Designing piping for gravity flow

Gas entrained in liquid flowing by means of gravity from a vessel can reduce the outlet pipe's capacity and cause flow to surge cyclically. These problems can be avoided by carefully designing for either full-liquid or two-phase flow.

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☐ Entrainment curtails liquid gravity flow from vessels by raising the pressure drop (above that for single-phase flow) through the outlet piping, and reducing the static head available for overcoming the pressure drop. A similar problem can arise when a liquid is near its boiling point, or contains dissolved gas, especially if the absolute pressure at any point in the piping falls below atmospheric pressure, as occurs in a syphon.

Consider the case of liquid flowing from the bottom of an absorption column through a pipe that has been sized for full liquid flow (Fig. 1).

When the liquid level in the column is low enough, the liquid entrains gas (Fig. 1a). The resulting increase in pressure drop and reduction of head restrict the flowrate, and the liquid level rises (Fig. 1b). Eventually, the level rises high enough to stop entrainment (Fig. 1c). However, gas still in the outlet pipe causes the level to continue to rise until the gas is all swept out (Fig. 1d). Now, the outlet pipe is running full flow (as was assumed in the design), but the static head, becoming higher than was assumed, creates excessive flow, which causes the level to fall until entrainment occurs again and the cycle is repeated (Fig. 1e).

Such oscillations can be severe, depending on system geometry. In one case, the peak flow from a tank exceeded the capacity of the vacuum breaker sufficiently to collapse it.

General expression for liquid flowrate

In this article, liquid flowrates are generally expressed in terms of a dimensionless superficial volumetric flux, J_L^*, which is defined by:

$$J_L^* = 4Q_L/\pi d^2(gd)^{1/2} \qquad (1)$$

Here, Q_L is the volumetric flowrate; d is the pipe I.D.; and g is the gravitational acceleration. Eq. (1) is similar to the Froude number. It is used in preference to the Froude number, because the latter's definition varies, depending on circumstances. All equations in this article are in consistent units.

Designing for gravity flow

Three approaches to the design of gravity drainage systems are possible:

1. For full flow, with the outlet piping size based on single-phase criteria.
2. For self-venting, with the liquid velocity in the outlet pipe kept low enough to allow gas to flow countercurrently to the liquid.
3. For gas entrainment, but with the system designed to accommodate it.

In general, the first approach can be expected to result in the smallest pipe diameter and should be given preference. However, in many instances, it is not possible to ensure full pipe flow—in which case, the alternatives may have to be adopted.

Designing for flooded flow

To avoid gas entrainment in the full-pipe-flow design, the liquid level in the vessel must always be high enough to keep the pipe inlet flooded. To achieve this, some form of control will be necessary, such as via a control valve (Fig. 2a) or a vertical loop in the piping (Fig. 2b). If the latter is used, a syphon break will be necessary (shown in Fig. 2b), and the piping downstream of the syphon break cannot be assumed to run flooded because gas is likely to be entrained at the syphon break. Of course, either arrangement will increase the system pressure drop and reduce somewhat the benefits of the flooded-flow design.

Single-phase criteria can be applied to designing sections of outlet piping in which flow can be expected to be flooded. If piping that is certain to be flooded is preceded by a self-venting section, the self-venting section's minimum length should be 0.5 m, to provide for gas disengagement, before the piping is reduced for single-phase flow (Fig. 2c).

The criteria for flooded outlets are Eq. (2) for outlets from the base of vessels, and Eq. (3) for outlets from the side of vessels:

$$J_L^* < 1.6(h/d)^2 : h > 0.892[(Q_L)^2/gd]^{0.25} \qquad (2)$$

Here, h is the liquid depth in the vessel away from the region of the outlet.

$$J_L^* < (2h/d)^{1/2} : h > 0.811(Q_L)^2/gd^4 \qquad (3)$$

Here, h is the liquid height above the top of the outlet away from the region of the outlet.

Designing unflooded (self-venting) piping

Side-outlet piping—Coming off from the side of a vessel, piping should be sized such that:

d = mm
Q = m³/h

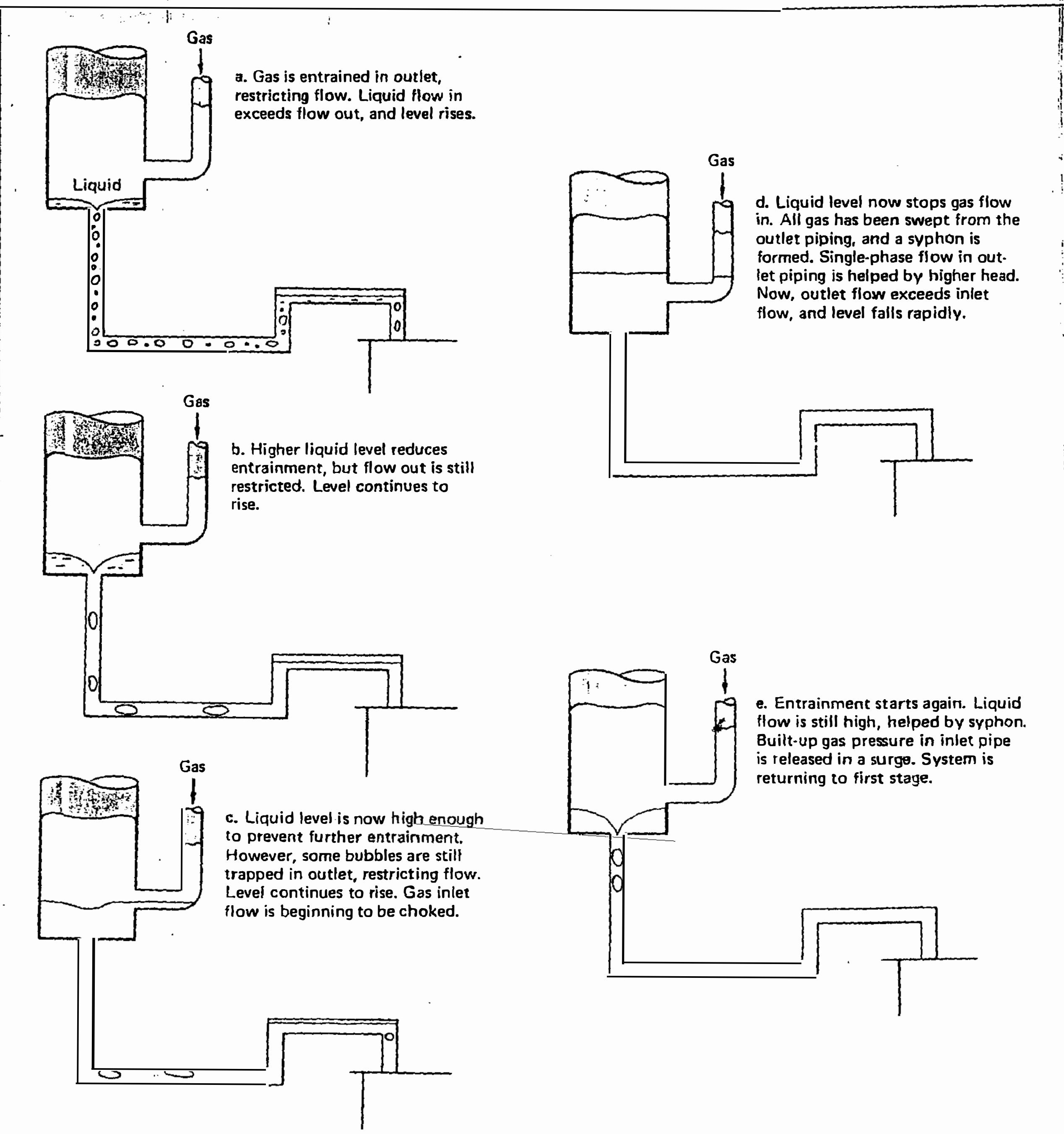
$$J_L^* < 0.3: d > (4Q_L/(0.3\pi g^{1/2}))^{0.4} \qquad (4)$$

$d = 43Q^{0.4}$

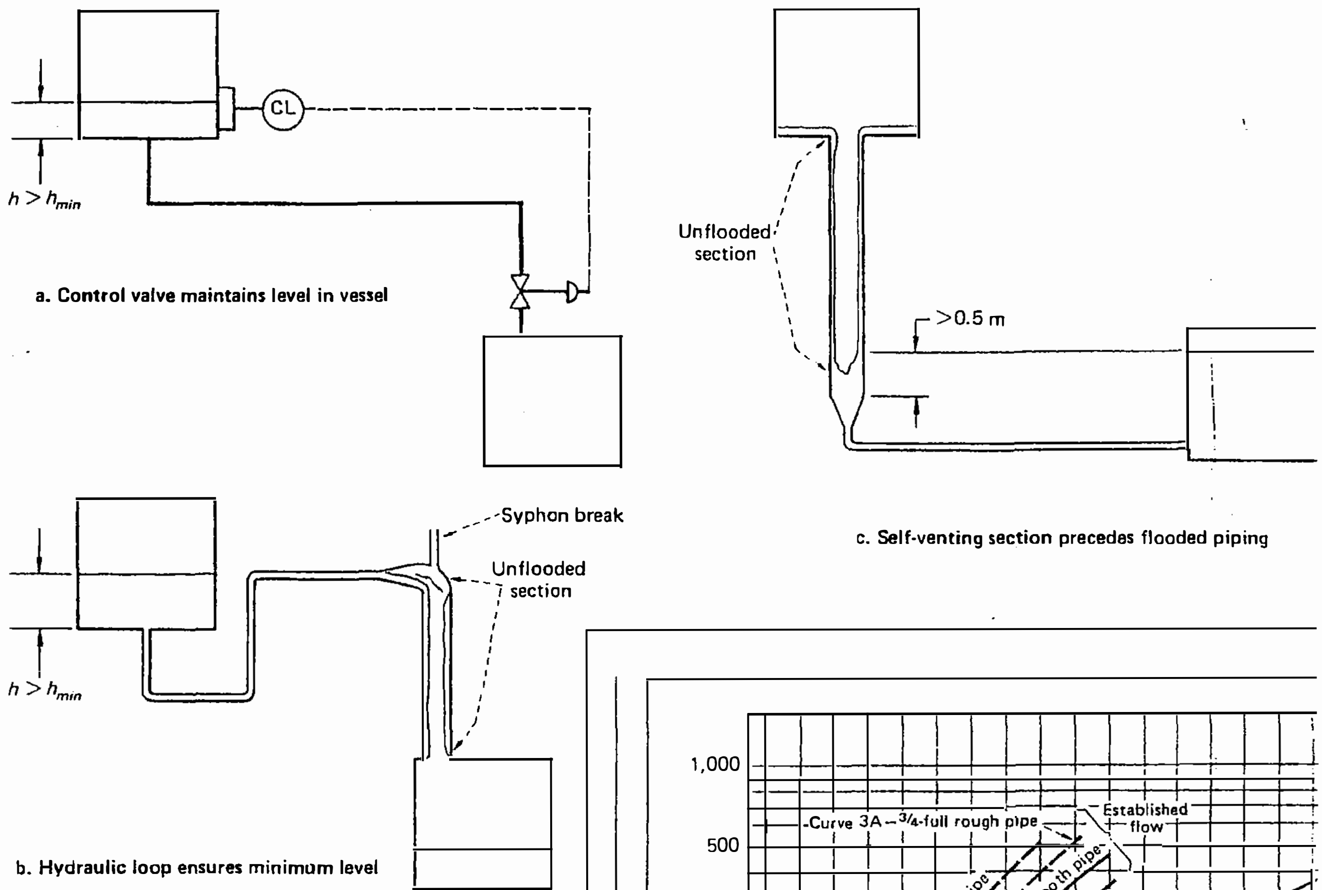
This ensures that the line will run less than half full at its entrance. The level in the vessel away from the outlet will be less than 0.8 d above the base of the line. The capacity of such an overflow line can be found from Curve 1 in Fig. 3.

Near-horizontal piping—If such a pipeline will run only partially full, it must be inclined to provide the static head to overcome friction losses. A minimum slope of 1:40 is recommended.

To avoid having the liquid carrying gas forward, adequate free area must be left in the pipe to allow gas to pass backward. For pipes up to 200 mm dia., liquid depths should not be more than half the pipe diameter. For larger pipes, depths up to three-fourths of the diameter may be possible.



Entrainment causes surging by increasing pressure drop in piping and lowering head in vessel **Fig. 1**



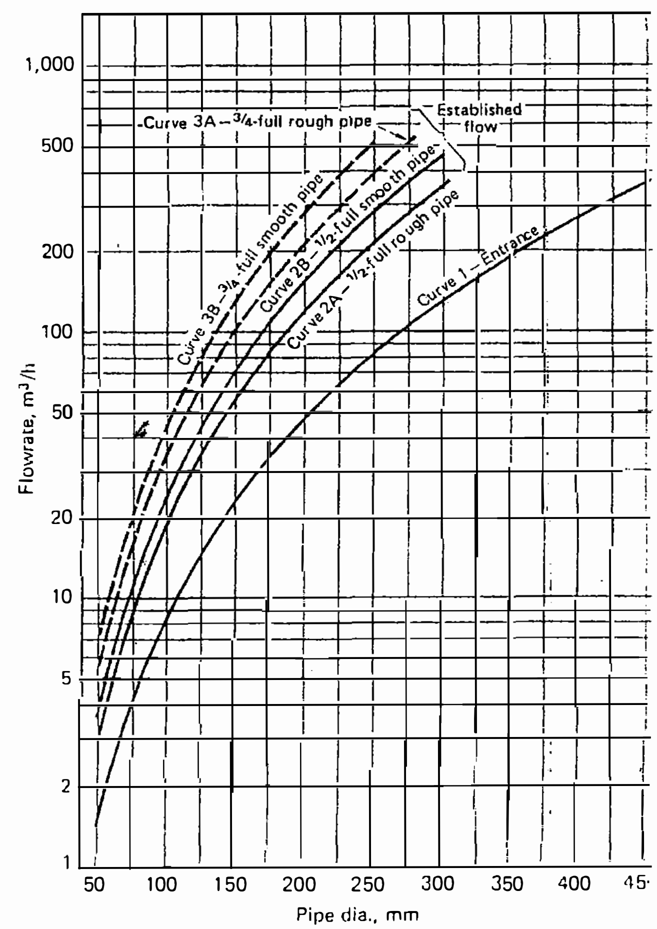
Designs ensure flooded flow in outlet piping **Fig. 2**

When flow in a partially filled pipe is uniform (i.e., constant depth), the energy lost through friction is balanced by the potential-energy change due to the inclination of the pipe. In such a case, the mean velocity, $\bar{V}_L$, is related to the inclination and the depth of flowing liquid by Eq. (5) *[1]*:

$$\bar{V}_L = (32gmi)^{1/2} \log\{[\epsilon/14.8m] + [0.22\nu/m(g_n mi)^{1/2}]\} \quad (5)$$

Here, m is the hydraulic mean depth (flow area/wetted perimeter); i is the inclination of the pipe from the horizontal; ϵ is the pipe roughness; and ν is the kinematic viscosity.

Fig. 3 gives the volumetric capacity for established flow in half-full and three-quarters-full rough and smooth pipes. The curves were calculated via Eq. (5) for pipes of slope 1:40 and a fluid having a kinematic viscosity of 10^{-6} m^2/s (e.g., water at 20°C). The absolute roughness used for the rough pipes was 0.25 mm (moderately rusty mild steel). The results are not very sensitive to liquid viscosity. The capacity of a rough pipe is increased by about 1% for a totally inviscid liquid, and is only reduced by about 10% for a liquid having a kinematic viscosity of 10^{-5} m^2/s. Thus, the Fig. 3 water curves can be safely used for most liquids.



Capacities for established flows in unflooded pipelines **Fig. 3**

The initial velocity in an outlet line designed to run half full is less than the equilibrium velocity in a pipe having a slope of 1:40. As the liquid accelerates down the pipe, the liquid depth diminishes with distance to that of the depth corresponding to the established flow at a given flowrate. To maintain a constant relative depth, a tapered pipe would be necessary. As this is impractical, reducing the pipe diameter stepwise is recommended. Tapered reducers should be installed to avoid sudden disturbances in the flow.

For long lengths of pipes, the following design approach is suggested:

1. Size the outlet line on the side of a vessel for $J_L^* = 0.3$ (Curve 1 of Fig. 3). If the resulting pipe size is not standard, choose the standard size higher than the calculated size. Continue the size so chosen for at least ten pipe diameters.
2. Determine the pipe diameter corresponding to half-full established flow for the required flowrate (using Curve 2A or 2B of Fig. 3). Again, select the nearest standard pipe size higher than the calculated size.
3. Reduce the pipe diameter from the outlet size to the established-flow size, using an eccentric reducer that will not change the slope of the bottom of the pipe. Preferably, the reducer's minimum length should be twice that of the upstream pipe diameter.

If the foregoing procedure is followed for pipes of 1:40 slope, the liquid depth after the reducer will not exceed 75% of the pipe diameter.

For long, large-diameter (>200 mm) inclined pipes, it may be worth considering a second reduction down to the size corresponding to an established-flow relative depth of 75%. This reduction can be made after 50 pipe diameters (see Curve 3A or 3B of Fig. 3).

For short pipe runs, the additional cost of tapered reducers—especially if of a gentle angle, as recommended (which may not be standard), or of lined pipe—may exceed the savings in going to smaller-diameter piping. In such cases, the entire length of the pipe should be of the large size.

Self-venting flow in vertical pipes

Liquid flowing vertically down does so as an annular film. In such cases, low superficial velocities are necessary to avoid gas being sucked down with the liquid. Simpson's suggestion of basing pipe outlet diameters on a limiting Froude number of 0.3 is recommended *[2]*:

$$J_L^* < 0.3 \qquad (6)$$

Eq. (6) being the same as Eq. (4), pipe diameters can be determined from Curve 1 in Fig. 3.

This approach should be adopted when gas entrainment is to be avoided, as when a vertical pipe extends into a vessel to below the liquid surface, or when the downstream piping must be designed for flooded flow. Smaller pipe than that dictated by Eq. (6) can be expected to cause surging.

Self-venting flow in complex systems

Little information is available on unflooded flow in systems that include bends, especially for flow changes from vertical to nearly horizontal, and vice versa. Limited evidence suggests that even if the pipe diameter is chosen for self-venting flow (as in a prior section on designing unflooded piping), entrainment and surging may still occur due to the effects of the bends. The design recommendations now given are, therefore, offered only tentatively.

Bends in the horizontal (or nearly horizontal) plane will not necessarily cause problems if the 1:40 slope is continued with the bend and the bend is gentle (preferably, the radius equaling five diameters).

In the vertical plane, the number of bends should be limited as much as possible. Gently sloping piping is preferable to vertical runs. The radius of bends should be at least five diameters.

Bends from, or to, vertical sections should be sized as for vertical piping. Inclined piping following a vertical section can be sized for half-full established flow via the criteria for near-horizontal piping in the previous discussion on designing unflooded (self-venting) piping. Changes in diameter should be made by means of asymmetric tapered reducers whose lengths are equal to twice the larger diameter, and which are installed so that the bottom of the reducer has a slope equal to that of the piping at either end.

If entrainment is acceptable

There are many occasions when it is not necessary to prevent entrainment. Sometimes, moderate surging will not present a problem. In such cases, piping can be sized for smaller diameters at considerable savings.

Sometimes, surging caused by gas entrainment can be reduced by providing a means for the gas to escape at a point downstream in the outlet pipe, such as via some type of gas-liquid separator. If this is practical, the piping can be of smaller diameter. However, because it is not possible to predict the extent of entrainment—and, hence, calculate the pressure drop with certainty—any such approach should be adopted cautiously.

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