8) yields:

$$(1-\gamma) RK_2 \frac{A_1}{V} \mathrm{d}t = \frac{\mathrm{d}T}{T^{\frac{3}{2}}} \quad . \quad . \quad (10)$$

This may be integrated with the boundary condition $T = T_0$ at $t = 0$ to give:

$$\frac{T}{T_0} = \left(\frac{\gamma-1}{2} RK_2 \frac{A_1 T_0^{\frac{1}{2}}}{V} t+1\right)^{-2} \quad . \quad (11)$$

where T_0 is the initial temperature in the container.

Since the process is assumed adiabatic:

$$\frac{T}{T_0} = \left(\frac{p}{p_0}\right)^{\gamma-1/\gamma} \quad . \quad . \quad (12)$$

Hence:

$$\frac{p}{p_0} = \left(\frac{\gamma-1}{2} RK_2 \frac{A_1 T_0^{\frac{1}{2}}}{V} t+1\right)^{-2\gamma/\gamma-1} \quad . \quad (13)$$

It can be shown that:

$$T_0^{\frac{1}{2}} RK_2 = a_0 \frac{\rho_1}{\rho} \frac{a_1}{a}$$

Therefore equation (13) becomes:

$$\frac{p}{p_0} = \left(\frac{\gamma-1}{2} \frac{\rho_1}{\rho} \frac{a_1}{a_0} \frac{A_1 a_0}{V} t+1\right)^{-2\gamma/\gamma-1} \quad . \quad (14)$$

The mass of gas, M, in the container at time t is given by:

$$M = \rho V \qquad (15)$$

Using equations (5) and (14), this may be written as:

$$\frac{M}{M_0} = \left(\frac{\gamma-1}{2} \frac{\rho_1}{\rho} \frac{a_1}{a} \frac{A_1 a_0 t}{V} +1\right)^{-2/\gamma-1}. \qquad (16)$$

Using equations (4), (12), and (14) the mass flow may be written as:

$$\frac{q}{a_0 \rho_0 A_1} = K_1\left(\frac{\gamma-1}{2} K_1 \frac{A_1 a_0}{V} t+1\right)^{-\gamma-1/\gamma-1} \qquad (17)$$

Discussion of the results

The results obtained above hold for internal pressures great enough to maintain sonic flow through the throat. The sonic-flow regime will break down when the internal pressure becomes less than that given by:

$$\frac{p}{p_2} = \left(\frac{\gamma+1}{2}\right)^{\gamma/\gamma-1} \quad . \quad . \quad . \quad (18)$$

where p_2 is the atmospheric pressure (see, for example, Shapiro, *1953*).

For air, with $\gamma = 1{\cdot}4$, the critical pressure given by equation (18) is:

$$\frac{p_0}{p_2} = 1{\cdot}893$$

If τ is the time required to reach this pressure, substitution in equation (14) yields:

$$\frac{p_0}{p_2} = \left(0{\cdot}127 \frac{a_0 A_1}{V} \tau+1{\cdot}095\right)^7 \quad . \quad (19)$$

This relation is shown in Fig. 1 for a range of pressures up to 200 atmospheres.

When the sonic-flow regime breaks down the gas will continue to discharge from the container but at subsonic velocities. The original mass of gas in the container is given by:

$$M_0 = \rho_0 V = B p_0^{5/7} V$$

When the critical pressure is reached, the mass remaining, M_c, is:

$$M_c = B_1(1{\cdot}893 p_2)^{5/7}$$

Hence:

$$\frac{M_c}{M_0} = \left(1{\cdot}893 \frac{p_2}{p_0}\right)^{5/7}$$

For a container originally at a pressure of 60 atmospheres, for example:

$$\frac{M_c}{M_0} = 0{\cdot}085$$

so that for this initial pressure the amount of gas remaining in the container is small compared with the initial mass.

Provided the initial pressure is not too small, it can be shown that most of the gas is discharged before the subsonic flow is established. Hence the time given by combination of equation (18) and equation (14) will give the time of sonic discharge of gas from the container. For a container filled

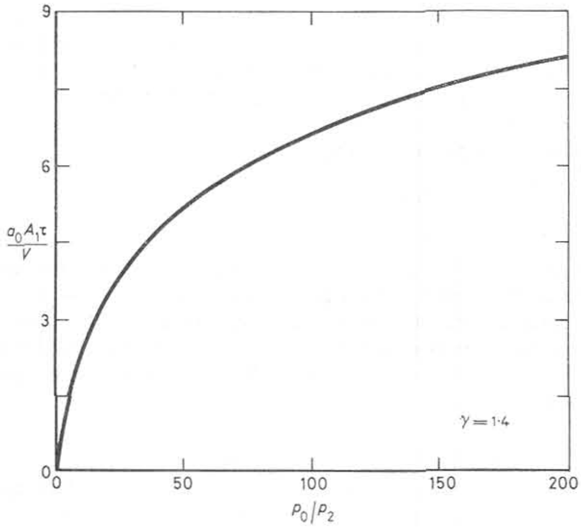

Fig. 1.—*The time of discharge of a high-pressure container*

to 50 atmospheres with gas having $\gamma = 1{\cdot}4$, from Fig. 1:

$$\frac{a_0 A_1 \tau}{V} = 5{\cdot}2$$

and τ can be deduced from this as follows:
If the container has a sphere of 10 m diameter and a breach occurs in a 0·5 m diameter pipe, then:

$$\tau = 50{\cdot}4 \text{ s}$$

assuming $a_0 = 1100$ ft/s, that is a temperature of 18°C.

Hence remedial action would have to be taken in much less than 50 s if most of the gas was not to be released into the atmosphere.

Figure 2 shows a similar graph for time of discharge for a gas, but with $\gamma = 1{\cdot}28$ and for a pressure range up to 30 atmospheres. For a container at 10 atmospheres:

$$\frac{A_1 a_0 \tau}{V} = 2{\cdot}5$$

Consider a spherical container of diameter 20 m, containing gas at 390°C and at 10 atmospheres, with a breached pipe 1·5 m diameter. Then:

$$\tau = 15{\cdot}3 \text{ s (taking } a_0 = 387 \text{ m/s),}$$

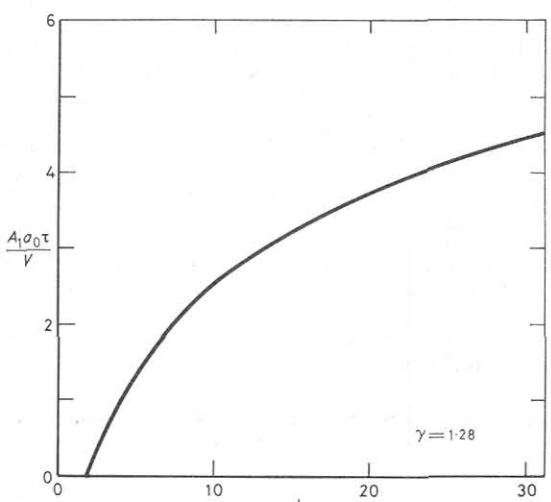

Fig. 2.—*The time of discharge of a high-pressure container*

that is, most of the gas would be discharged in about 15 seconds.

In the above examples it has been assumed that the throat area is equivalent to the area of the breached pipe. However, unless there are fairly good entry conditions into the breach, the flow area will be somewhat less than the actual pipe area. Some small-scale experiments suggest that a discharge coefficient of about 0·62 should be used, *i.e.*, the throat area should be taken as 0·62 of the actual breached area. This figure was arrived at by comparing the measured fall in pressure as a function of time, with a pressure-time curve calculated from equation (14). Taking this discharge coefficient into account in the above example, the discharge time is increased to 25 s.

Dispersal in the atmosphere

As the gas is discharged from the breached pipe it mixes with the surrounding atmosphere. During the discharge described in the " Basic results " section the gas emerges from the pipe as a turbulent sonic jet and conditions in the container are changing with time. Hence we need to consider the mixing of unsteady turbulent sonic jets with an atmosphere which may be calm or windy. This is a very difficult problem and as a first step a steady turbulent sonic jet issuing from a duct 45 m above the ground has been considered. The calculations (to be published elsewhere) suggest that the maximum ground-level concentration will be of the order of one *per cent*.

The disperal in the atmosphere will be complicated if there are buildings in the vicinity of the breached pipe. Some work on this is proceeding but it seems unlikely that any general rules can be established, If detailed answers are required it may be necessary to resort to testing models of the site in a wind-tunnel. But even then there will be difficulties in the scaling of a turbulent jet issuing from the pipe.

Buoyancy-driven Flows

In previous sections of this paper we considered the displacement of gas from a ruptured pressure vessel. When the gas in the container reaches atmospheric pressure it is still possible for more gas to be released if the density of the gas remaining in the container is different from that of the surrounding atmosphere. The flow set up depends upon the density difference and not upon whether the container was originally pressurised or not. The flow differs fundamentally from that discussed previously since there is a flow of air into the container which replaces the gas flowing out of it.

To fix our ideas, consider the system shown in Fig. 3. Let us assume that the pipe connecting the container to the rest of the plant is breached at A, thus connecting the container to the atmosphere. We also assume that the gas in the container is more dense than the surrounding atmosphere and that the pipe is horizontal. Experiments show us that a flow is set up as is shown diagrammatically in Fig. 4. The heavy gas flows out along the bottom of the pipe and air flows in along the top. Some mixing of the two streams takes place across the interface. So far, only crude theories of this type

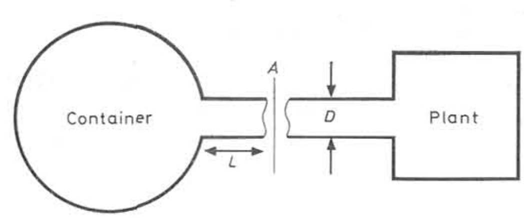

Fig. 3.—*Geometry of the case of buoyancy–driven flows*

Fig. 4.—*Flow in breached duct*

of flow have been developed but a dimensional analysis of the problem indicates the factors on which the flows would be expected to depend. The independent variables of the problem are ρ, the density of the heavy gas, ρ_2, the air density, ν and ν_2, the kinematic viscosity of the gas and air respectively, D and L, the diameter and length of pipe respectively, K, a length scale of the roughness of the pipe, and g, acceleration due to gravity. If we choose the volume flow-rate, Q, as the dependent variable, then Q may be expressed as:

$$Q = f_1(\rho, \rho_2, \nu, \nu_2, D, L, K, g)$$

Applying dimensional analysis techniques this may be re-written as:

$$\frac{Q}{\sqrt{(gD^5)}} = f_2\left[\frac{\Delta\rho}{\rho}, \frac{L}{D}, \frac{K}{D}, \frac{(gD^3)^{\frac{1}{2}}}{\nu} \frac{(gD^3)^{\frac{1}{2}}}{\nu_2}\right] \quad (20)$$

where:

$$\frac{\Delta\rho}{\rho} = \frac{\rho-\rho_2}{\rho}$$

The last two terms in function f_2 are Reynolds numbers and if they are large enough should not affect the flow-rate too much. The effects of K/D are thought to be small (as in the friction due to interfacial mixing). Hence equation (20) may be reduced to:

$$\frac{Q}{\sqrt{(gD^5)}} = f_3\left(\frac{\Delta\rho}{\rho}, \frac{L}{D}\right) \quad . \quad . \quad (21)$$

Experiments have been used to find the form of the function f_3. These experiments have been reported in S.M.R.E. Annual Reports.[3] They used a sealed box, about one metre cube containing brine to represent the container and its heavy gas. The cube was connected by a pipe to an open tank of water (representing the atmosphere). The brine was allowed to flow under gravity out of the box; water flowed into the box to replace it. The rate of flow was obtained from measuring the rate of change in the mass of the sealed box. By using various pipes, they covered a range of L/D from 0·5 to 20 and obtained for equation (21):

$$Q = 0{\cdot}1\left(g\frac{\Delta\rho}{\rho}D^5\right)^{\frac{1}{2}} \quad . \quad . \quad (22)$$

This expression is independent of L/D in the range 0·5 to 20.

The above result applies to horizontal pipes only. The work is being extended by A. Mercer at the Safety in Mines Research Establishment, Sheffield, to include inclined pipes and will be reported in due course. So far the results indicate that the maximum flow-rate is obtained at an inclination of about 10 to 15° to the horizontal, but in general the flow-rates are less than those through horizontal ducts. They now appear to show some dependence on L/D.

Discussion of the results

Equation (22) allows us to calculate the volume flow of gas out of the container. Since the container is sealed, apart from the breach being considered, this flow-rate is also the volume flow of air into the container.

If we consider a 1 m duct with:

$$\frac{\Delta\rho}{\rho} = 0{\cdot}2, \text{ then } Q = 0{\cdot}14\,\text{m}^3/\text{s}.$$

Hence 0·14 m^3/s of air would be flowing into the container with displacement of gas out of the container at the same rate. Of course with larger ducts much larger flow–rates are obtained. For example, with a duct three metres in diameter and with a relative density difference of 0·4, the flow-rate is about 3·1 m^3/s.

Dispersal in the atmosphere

The gas displaced from the container by the buoyancy-driven flow will be dispersed in the atmosphere. As with the dispersion mentioned in the second section, the effect of buildings and the condition of the atmosphere need to be taken into account. At a large distance from the source the usual type of diffusion equation may be applied (see, for example, Pasquill,[4] and Scorer.[5] A good summary and details of calculations are given in Smith[6]).

In the vicinity of the source the usual equations may not apply. Apart from the presence of buildings, the geometry of the breach and the density of gas affect the mixing with the atmosphere. Experiments in the laboratory have indicated that given ground concentrations can be obtained at different distances depending on the source geometry (S.M.R.E. Annual Report 1969).[7] Little work appears to have been done on the effect of the source geometry and the density of gas issuing from the source upon the mixing of gas with the atmosphere. The work at S.M.R.E. on the detailed structure of layers mixing with flows of different density should provide some of the information required for this consideration.

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