GBH Enterprises, Ltd.

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Process Engineering Guide:

GBHE-PEG-FLO-301

Overflows and Gravity Drainage Systems

Process Engineering Guide: **Overflows and Gravity Drainage Systems**

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0 INTRODUCTION / PURPOSE

Gravity drainage systems occur frequently on chemical plants. Typical examples are:

(a) the condensate off-take from a condenser;

(b) the liquid off-take from the base of an absorption column;

(c) the emergency overflow from an atmospheric pressure storage tank.

Gas entrained in a liquid flowing by gravity from a vessel will reduce the volume of liquid flowing through the pipe and could cause surging flows.

1 SCOPE

This Process Engineering Guide (PEG) describes the problems which are associated with gravity systems and recommends design criteria to avoid such problems.

2 FIELD OF APPLICATION

This Guide applies to the process engineering community in **GBH Enterprises** worldwide.

3 DEFINITIONS

For the purposes of this Guide no specific definitions apply.

4 OUTLINE OF THE PROBLEM

Whenever liquid flows by gravity out of a vessel or down a pipe there is a potential problem of entrainment of gas by the liquid. Apart from any process concerns:

(a) Entrained gas not only raises the pressure drop above the single phase value but also reduces the static head available to drive the flow. These effects can reduce the flow rate drastically below the design value.

(b) Entrained gas can give rise to unsteady flow conditions (surging) which, in extreme cases, can result in equipment failure. Figure 1 shows a typical sequence which may occur for an absorption column with an undersized liquid outlet.

A further description of gravity drainage problems and a review of published information. For information on flow in partially filled near-horizontal channels, consult a suitable fluid mechanics textbook (e.g. see 10(a)).

Three approaches to the design of gravity systems are possible, namely:

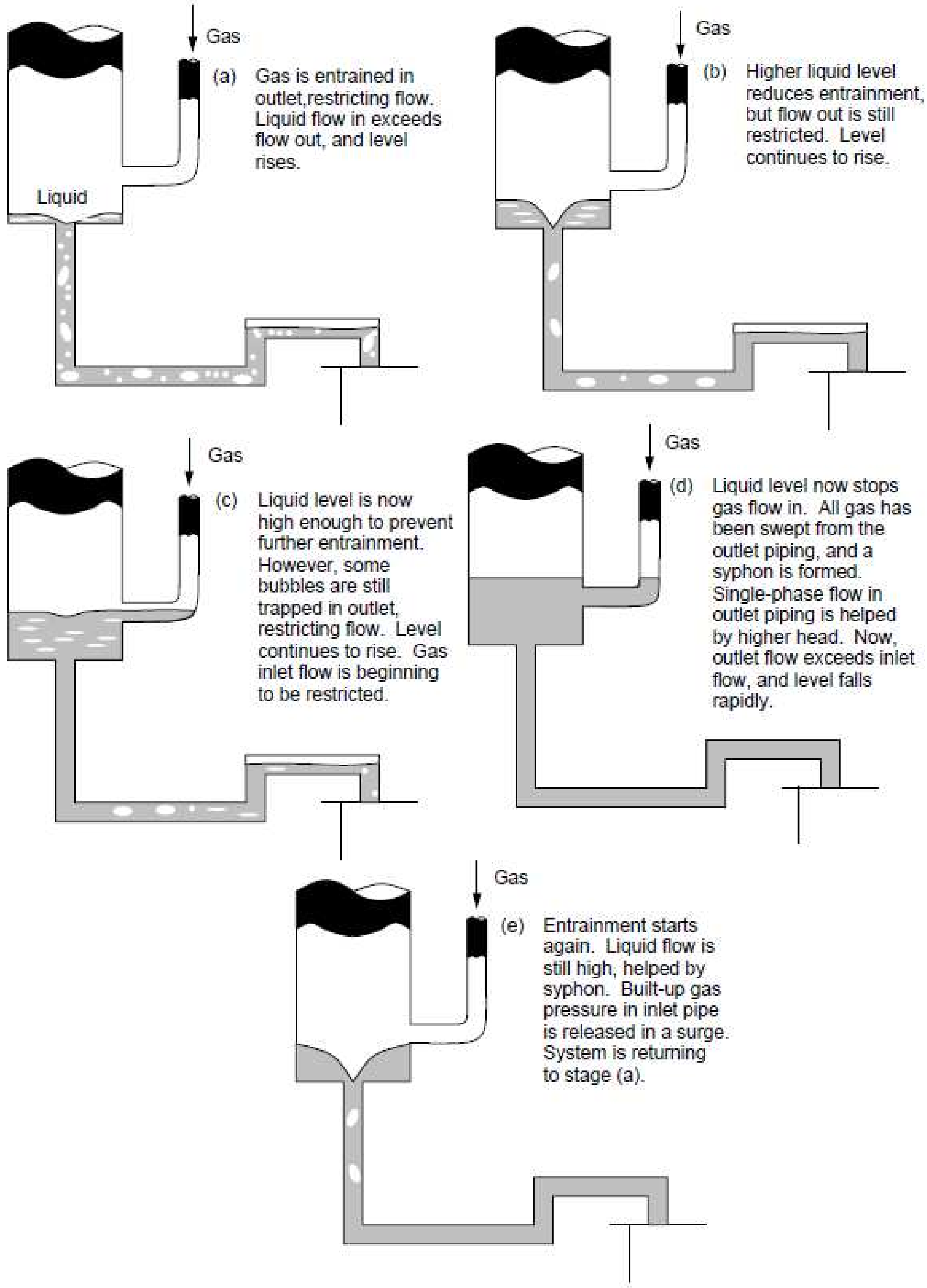
(1) The system can be designed to run full bore at all times. Single phase criteria can then be used for pipework sizing.

(2) The system can be designed to be self venting. Liquid velocities are kept sufficiently low to allow any entrained gas to flow countercurrent to the liquid flow.

(3) Gas entrainment can be allowed to occur and the system designed to accommodate potential problems.

In general, approach (1) can be expected to result in the smallest pipe sizes and should be considered first. However, in many instances it is not possible to ensure full pipe flow and the methods contained in Clauses 5, 6 and 7 should be adopted.

FIGURE 1 TYPICAL SEQUENCE OF SURGING FLOW



In this Guide, liquid flowrates are generally expressed in terms of a dimensionless superficial volumetric flux *j*L* defined by:

$$j_L^* = \frac{4Q_L}{\pi d^2 \sqrt{g'd}} \quad \textit{where} \quad g' = \frac{g\rho_L}{\rho_L - \rho_G} \qquad \text{......(1)}$$

This is similar in form to a Froude number. It is used in preference to the Froude number, which has several different definitions depending on circumstances.

Note:

At low pressures $\rho L >> \rho G$ and $g' \simeq g$

All equations in this Guide are based on units as shown in Clause 11.

5 DESIGNING FOR FLOODED FLOW

If at all times the pipeline runs full of liquid, then normal single phase methods can be used for sizing the pipework. In order to avoid gas entrainment, the liquid in the vessel should be maintained at such a level as to keep the pipe inlet submerged, allowing for depression of the surface near to the outlet.

Criteria for flooded outlets are as follows:

(a) For outlets from the base of vessels:

$$j_L^* < 1.6 \left(\frac{h}{d}\right)^2 \quad \textit{this equation is equivalent to } h > 0.892 \quad \sqrt{Q_L} \; (g'd)^{-0.25} \qquad \text{......(2)}$$

where *h* is the liquid depth in the vessel away from the region of the outlet.

This equation assumes irrotational flow. Vortexing can result in gas entrainment even if the minimum depth is achieved (the 'bath plug' effect). A vortex breaker should be used to prevent this. A suitable design is shown on Standard Sheet 11 0050. Detailed guidelines for the optimum sizing of vortex breakers are contained in the documents quoted in 10(b) and 10(c).

(b) For outlets from the side of vessels

$$j_L^* < \sqrt{\frac{2h}{d}} \quad \textit{this equation is equivalent to} \quad h > 0.811 \frac{Q_L^2}{g'd^4} \qquad \text{......(3)}$$

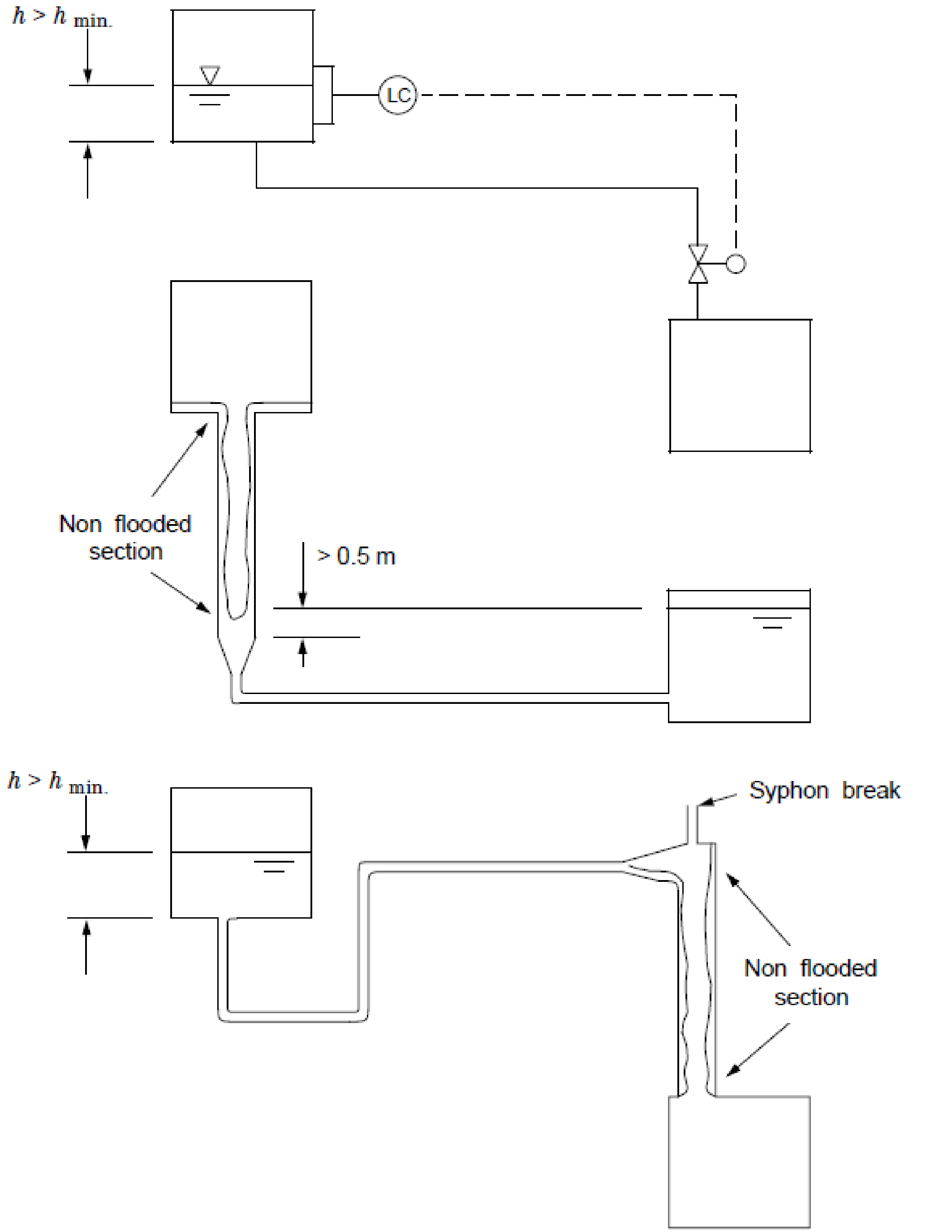
where *h* is the liquid height above the top of the outlet away from the region of the outlet.

In order to ensure that the surface is maintained above the required level some form of control may be necessary. This could be via a control valve or a lute. Such devices will increase the system pressure drop and to some extent reduce the benefits of going to flooded flow. If a lute is used a siphon break may be necessary; pipework downstream of the siphon break cannot be assumed to run flooded.

Single phase design criteria can also be applied to sections of gravity drainage systems where it is certain the pipe is flooded. If these sections are preceded by a self venting vertical section, a minimum length for disengagement of 0.5 m should be provided before reducing the pipe diameter to the single phase value.

Figure 2 shows some examples of systems designed for flooded flow.

FIGURE 2 DESIGNING FOR FLOODED FLOW



6 DESIGNING NON-FLOODED PIPELINES

6.1 Vertical Pipework

A slug of gas will be entrained in a liquid flowing down a vertical pipe if the value of j^*L exceeds about 0.32. For values of j^*L less than this, the gas slug will rise against the liquid flow. This forms the basis of the design method for self venting flow, which is that j^*L should be less than 0.3.

The capacity of a pipe designed for j^*L = 0.3 is shown on Curve 1 of Figure 3.

Although designing to this criterion will avoid gross entrainment of gas in the form of slugs, it will not prevent entrainment of small bubbles whose Stokes Law velocity is less than the liquid velocity.

6.2 From the Side of a Vessel

If a liquid is flowing from the side of a vessel into a partly full circular pipe inclined at more than a critical slope, the flow in the entrance region will be 'critical', with a Froude number (defined as the ratio of the surface wave speed to the actual liquid velocity) of one. With a value of j^*L of 0.3, the pipe entrance will be less than half full and the liquid level in the stagnant region away from the overflow will be less than 80% of the pipe diameter above the bottom of the pipe (see Figure 4). Thus the same design criterion can be used as for vertical pipes.

The critical slope to ensure critical flow in the entrance region decreases with pipe diameter and increases with the depth of liquid in the pipe. However, for the range of pipe sizes used in practice, and assuming typical pipe roughnesses, the critical slope is always less than 1:100. For design purposes, a minimum slope of 1:40 is recommended for the off-take pipework, although civil engineering installations such as drains are often designed to a fall of 1:100.

The use of an overflow from near the top of a vessel, sized for a large flowrate, requires the provision of considerable extra height on the vessel above the maximum working level, which may be expensive.

Two ways are suggested for avoiding this, namely:

(a) Provide a vertical stand-pipe within the vessel, sized by the methods detailed in 6.1 (see also Figure 5(a)).

(b) Replace the circular side branch by a 'letter box' (see Figure 5(b)).

The liquid height over the base of such an outlet is given by the weir formula:

$$h = 1.65\left(\frac{Q_L^2}{gW^2}\right) \quad \text{.......(4)}$$

where *W* is the width of the weir.

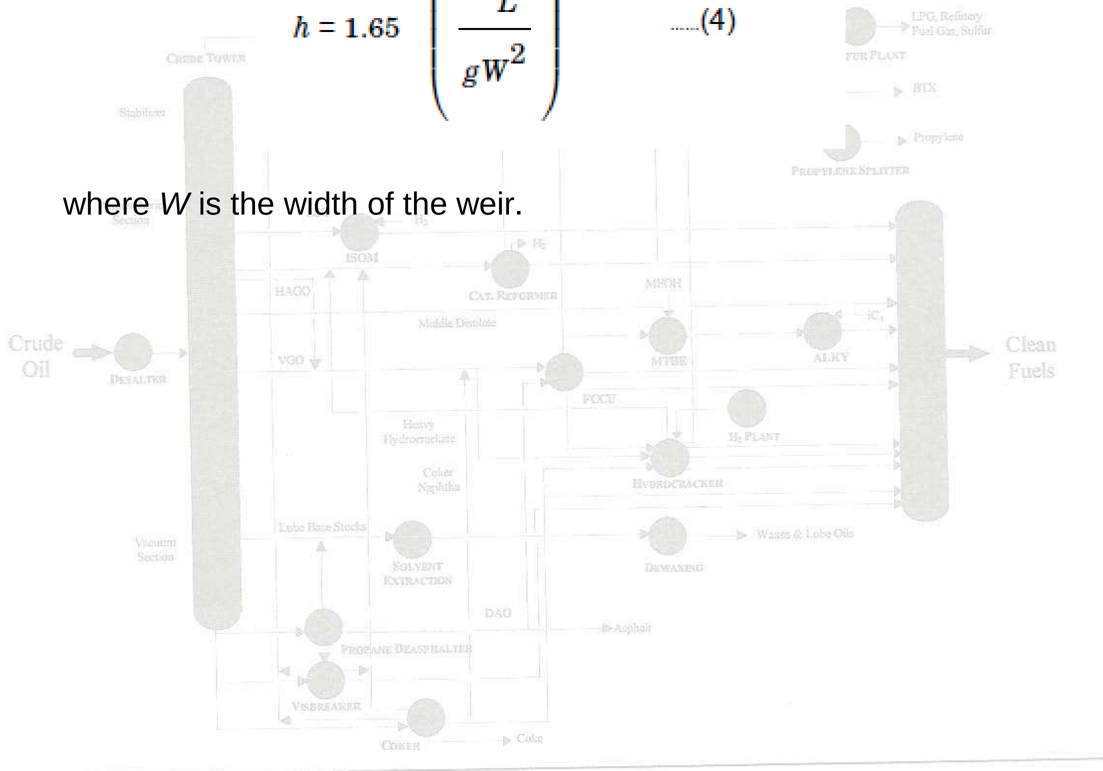
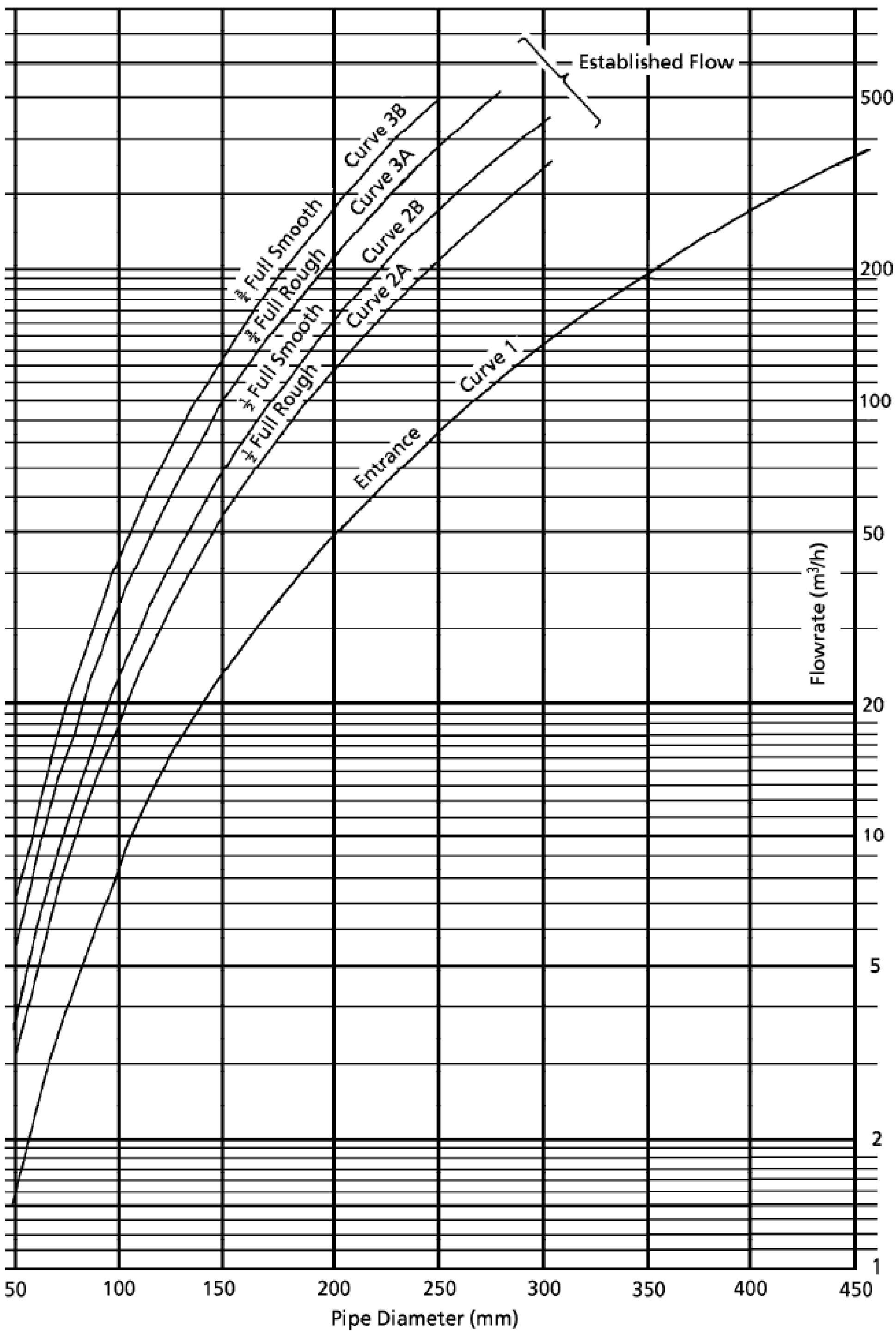


FIGURE 3 CAPACITY OF SLOPING PIPELINES



Clean
Fuels

FIGURE 4 OVERFLOW FROM SIDE OF VESSEL

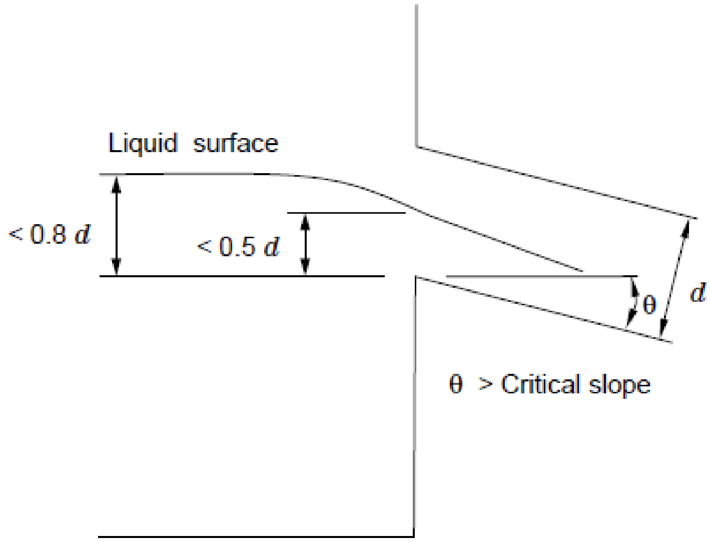
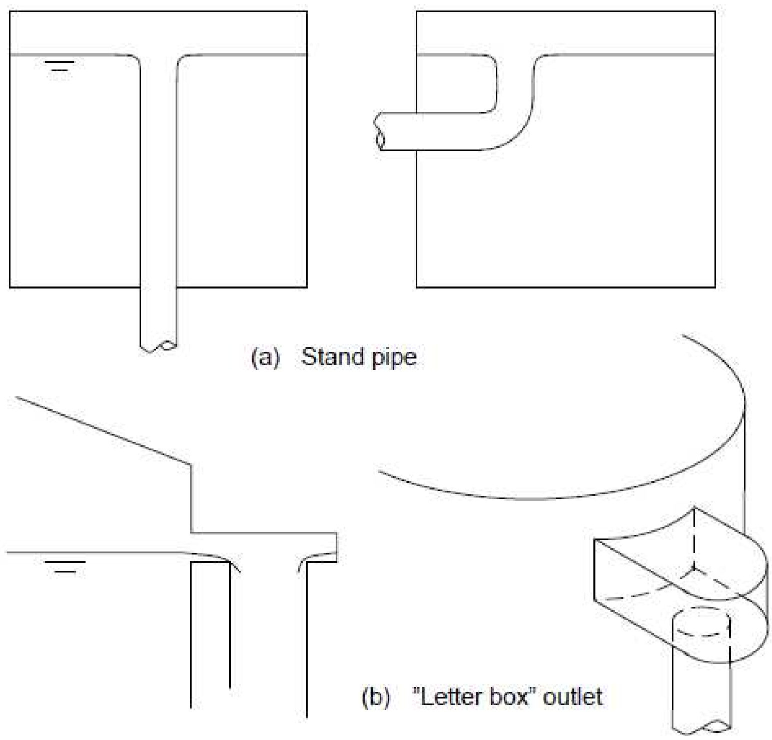


FIGURE 5 METHODS OF AVOIDING LARGE CIRCULAR SIDE OVERFLOWS



6.3 Established (uniform) Flow in Near-horizontal Pipes

For a uniform (i.e. constant depth) flow in a partially filled inclined pipe, the energy lost by friction is balanced by the potential energy change due to the inclination of the pipe. The mean velocity is related to the inclination and depth of flow by the equation:

$$v = -\sqrt{32\,gmi}\;\; log_{10}\left(\frac{\varepsilon}{14.8m} + \frac{0.22\nu}{m\sqrt{gmi}}\right) \quad ......(5)$$

where:

- m is the hydraulic mean depth (area for flow a divided by wetted perimeter P). Values of m as a function of relative depth are given in Table 1.
- ε is the pipe roughness
- ν is the kinematic viscosity
- i is the pipe inclination (the tangent of the angle to the horizontal).

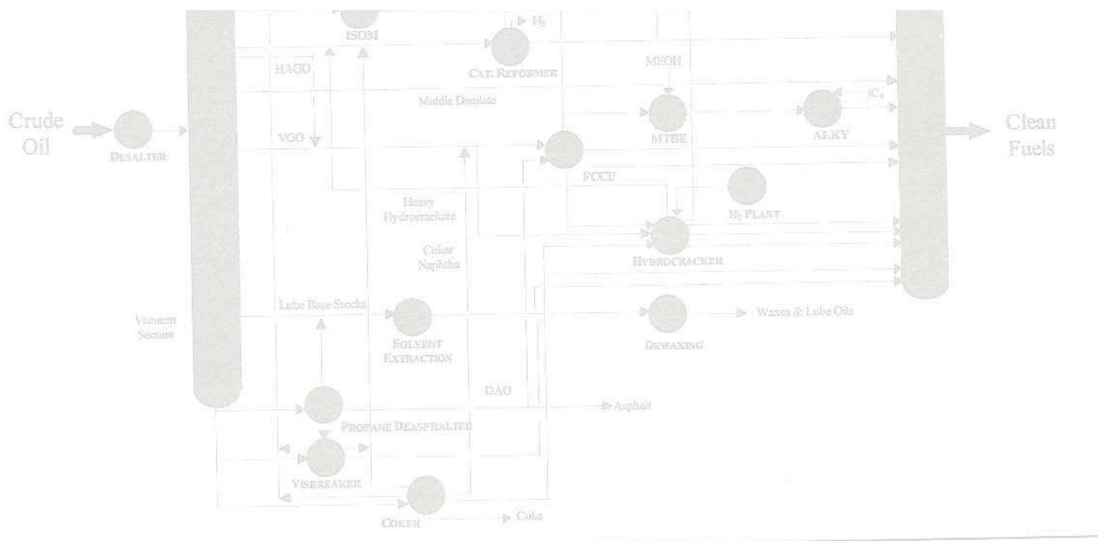


TABLE 1 GEOMETRICAL FUNCTIONS OF PART-FULL PIPES

$\frac{H_p}{d}$	$\frac{4a}{\pi d^2}$	$\frac{p}{\pi d}$	$\frac{4m}{d}$	$\frac{\bar{H}}{d}$	$\frac{Fr}{j^*_L}$	$\frac{b}{d}$
0.05	0.019	0.144	0.130	0.034	285.000	0.436
0.10	0.052	0.205	0.254	0.068	73.700	0.600
0.15	0.094	0.253	0.371	0.103	33.100	0.714
0.20	0.142	0.295	0.482	0.140	18.820	0.800
0.25	0.196	0.333	0.587	0.177	12.120	0.866
0.30	0.252	0.369	0.684	0.216	8.540	0.917
0.35	0.312	0.403	0.774	0.257	6.320	0.954
0.40	0.373	0.436	0.857	0.299	4.900	0.980
0.45	0.436	0.468	0.932	0.345	3.900	0.995
0.50	0.500	0.500	1.000	0.393	3.190	1.000
0.55	0.564	0.532	1.059	0.445	2.660	0.995
0.60	0.625	0.564	1.111	0.502	2.260	0.980
0.65	0.688	0.597	1.153	0.567	1.930	0.954
0.70	0.748	0.631	1.185	0.641	1.670	0.917
0.75	0.805	0.667	1.207	0.730	1.454	0.866
0.80	0.858	0.705	1.217	0.842	1.270	0.800
0.85	0.906	0.747	1.213	0.996	1.106	0.714
0.90	0.948	0.795	1.192	1.241	0.947	0.600
0.95	0.981	0.856	1.146	1.768	0.767	0.436
0.99	0.998	0.936	1.067	3.940	0.505	0.199
1.00	1.000	1.000	1.000	∞	0.000	0.000

Figure 3 gives the volumetric capacity for established flow in half full and three quarters full rough and smooth pipes. The curves were calculated from equation (5) for pipes of slope 1:40 and a fluid with kinematic viscosity of 10-6 m2/s (e.g. water at 20℃). The absolute roughness used for the rough pipes was 0.25 mm (moderately rusty carbon steel).

The results are not very sensitive to liquid viscosity; the capacity of a rough pipe is increased by about 1% for an inviscid fluid, and reduced by about 10% for a fluid with a kinematic viscosity of 10-5 m^2/s.
Thus the curves can safely be used for most liquids.

Figure 6 shows the variation in capacity of a sloping pipe as a function of relative depth. The peak capacity occurs for a relative depth of approximately 0.95. Operating beyond the peak represents an unstable situation, where an increase in depth causes a fall-off in capacity. It is recommended that partially full pipes be limited to a relative depth of 0.75.

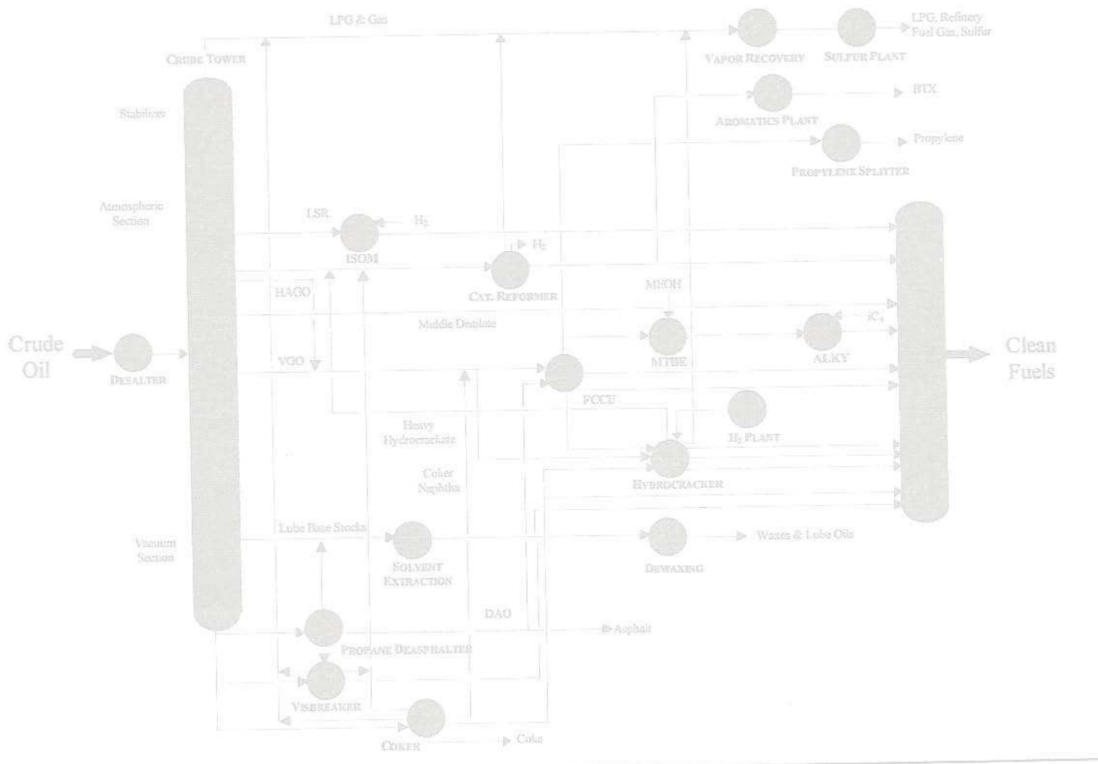
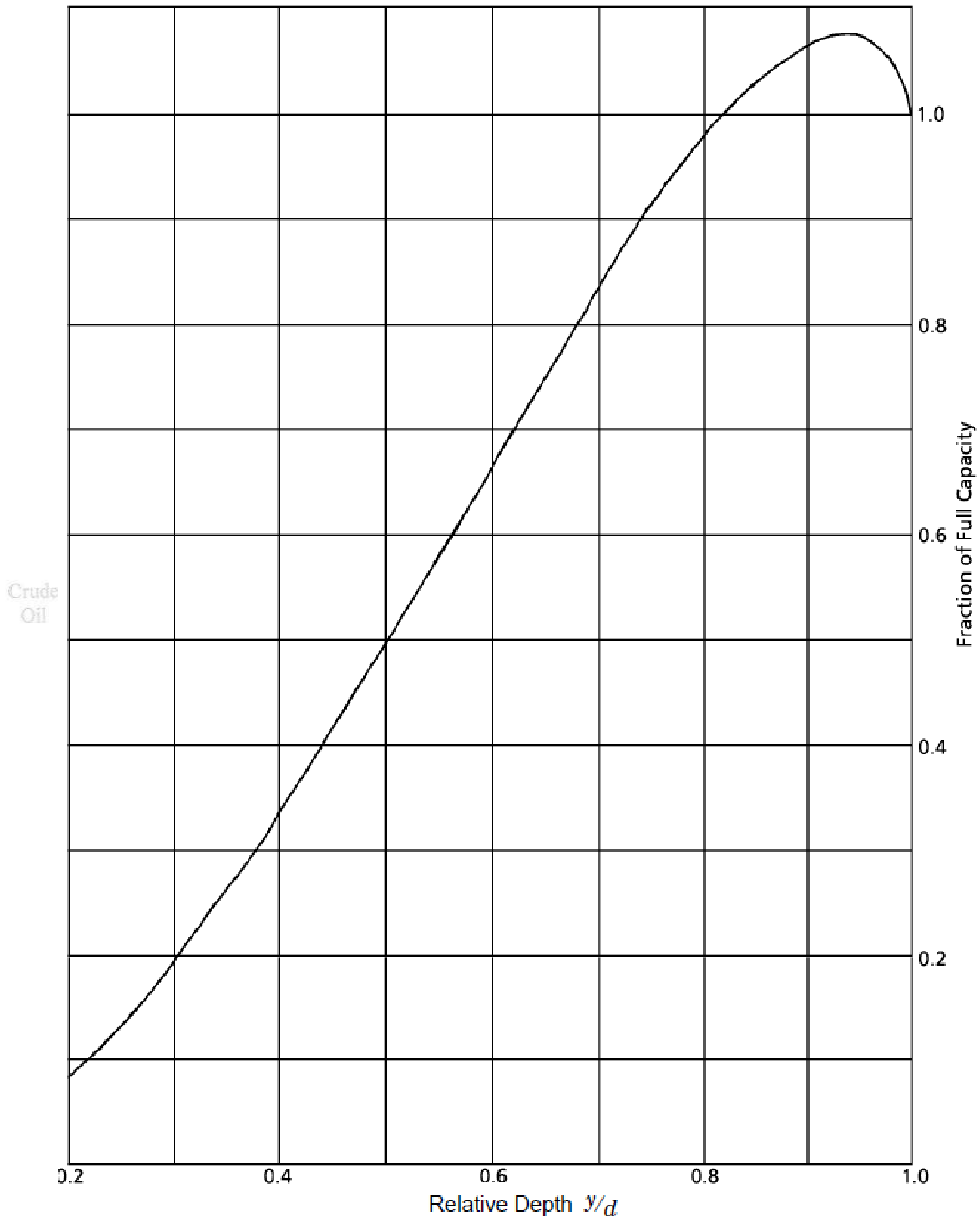


FIGURE 6 CAPACITY OF A GENTLY SLOPING PIPE AS A FUNCTION OF LIQUID DEPTH



6.4 Non-uniform Flow

The velocity of fluid in the off-take from a vessel designed to run half full (*j**L*= 0.3) is less than the equilibrium value for a pipe with a slope greater than the critical value. The liquid accelerates down the pipe, the depth falling with distance towards the depth corresponding to established flow at the given flowrate.

This reduction in depth with distance gives the possibility of reducing the pipe size for long near-horizontal pipes. To do this safely, it is necessary to solve the energy equation to determine the change in relative depth with distance. The following design method is based on this approach.

(a) Size the off-take branch on the side of the vessel for $j^*L = 0.3$ (Curve 1 of Figure 3). If this is a non-standard pipe size, choose the next standard size above the calculated value. Continue this size for at least ten pipe diameters.
(b) Determine the pipe diameter corresponding to half full established flow for the required flowrate (use Curve 2A or 2B of Figure 3). Again select the nearest standard size above the calculated value.
(c) Reduce the pipe size from the off-take size to the established size using an eccentric reducer such that there is no change in the slope of the bottom of the pipe. The reducer should have a minimum length of twice the upstream diameter.

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

For long inclined pipes it may be worth considering a second reduction down to the size corresponding to an established flow relative depth of 0.75. This reduction can take place after a further fifty diameters.

For short pipe runs the additional cost of tapered reducers, especially if made with a gentle angle as recommended, which may be non-standard, or with lined pipe, may exceed the savings achieved by use of smaller bore pipework. In such cases the pipe should be run in the large size throughout.

7 NON-FLOODED FLOW IN COMPLEX SYSTEMS

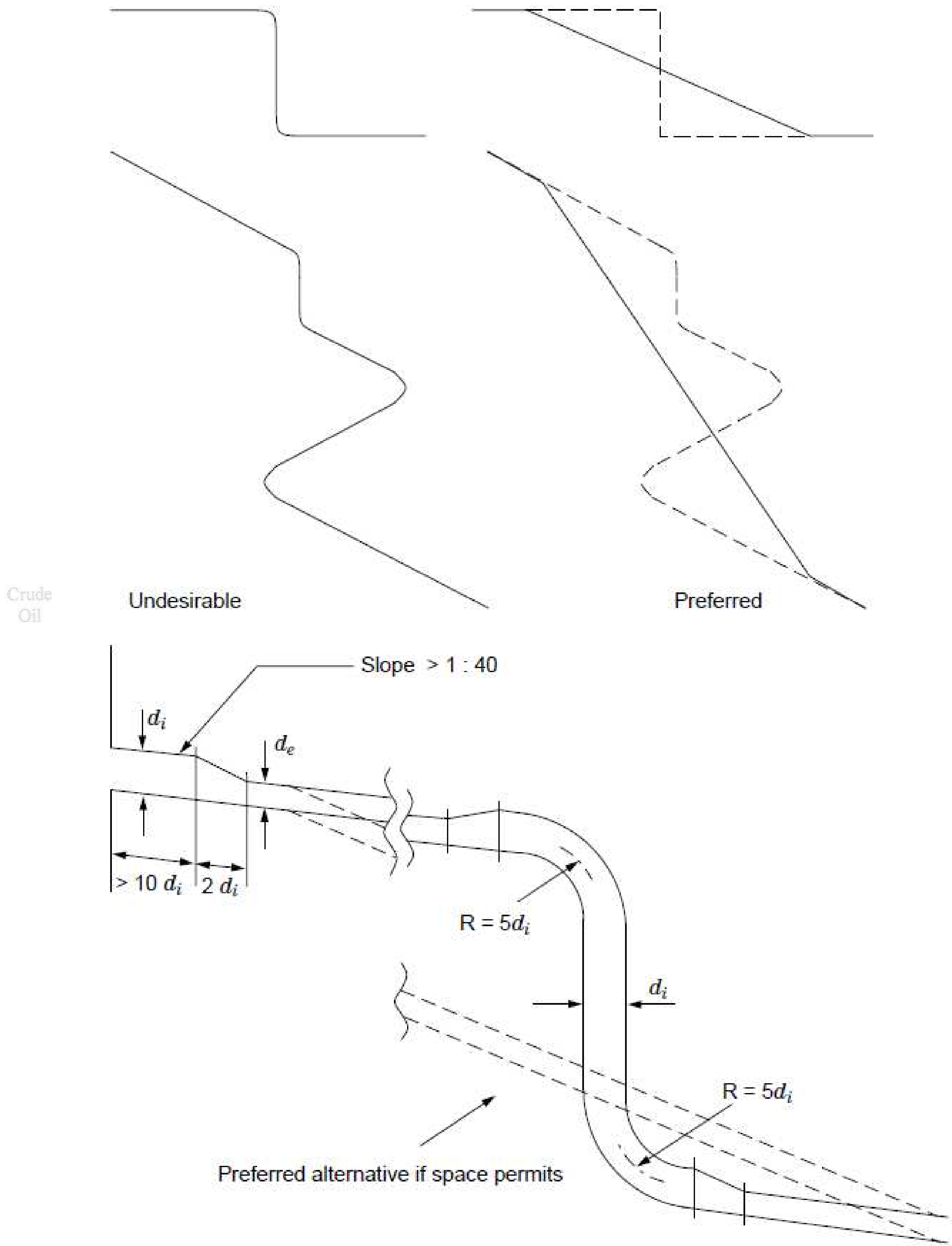
There is little information available on non-flooded flow in systems including bends, especially for changes from vertical to near horizontal flow or vice versa. What evidence there is suggests that even if the pipe diameter is chosen for self venting flow as detailed in Clause 6, entrainment and surging may still occur due to the effects of the bends. As a result the following design recommendations are only tentative.

All nominally horizontal sections should have a minimum slope of 1:40. Bends in the ’horizontal’ plane are not expected to cause problems provided the slope of 1:40 is continued round the bend and the bend is gentle (say radius equals five diameters).

In the vertical plane, the number of bends should be reduced as far as possible. Vertical sections should be replaced by gently sloping sections if practicable. Bends should have a minimum radius of five diameters.

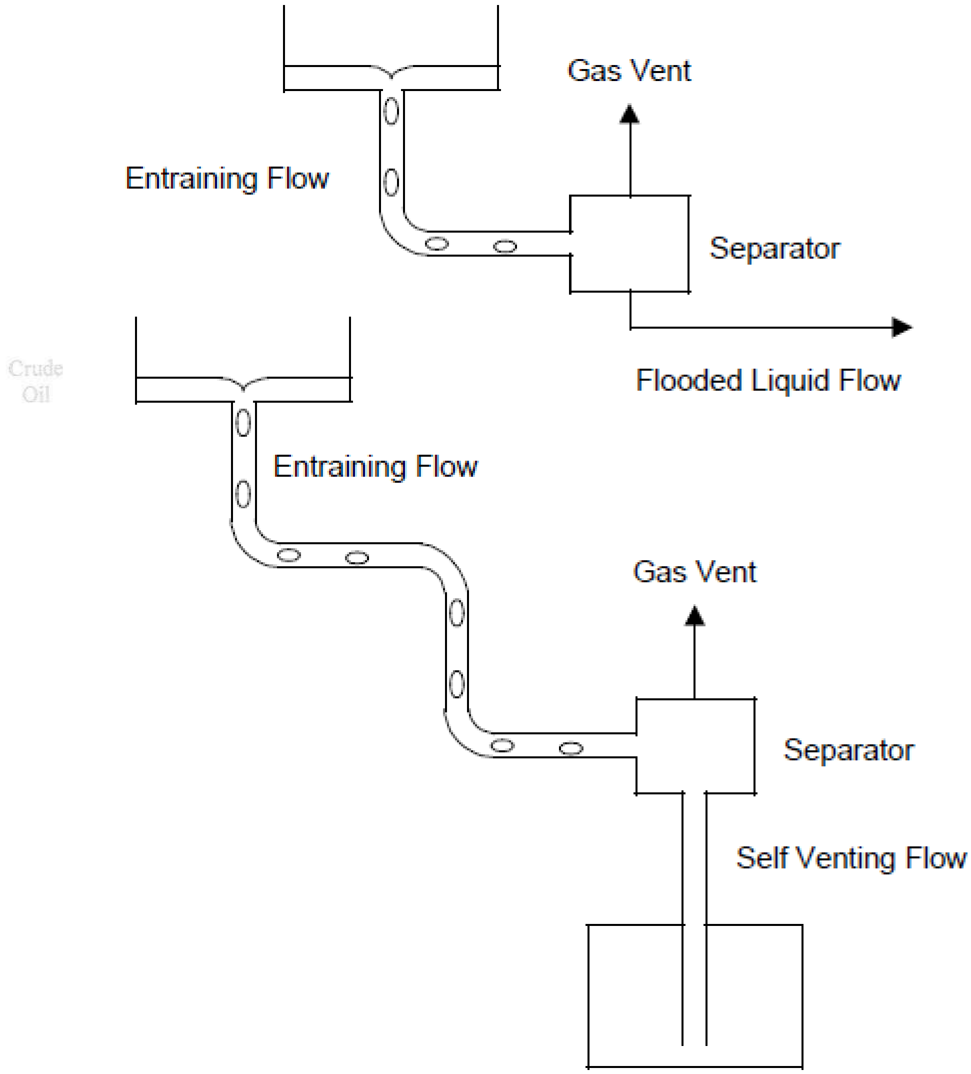
Vertical pipework, including bends from or to vertical sections, should be sized for j^*L < 0.3. Long inclined pipes can be sized for half full established flow by the criteria given in 6.4, but should be increased back to the full diameter before any vertical sections. Changes in diameter should be by asymmetric tapered reducers of length equal to twice the larger diameter and arranged such that the bottom of the reducer has a slope equal to that of the pipework on either side. Figure 7 illustrates some of these points.

FIGURE 7 COMPLEX PIPE SYSTEMS



Surging and similar problems caused by gas entrainment can sometimes be reduced by providing a means for gas escape at key points. It may be necessary to provide some form of gas/liquid separator at these points. This may enable most of the pipework to be designed to a smaller size. However, it should be remembered that it is not possible to predict the degree of gas entrainment that would result and hence the pressure drop cannot be calculated with any certainty. Two possible methods for the removal of entrained gases are shown in Figure 8.

FIGURE 8 REMOVAL OF ENTRAINED GASES



8 ENTRAINING FLOW

If the liquid flowrate is such that *j*L* exceeds 0.3 then the liquid will tend to carry gas forward with it. The established film thickness for a falling film flow can be calculated from the equation:

$$\frac{y}{d} = 0.068 \left(j_L^* \right) \qquad \text{......(6)}$$

provided the film is thin compared with the pipe diameter. For *j*L* = 2 this gives a relative film thickness of 0.11. However, in the entry region the film thickness will be greater than this and bridging of the pipe may occur.

Simpson (see 10(d)), in experiments with a 13/16 inch vertical pipe, open at the bottom and fed through a bend at the top, found the vertical pipe ran full at *j*L* = 2. However, a simple vertical pipe of typical roughness, open at both ends, with the frictional resistance balancing the gravitation, will run full with a liquid flow equivalent to *j*L* = 10. Operation with *j*L* > 0.3 tends to give intermittent flow with severe entrainment and slugging, especially if there is no easy escape path for the gas. It is not recommended for other than simple systems.

9 SIMPLE TANK OVERFLOWS

Although the self venting criterion represents a safe design basis, it often results in a requirement for very large, and hence expensive, overflows. It has been recognized for some time that there are many cases where such a design is unnecessary, and a smaller size of overflow would suffice.

Because of this, and the absence of any firm guidelines, an experimental program was undertaken using overflows of 2" diameter with water as the liquid. Although it is recognized that this size is small compared with many overflow systems, Dr P B Whalley of Oxford University, one of the world's leading authorities on two phase flow, considered that any extrapolation of the conclusions to larger pipe sizes was likely to be conservative. This is because slug flow in large diameter tubes tends to be unstable, and the slug velocity tends to be greater than that given in 6.1. Note however that sizeable bubbles of gas could still be dragged down by the liquid flow even if full size slugs could not. The recommendations are based on this consideration and the method is subject to the following constraints:

(a) The overflow should be simple; that is, it should consist of a side outlet followed immediately by a vertical pipe to grade. There may be a seal pot on the base if required. Overflows which include several bends and/or are proceeded by tortuous routes are excluded from this method.

(b) Entrainment of gas from the tank into the overflow is allowable.

(b) Intermittent or variable flow in the overflow is permissible.

(c) Some variation in the level of liquid in the tank during the overflow operation is acceptable.

(d) The tank is fitted with an adequate venting/in-breathing system (see 9.1).

Provided that the above criteria are met, the overflow can be sized to have half the diameter of an overflow sized for self venting flow at the same flowrate by the method given in Clause 6.

If the above criteria cannot be met, it is recommended that the overflow be designed to be self venting.

9.1 Venting of the Tank

A non-self venting overflow designed by the method detailed in Clause 9 can act as an efficient ejector, sucking gas from the vapor space above the liquid level. It is therefore essential that adequate provision be made for in-breathing. It is not possible to estimate with any certainty the required in-breathing rate. However, a maximum can be placed upon it. This is obtained by assuming that at some stage during the venting cycle the overflow will be running full bore. The corresponding flowrate can be obtained by balancing the head from the liquid level to the bottom of the overflow against frictional losses in the pipework. It will be found that this maximum flowrate is up to 30 times the mean rate. However, the provision of a vent to allow inbreathing at this rate does not usually represent a serious problem.

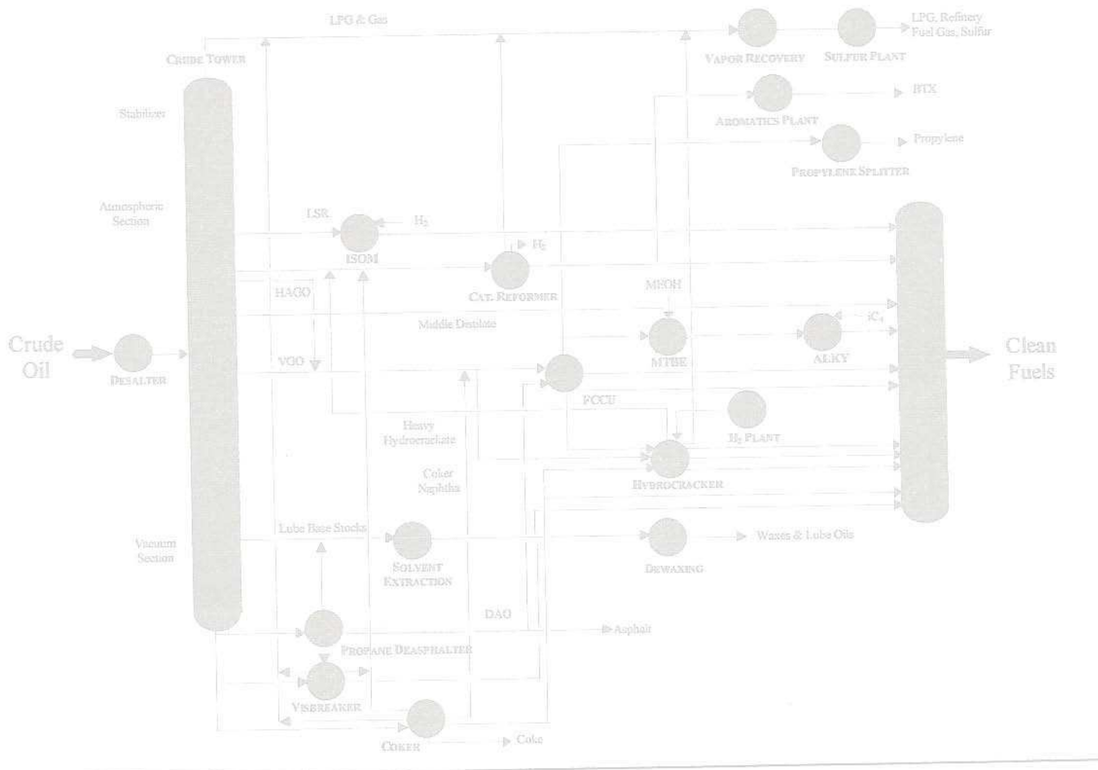
10 BIBLIOGRAPHY

(a) J K Vennard ’Elementary Fluid Mechanics’ 4th Edition, Chapter 10, Wiley, 1962.

(b) F M Patterson, Oil & Gas Journal, August 4th, 1969, Page 118.

(c) S Waliullah, Chemical Engineering, May 9th, 1988, Page 108.

(d) L L Simpson ’Sizing Piping for Process Plants’ Chemical Engineering, 75 No13, Page 19, 2 June 1968.



11 NOMENCLATURE

Symbol	Meaning	Unit
a	Cross sectional area of flow in partially full sloping pipe	m^2
b	Width of liquid surface in partially full sloping pipe	m
d	Pipe diameter	m
Fr	Froude number $= \dfrac{\text{liquid mean velocity } v}{\text{wave speed}}$	-
g	Gravitational acceleration	m/s^2
g'	$\dfrac{g\rho_L}{(\rho_L - \rho_G)}$	m/s^2
h	(a) Liquid depth above base of vessel (bottom outlets) (b) Liquid depth above top of outlet (side outlets) (c) Liquid depth in 'letter box' outlet	m m m
$\bar{H}$	Mean depth $= \dfrac{\text{area for flow } a}{\text{width of surface } b}$	m
H_p	Liquid depth in partially full sloping pipe	m
i	Pipe inclination (the tangent of the angle to the horizontal)	-
j^*_L	Dimensionless superficial volumetric flux (see equation (1))	-
m	Hydraulic mean depth $= \dfrac{\text{area for flow } a}{\text{wetted perimeter } P}$	m
P	Wetted perimeter of partially full pipe	m
Q_L	Liquid flowrate	m^3/s
v	Mean velocity of liquid flow in a partially filled sloping pipe	m/s
W	Width of weir	m
y	Film thickness of annular falling film	m
ε	Pipe roughness	m
ρ_L	Liquid density	kg/m^3
ρ_G	Vapour / gas density	kg/m^3
ν	Kinematic viscosity of the liquid	m^2/s

DOCUMENTS REFERRED TO IN THIS PROCESS ENGINEERING GUIDE

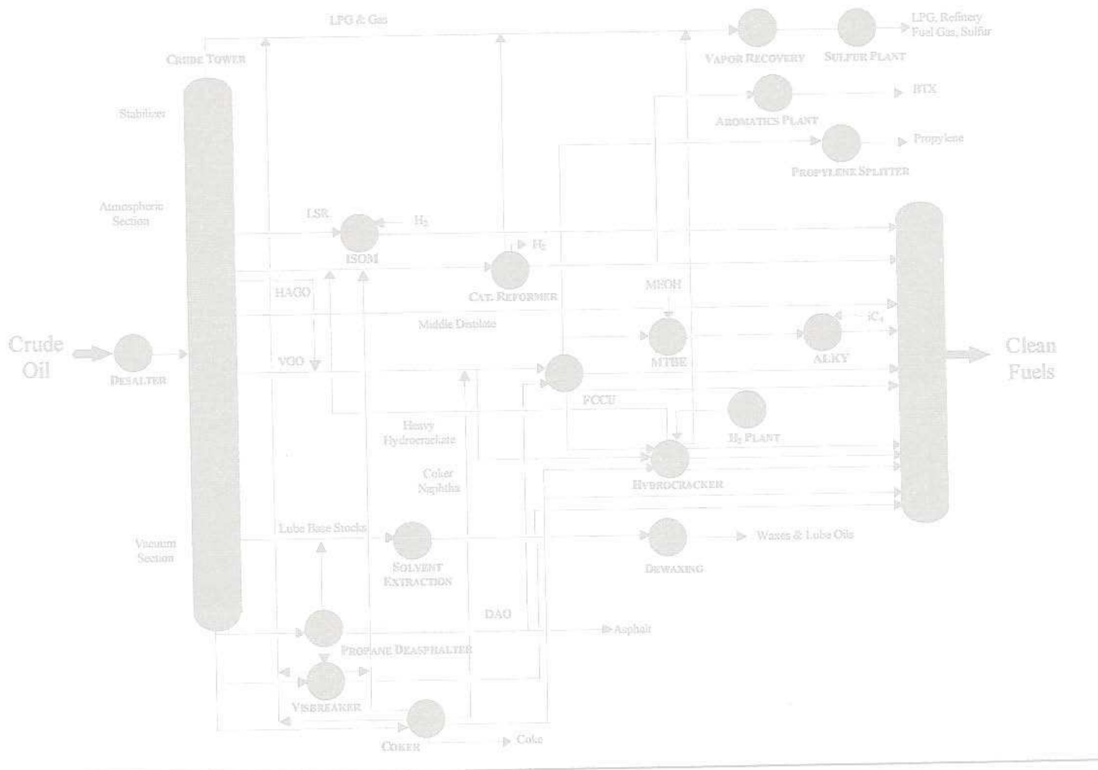
This Process Engineering Guide makes reference to the following documents:

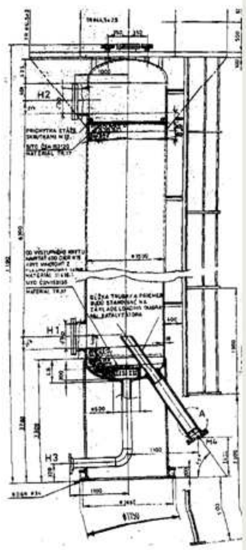
STANDARD SHEET

Vortex Breakers. Carbon Steel and Stainless Steel (referred to in Clause 5(a))

GBHE REPORT

Gravity Flow of Liquids in Pipes (referred to in Clause 4).





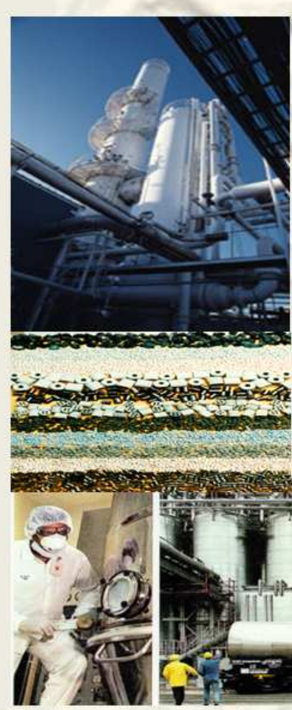
GBH ENTERPRISES, LTD

VULCAN Catalyst Process Technology Consultancy
Sales and Service

Gerard B. Hawkins
Managing Director, C.E.O.

Skype: GBHEnterprises
Office: +1-312-235-2610
Cell: +52 55 2108 3070

GBH@GBHEnterprises.com
HawkinsGerardB@gmail.com
www.gbhenterprises.com
www.linkedin.com/in/gerardbhawkins
www.gplus.to/GBHEnterprises
www.renaltenergy.com



Refinery Process Stream Purification Refinery Process Catalysts Troubleshooting Refinery Process Catalyst Start-Up / Shutdown Activation Reduction In-situ Ex-situ Sulfiding Specializing in Refinery Process Catalyst Performance Evaluation Heat & Mass Balance Analysis Catalyst Remaining Life Determination Catalyst Deactivation Assessment Catalyst Performance Characterization Refining & Gas Processing & Petrochemical Industries Catalysts / Process Technology - Hydrogen Catalysts / Process Technology – Ammonia Catalyst Process Technology - Methanol Catalysts / process Technology – Petrochemicals Specializing in the Development & Commercialization of New Technology in the Refining & Petrochemical Industries

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