MANUAL

LIQUID/LIQUID AND GAS/LIQUID/LIQUID SEPARATORS - TYPE SELECTION AND DESIGN RULES

DEP 31.22.05.12-Gen.

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DESIGN AND ENGINEERING PRACTICE

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TABLE OF CONTENTS

APPENDICES

1. INTRODUCTION

1.1 SCOPE

This DEP specifies requirements and gives recommendations for the selection and design of liquid/liquid and three-phase (gas/liquid/liquid) separators. Design rules are given only for **vessel** separators. Settling tanks, e.g. those used for the dewatering of crude, and basin-type settlers such as the API interceptor used for de-oiling of oil-contaminated surface water, are excluded from the scope of this DEP.

The scope is further focused on the use of separators in duties in which settling is the controlling factor in the separation process, i.e. separation of coarse dispersions with a relatively low dispersed phase concentration and relatively low liquid viscosities. The design of production separators for the removal of gas and water from crude oil, and settlers in mixer/settler plants require a different approach, see Appendix I and example V.4.

Also excluded from the scope of this DEP are gas/liquid separators; these are covered by DEP 31.22.05.11-Gen. (which is also applicable to the gas/liquid separation part of three-phase separators).

In this DEP two-phase and three-phase separators are also referred to as two-phase and three-phase settlers, respectively. The term "settling" will also be used for the separation of light-phase droplets in this DEP in order to be consistent with the term "settlers" which is used both for the separation of light-phase and heavy-phase droplets.

Design rules are given for the following types of separators (or settlers):

- L/L separators (in Section 3):
  - Horizontal open settler
  - Horizontal settler with plate pack
  - Coalescers (with either a coalescer bed, mat or cartridges)
- G/L/L separators (in Section 4):
  - Horizontal open settler
  - Plate pack settlers (both horizontal and vertical)

Users of this DEP should first consult Section 2 to make an initial selection of a suitable type of separator for a given duty.

After selection of the desired separator the design rules can be obtained from either Section 3 or 4.

Information on the vessel internals, L/L separation mechanism and the vessel sizing calculation schemes are given in the Appendices.

This DEP is a revision of the DEP with the same number dated December 1996; a summary of the main changes is given in (1.5).

1.2 DISTRIBUTION, INTENDED USE AND REGULATORY CONSIDERATIONS

Unless otherwise authorised by Shell GSI, the distribution of this DEP is confined to Shell companies and, where necessary, to Contractors and Manufacturers/Suppliers nominated by them.

This DEP is intended for use in oil refineries, chemical plants, gas plants, exploration and production facilities and supply/distribution installations.

When DEPs are applied, a Management of Change (MOC) process should be implemented; this is of particular importance when existing facilities are to be modified.

If national and/or local regulations exist in which some of the requirements may be more stringent than in this DEP, the Contractor shall determine by careful scrutiny which of the requirements are the more stringent and which combination of requirements will be acceptable with regard to the safety, environmental, economic and legal aspects. In all cases the Contractor shall inform the Principal of any deviation from the requirements of this DEP which is considered to be necessary in order to comply with national and/or local

regulations. The Principal may then negotiate with the Authorities concerned, the objective being to obtain agreement to follow this DEP as closely as possible.

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The **Principal** is the party which initiates the project and ultimately pays for its design and construction. The Principal will generally specify the technical requirements. The Principal may also include an agent or consultant authorised to act for, and on behalf of, the Principal.

The word **shall** indicates a requirement.

The word **should** indicates a recommendation.

1.4 CROSS-REFERENCES

Where cross-references are made, the number of the section or sub-section referred to is shown in brackets.

All documents referenced in this DEP are listed in (6).

1.5 CHANGES SINCE PREVIOUS EDITION

This DEP is an interim revision of the DEP with the same number dated December 2004. A summary of the main changes since the previous edition is given below:

Section	**Change**
2.	Added new section 2.6 to cover separators subjected to motion.
4.	Replaced section 4.3.3. by a a more generic description of vertical three-phase separators including liquid separation compartments without internals, or with a double weir arrangement.
4.3	Moved to new section 4.4. Application window of a vertical three-phase separator with plate pack narrowed down to dilute dispersions of light hydrocarbons and water.
Appendix I	Included guidelines and data for the design of production separators (crude dehydration service).
Appendix II	NFA of distributor plate corrected to 20 %.
Appendix V	Adapted oil and water flow rates in example V.3. in line with the revised application window of vertical separators with a plate pack.
Appendix V	Added new example V.4.

1.6 SYMBOLS AND ABBREVIATIONS

Unless explicitly stated otherwise, all symbols used in this DEP are expressed in the units given below.

A	Area	m^2
BTL	bottom tangent line	
conc	local volumetric fraction of dispersed phase	-
D	internal diameter of vessel, skirt, large pipe, etc. (if no subscript, internal diameter of vessel)	m
d	diameter of pipe, nozzle, bubble or droplet plate distance (e.g. of plates in plate pack)	m
F	correction factor (in plate pack design)	-
Fr_G	gas Froude number: $Fr_G = v_G \sqrt{\frac{\rho_G}{(\rho_L - \rho_G) gD}}$	-
Fr_L	liquid Froude number: $Fr_L = v_L \sqrt{\frac{\rho_L}{(\rho_L - \rho_G) gD}}$	-
f	correction factor	-
G	gas	
g	acceleration due to gravity	m/s^2
H	height	m
h	height of vessel for liquid hold-up (to LZA(HH))	m
ID	inside diameter	m
IL	interface level (normally used for L/L interface)	
L	length liquid	m
LA(H)	high level pre-alarm	
LA(L)	low level pre-alarm	
LZA(HH)	high level trip	
LZA(LL)	low level trip	
NFA	net free area	-
NL	normal level	
$max(a_1,a_2)$	maximum value of the numbers a_1 and a_2	
$min(a_1,a_2)$	minimum value of the numbers a_1 and a_2	
n	number	
P	pressure	Pa
p	pressure	Pa
Q	volumetric flow rate	m^3/s

Re	Reynolds number: Re = $\rho v d_H/\eta$	-
SMS	Shell-proprietary G/L separator with Schoepentoeter, Mistmat and Swirldeck	
TFC	Shell Twin-Flange Coalescer	
TTL	top tangent line	
t	thickness (e.g. of plates in plate pack) duration	m sec
V	volume	m^3
v	velocity	m/s
W	width	m
w	width	m
X	distance	m

Greek symbols:

α	ratio of the short and long axes of the vessel head	
Δ	difference (used in conjunction with other symbols)	
η	dynamic viscosity	Pa.s
θ	angle	degrees
λ	load factor	m/s
λ_G	gas load factor: $\lambda_G = \frac{Q_G}{A_G}\sqrt{\frac{\rho_G}{(\rho_l - \rho_G)}}$	m/s
ρ	density	kg/m^3
φ	liquid flux = Q_L/A_L	m/s
σ	interfacial tension	N/m

Subscripts:

ax	Axial
bed	coalescer bed
d	dispersed phase
c	continuous phase
col	collection compartment
coleff	effective length of collection compartment
con	control requirements or specific control band
conc	local volumetric fraction of dispersed phase
contot	total control band
crit	Critical
cs	cross section or cross-sectional area

db	dispersion band
dh	droplet of heavy liquid phase
dl	droplet of light liquid phase
f	front
feed	feed flow
fp	feed pipe (perforated) front plate of L/L separation plate pack
fw	front weir of a collection compartment
G	gas
H	hydraulic diameter
h	heavy liquid phase
hd	header
in	inlet
int	L/L interface
L	liquid (in general)
l	light liquid phase
laminar	laminar flow
loss	part of plate pack front face available for flow
low	lower part
m	mixture
max	maximum
min	minimum
out	outlet
ow	overflow weir of a collection compartment in horizontal three-phase settler with double weir
p	droplet or particle
pp	plate pack for L/L separation
ret	retention time
set	settling compartment or settling process
spec	specified
tl	transition from turbulent to laminar flow
turbulent	turbulent flow
up	upper part underflow passage of front weir of heavy-phase compartment in horizontal three-phase settler with double weir
ves	vessel
ww	the two heavy-phase weirs in horizontal three-phase settler with weir configuration
1	feed inlet
2	gas outlet
3	outlet of the light liquid phase

4 outlet of the heavy liquid phase

(numbers 0 to 6 inclusive also refer to principal distances/clearances in the separator vessels (see the individual layout drawings and Appendix VI))

Superscript:

* dimensionless representation of length or area (see Appendix VI)

1.7 COMMENTS ON THIS DEP

Comments on this DEP may be sent to the DEP Administrator at standards@shell.com. Shell staff may also post comments on this DEP on the Surface Global Network (SGN) under the Standards folder.

2. SELECTION OF L/L AND G/L/L (THREE-PHASE) SEPARATORS

2.1 GENERAL

The selection of a suitable L/L or G/L/L separator for a given application depends on several factors, such as:

- feed composition, i.e. the phase ratio of the liquid phases
- required separation efficiency
- required gas and liquid handling capacity
- whether L/L separation or G/L separation is the controlling factor (in G/L/L separators)
- required fouling tolerance.

These requirements may be conflicting, such as high fouling tolerance and high separation efficiency.

To facilitate the choice of suitable separator types for a given application, Table 2.1 has been included, indicating for each separator described in this DEP those applications for which it is recommended or shall not be used.

It serves as a first selection guide, after which a final choice can be made after consulting the parts of the DEP where the provisionally selected separator types are described.

Each of these parts starts with the profile of the separator (e.g. detailed characteristics and typical process applications) and then subsequently gives the sizing rules to be followed for a proper design. The detailed vessel sizing procedures are given, and illustrated with examples, in the corresponding appendices.

The various terms used in the first column of Table 2.1 are explained below and the relevant sizing criteria for L/L and G/L/L separators are defined.

2.2 L/L SEPARATION

2.2.1 Separation efficiency

Normally, the separation efficiency of L/L separators is specified in terms of the "**cut-off diameter**". This is the diameter of the smallest droplets removed with an efficiency of 100 %.

The separation efficiency depends on the droplet size distribution of the dispersed phase. It is customary to distinguish between primary and secondary dispersions. A primary dispersion is one in which the majority of the dispersed droplets are larger than 30 μm. These are droplets large enough to separate from the dispersion by gravity settling. A secondary dispersion is one in which the majority of the dispersed droplets are smaller than 30 μm. To separate these dispersions the droplet size shall be increased first by means of a coalescer or use shall be made of hydrocyclones or centrifuges.

The term ‘bulk separation’ is used for separation in open settlers designed for a cut-off diameter of 150 μm. This is equivalent to an entrainment rate of ≤1.5 %v.

More efficient separation is achievable by installing internals such as a plate pack, a coalescer mat or coalescer cartridges. A plate pack is designed for a cut-off diameter of 50 μm, which reduces the dispersed phase entrainment to ≤ 0.2 %v. Coalescers can reduce this to between 50 ppmv and 500 ppmv.

Hydrocyclones and centrifuges fall outside the scope of this DEP.

2.2.2 Liquid handling capacity

The liquid handling capacity of a separator depends on the liquid flux ϕ:

$$\varphi = \frac{Q_L}{A_L} \quad \text{[m/s]}$$

where Q_L is the liquid feed flowrate and A_L is the area available for separation. In vertical vessels this is the cross section of the vessel, in horizontal vessels the cross-sectional area of the separation compartment.

For low dispersed phase concentrations (≤ 5 %) the flux is directly related to the cut off droplet size via the Stokes settling velocity. For higher dispersed phase concentrations the interaction between the dispersed phase droplets shall be taken into account. This will be discussed in more detail in Appendix I.

2.3 G/L SEPARATION:

2.3.1 Separation efficiency

It is common practice to characterise the separation efficiency of G/L separators in terms of percentage removal. This is justified for the more efficient G/L separators, where the liquid remaining in the gas stream after passing through the separator consists of re-entrained droplets of which the size is little affected by the droplet size distribution in the feed.

A bulk G/L separation is defined as a separation where less than 90 % to 95 % of the liquid is removed from the gas phase. This can be achieved in separators without demisting internals.

The efficiency of G/L separators equipped with a mist mat, vane pack or swirl deck (or a combination of these internals) is higher.

For more information see DEP 31.22.05.11-Gen.

2.3.2 Gas handling capacity

The gas handling capacity in three-phase separators is characterised by the gas load factor, λ_G:

$$\lambda_G = \frac{Q_G}{A_G}\sqrt{\frac{\rho_G}{(\rho_l - \rho_G)}} \quad \text{[m/s]}$$

where Q_G is the volumetric gas flow rate,

ρ_l and ρ_G are the densities of the lightest liquid phase and the gas phase respectively.

If the volumetric flow rate of the light liquid phase is less than 5 % of the total volumetric liquid flow rate, then ρ_l should be replaced by a flow rate averaged liquid density, ρ_L (see also Appendix VII for definition of ρ_L).

A_G is the area available for gas flow. In vertical separators this is the vessel cross-sectional area, whereas in horizontal separators it is the cross sectional area of the gas cap.

The separator shall be sized so that it is able to handle the gas flow rate under the most severe process conditions. The gas load factor shall not exceed a critical value, the maximum allowable gas load factor λ_{max}, whose value is dependent on the type of G/L separation used. For more information see DEP 31.22.05.11-Gen.

2.4 G/L/L SEPARATORS: LIQUID HANDLING OR GAS HANDLING CONTROLLED

A three-phase separator is liquid handling controlled if

- the feed to the separator is mainly liquid;

and/or

- a low superficial liquid velocity is required (for de-gassing or foam handling purposes, or in cases of difficult L/L separation).

Normally, a horizontal vessel will then be selected.

If the three-phase separator is gas handling controlled, e.g. if a relatively large gas flow rate has to be handled, the first choice will be a vertical vessel.

2.5 FOULING SERVICE

The requirements of high fouling tolerance and high separation efficiency are conflicting, because the internals required for efficient separation are sensitive to fouling. Fouling service requires provisions to keep the settler clean, such as sand-wash facilities in E&P applications.

Under severe fouling conditions it may be advantageous to select a vertical settler with a conical lower end to facilitate the removal of solids.

Plate packs may only be used under (at most) moderately fouling conditions. If used under such conditions the plate pack layout and supports should be adapted to facilitate the removal of solids.

Upstream of Shell Twin Flange coalescers and cartridge coalescers, prefiltering is always required.

2.6 SEPARATORS SUBJECT TO MOTION

More and more separators are installed on floaters and other installations subject to motion, e.g. Tension Leg Platforms. The performance of these separators can be adversely affected by the motion imposed by waves and wind. The accompanying sloshing will compromise liquid handling capacity, separation efficiency and the functioning of level instrumentation. Mitigation of these effects will require the installation of additional internals and other measures.

Guidelines for the design of separators subject to motion are being developed and will be listed in a new Appendix in the future. For the present, the Principal shall be consulted for the further advice.

Table 2.1 Screening of L/L and G/L/L separators

	L/L separators					G/L/L separators			
Separator types	**L1**	**L2**	**C1**	**C2**	**C3**	**T1**	**T2**	**T3**	**T4 /T5**
L/L separation									
primary dispersion	√	√		√		√	√	√	√
bulk separation	√					√	√		√
efficient separation		√		√				√	√
secondary dispersion	X	X	√ [1]	X	√	X	X	X	X
ill-defined L/L interface	X	X					√ [2]	√ [2]	
G/L separation									
bulk separation						√	√	√	
efficient separation									√ [3]
liquid handling controlled (in G/L/L separators)						√	√	√	X
gas handling controlled (in G/L/L separators)								X	√
Fouling service	√		X	X	X	√	√		
High temperature			X	X	X				

√ : Recommended use X : Shall not be used

[1] If properly packed and **NO compressed** crinkled wiremat is installed.

[2] Provided there is a double weir arrangement with no IL control; also to be used if there are corresponding L/L separators.

[3] If wiremesh or wiremesh / swirl deck assembly is installed.

L1: Horizontal open two-phase settler (3.1 and Appendix IV)

L2: Horizontal two-phase settler with plate pack (3.2 and Appendix IV)

C1: Coalescer with compressed coalescer bed (3.3.1)

C2: Coalescer fitted with a prefabricated coalescer mat (3.3.2)

C3: Coalescer fitted with coalescer cartridges (3.3.3 and Appendix III)

T1: Horizontal open three-phase settler with boot (4.1.1 and Appendix V.1)

T2: Horizontal open three-phase settler with weir arrangement (4.1.2 and Appendix V.2)

T3: Horizontal three-phase settler with plate pack and weir arrangement (4.2 and Appendix V.2)

T4: Vertical three-phase settler (4.3)

T5: Vertical three-phase settler with plate pack (4.4 and Appendix V.3)

3. DESIGN RULES FOR L/L SEPARATORS

In this Section the design rules for the various liquid/ liquid separators are given.

If the separators do not contain L/L separation internals, then they are referred to as "open settlers".

For information on the mechanism of liquid/liquid separation, see Appendix I.

Unless explicitly stated otherwise, the liquid flow rates will contain a design margin or surge factor as defined in Appendix IX.

3.1 HORIZONTAL OPEN TWO-PHASE SETTLER (**L1**)

3.1.1 Selection criteria

Application:
Bulk separation of primary dispersions with good separation characteristics (i.e. relatively low viscosity of the continuous phase, relatively large droplets and low dispersed phase concentration).

Characteristics:
- insensitive to fouling;
- only for separation of a primary dispersion.

Recommended use:
- where only bulk separation is required;
- fouling service.

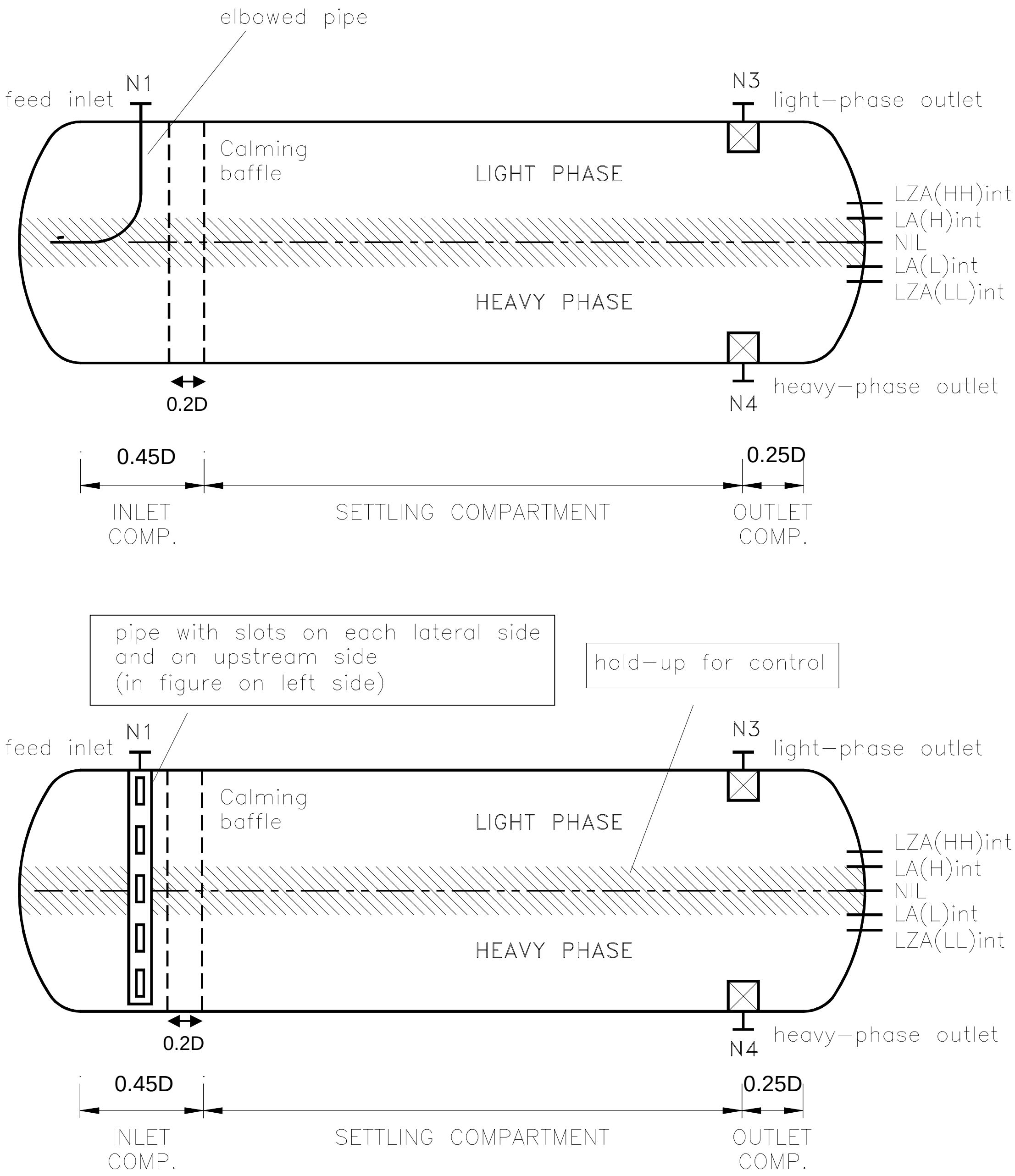
Not recommended:

- for secondary dispersions (i.e. droplets smaller than 30 μm);
- where a high separation efficiency is required;
- where the interface is ill-defined (this will affect the interface level control).

If the interface is ill-defined, or if there is an other reason to avoid direct IL control, the three-phase separator layout with a double weir system (**T2**) should be used (see also (4.1)).

Typical process applications:
- settler in mixer/settler arrays in extraction processes (outside the scope of this DEP);
- side decanter;
- rectifying absorber side draw-off vessel.

Figure 3.1 Horizontal open two-phase settler (feed internal either elbowed or slotted pipe)



3.1.2 General description

Figure 3.1 shows a typical layout of a horizontal open two-phase settler for cases where both phases have to be cleaned. Basically the settler consists of three compartments: an inlet compartment, a settling compartment and an outlet compartment containing the outlet nozzles.

The feed enters the inlet compartment via the feed nozzle equipped with a feed inlet device.

There are two possibilities for the inlet device: a pipe directed to the vessel head or a slotted pipe (as shown in the upper and lower part of Figure 3.1, respectively).

Between the inlet and settling compartment a double calming baffle (perforated plates) shall be installed to prevent flow maldistribution in the settling compartment. The resulting even flow in the settling compartment will facilitate the separation of the two liquid phases.

The settling compartment ends at the liquid outlet nozzles which are both fitted with vortex breakers.

If the cleaning of only one phase is required and the other phase is only a small fraction of the total flow (typically less than 5 %), it is not necessary to perform the separation in the vessel itself. In that case a dome or boot is used to collect the dispersed phase (e.g. in a rectifying absorber side draw-off vessel). For the use of a boot see also the sizing of three-phase settlers equipped with a boot (4.1.1).

3.1.3 Inlet and outlet compartments

The inlet compartment shall be sufficiently large to accommodate the feed inlet device and to allow a reasonable flow path length of the feed to the calming baffle.

The inlet compartment should have a length of at least 0.45D (distance between tangent line and second calming baffle).

The calming baffles shall be mounted with a gasket on a full perimeter support ring and occupy the whole vessel cross-section. At the bottom a small opening (≤ 150 mm) is allowed for cleaning purposes.

The Net Free Area is 30 % for the first baffle and 50 % for the second baffle with 12 mm diameter holes (± 0.1 mm).

The baffle thickness should be at least 3 mm, excluding corrosion allowance.

The distance between the baffles is 0.2D.

There shall be sufficient clearance between the first calming baffle and the tangent line to accommodate the feed inlet device. Therefore the minimum length upstream of the first baffle is either 0.25D or = 150 mm + $ID_{\text{inlet nozzle}}$ + max(150 mm, 0.5*$ID_{\text{inlet nozzle}}$), whichever is the larger.

The outlet compartment shall be sufficiently large to accommodate the outlet nozzles. Its length is typically 0.25D.

3.1.4 Settling compartment

The settling compartment is divided into three horizontal zones:

- An upper zone through which in every flow scenario the light phase flows and from which the heavy-phase droplets have to be separated. This is the zone above high interface trip level, $LZA(HH)_{int}$.
- An intermediate zone for level control and accommodation of an eventual dispersion band (see Figure I.1 in Appendix I).
- A lower zone through which in every flow scenario the heavy phase flows and from which the light-phase droplets have to be separated.
  This is the zone below low interface trip level, $LZA(LL)_{int}$.

3.1.5 Sizing of the settler

For a proper sizing of the settler the following main rules apply:

1. The cross-sectional area of the upper and lower zones shall be at least 14.2 % of the vessel cross-sectional area. (This is equivalent to a minimum central height of these cross-sectional areas of 0.2D).
2. The minimum height of $LZA(LL)_{int}$ is equal to the nozzle ID of the heavy liquid outlet.
3. The horizontal cross section of the settling compartment shall be sufficient to achieve the specified separation efficiency in terms of droplet cut off size i.e <150 µm. A practical approximation of this area is $A_{set}=L_{set}xDx0.8$, where the factor 0.8 accounts for the fact that the interface is generally not located in the midplane of the separator and provides some allowance for flow maldistribution.
4. The control volume (contained between $LA(L)_{int}$ and $LA(H)_{int}$) shall be sufficiently large to meet the specified interface level control time (see Appendix X).
5. The cross-sectional area of the zones above and below NIL shall be sufficiently large to limit the axial velocity in the light and heavy phase to $\leq$ 0.015 m/s.
6. Preferably $2.5 \leq L/D \leq 6$.

In Appendix IV the procedure is presented for checking the sizing of an existing settler. It can also be treated as the sizing procedure for a new settler starting with the specification of the vessel diameter and length and interface level control heights.

If certain criteria cannot be met, the procedure has to be repeated with adjusted vessel dimensions and level control heights.

A calculation example is given in Appendix IV.

3.1.6 Nozzles

The feed nozzle should be fitted with an inlet device.
There are two options for this:

- an elbowed pipe directed towards the vessel head (as is shown in the upper part of Figure 3.1);
- a vertical pipe with rectangular slots (as is shown in the lower part of Figure 3.1).
  The total area of the slots is typically 3.3 times the cross-sectional area of the feed nozzle. A feed inlet velocity of 1 m/s maximum will then be reduced to 0.3 m/s maximum in the slots. The slots should be on each lateral side and on the upstream side (i.e. the side facing the nearest vessel head, as shown in Figure 3.1).

For the sizing of the feed nozzle, see Appendix VIII.

For the sizing of the outlet nozzles and the specification of the required vortex breakers, see Appendix VIII.

The vortex breaker shall be at least a half nozzle diameter away from the corresponding control level, $LZA(LL)_{int}$ (heavy-phase outlet) and $LZA(HH)_{int}$ (light-phase outlet).

3.2 HORIZONTAL TWO-PHASE SETTLER WITH PLATE PACK (**L2**)

3.2.1 Selection criteria

Application:
Efficient separation of primary dispersions.

Characteristics:
- efficient separation, provided the dispersion is of the primary type;
- Moderately robust to fouling; a certain degree of fouling can be accommodated by e.g. selecting a relatively large plate distance and plate angle.

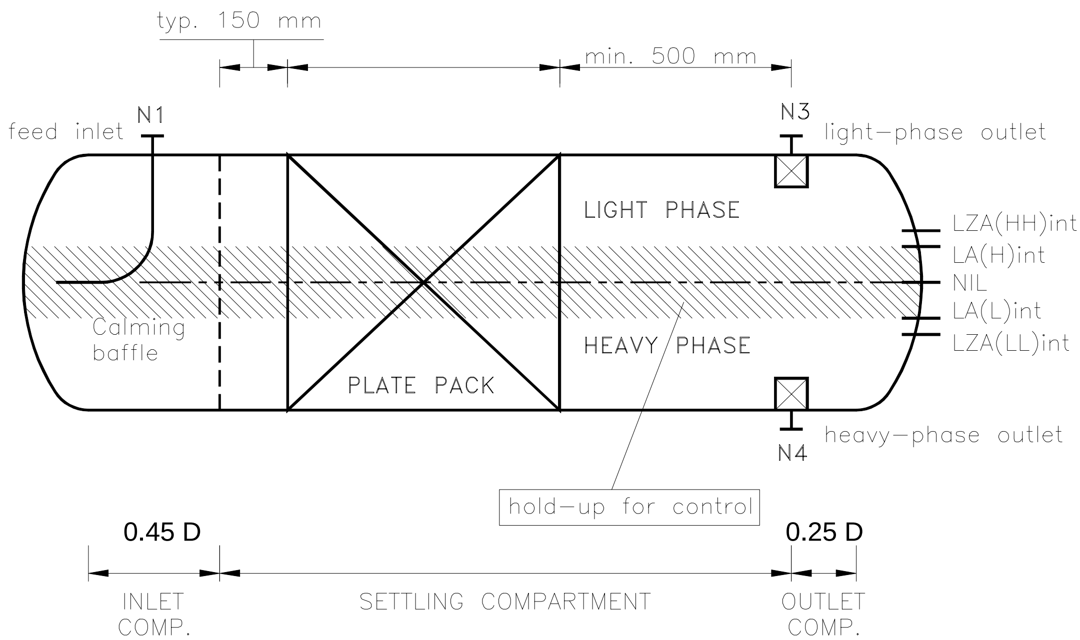
Recommended use:
For the efficient separation of a primary dispersion provided:
- the L/L interface is well-defined;
- the service is at most moderately fouling.

Not recommended:
- for secondary dispersions;
- in heavy fouling service.

Where the interface is ill-defined (this will affect the interface level control) or if there is some other reason to avoid direct IL control, the three-phase separator layout with a double weir system (**T3**) should be used. (see also (4.2)).

Typical process applications:
- acid settler of HF-alkylation plant
- water draw off vessel in condensate stabiliser plant.

Figure 3.2 Horizontal two-phase settler with plate pack



3.2.2 General description

Figure 3.2 shows a typical layout of a horizontal two-phase settler, fitted with a plate pack, for cases where both phases have to be cleaned from the other liquid phase.

The feed inlet shown is a pipe directed to the nearest vessel head, but alternatively a slotted pipe can be used (see (3.1.2)).

The manholes shall be located so that the plate pack internals can easily be installed, and are accessible from both sides.

Other features are equivalent to those described in (3.1.2).

3.2.3 Inlet and outlet compartments

Requirements for inlet and outlet compartments are equivalent to those described in (3.1.3), with the difference that only one baffle is installed. The Net Free Area of this baffle should be 20 %.

3.2.4 Settling compartment

The settling compartment contains a plate pack. In the standard layout a cross-flow plate pack is used. For more information on plate packs and their design, see Appendix II.

The distance from the calming baffle to the plate pack should be 150 mm.

The minimum distance from the plate pack to the outlet nozzles should be 500 mm.

To prevent bypass, the clearance between the plate pack and the vessel wall shall be sealed, apart from a small opening underneath the plate pack required for cleaning purposes.

3.2.5 Sizing of the settler

For a proper sizing of the settler the following main rules apply:

1. The cross-sectional area of the upper and lower zones in the plate pack shall be sufficiently large, to ensure that the flow is laminar.
2. The cross-sectional area of the upper and lower zones shall be at least 14.2 % of the vessel cross-sectional area. (This is equivalent to a minimum central height of these cross-sectional areas of 0.2D).
3. The length of the settling compartment (distance between calming baffle and outlet nozzles) should be at least the length of the required plate pack + 650 mm.
4. The control volume (contained between $LA(L)_{int}$ and $LA(H)_{int}$) shall be sufficiently large to meet the specified interface level control time (see Appendix X).
5. Preferably $2.5 \leq L/D \leq 6$.

In Appendix IV the procedure is presented for upgrading an existing open settler by installing a plate pack.

It can also be treated as the sizing procedure for a new settler starting with the specification of the vessel diameter and length and interface level control heights.

If certain criteria cannot be met, the procedure has to be repeated with adjusted dimensions.

A calculation example is given in Appendix IV.

3.2.6 Nozzles

Requirements for feed nozzle and outlet nozzles are equivalent to those described in (3.1.6).

3.3 COALESCERS (**C1**, **C2**, **C3**)

3.3.1 Selection criteria

Application:

Coalescence and removal of low concentrations (5 % or less) of dispersed droplets from primary or secondary dispersions. Coalescers are not suitable for bulk separation.
Coalescers should not be applied for liquids with a kinematic viscosity above 15 mm^2/s.

Characteristics:

- In situ compressed coalescer mats (**C1**)
  - suitable for the coalescence of primary and secondary dispersions;
  - economic, because of low-cost material and possibility of backwashing;
  - manually packed: packing should be installed by properly trained personnel to avoid channelling and bypassing;
  - sensitive to fouling: prefiltering is required, unless service is absolutely clean.

- Prefabricated coalescer mat (**C2**)
  - suitable for the coalescence of primary dispersions only;
  - little likelihood of channelling or bypassing since it is pre-fabricated;
  - density is lower than that of **C1** and **C2** hence less sensitive to fouling.

- Cartridge coalescers (**C3**)
  - suitable for the coalescence of primary and secondary dispersions;
  - little likelihood of bypassing because the cartridges are pre-fabricated;
  - sensitive to fouling: prefiltering is required, unless service is absolutely clean.

Recommended use:

- Compressed coalescer bed:
  - for secondary dispersions, if properly packed and **NO compressed** crinkled wiremat is installed;
  - vertical vessels only.
- Coalescer mat:
  - for primary dispersions;
  - if local phase inversion can occur (i.e. the dispersed phase becomes locally the continuous phase), use dual material (e.g. stainless steel and polymer filaments).
- Coalescer cartridges:
  - for secondary dispersions;
  - to upgrade Shell Twin-Flange Coalescers (equipped with compressed coalescer bed): with cartridges a wider choice of packing materials is possible.

Not recommended:

- In fouling service without pre-filtering.

Material considerations: The thermal, mechanical and chemical stability of the coalescer material should be considered as well:

- Polypropylene shall not be used if the operating temperature exceeds 80 °C. Teflon should not be used above 200 ^{o}C.
- Fibre glass should not be used in systems with pH > 9.
- Because fibre glass is brittle, it should not be used in the open structured mats of type **C2** coalescers.

Typical process application:

- Dewatering of hydrocarbons (ranging from LPG to gasoil fractions).

3.3.2 General description

A coalescer is a separator which makes use of the fact that droplets in dispersions grow in size when they pass through fibrous packed beds. The enlarged droplets are subsequently removed in a settling compartment, which can be either downstream or upstream of the packed bed, or eventually in a separate vessel.

The packed bed can be either a mat, compressed in situ (**C1**), or pre-fabricated (**C2**), or an arrangement of parallel cartridges (**C3**). The packing material can be stainless steel, glass fibre or a polymer, like polypropylene, PTFE, or poly-aramid. Combinations of these materials are applied as well and have interesting synergies.

Coalescers of type **C1** and **C3** are intended for secondary dispersions (droplets smaller than 30 micron). The droplets grow as a result of interception by and adhesion to the fibres. Therefore the fibre structure, filament size and free volume of the packing medium are the important parameters. The packing in these coalescers has a relatively high density and the fibres are relatively fine. The finer the filament the more effective the coalescence process will be. Droplet growth will continue until viscous drag forces, acting on the droplets as a result of the continuous flow of the mixture through the coalescer medium, exceed the force of adhesion. Normally, this coalescence process will subsequently convert the secondary dispersion into a primary dispersion, which can be separated by gravity.

Coalescers of type **C2** with a prefabricated coalescer mat are intended for primary dispersions. The choice of the coalescer material is determined by the criterion that the dispersed phase shall preferentially wet the packing surface. In de-oiling service polymers such as polypropylene or Teflon should be used, for water removal stainless steel is required.

It is of course also possible to use combinations of coalescers, e.g. C3 followed by C2, or a combination of coalescers and plate pack separators.

3.3.3 Treatment of the coalescer feed

3.3.3.1 Selection of feed pump

Normally centrifugal pumps are used to pump the feed to the coalescer. However, due to the high level of energy dissipation in this type of pump, the droplets in the feed will be dispersed further to smaller droplets and more stable dispersions will be formed.

In critical systems where degradation can readily take place, other types of pumps should be used in which less energy is dissipated, e.g. displacement pumps.

3.3.3.2 Measures to avoid flashing in the coalescer

In cases where the feed of the coalescer originates from a three-phase separator in which vapour and liquids are in equilibrium and no pump upstream of the coalescer is used, precautions have to be taken to avoid flashing in the coalescer due to the pressure drop across the coalescer bed.

This can be done by placing the upstream three-phase vessel at a higher elevation relative to the coalescer. Further, the coalescer vessel shall always be equipped with a vent.

3.3.3.3 Prefilters

In fouling service pre-filtering should be done upstream of a coalescer.

Two pre-filters should be used in parallel, with one in use and the other on standby. Measurement of the pressure drop across the prefilter in use will indicate the degree of fouling.

If the pressure drop across the pre-filter in operation has exceeded the maximum, then the flow to be cleaned out has to be routed via the other pre-filter. This will allow the fouled pre-filter to be cleaned out without putting the coalescer at risk.

Within the Group both cartridge and filter basket (which may include a filter bag) systems are applied; cartridge systems should normally be used and are now the industry standard. Both cleanable (steel) and propylene/cellulose paper cartridges are used. Steel type filters, typically cleaned with LP steam, are used in high temperature applications or in systems which require frequent cleaning.

Sometimes, filter cartridges are classified by the Manufacturer as absolute rated for a given particle size. This means that the pores of the filter cartridge are smaller than that particle size. (If the pores of the cartridge are larger than the particle size, the particles will penetrate the filter medium where they will be trapped by adhesion and other mechanisms.)

The pre-filter shall retain all solid particles larger in size than the pore size of the coalescer cartridge. This would rarely be larger than 5 μm.

Normally the pre-filters are sized so that under the prevailing flow conditions the pressure drop across the clean cartridges is 0.1 bar. Change-out is done when the cartridge pressure drop reaches a given limit, as recommended by the Manufacturer, which is typically 3 bar for absolute rated pre-filters and 1 bar for other types.

The area and number of cartridges and the sizing of the pre-filter pressure vessel shall be specified by the pre-filter Manufacturer.

Since the velocity through the filter medium can be higher than that through the coalescer cartridges and therefore less cartridge surface area is required, a pre-filter vessel will be smaller than a coalescer vessel for a given feed flow rate.

3.3.4 Coalescer fitted with a compressed coalescer bed (Shell Twin-Flange Coalescer)

3.3.4.1 General

The Shell Twin-Flange Coalescer (TFC) has always been the standard coalescer within the Shell Group.

A schematic layout is presented in Figure 3.3.

The detailed layout is defined in Standard Drawing S 22.007.

The TFC is a top-flanged vessel of which the lower part has a larger diameter than the upper part. The coalescer bed is compressed in a skirt between two grids. The feed (in most cases a hydrocarbon feed which has to be dewatered) flows downwards through the bed where coalescence of the dispersed phase takes place. After this the heavy liquid phase leaves the vessel via a bottom outlet and the light liquid phase leaves via four side outlets. These side outlets are located just below where the skirt is attached to the vessel wall. A vent is connected to the upper part of this annular compartment to evacuate any vapour formed locally.

The sizing rules of the Shell Twin-Flange Coalescer are given below.

3.3.4.2 Skirt and coalescer bed

In its standard layout the coalescer bed consists of compressed polypropylene wool of which the fibres have typically a diameter of 30 µm.

If polypropylene is used, no steaming out can be applied since the maximum allowable temperature is 80°C. Where steaming out, or any other process where the temperature will rise above this limit, is required, more heat-resistant material shall be used. In a non-corrosive environment stainless steel wool may be an alternative, and the filament diameter should also be 30 µm.

The uncompressed bed shall not extend above the lower flange face.

The bed is manually packed by means of rolls/blankets of uncompressed coalescer material. Proper packing is important to avoid channelling. The top grid is provided with a rim which fits into an inner groove of the face of the top flange. The bed is compressed by the top cover being placed on the top grid and pulled down onto the lower flange face by means of long bolts.

After packing and compression the bed shall satisfy the following requirements:

If made from polypropylene filaments:

- Bulk density 110 kg/m^3 and typical height in range of 540 mm to 700 mm.

If made from stainless steel filaments:

- Bulk density in the range of 400 - 425 kg/m^3 and typical height in range of 640 mm to 800 mm.

NO crinkled wiremat shall be used underneath the PP-wool bed **unless** measures are taken to prevent the compression of the mat during the compression of the PP-wool bed, since a compressed mat will spoil the effect of the PP-wool bed. The reason for this adverse effect is that, due to this compression, the bulk density of liquid velocity in the bed become too high. This will spoil the coalescence process because the relatively high velocities will lead to re-dispersion of the coalesced droplets.

For the same reason propylene felt mats should not be used as an alternative for polypropylene wool.

In Standard Drawing S 22.007 two options are given for the packing in the TFC:

1. PP-wool bed alone;
2. PP-wool bed with one underlying layer of crinkled wiremat which is safeguarded against compression.

Before the coalescer can be used it shall be de-gassed first by being filled with either the process liquid or mains water via the utility connection. It will then be degassed via a venting connection on the feed piping.

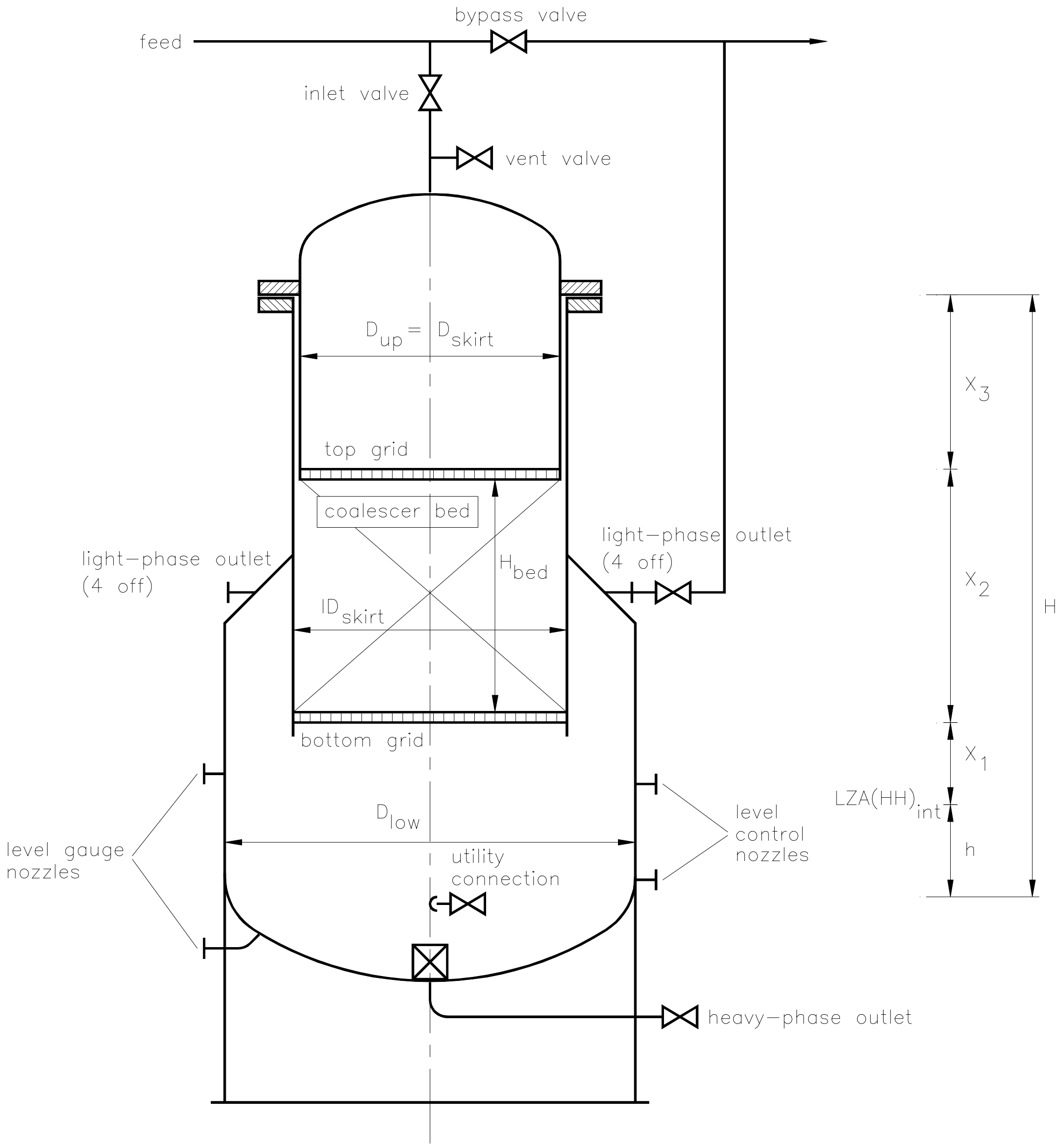
The ID of the skirt shall be sufficiently large to limit the average velocity of the total liquid flow through the bed to at most 0.015 m/s.

$$ID_{skirt} \geq 9.21\sqrt{Q_l + Q_h} \qquad [m]$$

Q_h and Q_l are the volumetric flow rates of the heavy and light liquid phase respectively.

The Net Free Area of the grids of the bed shall be at least 80 %.

Figure 3.3 Schematic layout of the shell twin-flange coalescer



3.3.4.3 Upper and lower vessel diameter

The inner diameter of the upper part of the coalescer vessel, D_{up}, is equal to the inner diameter of the skirt.

The inner diameter of the lower part of the coalescer vessel, D_{low}, should be selected so that the upward velocity of the continuous light phase in the entrance of the annular space between the vessel wall and coalescing bed is equal to the superficial velocity of this phase through the bed.

Consequently, ignoring the wall thickness of the skirt

$$D_{low} = D_{up}\sqrt{2} = ID_{skirt}\sqrt{2} \geq 13\sqrt{Q_l + Q_h} \quad [m]$$

3.3.4.4 Vessel tangent-tangent (H)

The bottom compartment of the TFC shall be sufficiently large to provide a sufficiently long control time of the interface level.

Moreover, the distance between the highest level of the interface ($LZA(HH)_{int}$) and the bottom of the skirt, X_1 shall be such that the local velocity of the continuous light phase is not higher than its superficial velocity in the bed, hence X_1 is at least $0.25D_{up}$.

Let h be the height required for interface level control (up to $LZA(HH)_{int}$), then:

$H = h + X_1 + X_2 + X_3$ [m] (see also Figure 3.3)

$X_1 = 0.25\ D_{up}$
$X_2 = H_{bed} + 2\ H_{grid}$
X_3 is typically 450 mm for stainless steel packing and 650 mm for polypropylene packing

X_3 shall be sufficiently large to accommodate the coalescer material before compression.

3.3.4.5 Nozzles

The feed nozzle should be sized so that the velocity does not exceed 1 m/s. It should be provided with a baffle plate in accordance with standard drawing S.22.007.

For the sizing of the outlet nozzles and the specification of the required vortex breakers, see Appendix VIII.

The vent connection on the vessel and the utility connection shall both have a minimum diameter of 50 mm.

3.3.4.6 Pressure drop

The pressure drop across a clean standard compressed polypropylene coalescer bed with a bulk density of 110 kg/m^3 is about 0.1 bar at a total superficial liquid velocity of 0.015 m/s and a dynamic viscosity of about 1 mPa.s. However, the pressure drop will increase due to fouling.

To monitor the degree of fouling during service, a facility should be installed for pressure differential measurement across the coalescer bed. It is common practice to allow a maximum pressure drop of 1 bar across the bed before the bed is exchanged or back-washed.

3.3.5 Coalescer fitted with a prefabricated coalescer mat

3.3.5.1 General

Prefabricated coalescer mats can be used both in horizontal and in vertical coalescer vessels. Due to their relatively open structure plugging is less of a concern.

A schematic layout of a horizontal coalescer vessel equipped with boot is shown in Figure 3.4. For the sizing of the boot, see (4.1.3) in which the sizing of open three-phase settlers equipped with a boot is given.

A vertical vessel with upflow is preferred in slugging service, to avoid flooding of the coalescer mat. The efficiency is somewhat lower due to the countercurrent flow of the feed and the separated dispersed phase.

3.3.5.2 Vessel diameter

The cross-section of the mat shall be sufficiently large to limit the average velocity of the total liquid flow to at most 0.015 m/s. In vertical vessels the velocity should further be limited to a cut-off droplet size for water droplets of 200 μm to ensure sufficient draining.

3.3.5.3 Coalescer mat

The depth of the coalescer mat should be 500 mm to 700 mm.

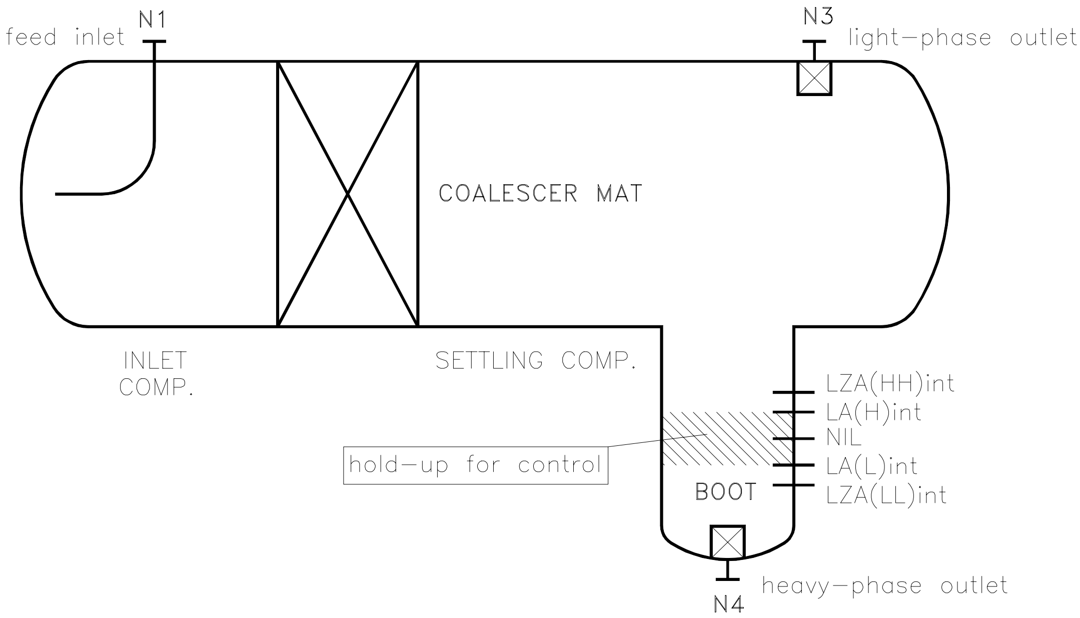
3.3.5.4 Pressure drop

The pressure drop across the coalescer mat is relatively low, typically ≤ 20 mbar. This gives sufficient homogenization of the flow through the vessel so that a calming baffle is not required.

3.3.5.5 Nozzles

Requirements for feed nozzle and outlet nozzles are equivalent to those described in (3.1.6).

Figure 3.4 Schematic layout of coalescer vessel with boot and with prefabricated coalescer mat



3.3.6 Coalescer (retro)fitted with coalescer cartridges (C3)

3.3.6.1 General

Cartridges can be applied in horizontal as well as vertical vessels. For a new design the Shell Twin Flange Coalescer configuration is the preferred starting point. The vessel and its internals can be built around the required number of cartridges.

Knitmesh Dusec coalescer cartridges have frequently been retrofitted into Shell Twin Flange Coalescers to replace the polypropylene wool bed. Since the cartridges are pre-fabricated, channelling is avoided. Within a vessel of a certain size a larger surface area can be accommodated, so the liquid handling capacity is increased.

The dispersion to be treated should enter the cartridge in the centre and flow from in to out. The coalescer material is normally wound in layers around a central perforated cylinder. Usually there is a gradient in the grade of the packing material. The finer fibres, which have to deal with the original secondary dispersion, are closest to the centre. The coarse fibres are closer to the periphery where the droplets have grown into the range of primary dispersions.

In Figure 3.5 a schematic layout is shown of a Shell Twin-Flange Coalescer fitted with coalescer cartridges. As shown, use is made of the skirt in which originally the coalescer bed was installed.

The cartridges are suspended from a plate mounted in the skirt.

The feed flows downward through the cartridges from in to out.

In general, the interface level is below the cartridges. The presence of the skirt prevents short-circuiting of the light phase to the light phase outlet.

3.3.6.2 Cartridge area

The design capacity of a cartridge depends on the application, more particularly on the viscosity of the feed. For coalescers for the deep removal of water from kerosene or gasoil, 20 m^3/m^2h (based on inner surface of the cartridge) appears to be a dependable figure. For PP/LPG 25 m^3/m^2h is acceptable.

Systems with a pH > 9 require alternative more resistant coalescer materials and it may be necessary to derate the design capacity. The Principal should be consulted for further advice.

3.3.6.3 Vessel sizing

To avoid re-entrainment the total cross section of the cartridges should not exceed 40 % of the cross section of the vessel compartment in which they are contained.

For coalescer vessels with a size larger than 2 m a top flange is not practical. In these vessels the mounting plate is fixed, and provided with a removable section which can be used as internal manway.

3.3.6.4 Pressure drop

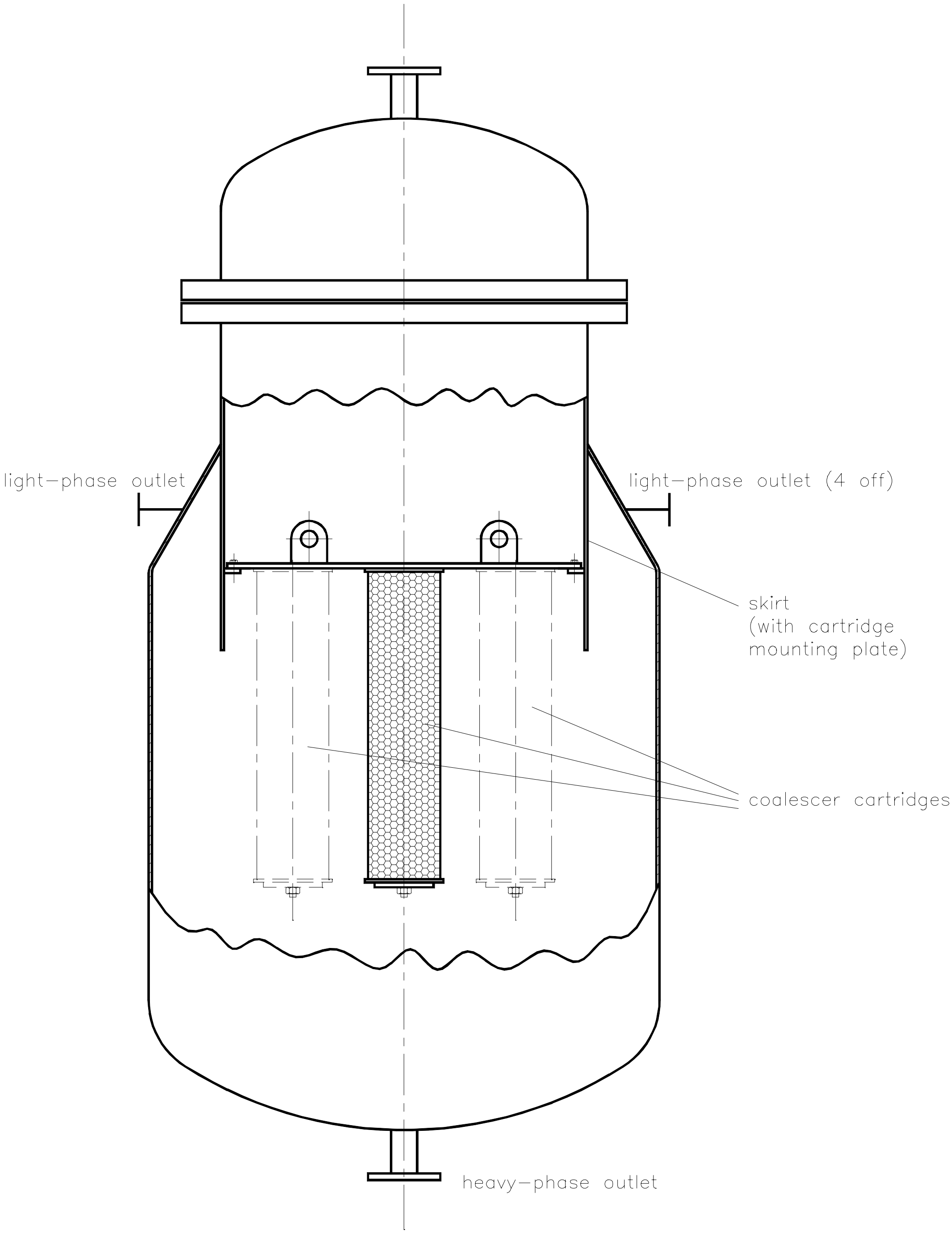
The pressure drop across the cartridges in clean conditions is of the order of 0.1 bar. The cartridges should be replaced when the pressure drop exceeds 1 bar.

3.3.6.5 Nozzles

Requirements for feed nozzle and outlet nozzles are equivalent to those described in (3.3.4.5).

A calculation example of the design of a cartridge coalescer is given in Appendix III.

Figure 3.5 Shell twin-flange coalescer with coalescer cartridges



3.3.7 Manufacturer-proprietary coalescer vessels, equipped with cartridges.

It is also possible to procure a Manufacturer-proprietary coalescer with cartridges. This is supplied as a complete package of vessel and internals based on a Manufacturer-proprietary design. For details of Shell-approved Manufacturers the Principal should be consulted.

Although the design of the separator is the primary responsibility of the Manufacturer, the guidelines given in 3.3.6. should be used to check the number of cartridges and the vessel design. Special attention shall be paid to the proper choice of coalescer material of the cartridges. As to maximum allowable temperature and pH of the feed, the same restrictions apply as indicated above.

4. DESIGN RULES FOR G/L/L (THREE-PHASE) SEPARATORS

In this section the design rules are given for a number of G/L/L (three-phase) separators.

If the separators do not contain L/L separation internals (apart from a weir arrangement), then they are referred to as "open settlers".

Unless explicitly stated otherwise, the maximum liquid flow rates and slug volume will contain a design margin or surge factor as defined in Appendix IX.

NOTE Often L/L separators are designed as a vessel with a gas cap to facilitate the IL control of the two phases. This converts them, strictly speaking, into a three-phase separator geometry.

4.1 HORIZONTAL OPEN THREE-PHASE SETTLER

4.1.1 Selection criteria:

Types:
1. SETTLER WITH BOOT
2. SETTLER WITH WEIR ARRANGEMENT

Application:
Bulk separation of primary L/L dispersion and a relatively small gas flow rate.

Characteristics:
- large liquid handling capacity;
- insensitive to fouling.

Recommended use:
- General:
  - where the L/L separation is the controlling factor and only bulk L/L separation is required;
  - fouling service.
- Settler with boot:
  - where the volume concentration of the heavy phase in the feed is smaller than 5 % and the de-oiling of the heavy phase is not critical.
- Settler with weir arrangement:
  - ill-defined L/L interface (use double weir arrangement with no IL control);
  - where de-oiling of the heavy phase is required.

Not recommended:
- for efficient L/L separation.

Typical process applications:
- Crude/water separators (in E&P applications)
- Overhead Accumulators (in refinery applications)
- Ejector Effluent Separators (in refinery applications)

4.1.2 General description

In general the horizontal open three-phase settler consists of three compartments (see Figures 4.1 - 4.5).

- inlet compartment;
- settling compartment;
- outlet compartment.

  If the settler has a boot, this is the part of the vessel downstream of the boot.
  if the settler has a weir arrangement, this compartment contains the liquid collection compartment(s).

In the following the design rules are given for the two main types (equipped with either a boot or weirs) which will lead to a proper sizing of the settler and its internals.

In Appendix V the sizing procedure is elaborated in more detail.

Apart from the sizing procedure for new settlers, a retrofit procedure is also given in Appendix V to optimise existing open settlers by installing weirs.

4.1.3 Settler with boot

4.1.3.1 Inlet compartment

As shown in Figure 4.1, the feed enters the inlet compartment through a top entry with an inlet device connected by an elbow. For details of feed inlet device see (4.1.3.5).

The length of the inlet compartment (i.e. distance from inlet tangent line to second baffle) is typically minimum 0.45D.

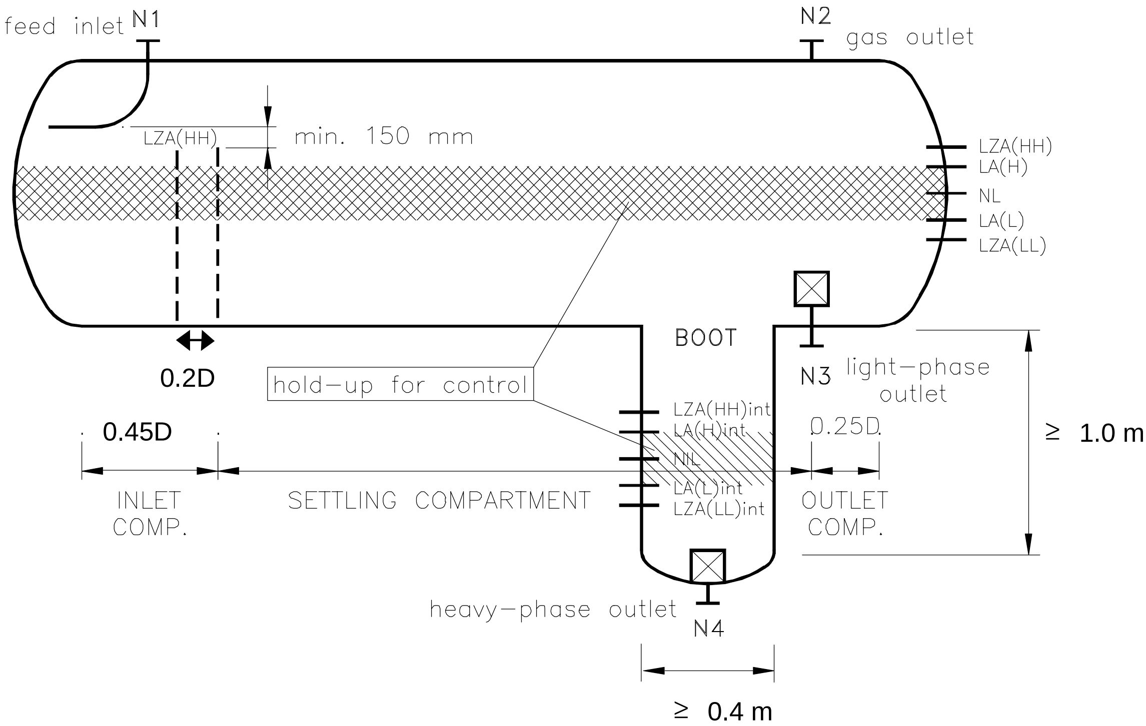
Double calming baffles (perforated plates) shall be installed between the inlet and settling compartment of the vessel. The function of these baffles is to promote an even flow in the settling compartment which will facilitate the separation of the two liquid phases.

Recommended calming baffle characteristics:

- the net free area (NFA) is 30 % and 50 % for the first and second baffle, respectively;
- the hole diameter is typically 12 mm;
- the baffle thickness should be at least 3 mm;
- the distance between the baffles is 0.2D;
- the baffles shall extend from the vessel bottom to LZA(HH) with at the bottom a small opening for cleaning purposes.

Sufficient clearance is required between the vertical TL and the first baffle to accommodate the feed inlet device. The minimum is ($5xID_{inlet\ nozzle}$) or 0.25 D, whichever is the larger.

Figure 4.1 Horizontal open three-phase settler fitted with boot



4.1.3.2 Settling compartment

In this compartment the separation of the two liquid phases takes place.

It extends from the second calming baffle to the outlet of the light liquid phase and it contains the boot. The liquid/liquid interface and the heavy phase outlet are situated in the boot.

4.1.3.3 Boot

The boot will be used to withdraw the heavy phase from the vessel.

Also some additional "de-oiling" will be achieved.

The minimum boot length (i.e. the distance between the bottom of the vessel and the boot bottom tangent line) and the boot diameter should be 1 m and 0.4 m, respectively.

By maximising the boot diameter, the de-oiling of the heavy phase collected in the boot will be improved, because the downflow rate of the heavy phase will be minimised. Theoretically, all light-phase droplets larger than the critical droplet having a rising velocity equal to the heavy-phase downflow velocity are able to escape. However, in practice, the flow of the heavy phase into the boot will not be uniform, which will adversely affect the de-oiling process.

If the various control volumes are fixed (= flow rate of the heavy-phase times the specified control time), maximising the boot diameter will lead to a shorter boot. The boot shall still be sufficiently long to enable proper interface level control and the proper accommodation of all the nozzles required for IL control.

The boot outlet shall be equipped with a vortex breaker. The boot should be located as far from the inlet as possible (whilst still leaving space downstream for the outlet of the light liquid phase), in order to minimise disturbance of the settling process in the settling compartment.

The outlet of the light liquid phase shall protrude into the vessel (by typically 150 mm) and it should be located downstream of the boot. It shall be equipped with a vortex breaker.

4.1.3.4 Sizing of the settler

For a proper sizing of the settler the following main rules apply:

1. The cross-section of the gas cap above LZA(HH) shall be large enough for adequate liquid knockout (for bulk separation the maximum allowable gas load factor is 0.07 m/s).
   The central height shall be at least 0.3 m.
2. The cross-sectional area above LZA(HH) (A_G) and below LZA(LL) shall both be at least 14.2 % of the vessel cross-sectional area. (This is equivalent to a minimum central height of these areas of 0.2D).
3. The minimum elevation of LZA(LL) is equal to the nozzle ID of the light product outlet. If the outlet nozzle is elevated, the minimum elevation is equal to the height of the outlet line plus the nozzle diameter.
4. In slugging flow service the volume of the G/L interface control zone contained between LA(H) and normal level, NL, shall be sufficiently large to contain the hold-up volume required for the light liquid phase PLUS the hold-up volume required for the heavy liquid phase PLUS the slug volume. The size of the anticipated slug is the product of the estimated time that the feed pipe is 100 % liquid-filled and the gas volumetric flow rate prevailing under non-slugging conditions. See Appendix X for a default estimate of the slug volume.
5. The vessel cross-section below NL shall be sufficiently large to ensure that the axial total liquid velocity in that zone is limited to 0.015 m/s.
6. The boot shall be sized so that the velocity of the heavy phase in the boot does not exceed the settling velocity of the smallest light-phase droplet to be separated.
7. The diameter of the boot should preferably be about 1/3 of the vessel diameter. The length of the settling compartment (i.e. the distance between the calming baffle and the light-phase outlet) shall be sufficient to meet the separation specifications (in terms of smallest heavy-phase droplet size to be separated).
8. If de-gassing and/or de-foaming are required, it has to be verified whether the vessel has sufficient capacity for this. For the criteria to be applied, see Appendix V.1 (calculation steps 1 and 2). The foam has to be accommodated between LA(H) and LZA(HH). Between these two levels an additional foam allowance of 250 mm shall therefore be included.
9. It has to be verified whether the gas cap is sufficiently large to accommodate the inlet device including a clearance of 150 mm above LZA(HH). The vertical space requirement of an inlet device is typically twice the inlet nozzle diameter plus 50 mm.
10. Preferably $2.5 \leq L/D \leq 6$.

4.1.3.5 Nozzles

Feed nozzle:

A top feed inlet equipped with an inlet device should be used. This device is connected to the inlet via an elbow and shall be directed to the nearest vessel head. Its location shall be at least 150 mm above LZA(HH).

The choice of the feed inlet device depends on the following factors:

- If the gas volumetric fraction of the feed is less than 0.15, the inlet device is a horizontal pipe section.
- If the gas volumetric fraction of the feed is between 0.15 and 0.7 the inlet device is a horizontal half-open pipe and its opening is directed upwards.
- If the gas volumetric fraction is larger than 0.7, then a Schoepentoeter should be

selected.

If the gas flow is negligible and/or the separator has a sealing function (in the case of an Ejector Effluent Separator, for instance) a bottom rather than a top inlet is used.

For the sizing of the feed inlet nozzle, see Appendix VIII.

For the detailed design of a Schoepentoeter see Appendix III of DEP 31.22.05.11-Gen.

Outlet nozzles:

The outlet of the light liquid phase shall be elevated (typically 150 mm).

Both liquid outlet nozzles shall be equipped with a vortex breaker in accordance with Standard Drawing S 10.010.

The diameter of the liquid outlet nozzles shall be chosen so that the liquid velocity does not exceed 1 m/s. The minimum diameter is 50 mm (or 2 inch).

The top of its vortex breaker shall be at least a half nozzle diameter below the corresponding lowest control level (LZA(LL) for the light-phase outlet and $LZA(LL)_{int}$ for the heavy-phase outlet). The bottom of the light-phase vortex breaker shall be at least 150 mm below LZA(LL).

In Appendix V.1 the procedure is presented for checking the dimensions of an existing three-phase settler fitted with a boot. It can also be treated as the sizing procedure for a new settler starting with the specification of the vessel dimensions and the various level control heights.

If certain criteria cannot be met (for instance, the settling compartment is too short) the procedure has to be repeated with adjusted vessel dimensions.

A calculation example is given in Appendix V.1.

4.1.4 Settler with weir arrangement

4.1.4.1 Inlet compartment

The inlet compartment (including feed inlet) is identical to that of the settler with boot.

4.1.4.2 Settling compartment

Since in general the cleaning of both liquid phases is required ("dewatering" and "de-oiling"), a liquid/liquid interface has to be maintained in this compartment (either via direct IL control or via a combination of two weirs).

4.1.4.3 Collection compartment(s)

Figures 4.2 - 4.5 show a number of possible arrangements.

The configuration with only one collection compartment (for the light liquid phase) with either a submerged or an overflow weir is shown in Figure 4.2. In both cases direct control of the interface is required. In a submerged weir, the gas/liquid interface varies in the same way throughout the vessel, whereas in an overflow weir the gas/liquid interface upstream of the weir is fairly constant (apart from variations in the height of the weir crest due to changes in the flow rate of the light liquid phase).

If the liquid/ liquid interface is ill-defined, however, direct IL control should be avoided. Possible weir arrangements are then as shown in Figures 4.3 to 4.5. The heights of the light- and heavy-phase overflow weirs plus their weir crest heights will determine the location of the interface level. The advantage of this configuration is that the liquid/liquid interface is self-controlling. Even an incoming slug (temporarily replacing the gas flow in the feed) will hardly have an effect, provided the collection compartments can accommodate the slug.

The weirs shall have hand holes for cleaning or removable weir panels. The minimum thickness of the weirs is 3 mm.

The gutter configuration shown in Figure 4.3 can be applied to small light phase flows. A gutter side nozzle could alternatively be used instead of the nozzle with internal piping.

Otherwise the weir arrangement shown in Figure 4.4 should be used. If Q_l/Q_h is either relatively low or relatively high this can be further refined to the configurations shown in Figure 4.5. The arrangement for small Q_l/Q_h, shown in Figure 4.5 should be used rather than an arrangement in which the width of the light-phase collection compartment has been made smaller by shifting the separation plate between the two collection compartments (because this could result in unfavourable sizing of the light-phase collection compartment and the need to have a light-phase outlet at the side of the vessel).

An oil skimming pipe should be installed in the water collection compartment, entering from the vessel bottom and extending to LA(H) for the periodic removal of the oil film which will inevitably form on top of the water.

In general, in the two collection compartments the gas/liquid interface will be controlled. The specified control times in conjunction with the liquid flows will determine the size of the collection compartments and, ultimately for a given diameter, the length of the vessel downstream of the hydrocarbon overflow weir.

NOTE Sometimes a three-phase flow settler geometry is adopted in practice with a combined inlet/settling compartment in the central part of the separator and with the collection compartments for the two liquid phases at the opposite sides of the vessel.

This geometry shall **NOT** be used because:

1. The entry of the feed into the central compartment causes disturbance which adversely affects the separation of the two liquid phases.
2. Assuming that the feed enters in the centre of the central compartment at most only half the compartment can be utilised for separation.

Figure 4.2 Horizontal open three-phase settler with single weir (submerged or overflow)

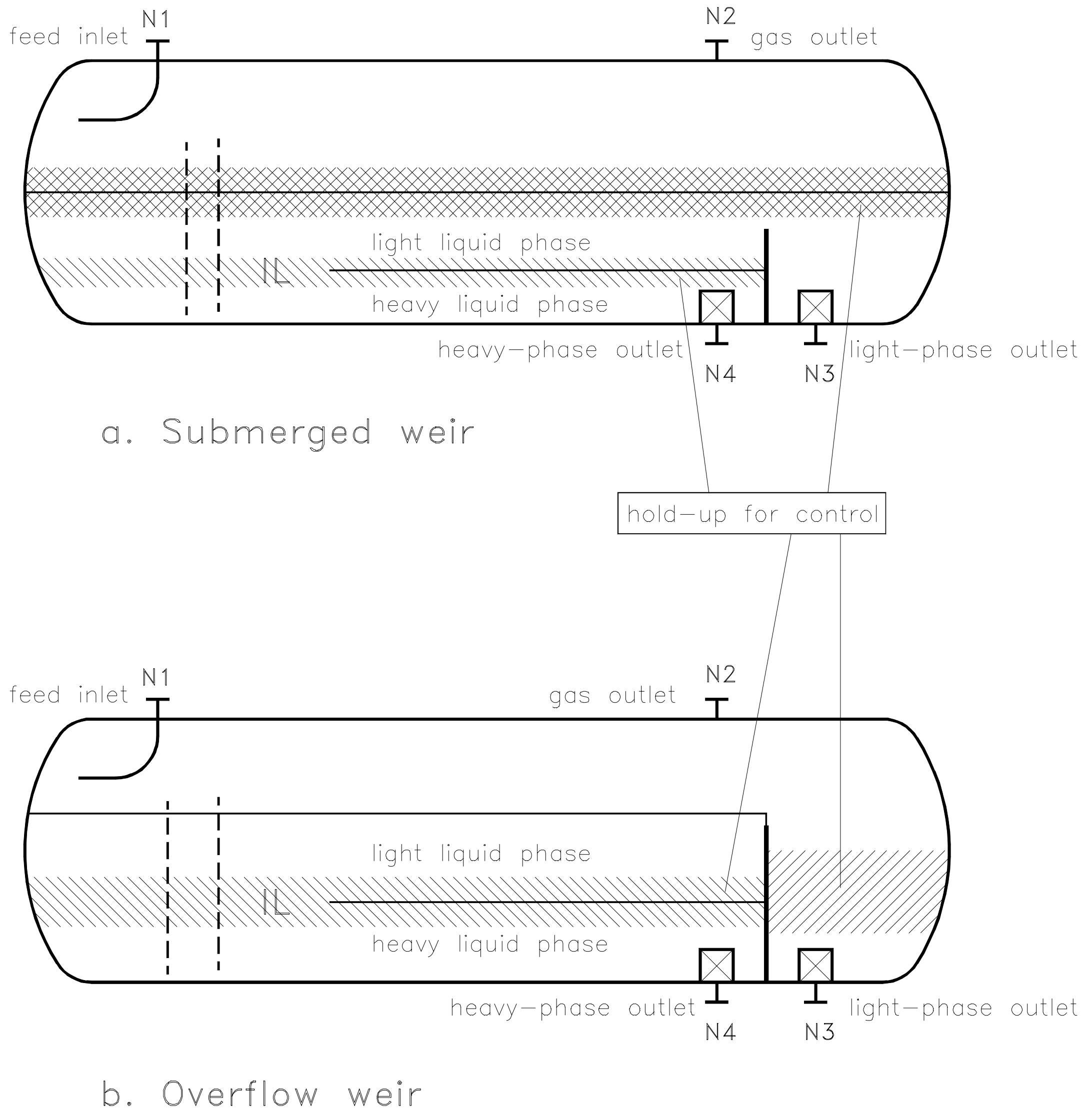


Figure 4.3 Horizontal open three-phase settler with gutter and single weir

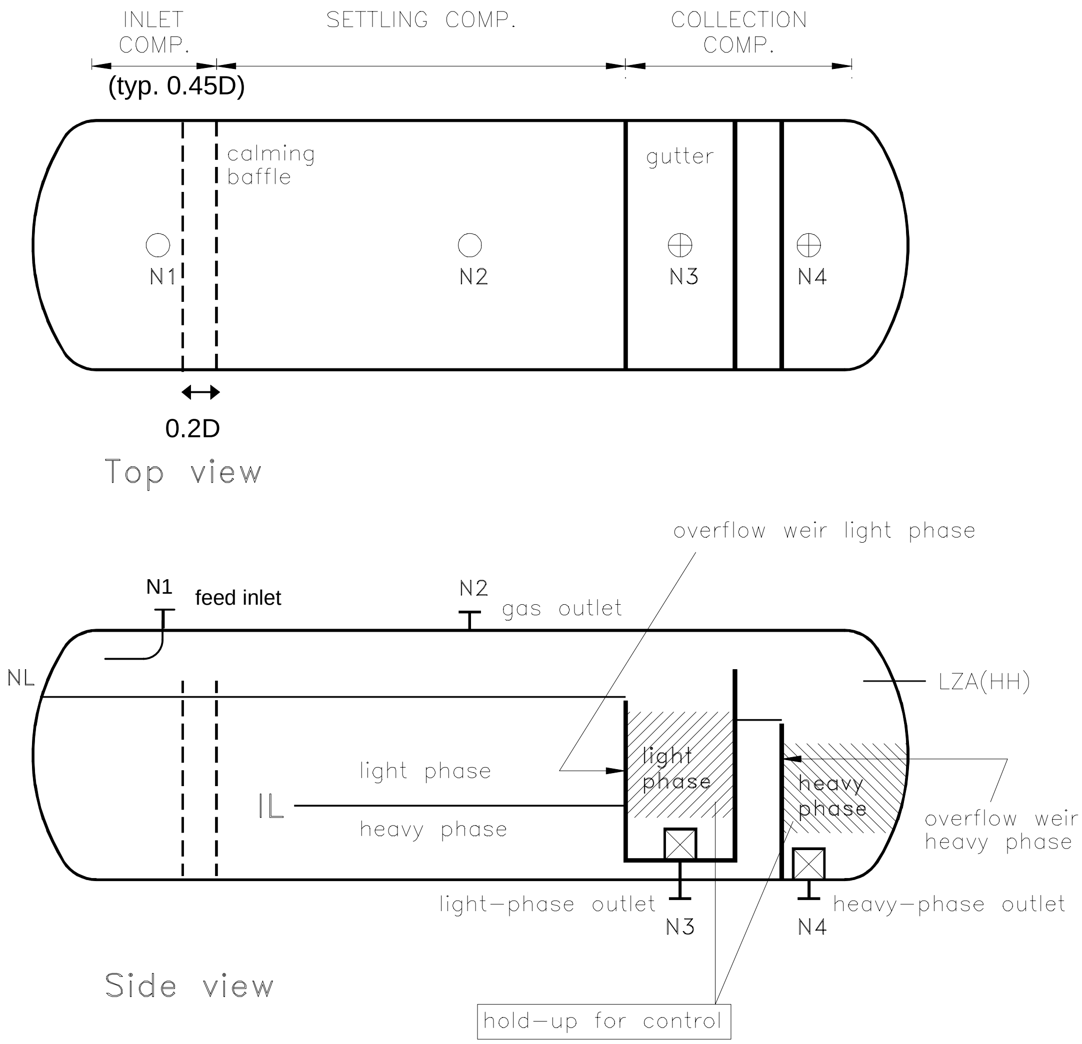
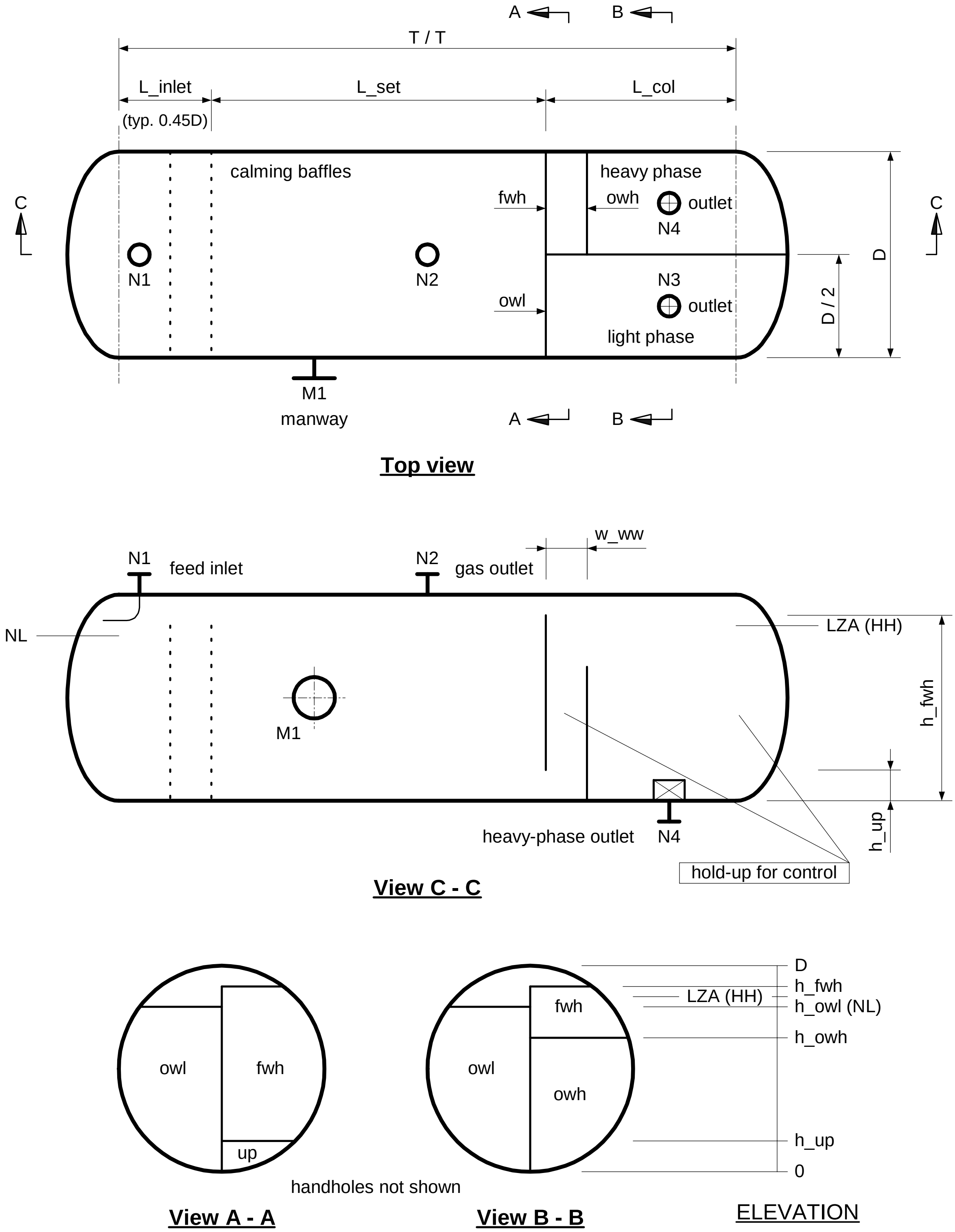


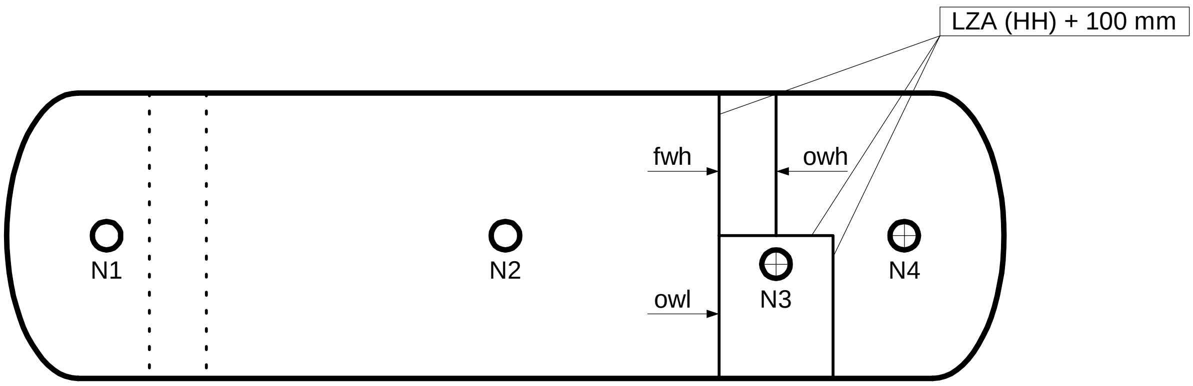
Figure 4.4 Horizontal open three-phase settler with double weir



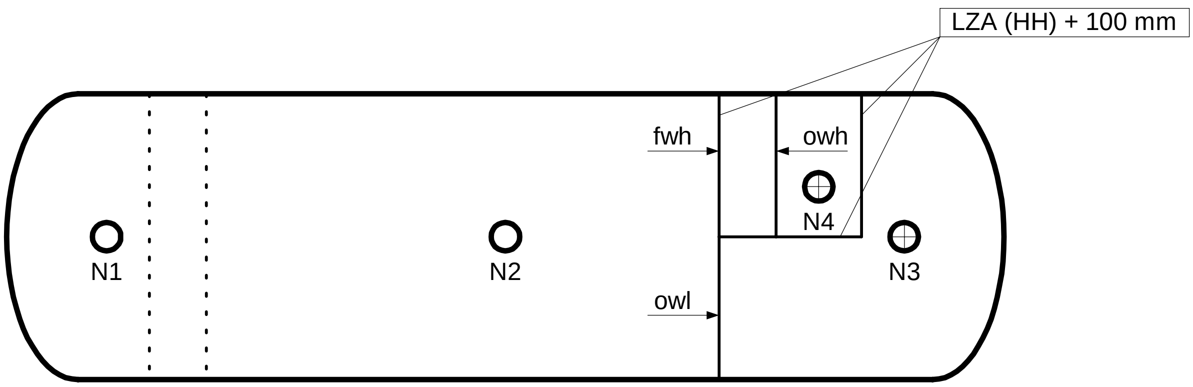
Explanation of principal abbreviations and symbols used in the figure

col : refers to collection compartments
fwh : front weir of the heavy-phase compartment
owh : overflow weir of the heavy-phase compartment
owl : overflow weir of the light phase compartment
set : refers to the settling compartments
up : uderflow passage of the front weir of the heavy-phase compartment
w-ww : width of the gap between th two heavy-phase weirs

Figure 4.5 Horizontal open three-phase settler with double weir for either a small or a large Q_l/Q_h ratio (top view)



Small Q_l / Q_h ratio



Large Q_l / Q_h ratio

fwh : front weir of the heavy-phase compartment
owh: overflow weir of the heavy-phase compartment
owl : overflow weir of the light phase compartment

4.1.4.4 Sizing of the settler

The sizing rules for the settler with double weir arrangement (as one of the various options possible) are given below.

In this type of three-phase settler no IL control is required since the liquid/liquid interface is determined by the heights of the overflow weirs for the light and heavy liquid phase.

Moreover, the gas/liquid interface in the vessel upstream of the weirs (NL) is almost constant (apart from variations in the weir crest height due to changes in the flow rate).

For a proper sizing of the settler the following main rules apply:

1. The cross-section of the gas cap above LZA(HH) shall be large enough for adequate liquid knockout (for bulk separation the maximum allowable gas load factor is 0.07 m/s). Although strictly speaking these separators will not have a high level trip setting, LZA(HH) will be used in the remainder of this section as a reference for the maximum liquid level. The central height shall be at least 0.3 m.

2. If liquid slugs or foaming are expected, in this type of settler this shall be accommodated between NL and LZA(HH). If foaming is likely the distance between NL and LZA(HH) has to include a foaming allowance of 0.25 m.
   To prevent carry-over into the heavy-phase compartment, the height of the underflow weir of the heavy-phase compartment shall exceed LZA(HH) by typically 0.1 m.

3. The vessel cross-sections below IL (or liquid/liquid dispersion band if present) and between IL and NL shall be large enough for the axial velocity in each zone to be at most 0.015 m/s.

4. The vessel cross-section below IL (or liquid/liquid dispersion band if present) shall be at least 14.2 % of the vessel cross-sectional area. (This is equivalent to a minimum central height of this area of 0.2D).

5. The interface level should be halfway between the top of the underflow passage of the heavy-phase underflow weir and the top of the overflow weir of the light phase, in order to minimise the likelihood of carry-over to the liquid compartments.

   At any rate, under normal-flow conditions (i.e. gas/liquid interface controlled by the light phase overflow weir), the interface level (or the dispersion band, if present) shall be at a distance of at least 0.2 m from either the lower rim of the heavy-phase under flow weir or from the upper rim of the light-phase overflow weir. (If a dispersion band is expected but its width cannot be reliably estimated, 0.2 m should be taken as dispersion band width.)

6. The settling compartment shall be large enough to meet the separation specifications (in terms of smallest droplets to be separated).

7. If de-gassing and/or de-foaming are required, it has to be verified whether the vessel has sufficient capacity for this. For the criteria to be applied, see Appendix V.2 (calculation steps 7 and 8).
   The foam has to be accommodated between LA(H) and LZA(HH). Between these two levels an additional foam allowance of 0.25 m has to be included.

8. If a feed inlet device in the gas cap is required and the gas load is high, it has to be verified whether the gas cap is sufficiently large to accommodate the inlet device including a clearance of 150 mm above LZA(HH). The vertical space requirement of an inlet device is typically twice the inlet nozzle diameter plus 50 mm.

9. Preferably $2.5 \leq L/D \leq 6$.

10. If the vessel has a sealing function (e.g. in the case of Ejector Effluent Separators), the inlet and collection compartment shall contain sufficient liquid to satisfy this requirement. In that case a bottom feed inlet shall also be used.

4.1.4.5 Nozzles

Requirements for the feed nozzle and outlet nozzles are similar to those described in (4.1.3.5).

In Appendix V.2 the procedure is given for converting an existing empty horizontal vessel into an open three-phase settler fitted with a weir configuration.

This procedure can also be used for the sizing of new settlers starting from given vessel dimensions and can also be treated as the sizing procedure for a new settler starting with the specification of the vessel dimensions and the various level control heights.

A calculation example is given in Appendix V.2.

4.2 HORIZONTAL THREE-PHASE SETTLER WITH PLATE PACK

4.2.1 Selection criteria

Application
- Efficient separation of primary L/L dispersion and a relatively small gas flow rate.

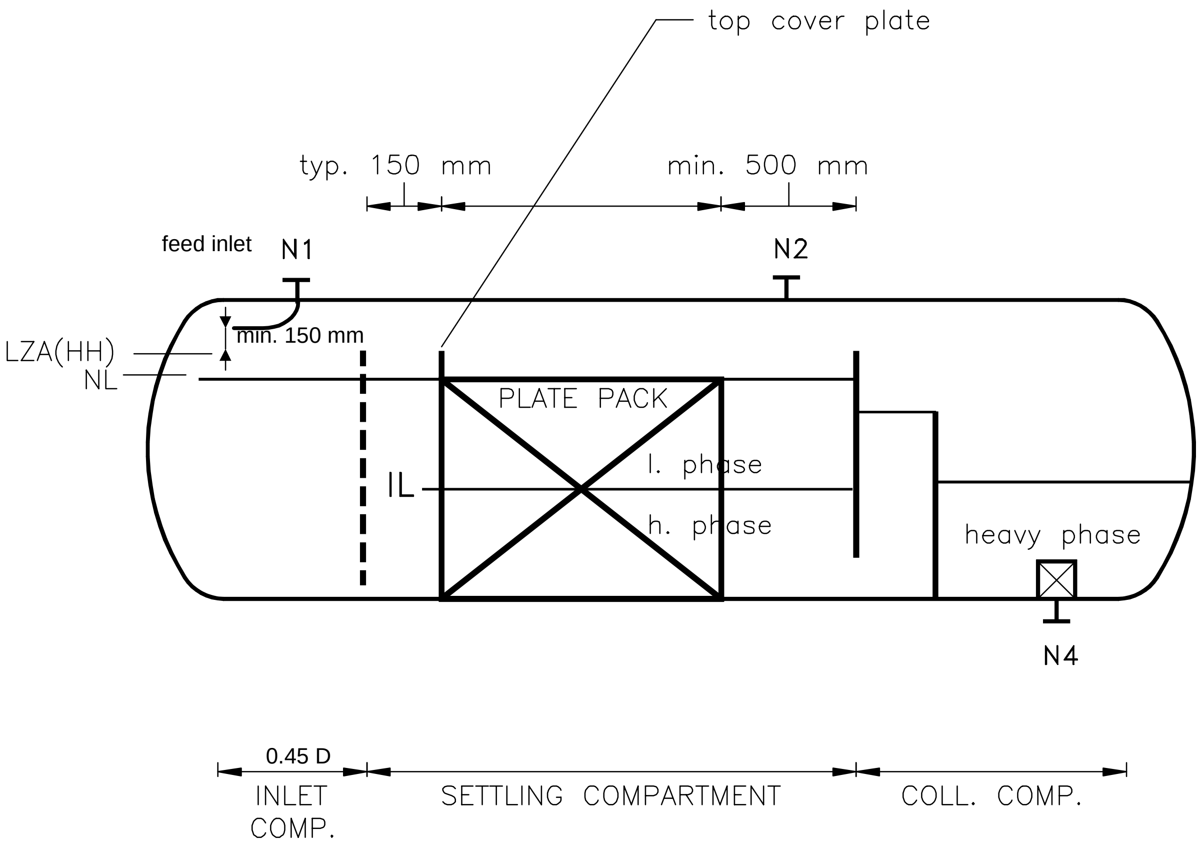
Characteristics
- efficient separation, provided the dispersion is of the primary type;
- not too sensitive to fouling (a certain degree of fouling can be accommodated by selecting a relatively large plate distance and plate angle).

Recommended use
- for the efficient separation of a primary dispersion in a not too fouling service;
- if the L/L interface is ill-defined, use plate pack settler with weir arrangement.

Not recommended
- for secondary dispersions;
- in heavy fouling service.

Typical process application
- Cold Low Pressure Separators in hydroprocessing.

Figure 4.6 Horizontal three-phase settler with plate pack and double weir arrangement - Side view (see view C-C of Figure 4.4)



4.2.2 General description

A schematic layout of this type of three-phase settler is shown in Figure 4.6.

Like the horizontal open three-phase settler, this settler also consists of three compartments:

- inlet compartment;
- settling compartment (equipped with plate pack);
- liquid collection compartment.

4.2.3 Inlet compartment

The design philosophy of the inlet compartment (including feed inlet) is identical to that of the horizontal open three-phase settler with boot, described in (4.1.3), except that only one calming baffle is installed, with an NFA of 20 %.

4.2.4 Settling compartment

In this compartment a plate pack has been installed. In the standard layout a transversal plate pack (i.e. with the face of the plate pack perpendicular to the central vessel axis) is used.

For more information on plate packs, see Appendix II.

In general a liquid/liquid interface has to be maintained in this compartment either via direct IL control or via a weir arrangement, as described in (4.1.4) and shown in Figures 4.4 and 4.5.

For maintaining an interface level, the latter alternative should be used because:

1. IL is independent of the liquid flow rates, provided the light phase flows over the overflow weir.
2. Economic use is made of the plate pack, because the gas/liquid interface is fairly constant (apart from small variations in the height of the weir crest).
3. The feature that no IL control is required is advantageous if the liquid/liquid interface is poorly defined.

The distance between the plate pack and the calming baffle should be 150 mm.

The distance between the plate pack and the collection compartments shall be at least 500 mm.

If the weir system determines the gas/liquid interface level, the top of the plate pack will be at NL.

A top cover plate shall be fitted at the front face of the plate pack, extending from the top of the plate pack to typically 50 mm above LZA(HH), to prevent liquid bypassing. It shall also cover the plate pack over its full length.

To facilitate the installation of the plate pack, the manhole shall be upstream of the weir arrangement.

4.2.5 Collection compartment(s)

If a weir arrangement with no direct IL control has been adopted, then the collection compartments are sized similar to those in the horizontal open three-phase settler (4.1.4.3).

The schematic layout of a settler with a weir arrangement is shown in Figure 4.6.

4.2.6 Sizing of the settler

The sizing rules of the plate pack settler with a double weir arrangement as given in Figure 4.6 are given below. Also it has been assumed that a transversal plate pack (i.e. with its face perpendicular to the central vessel axis) has been installed.

As stated before, in this type of three-phase settler no IL control is required since the liquid/liquid interface is determined by the heights of the overflow weirs for the light and heavy liquid phases.

Also the gas/liquid interface in the vessel upstream of the weirs (NL) is fairly constant (apart from variations in the weir crest height due to changes in the flow rate).

For a proper sizing of the settler the following main rules apply:

1. The cross-section of the gas cap above LZA(HH) shall be large enough for adequate liquid knockout (for bulk separation the maximum allowable gas load factor is 0.07 m/s). The central height shall be at least 0.3 m.

2. If liquid slugs or foaming are expected, this shall be accommodated between NL and LZA(HH). This means that the height of the underflow weir of the heavy phase compartment shall exceed LZA(HH) by typically 0.1 m.

3. The vessel cross-section below NL shall be sufficiently large to contain the plate pack required to achieve the separation specifications.

4. The cross-sectional area above LZA(HH) (gas cap) and below the liquid/liquid interface (heavy-phase zone) shall be at least 14.2 % of the vessel cross-sectional area.

5. The interface level should be halfway between the top of the underflow passage of the heavy-phase underflow weir and the top of the overflow weir of the light phase, in order to minimise the likelihood of carry-over to the liquid compartments.

   At any rate, under normal-flow conditions (i.e. gas/liquid interface controlled by the light phase overflow weir), the interface level shall be at a distance of at least 0.2 m from either the lower rim of the heavy-phase underflow weir or from the upper rim of the light-phase overflow weir. If a dispersion band is expected but its width cannot be reliably estimated, 0.2 m should be taken as dispersion band width. See Appendix I.

6. The length of the settling compartment shall be at least 650 mm + the length of the plate pack.
7. If de-gassing and/or de-foaming are required, it has to be verified whether the vessel has sufficient capacity for this. For the criteria to be applied, see Appendix V.2 (calculation steps 7 and 8).
   The foam has to be accommodated between LA(H) and LZA(HH). Between these two levels an additional foam allowance of 250 mm has to be included.
8. If a feed inlet is required and the gas load is high, it has to be verified whether the gas cap is sufficiently large to accommodate the inlet device including a clearance of 150 mm above LZA(HH). The vertical space requirement of an inlet device is typically twice the inlet nozzle diameter plus 50 mm. (If the gas load is high, the feed inlet should not be submerged in the liquid).
9. Preferably $2.5 \leq L/D \leq 6$.

In Appendix V.2 the procedure is given for converting an existing empty horizontal vessel into a three-phase separator fitted with a weir configuration and a plate pack.

A calculation example is given in Appendix V.2.

This procedure can also be treated as the sizing procedure for a new settler starting with the specification of the vessel dimensions and the various level control heights.

4.2.7 Nozzles

Requirements for feed nozzle and outlet nozzles are identical to the ones described in (4.1.3.5).

4.3 VERTICAL THREE-PHASE SETTLER

There are many cases where a large gas flow with a relatively small amount of liquid must be handled, for example in inlet separators of gas plants, cold separators and water wash vessels. In these cases a vertical vessel will be chosen.

When the liquid is a mixture of water and hydrocarbons it may be necessary to provide separate outlets for the aqueous and the hydrocarbon phase, for example to prevent problems with level control, or to avoid the formation of tight oil/water dispersions due to a high pressure drop across the outlet valve. In principle the same configurations can be chosen as in horizontal separators, provided that the liquid handling compartment is properly separated from the gas handling compartment such that the liquid/liquid separation process is not disturbed and bypassing is prevented.

4.3.1 Selection criteria

Types:

1. OPEN SETTLER
2. SETTLER WITH WEIR ARRANGEMENT

Application:

- bulk separation of a primary L/L dispersion at a relatively high gas load;
- efficient G/L separation provided appropriate separation internals (e.g. mist mat or SMS-internals) are installed.

Characteristics:

- compact;
- high gas handling capacity can be achieved (depends on G/L separation internals);
- not prone to fouling

Recommended use:

- if the gas load is high and L/L separation is readily accomplished (i.e. low viscosity, primary dispersions).
- A weir arrangement can be considered in cases where the L/L interface is difficult to control, and where deoiling of the heavy phase is required

Not recommended:

- if gas load is low;
- if L/L separation is difficult, i.e. when the dispersed phase droplets are small, or when the continuous phase viscosity is high.

Typical process applications:

- Primary condensate water separators
- Gas/liquid separators with a water wash.

4.3.2 General description

A schematic layout of this type of three-phase separator (or settler) is shown in Figure 4.7a.

Basically, it consists of two compartments:

- a vapour compartment equipped with a feed inlet device and gas/liquid separation internal(s);
- a liquid compartment for liquid/ liquid separation;
- the vapour and liquid handling compartment are separated by means of a liquid collector tray with downpipes, which collects the separated liquid and feeds it at the appropriate place into the liquid separation compartment.

4.3.3 Vapour compartment

Feed inlet

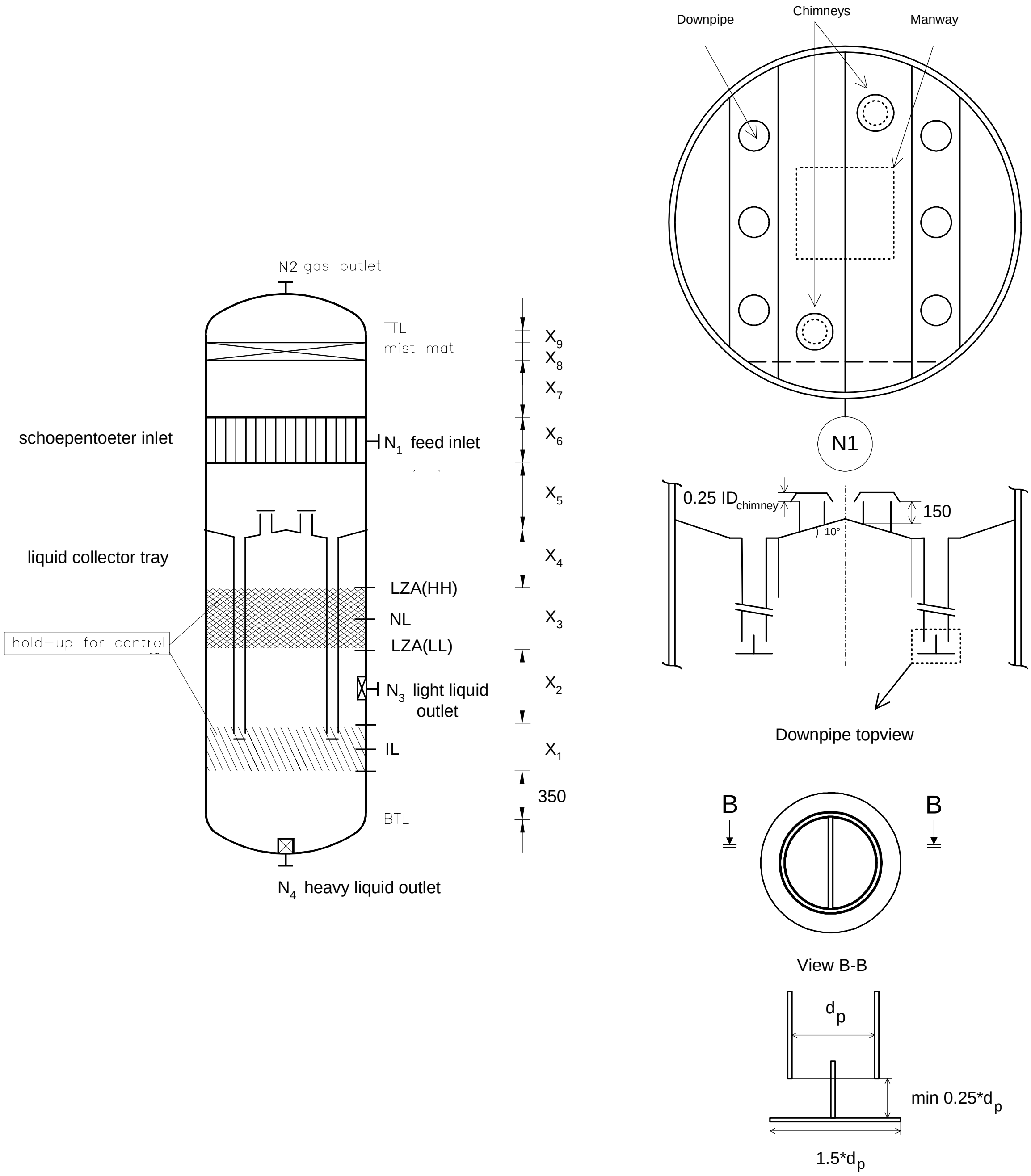
A Schoepentoeter shall be used as feed inlet.

Demisting internals

Normally, a wire mesh is selected for the gas/liquid separation, but - depending on the desired gas/liquid separation capacity - other gas/liquid separation internals such as a swirltube demister can also be selected.

The strategy for the choice of the type of gas/liquid separation internals and the design rules for the sizing of the vapour compartment are given in DEP 31.22.05.11-Gen.

Figure 4.7a Vertical three-phase settler and liquid collector tray details.



4.3.4 Liquid collector tray

The collector tray is an assembly of inclined panels which discharge into gutters with downcomers.

The liquid separated from the gas in the schoepentoeter inlet and in the demister falls down and flows via the downcomers of the collector tray into the liquid compartment, typically at 150 mm above the normal interface level.

The collector tray minimises turbulence in the liquid compartment and also prevents liquid bypassing.

The inclination of the panels should be 10 degrees. The number and size of the downpipes should be chosen such as to avoid gas carry-under, i.e.

$$D_n \geq 1.28 Q_n^{0.4}$$

where D_n is the inner diameter of the pipe (m), and Q_n the liquid flow per pipe (m^3/s). This will also minimize liquid back-up on the tray.

The tray shall be equipped with chimneys (minimum diameter 150 mm) to vent the gas released from the liquid compartment.

4.3.5 Liquid compartment

The liquid compartment contains the control bands for the light and heavy liquid phase, see Appendix X.

The respective spaces between $LZA(HH)_{int}$ and the light liquid outlet nozzle, and between the light liquid outlet nozzle and LZA(LL), should be at least equal to the diameter of the outlet nozzle with a minimum of 200 mm.

It should be checked whether the droplet cut off sizes of the light and heavy phase are sufficiently small to warrant bulk separation, i.e. well below 150 µm. If this is not the case liquid/liquid separation will have to be performed in a dedicated downstream separator, or a horizontal separator configuration should be considered.

4.3.6 Vessel diameter

The diameter of the separator shall be sufficiently large to:

1. satisfy the gas handling criterion:

   $D \geq 1.128\ (Q_G/\lambda_{max})^{0.5}\{\rho_G/(\rho_l - \rho_G)\}^{0.25}$ [m]

   λ_{max} is the maximum allowable gas load factor and is determined by the choice of the G/L separation internal(s) as prescribed in DEP 31.22.05.11-Gen.

2. satisfy the de-gassing criterion (if required):

   $D \geq 7608\ \{(Q_l + Q_h)(\max(\eta_l,\eta_h))/(\rho_l - \rho_G)\}^{0.5}$ [m]

3. satisfy the de-foaming criterion (if required)

   $D \geq 95(Q_l + Q_h)_{max}^{0.5}\{(\max(\eta_l,\eta_h))/(\rho_l - \rho_G)\}^{0.14}$ [m]

Both in the de-gassing and the de-foaming criterion the viscosity of the most viscous phase, max. (η_l,η_h), shall be taken.

4.3.7 Height

The height of the vessel (from BTL to TTL; see also Figure 4.7a) is calculated with the following formula:

$H = 350 + X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9$ [m]

X_1 is the total control volume required for interface level control.

Rules for the calculation of the required liquid volume are given in Appendix X.

The interspace X2 is equal to 3d3 or d3+400 mm, whichever is the largest, where d3 is the diameter of the light liquid outlet nozzle.

X3 is the total control volume for the gas/liquid interface level control, see Appendix X.

X4 is the distance between LZA(HH) and the bottom of the liquid collector tray

X_4 = 0. 05 D with a minimum of 0.3 m.

X_5 is the distance between top of the liquid collector tray and the bottom of the Schoepentoeter.

X_5 = 0. 05 D with a minimum of 0.3 m.

X_6 is the height of the Schoepentoeter.

X_6= d_1 + 0.02 m.

d_1 is the feed nozzle diameter.

X_7 is the distance between the top of the Schoepentoeter and the bottom of the demisting internal. In case of a mist mat: X_7 = d_1 with a minimum of 0.3 m.

X_8 is the height (or thickness) of the demisting internal.
In case of a mist mat: X_8 = 0.1 m. For a typical swirldeck separator X_8 will be 0.96 (SMS) or 1.26 m (SMSM).

X_9 is the distance between the top of the demisting internal and TTL.
X_9 = 0.15D with a minimum of 0.15 m and a maximum of 0.5 m.

4.3.8 Nozzles

- Feed nozzle

  The feed inlet shall be fitted with a Schoepentoeter.

  For the detailed design see Appendix III of DEP 31.22.05.11-Gen.

  For the sizing of the feed nozzle, see Appendix VIII.

- Outlet nozzles

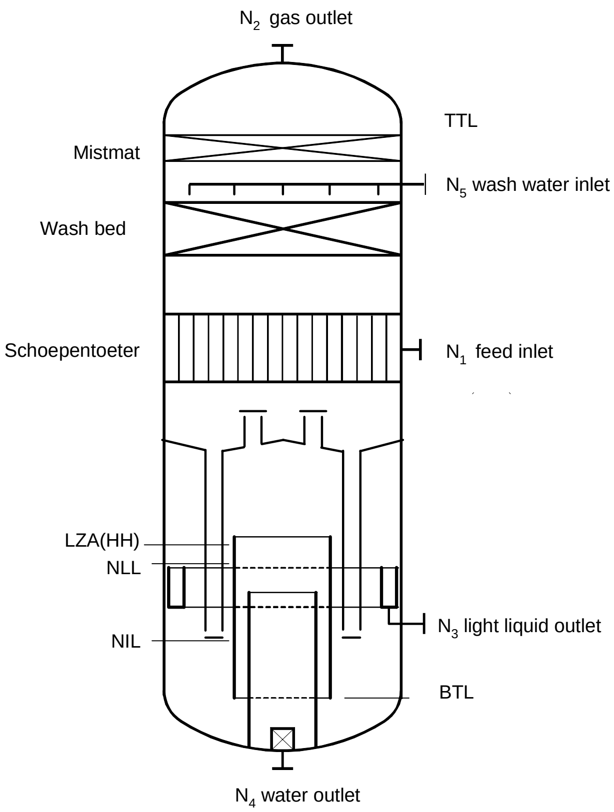
  For the sizing of the outlet nozzles and the specification of the required vortex breakers, see Appendix VIII.

4.3.9 Settler with weir arrangement

If interface control is difficult, for example when the concentration of one of the phases is relatively small, the bottom compartment of the three-phase separator can also be designed as a settler with a double weir arrangement, along the same lines as the horizontal three-phase separator described in section 4.1.4. By way of example Fig. 4.7b shows a diagram of a wash vessel with an internal liquid/liquid separator.

It should be checked whether the drop cut off sizes of the light and heavy phase are sufficiently small to warrant bulk separation, i.e. well below 150 µm. If this is not the case liquid/liquid separation will have to be performed in a dedicated downstream separator, or a horizontal separator configuration should be considered.

Figure 4.7b Vertical three-phase separator with double weir arrangement.



4.4 VERTICAL THREE-PHASE SETTLER WITH PLATE PACK

For specific applications such as condensate water separation in gas plants it is feasible to achieve efficient liquid/liquid separation as well as gas/liquid separation by installing a plate pack in the liquid handling compartment.

4.4.1 Selection criteria

Application:

- efficient L/L separation of primary dispersions of mixtures of light hydrocarbons and water at a relatively high gas load;
- efficient G/L separation provided appropriate separation internals (e.g. mist mat or SMS-internals) are installed.

Characteristics:

- compact;
- high gas handling capacity can be achieved (depends on G/L separation internals).

Recommended use:

- if the gas load is high and L/L separation is readily accomplished (i.e. low viscosity, i.e. $\eta \leq 1$ mPa.s, primary dispersion, and a low dispersed phase concentration of ≤10%v.

Not recommended:

- if gas load is low;
- for bulk separation
- if L/L separation is difficult, i.e. when the dispersed phase droplets are small, or when the continuous phase viscosity is high.

Typical process applications:

- Fractionator overhead vessels in the work-up section of Long Residue Catalytic Cracking Units.
- Condensate/water separators in gas plants.

4.4.2 General description

A schematic layout of this type of three-phase separator (or settler) is shown in Figure 4.7c.

Basically, it consists of two compartments:

- a vapour compartment equipped with a feed inlet device and gas/liquid separation internal(s);
- a liquid compartment where a plate pack has been installed for liquid/ liquid separation.

4.4.3 Vapour compartment

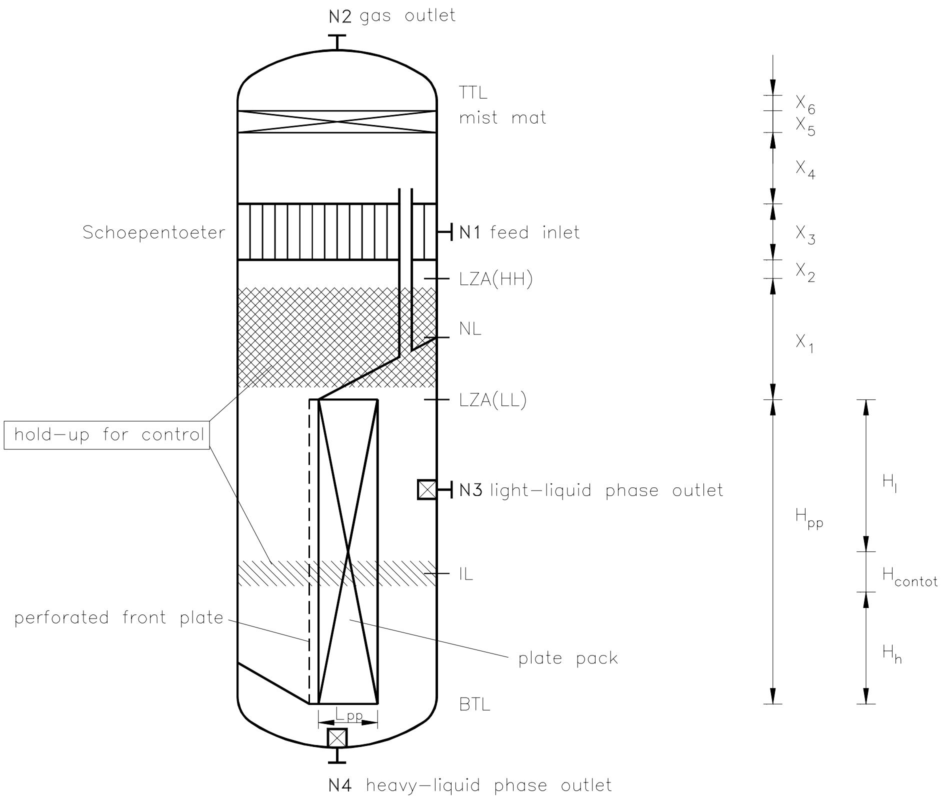
Feed internal

A Schoepentoeter shall be used for the feed internal.

Demisting internals

Normally, a wire mesh is selected for the gas/liquid separation, but depending on the desired gas/liquid separation capacity other gas/liquid separation internals such as a swirltube demister can also be selected. The strategy for the choice of the type of gas/liquid separation internals and the design rules for the sizing of the vapour compartment are given in DEP 31.22.05.11-Gen.

Figure 4.7c Vertical three-phase settler with plate pack



4.4.4 Liquid compartment

Inclined plate

The liquid separated from the gas in the Schoepentoeter flows into the liquid compartment down an inclined plate after which separation of the two liquid phases is achieved in the plate pack.

This plate minimises turbulence in the liquid compartment upstream of the plate pack and also prevents bypassing.

The inclination of this plate should be 10 degrees.

It shall be equipped with a pipe (minimum diameter 50 mm) to vent the gas released from the liquid compartment downstream of the plate pack.

Plate pack

The plate pack extends from the bottom tangent line (BTL) of the vessel to the low liquid level trip, LZA(LL).

The design rules for the plate pack are given in Appendix II.

To ensure an even flow over the plate pack, it shall be equipped with a perforated front plate (distance to plate pack should be 150 mm and the Net Free Area (NFA) is typically 20 % with holes of 12 mm).

To prevent bypassing of the plate pack, clearances between the plate pack and the vessel shall be sealed and a bottom plate shall be installed in front of the plate pack.

This bottom plate slopes down towards to the plate pack with an angle of typically

10°.

4.4.5 Diameter

The diameter of the separator shall be sufficiently large to:

1. satisfy the gas handling criterion:

$$D \geq 1.128\ (Q_G/\lambda_{max})^{0.5}\{\rho_G/(\rho_l - \rho_G)\}^{0.25} \qquad [m]$$

λ_{max} is the maximum allowable gas load factor and is determined by the choice of the G/L separation internal(s) as prescribed in DEP 31.22.05.11-Gen.

2. satisfy the de-gassing criterion (if required):

$$D \geq 7608\ \{(Q_l + Q_h)(\max(\eta_l,\eta_h))/(\rho_l - \rho_G)\}^{0.5} \qquad [m]$$

If degassing appears to be limiting, the degassing capability of the plate pack should be evaluated as well. As long as the cut-off bubble size of the plate pack is smaller than 200 µm degassing is not a constraint.

3. satisfy the de-foaming criterion (if required)

$$D \geq 95(Q_l + Q_h)_{max}^{0.5}\{(\max(\eta_l,\eta_h))/(\rho_l - \rho_G)\}^{0.14} \qquad [m]$$

Both in the de-gassing and the de-foaming criterion the viscosity of the most viscous phase, max. (η_l,η_h), shall be taken.

4.4.6 Layout of plate pack

The width of the plate pack, W_{pp}, shall satisfy the following criterion:

$$W_{pp} < \sqrt{(D - 0.2)^2 - (L_{pp} + \Delta L_{fp\_pp})^2} \qquad [m]$$

L_{pp} is the length of the plate pack. L_{pp} should be between 0.3 m and one third of the vessel diameter.
ΔL_{fp_pp} is the distance between the front plate and the plate pack (typically 0.15 m).

It has been assumed in the above formula that the centre of the plate pack assembly (including front plate) is located on the central axis of the vessel.

The general case has been considered where the plate pack has to cleanup both liquid phases and contains a control band including trip levels and an allowance for a dispersion band. It is up to the designer to decide if all these controls are necessary.

The height of the plate pack, H_{pp}, is then given by the following relationship:

$$H_{pp} = H_h + H_{contot} + H_l \qquad [m]$$

H_h and H_l are the heights of the plate pack sections where the continuous phase is the heavy and light phase, respectively.

$$H_l = (A_{f,gross})_l/W_{pp} \qquad [m]$$
$$H_h = (A_{f,gross})_h/W_{pp} \qquad [m]$$

$(A_{f,gross})_l$ and $(A_{f,gross})_h$ are the gross frontal areas of the plate pack section associated with cleaning of the light and heavy liquid phase, respectively. These areas are calculated with the plate pack sizing rules presented in Appendix II. The net frontal area, $A_{f,net}$, of each plate pack section shall be sufficiently large to ensure laminar flow in the corresponding section. By allowing for the plate thickness and the presence of gutters, the gross frontal area is then obtained. The length of the plate pack, L_{pp}, will be determined by the required separation performance of the plate pack (expressed in terms of droplet cut-off diameter)

and the selected plate pack characteristics (e.g. frontal area, plate distance and plate angle) and is minimal 0.3 m.

To ensure proper separation, neither H_l and H_h should be smaller than 0.3 m. Moreover, the height/width ratio of both sections should be between 0.5 and 2. In extreme cases it may be necessary to select a larger vessel diameter than originally calculated in order to keep the height/width ratio down to reasonable proportions. However, then it should be checked first whether a vertical vessel was the right choice.

H_{contot} is the height of the total interface level control band.

$$H_{contot} = \Sigma H_{con} + H_{db} \qquad [m]$$

H_{db} is the operator-specified dispersion band.
(If a dispersion band is expected but its height cannot be reliably estimated by means of the formula given in Appendix I, H_{db} should be taken as 0.2 m.

ΣH_{con} is the sum of the heights of the control bands required for L/L control (see Appendix X). For each H_{con}

$$H_{con} \approx Q_h * t_{con} / (\pi/4\ D^2) \qquad [m]$$

t_{con} is the specified control time.

If H_{con} is less than the minimum span then the minimum shall be used (see Appendix X), The control heights shall be based on the liquid flow rate of the heavy liquid phase ONLY.

4.4.7 Height

The height of the vessel (from BTL to TTL; see also Figure 4.7c) is calculated with the following formula:

$$H = H_{pp} + X_1 + X_2 + X_3 + X_4 + X_5 + X_6 \qquad [m]$$

X_1 is the sum of the control bands required for G/L level control.

The liquid volume required is the sum of the holdup required for control of the light phase and the holdup required for control of the interface, which is based on the heavy phase flow.

Rules for the calculation of the required liquid volume are given in Appendix X.

X_2 is the distance between LZA(HH) and the bottom of the Schoepentoeter.
X_2 = 0.05D with a minimum of 0.15 m. If the demister is a swirldeck X_2 = 0.5m.

X_3 is the height of the Schoepentoeter.
$X_3 = d_1 + 0.02$ m.
d_1 is the feed nozzle diameter.

X_4 is the distance between the top of the Schoepentoeter and the bottom of the demisting internal. In case of a mist mat: $X_4 = d_1$ with a minimum of 0.3 m.

X_5 is the height (or thickness) of the demisting internal.
In case of a mist mat: X_5 = 0.1 m.

X_6 is the distance between the top of the demisting internal and TTL.
X_6 = 0.15D with a minimum of 0.15 m.

4.4.8 Nozzles

- Feed nozzle

  The feed inlet shall be fitted with a Schoepentoeter.

  For the detailed design see Appendix III of DEP 31.22.05.11-Gen.

  For the sizing of the feed nozzle, see Appendix VIII.

- Outlet nozzles

  For the sizing of the outlet nozzles and the specification of the required vortex breakers, see Appendix VIII.

  The top and bottom of the light product outlet nozzle should be at least 200 mm or one nozzle diameter away from respectively LZA(LL)and LZA(HH)$_{int}$, whichever is the largest.

A calculation example of the sizing of this type of separator is given in Appendix V.3.

5. CONNECTING PIPING REQUIREMENTS

Piping to and from the settler shall interfere as little as possible with the performance of the separator. The following constraints should be observed:

a. Valves, pipe expansions or contractions should not be fitted within ten pipe diameters of the inlet nozzle because of their tendency to generate relatively small liquid droplets (either in the gas phase or in the opposite liquid phase).
   If a valve has to be fitted in the feed line near to the settler, it shall be of the gate or ball type, fully open in normal operation. High pressure drops, which could generate small droplets, should be avoided in the feed pipe.
   If a pressure-reducing valve has to be fitted in the feed pipe, it shall be located as far upstream of the vessel as practicable.

b. Bends should not be fitted within ten pipe diameters of the inlet nozzle because they will generate flow maldistribution in the settler, in particular of the gas phase (in three-phase separators).
   If bends have to be fitted within ten pipe diameters of the inlet nozzle, the following rules shall apply:
   - in separators with a straight inlet, a bend in the feed pipe may only be fitted if it is in the vertical plane through the axis of the feed nozzle.
   - in settlers with a tangential inlet (not covered in this DEP), a bend in the feed pipe may only be fitted if it is in a horizontal plane and the curvature is in the same direction as the vortex induced by the tangential inlet.

c. If desired, a pipe reducer may be used in the vapour line leading from the three-phase settler, but it should be situated no closer than twice the outlet nozzle diameter from the top of the vessel.

If the above conditions cannot be satisfied, some loss of separation efficiency will result.

6. REFERENCES

In this DEP reference is made to the following publications:

NOTES: 1. Unless specifically designated by date, the latest edition of each publication shall be used, together with any amendments/supplements/revisions thereto.

2. For Shell users, DEPs and standard drawings are available on the Shell Wide Web, at address http://sww.shell.com/standards.

SHELL STANDARDS

Gas/ liquid separators - Type selection and design rules DEP 31.22.05.11-Gen.

STANDARD DRAWINGS

Vortex breakers for nozzles S 10.010

Twin-Flange Coalescer S 22.007

APPENDIX I THE MECHANISM OF LIQUID/LIQUID SEPARATION IN OPEN SETTLERS

In the liquid/liquid separation process in two-phase or three-phase open settler, the following two consecutive steps are identified:

Step 1
Settling of the dispersed phase droplets towards the interface formed by the already separated phases.

(The term "settling" will also be used for the separation of light-phase droplets in this DEP in order to be consistent with the term "settlers" which is used for the separation of both light-phase and heavy-phase droplets).

Step 2
The coalescing of the settled droplets once they have reached the interface.

I.1 SEPARATION DETERMINED BY THE RATE OF SETTLING (rate-determining step 1)

At a relatively low concentration of the dispersed phase (say below 5 vol. %) the rate-determining step in the separation process is the settling velocity of the dispersed phase. The coalescence of the droplets in the interface takes place relatively rapidly.

In the case of laminar flow with droplets larger than 40 μm and a very low dispersed phase concentration (say below 1 vol. %), Stokes law applies to the settling velocity, $v_{p,set}$, provided that for the droplet Reynolds number, $Re_p = \rho_c v_{p,set} d_p / \eta_c$, the following is true:

$Re_p \leq 1$ [-]

$v_{p,set} = |\rho_d - \rho_c|\, g d_p^2 / (18\eta_c)$ [m/s]

ρ_d and ρ_c are the densities of the dispersed and continuous phase, respectively,
g is the gravity constant,
d_p is the droplet diameter,
η_c is the dynamic viscosity of the continuous phase

1. In practice the condition $Re_p \leq 1$ is normally satisfied.
   If $Re_p > 1$ (in the case of relatively large droplets and/or a very low viscosity of the continuous phase) the above formula will give an over-prediction of the settling velocity.
   However, under these conditions liquid/liquid separation is very readily accomplished, and other requirements such as hold-up for control will determine the size of the settler.
2. The effect of droplet fluidity (degree of internal circulation) on settling velocity has been ignored.
   This internal circulation leads to a higher settling velocity than is given by the above formula. However, it has been observed in practice that this internal circulation is negligible if the droplet diameter is smaller than 1 mm, especially if surface-active agents are present.
3. The expression for $v_{p,set}$ only applies if the droplet diameter is sufficiently large that the settling is primarily determined by gravity. Other effects such as Brownian motion and flow convection effects induced by thermal gradients can then still be ignored.
   In general, this is the case if the droplet diameter is larger than 30 μm.
   A dispersion is classified as a primary dispersion if the majority of the dispersed droplets are larger than this value. Otherwise it is classified as a secondary dispersion.

4. In a open settler the flow is nearly always turbulent. The turbulence will hinder the settling process and a correction term has to be applied:

   $(v_{p,set})_{turbulent} \approx (v_{p,set})_{laminar} - 0.05 v_{c,ax}$ [m/s]

   The above formula predicts that settling will no longer take place if

   $v_{c,ax} \geq 20 * (v_{p,set})_{laminar}$ [m/s]

   It has hence been specified in the design of open settlers (see (3.1) and (4.1) in the main text) that $v_{c,ax} \leq 15 (v_{p,set})_{laminar}$ to guarantee that settling will still take place.

   The above formula is also applicable to the settling in a boot.
   Because in this case of a boot $(v_{p,set})_{turbulent} \approx v_{c,ax}$, it can be rewritten as:

   $(v_{p,set})_{turbulent} \approx (v_{p,set})_{laminar} / 1.05 \approx 0.95 (v_{p,set})_{laminar}$ [m/s]

5. If dispersion is less diluted the influence of the neighbouring droplets on the settling velocity can no longer be ignored.

   $(v_{p,set})_{conc} \approx (1\text{-conc})^{4.5} (v_{p,set})_{conc} \rightarrow 0$

   Where conc is the **local** volumetric fraction of the dispersed phase.

   Strictly, the exponent of 4.5 in the above equation only applies if $Re_p \leq 1$.

   For larger Reynolds numbers it decreases to a value of 2.4 at Re_p =1000, hence the above formula is conservative.

   Furthermore, in practice the effect of concentration will be much smaller than the effect of turbulence on the settling velocity of the smallest droplets to be separated (which start their settling process at the top of the vessel), since the majority of the other dispersed droplets will settle faster, leaving the immediate environment of the small droplets relatively clear so that local concentration is relatively low. In the case of heavy-phase droplets it is the settling velocity of these droplets, which determines the size of the settling compartment.

   Since the coalescence step takes place faster than the settling step, the interface of the two bulk phases will be well-defined with no intermediate layer (dispersion band).

I.2 SEPARATION DETERMINED BY THE RATE OF COALESCENCE (rate-determining step 2)

If the concentration of the dispersed phase and/or feed flow rate increases further, the coalescing step will eventually become the rate-determining step in the separation process.

The interface between the two liquid phases is no longer sharp because the coalescing process in the interface can no longer catch up with the settling process.

An intermediate layer or dispersion band will be formed between the two bulk phases. See Figure I.1.

If the **heavy** phase is the dispersed phase, the **upper** part of the band will consist of the sedimentation zone: a turbulent layer in which drops are in occasional contact but may nonetheless coalesce with one another after which they settle faster. Eventually the droplets arrive in the **lower** part of the band, the close-packed zone, where they are in close contact with their neighbours and are thereby distorted from the spherical shape.

See also Figure I.2 for the structure of the dispersion band.

In general the average thickness of the dispersion band, H_{db}, is a function of the vertical flux Q/A, where Q is the gross flow rate of the dispersed flow entering the separator, i.e. the total liquid flow, and A the area of the liquid/liquid interface.

The relationship is typically of the form:

$$H_{DB} = \frac{a(Q/A)}{1 - b(Q/A)}$$

Where a and b are constants, depending on the viscosity of the continuous phase, the phase ratio and the droplet size distribution of the dispersed phase. With this expression the dispersion band height can be estimated when the vertical flux in the separator is known. H_{DB} increases rapidly when Q/A increases.

The flux in its turn is limited by the maximum axial velocity in the light and heavy phase zone of 0.015 m/s. The latter is about equivalent to a maximum vertical flux of 0.008 m/s. Fig. I.3 shows the resulting dispersion band height as a function of continuous phase viscosity and dispersion stability.

In e.g. oily water separators and downstream applications such as overhead accumulators, oil and water will not be intensively mixed and the prevailing viscosities are low. Under these conditions the expansion of an eventual dispersion band will be limited and can be sufficiently covered by allowing 0.2 m extra height between LA(L) and LA(H).

Relatively stable and concentrated dispersions, as high as 40-50%, can be expected in production separators in oil fields and in the settlers of mixer/settler arrangements in extraction plants. Under the conditions prevailing in these separators Stokes law is not applicable. Cut-off droplet size criteria cannot be used and would grossly overpredict the required vessel size. The design of these separators must be based specifically on containment of the dispersion band. This means that the allowable flux is to be limited such that the dispersion band can be accommodated in the vessel.

In horizontal vessel separators the height of the dispersion band should not be larger than 15% of the diameter of the vessel. The area available for liquid/liquid separation can be estimated by

$$A = 0.8 \times D \times L_{TT} \qquad [m]$$

Where D is the diameter and L_{TT} the tan-tan length of the vessel. The corresponding maximum gross liquids flowrate can be established with the dispersion band expansion equation above. Values for the constants a and b are listed in table I.1. These can be used for the sizing of a single – or first stage dehydration vessel.

It is important to note that for proper functioning of a crude water separator adequate chemical treatment shall be in place, to neutralize the indigenous surfactants in the crude, which tend to stabilize the dispersions to be separated.

A calculation example of the design of a bulk separator is given in Appendix V.4.

When the separator size is limited, for example due to transport - or head space limitations, and the dispersion band can not be accommodated completely in the vessel, the separation will be incomplete and more separation stages will be required. The design of multistage separation processes, as well as of dedicated dehydration equipment such as wash tanks and electrostatic dehydrators is outside the scope of this DEP.

Table I.1 Dispersion band constants for first stage separators. The dimension of the dispersion band height is in [m], that of the corresponding fluxes is [mm/s].

viscosity, cS	a	b
1	0.051	0.032
2	0.093	0.052
5	0.203	0.101
10	0.367	0.166
20	0.664	0.273
50	1.454	0.529
100	2.630	0.871

Figure I.1 Formation of a dispersion band in the interface of a liquid/liquid separator

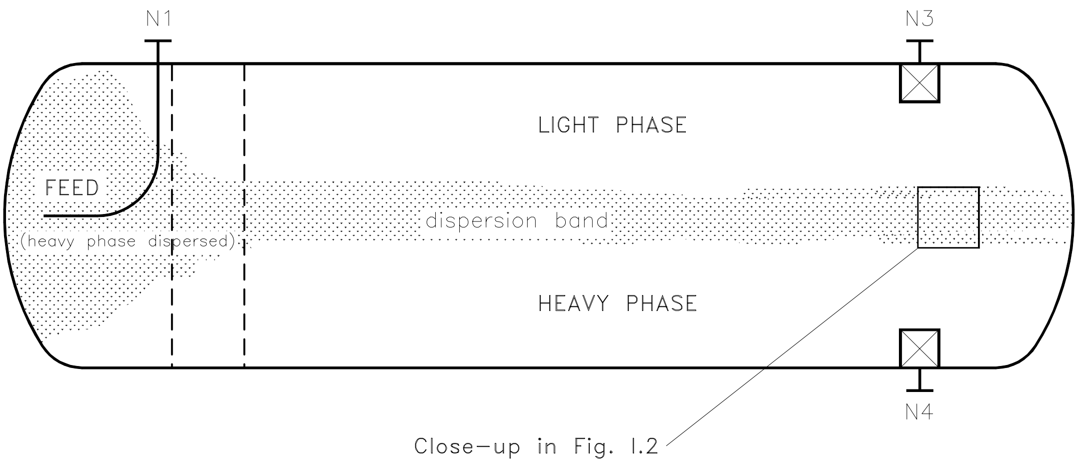


Figure I.2 Structure of the dispersion band (close-up of Figure I.1)

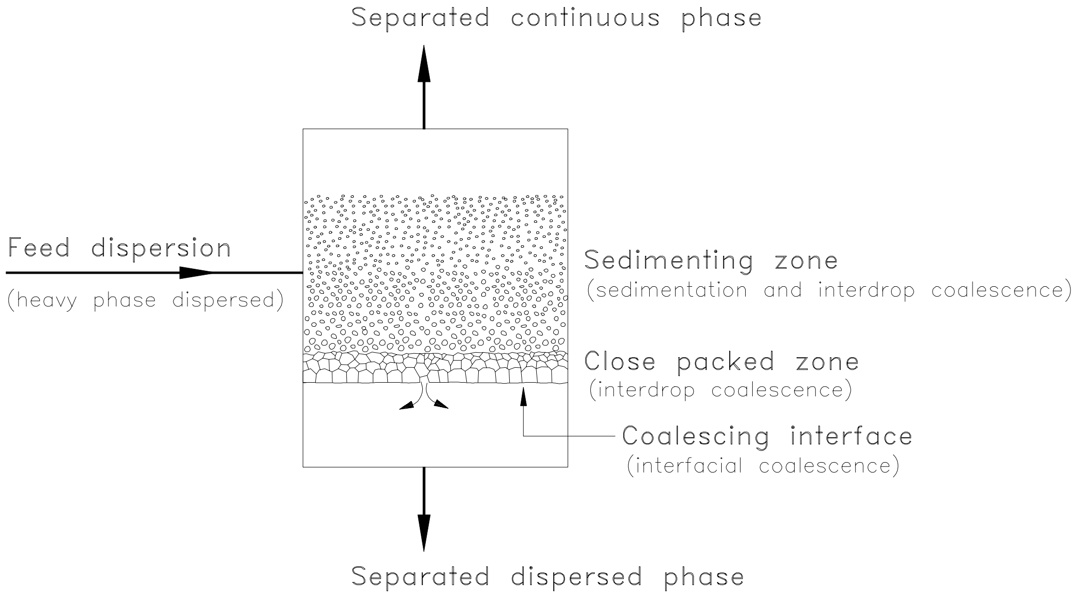
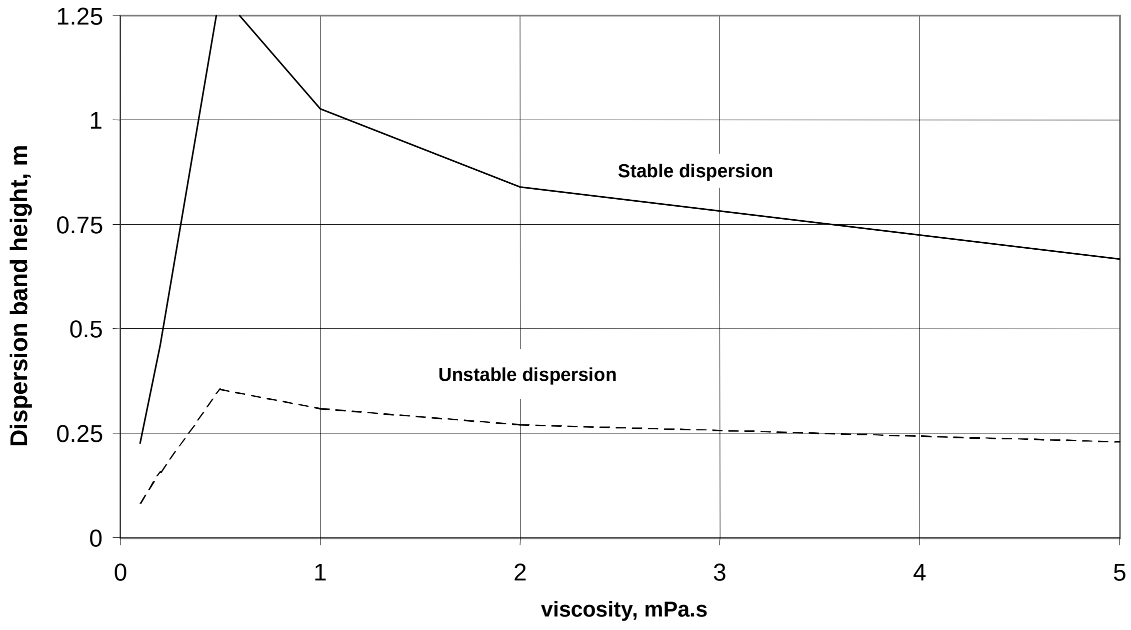


Figure I.3 Variation of maximum dispersion band height with viscosity



APPENDIX II PLATE PACKS

II.1. GENERAL CONSIDERATIONS

The function of a plate pack is to improve the efficiency of liquid/ liquid separation.

Settlers with plate packs are generally smaller than open settlers.

The main reasons for this increase in efficiency are:

1. The presence of the plates results in a substantial reduction of the settling distance of the droplets.
2. If the plate pack is properly sized, the flow between the plates is laminar.
   (By comparison, in an open settler the flow is nearly always turbulent which hampers the settling process.)

A plate pack is only effective for the separation of primary dispersions. This means that the dispersion droplets shall be large enough for their movement to be primarily caused by gravity. In practice this means that the droplets have to be larger than 30 μm to satisfy the above criterion. In the case of secondary dispersions (i.e. droplets generally smaller than 30 μm), separation can only be achieved with the aid of coalescers. See also Appendix III and (3.3) in the main text.

A plate pack consists of a set of parallel plates, which are either flat or corrugated. The plates are tilted to facilitate the removal of the separated phase. With a view to maintaining laminar flow in the plate pack it is advantageous to use flat rather than corrugated plates since with flat plates the flow remains laminar up to much higher flow rates than is possible with corrugated plates. However, plate packs with corrugated plates are less easily blocked by solids than plate packs equipped with flat plates. Flat plates should be provided with contours at their upstream and downstream ends to promote laminar flow and enable the removal of the collected dispersed phase.

The plate packs to be used in vessels should be of the cross-flow type. This means that the flow of separated product is perpendicular to the main flow through the plate pack. The main advantage of a cross-flow plate pack is that its geometry can easily be adapted to the geometry of the vessel and no excess space above or below the plates is required for the entry and exit of the liquid flows. This enables efficient use of the vessel volume resulting in a relatively small vessel.

Figure II.1 shows schematically the principle of the cross flow plate pack.

In the cross-flow plate pack the main flow is directed horizontally and the separated phase flows perpendicular to this via inclined plates.

The solids removal capacity is only moderate, but can be improved by increasing the inclination of the plates and/or by using corrugated rather than flat plates.

Both measures, however, will adversely affect liquid/liquid separation.

Since the cross-flow plate pack is the common type of plate pack used in vessels, only this type of plate pack will be described in detail in the remaining part of this Appendix.

II.2 LAYOUT OF THE PLATE PACK

In the standard layout of the cross-flow plate pack the face of the plate pack will be perpendicular to the central axis of the vessel as is shown in Figure II.2. The sides of the plate pack will follow to a large extent the curvature of the vessel wall, to maximise the use of the cross-sectional area.

Plate packs should be mounted in panels. Between the panels at least one gutter is present to transport the coalesced separated phase to its bulk phase. Measures shall be taken to prevent bypassing of the plate pack such as mounting a plate in front of the gutters and sealing the clearance between the plate pack and the vessel wall. The seal plate underneath the plate pack shall still have a small opening for cleaning purposes.

In a horizontal three-phase settler a cover plate shall be fitted extending from the top of the

plate pack to typically 50 mm above LZA(HH).

If fouling is expected a cleaning system should be installed.

Figure II.2 shows the configuration of a cross-flow plate pack in a three-phase separator.

A perforated baffle (typically NFA of 20 %, hole diameter of 12 mm and a thickness of at least 3 mm) shall be installed upstream of the plate pack to provide an even distribution of the flow over the plate pack. In practice this is the baffle which separates the inlet compartment from the settling compartment in the settler. The distance between the baffle and the front of plate pack should be 150 mm.

In a three-phase settler with a weir arrangement there should be at least 500 mm between the back of the plate pack and the weir arrangement in order to minimise the disturbance of the separation process (see Figure 4.6).

If viscosity is low, a relatively large plate pack front area is required to maintain laminar flow in the plate pack. In that case, a settler layout with only one plate pack may not be suitable, because it could result in an uneconomically large vessel diameter in order to accommodate the required front area of the plate pack. Then it would be advantageous to split the feed flow and to use two plate packs as is shown in Figure II.3a for an L/L separator.

An alternative solution is to adopt a layout in which the face of the plate pack is parallel to the central vessel axis (longitudinal plate pack) and the feed enters the vessel through two side nozzles. It is even possible to use two longitudinal plate packs. The feed will then enter the vessel through four feed nozzles, two on each side. The Principal should be consulted for more information on these alternative layouts.

II.3 MATERIAL SPECIFICATION AND MANUFACTURING

Plate packs are usually made of **stainless steel**.

However, sometimes other material is used. For instance, for plate packs to be used in an acid settler of an HF-alkylation plant, carbon steel is commonly used.

The Manufacturer of the plate pack shall supply to the Principal fully dimensioned and detailed drawings of the plate pack for the particular application. Such information shall be treated by the Principal as confidential.

Figure II.1 Principle of cross-flow plate packs (for de-oiling)

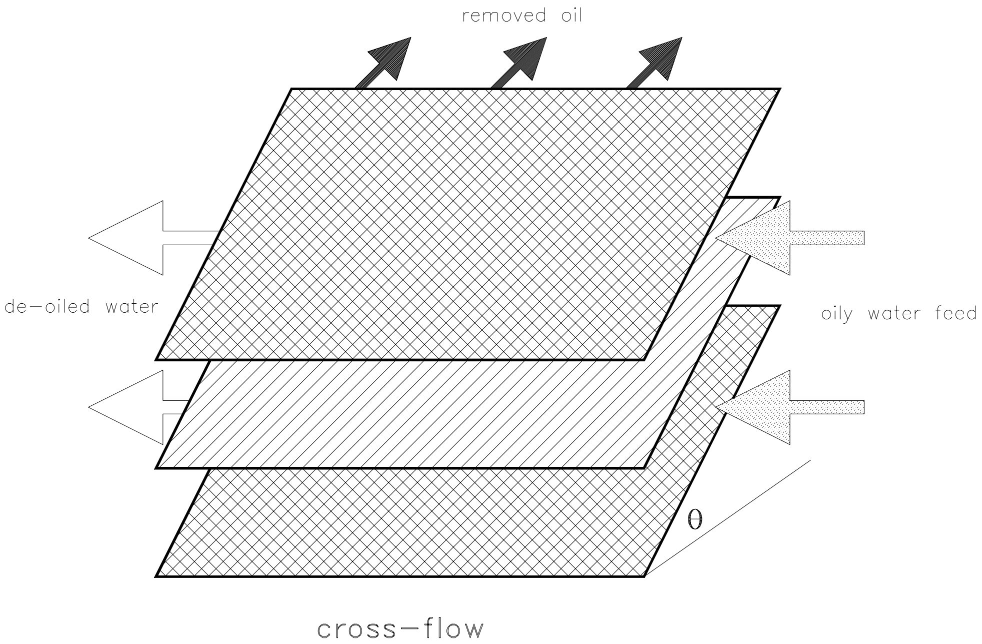


Figure II.2 Typical layout of transversal cross-flow plate pack inthree-phase separator (cover plates for gutters, bottom and side clearances not shown)

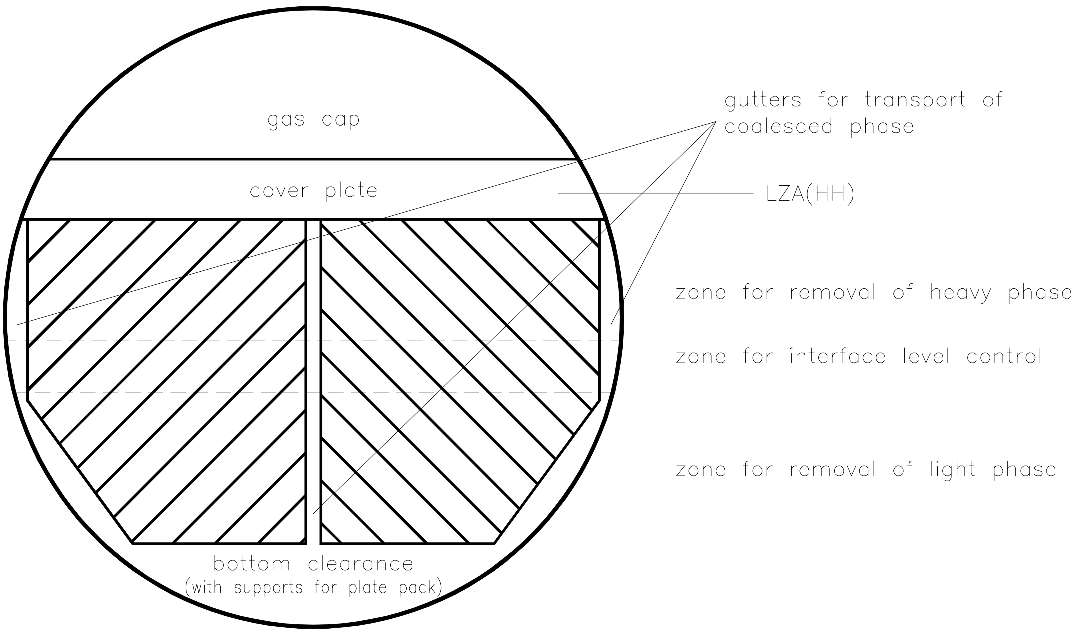
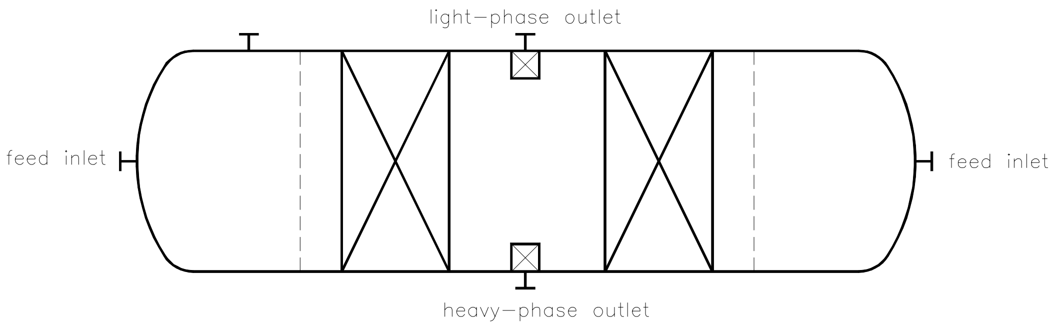


Figure II.3 Alternative plate pack configuration for L/L separators



II.4 DESIGN OF THE CROSS-FLOW PACK

In a plate pack a liquid/liquid interface level will generally be established.

If the liquid/liquid interface is constant and well-defined, two zones can be identified in a plate pack:

- An upper zone where the light liquid phase is the continuous phase
- A lower zone where the heavy liquid phase is the continuous phase

If interface level control and/or a dispersion band is present, allowance also has to be made for an intermediate zone.

The upper or lower part of the cross-flow plate pack will be sized separately. For practical reasons both parts will have the same length, plate spacing and plate inclination.

Sizing is performed in the following two steps:

1. First, the front area of each plate pack part is determined with the criterion that the flow between the plates shall be laminar.
2. Subsequently, the length of the plate pack is determined with the criterion that the pack shall be sufficiently long to separate the smallest droplet as defined by the specified cut-off diameter.

II.4.1 Sizing of front area of plate pack

In a cross-flow plate pack with flat plates, flow is no longer fully laminar at a Reynolds number higher than 850. (In theory with flat plates the transition would be at a Reynolds number of 2000, but in practice transition takes place at a lower Reynolds number, because of the presence of plate pack constructional elements needed to reinforce the plates and of gutters for removal of the separated phase from the plate pack).

If corrugated plates are used, this transition already takes place at a Reynolds number of 450. Corrugated plates should be used only if the solids concentration is high.

The upper and lower section of the plate pack are considered separately.
The Reynolds number for each plate pack section is defined as:

$$Re = d_H v_{pp} \rho_c / \eta_c \qquad [-]$$

where:

d_H is the hydraulic diameter;

$d_H = 4W_{pp}d_{pp}/(2W_{pp} + 2d_{pp}) \approx 2d_{pp}$ (since $W_{pp} >> d_{pp}$), with d_{pp} being the plate distance and W_{pp} the plate pack width.

v_{pp} is the mean velocity of the total liquid flow (both dispersed and continuous phase) through the plate pack section to be sized.

$v_{pp} \approx Q_c / A_{f,net}$ [m/s]

$A_{f,net}$ is the net frontal area of the plate pack section available for flow (corrections applied for finite plate thickness, etc.).

Q_c is the volumetric flow rate of the continuous phase.
ρ_c is the density of the continuous liquid phase.
η_c is the dynamic viscosity of the continuous phase.

Since only at most a few percent of the entrained phase will be present, it is correct to use the physical properties of the continuous phase only.

Based on above, for each plate pack part $A_{f,net}$ can be calculated.

$A_{f,net} = 2d_{pp}Q_c\rho_c/(\eta_c Re)$ [m^2]

The Reynolds number, Re, shall not be higher than 850 in the case of flat plates or 450 if corrugated plates are used.

The total gross frontal area of both parts is therefore:

$A_{f,gross} = \{(A_{f,net})_l + (A_{f,net})_h\}(t_{pp} + d_{pp})/(d_{pp} * F_{loss} * F_{PP}$)[m^2]

where:

t_{pp} is the plate thickness and is typically 1 mm.

F_{loss} is a correction factor to account for the fact that because of the presence of constructional elements, risers etc., not the whole frontal area can be used for liquid/liquid separation. F_{loss} is typically in the range of 0.90 to 0.95.

F_{pp} is a correction factor for the lost area between the plate pack modules and then vessel wall, see Fig. II.2. F_{pp} is typically ≈ 0.8 for horizontal vessels.

The plate pack height H_{pp} of a rectangular plate pack with specified width W_{pp} is therefore:

$H_{pp} = A_{f,gross}/W_{pp} + H_{contot} = H_l + H_h + H_{contot}$ [m]

where:

H_{contot} is the specified height of the control band if there is direct IL control. It also includes the height of the dispersion band (if required).

To guarantee proper separation, H_l and H_h shall be at least 0.3 m.

II.4.2 Determination of the plate pack length

The assumption is made that the settling of the droplets is the rate-determining step of the separation process in the plate pack.

This means that once the droplets have reached the plate surface of their flow channel, they will coalesce relatively rapidly into a film which will be immediately transported via vertical channels in the plate pack to the droplet bulk phase.

Calculate the plate pack length, L_{pp}, for each plate pack part using the following formula:

$L_{pp} = v_{pp}d_{pp}/(\cos(\theta)v_{p,set}) + f_{tl}L_{entry}$ [m]

where:

θ is the angle of the plates with the horizontal plane.
$v_{p,set}$ is the settling velocity of the smallest droplet to be separated (≥ 30 μm).

If this droplet is larger than 30 μm, the dispersed phase concentration is say below 1 vol % and $Re_p \le 1$, then $v_{p,set}$ is given by:

$v_{p,set} = |\rho_d - \rho_c|\, g d_p^2/(18\eta_c)$ [m/s]

where:

ρ_d and ρ_c are the densities of the dispersed and continuous phase, respectively,
g is the gravity constant,
d_p is the droplet diameter of the smallest droplet to be separated,
η_c is the dynamic viscosity of the continuous phase.

L_{entry} is the length of the entrance part of the plate pack where the transition of turbulent to laminar flow takes place and is a function of the Reynolds number of the plate pack part and of the plate pack spacing.

$L_{entry} \approx 0.02 d_{pp} Re$ [m]

For most applications L_{entry} is maximally about $16d_{pp}$.

f_{tl} is a correction factor for the fact that although the flow regime in the entrance part is somewhere between turbulent and laminar flow, there will still be some separation taking place.

$f_{tl} \approx 0.5$, so in practice, if Re = 800 and d_{pp} = 20 mm for instance, the length of the plate pack has to be increased by 160 mm (= $8d_{pp}$) in order to compensate for the non-laminar flow conditions in the entrance region of the plate pack.

The slightly conservative approach is taken that if the flow in the plate pack is laminar, the plate pack length has to be increased by $8d_{pp}$ to compensate for the entry effects.

Take for L_{pp} of the plate pack the largest of the two calculated values.

The minimum value is 0.3 m. The maximum value is 1.5 m.

II.4.3 Choice of plate type, plate spacing and plate angle

In clean service the angle θ of the plates with the horizontal plane is 45 degrees, but if solids are present the angle should be steeper (typically 60 degrees) to facilitate the removal of the solids. If many solids are present, the use of corrugated rather than flat plates should be considered.

The plate spacing in fouling service should be at least 40 mm, whereas in clean service the plate spacing may be as little as 10 mm. The choice of corrugated rather than flat plates and/ or the increase of the plate spacing will reduce the fouling risk but will also reduce the separation efficiency of the plate pack of given overall (width * height * length) dimensions.

II.5 RETROFIT OF A PLATE PACK IN AN EXISTING VESSEL

If a plate pack is to be retrofitted in an existing vessel where there is not sufficient space to install a plate pack in which the flow is laminar, or if highly efficient separation is not required, it may be acceptable to go to a higher limit for the plate pack Reynolds number, say 1200.

However, then the settling velocity of the droplets, $v_{p,set}$, shall be corrected for the influence of turbulent flow:

$(v_{p,set})_{turbulent} \approx (v_{p,set})_{laminar} - 0.05 v_{c,ax}$ [m/s]

with $v_{c,ax}$ being the axial velocity of the flow through the plate pack.

Further, the length of the entrance part of the plate, L_{entry}, has to be adjusted, using the expression:

$L_{entry} \approx 0.02 d_{pp} Re$ [m]

APPENDIX III COALESCERS

III.1. CALCULATION EXAMPLE : DESIGN OF A COALESCER FOR DEWATERING OF GASOIL

The design will be based on Knitmesh Dusec cartridges. These cartridges are 115 mm ID, 230 mm OD and 1 m. long. They can be made from a wide variety of materials to be tailored to the specific service.

- The design capacity of the coalescer is 800 t/sd. The density is 835 kg/m^3.
- The design margin is 1.1.

The gasoil flow rate is ≈ 40 m^3/h. On the basis of a liquid handling capacity of 20 m^3/m^2h a coalescer area of 2 m^2 is required. The inner surface of a Dusec cartridge is 0.36 m^2. Therefore 7 cartridges are required.

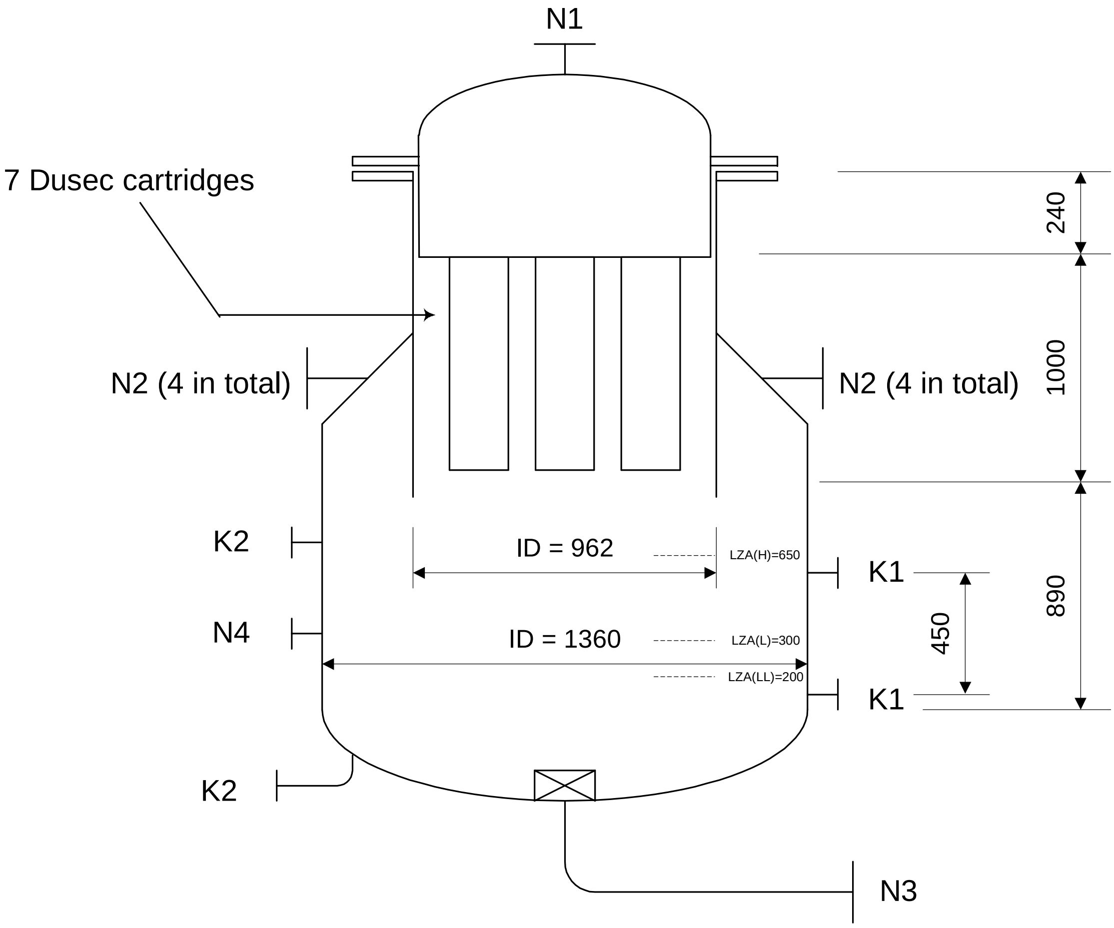
The cross sectional area of one cartridge is 0.04153 m^2. For 7 cartridges it is 0.29 m^2. To limit this area to 40 % of the vessel cross section the latter should be 0.727 m^2, which is equivalent to an inner diameter of 962 mm.

The rest of the vessel dimensions follows from the guidelines for the design of a TFC as given in (3.3.4).

- The inlet compartment is not determined by the required compression of the coalescer packing. Therefore it can be fixed at 0.25x Di. In this case 240 mm.
- The diameter of the separation compartment is 962x√2=1360 mm, and the height is also 0.25 Di = 240 mm
- Because of the small water flow the control volume is determined by the minimum spacing between the various levels. A high level trip is not required.

This results in a vessel TT length of 2130 mm.

Figure III.1 Shell twin flange coalescer (retro)fitted with Dusec cartridges



APPENDIX IV TWO-PHASE SETTLERS

IV.1. CHECK OF EXISTING HORIZONTAL OPEN TWO-PHASE SETTLERS (INCLUDING RETROFIT OPTION WITH PLATE PACK)

(See also main text (3.1) and (3.2) and Figures 3.1 and 3.2)

This procedure can also be treated as the sizing procedure for a new settler starting with the specification of the vessel dimensions and the various level control heights.

The various steps taken in the procedure are described below.

IV.1.1 Input

1. Vessel diameter and tangent/tangent length
2. Volumetric flow rate, density and dynamic viscosity of both liquid phases
3. Interfacial control levels, width of dispersion band (if any).

   If a dispersion band is present the distance between each pre-alarm and trip level has to be increased by half the width of the dispersion band.

   If there is insufficient information to estimate the width of the dispersion band, a width of 0.2 m should be taken.
4. Required minimum control times for L/L interface control.

IV.1.2 Calculations

1. **Calculation of A_l and A_h and corresponding axial velocities $v_{l,ax}$ and $v_{h,ax}$**

   From the vessel diameter D, and NIL, A_l and A_h are calculated using the formulae given in Appendix VI.

   Subsequently:

   $v_{l,ax} = Q_l/A_l$ [m/s]
   $v_{h,ax} = Q_h/A_h$ [m/s]

   where A_l and A_h are the cross section of the liquid layer above and below NIL.

2. **Size of the compartments**

   - Inlet compartment

     This is the part between the vessel tangent line closest to the feed inlet and the downstream calming baffle.

     Recommended: $L_{in} = 0.45D$

   - Outlet compartment

     This is the part of the vessel between the other vessel tangent line and the outlet nozzles (assuming both nozzles are in the same vertical plane which is perpendicular to the vessel axis).

     Typically: $L_{out} = 0.25D$

   - Settling compartment

     This is the intermediate part of the vessel where settling takes place.

     $L_{set} = L_{ves} - L_{in} - L_{out}$ [m]

     Obviously, if L_{set} is very small, a larger value for L_{ves} has to be taken if it is a new vessel, or a smaller value for L_{in} has to be accepted in an existing vessel.

3. Calculation of the smallest light-phase and smallest heavy-phase droplet which still can be separated

- Settling of heavy-phase droplet:

  $v_{dh,set} = Q_L / (0.8 x L_{set} x D)$ [m/s]

  $d_h = \sqrt{18 \eta_l (v_{dh,set} + 0.05 v_{l,ax}) / \{g(\rho_h - \rho_l)\}}$ [m]

  It shall be checked that $v_{l,ax}$ does not exceed 0.015 m/s, because this may result in a larger value of d_h than is given by above formula.
  $v_{l,ax}$ can be decreased by selecting a lower NL.

- Settling of light-phase droplet:

  $v_{dl,set} = Q_H / (0.8 x L_{set} x D)$

  $d_l = \sqrt{18 \eta_h (v_{dl,set} + 0.05 v_{h,ax}) / \{g(\rho_h - \rho_l)\}}$

  It shall be checked that $v_{h,ax}$ does not exceed 0.015 m/s, because this may result in a larger value of d_l than is given by above formula.
  $v_{h,ax}$ can be decreased by selecting a higher NL.

4. Calculation of the control times

From D, $LA(L)_{int}$, $LA(H)_{int}$ and L_{ves} the control volume, V_{con,H_L}, contained between the $LA(H)_{int}$ - and $LA(L)_{int}$ -level is calculated.

$t_{con,H\_L} = V_{con,H\_L} / Q_{con,H\_L}$ [sec]

$V_{con,H\_L} = A_{con,H\_L} L_{ves} + 2\, \Delta V_{hd,H\_L}$ [m³]

A_{con,H_L} and $\Delta V_{hd,H\_L}$ are the vessel cross-section and the vessel head volume respectively between $LA(H)_{int}$ and $LA(L)_{int}$. For their calculation, see Appendix VI.

Q_{con,H_L} is the flow rate of the liquid phase used for control.
This is normally the heavy liquid phase.

Similarly, t_{con,HH_H} and t_{con,L_LL}, the control times associated with the control zones between $(LZA(HH)_{int} - 0.5 H_{db})$ and $LA(H)_{int}$ and
between $LA(L)_{int}$ and $(LZA(LL)_{int} + 0.5 H_{db})$ respectively, can be calculated.

If the calculated control times are smaller than the specified minimum control times, then the calculations shall be repeated with adjusted control levels or (in the case of a new vessel) with larger vessel dimensions.

5. Installation of a plate pack in the settling compartment

The performance of the existing horizontal open two-phase settler can be upgraded by installing a plate pack.

The plate pack to be installed shall extend from vessel bottom to vessel top and its distance to the calming baffle of the inlet compartment and to the outlet nozzles is 150 mm and 500 mm respectively.

Its performance, as a function of the selected plate pack characteristics (plate spacing, angle between plates and horizontal plane and length of the plate pack) and of the flow conditions, can be assessed by means of the following procedure:

5a. Determine the part of the gross frontal area of the plate pack, $A_{f,gross}$, that can be accommodated in the vessel cross-sectional area between the top of the vessel and NIL and in the vessel cross-sectional area between NIL and the bottom of the vessel, respectively.

$(A_{f,gross})_l = F_{pp}A_l$
$(A_{f,gross})_h = F_{pp}A_h$ [m^2]

F_{pp} is assumed to be the same for both areas and is typically 0.8.
A_l and A_h have already been calculated in step 1.

5b. Calculate the corresponding net free area, $A_{f,net}$, taking into account the plate thickness t_{pp}, a selected plate distance d_{pp} and the loss factor F_{loss}

$(A_{f,net})_l = (A_{f,gross})_l * F_{loss} * d_{pp}/(t_{pp} + d_{pp})$ [m^2]
$(A_{f,net})_h = (A_{f,gross})_h * F_{loss} * d_{pp}/(t_{pp} + d_{pp})$ [m^2]

F_{loss} is typically in the range of 0.9 to 0.95.
t_{pp} is typically 1 mm.

5c. Check the selected d_{pp}.
The distance between the plates, d_{pp}, has to be selected so that it is sufficiently small to ensure laminar flow in the plate pack but it shall not be smaller than a given minimum distance, $d_{pp,min}$. This minimum distance is 10 mm for non-fouling conditions and 40 mm for fouling conditions.

The following two criteria should both be satisfied:

– for upper part of plate pack:
$d_{pp,min} \leq d_{pp} \leq (d_{pp,max})_l \approx Re_{crit}\eta_l(A_{f,net})_l/(2\rho_l Q_l)$ [m]

– for lower part of plate pack:
$d_{pp,min} \leq d_{pp} \leq (d_{pp,max})_h \approx Re_{crit}\eta_h(A_{f,net})_h/(2\rho_h Q_h)$ [m]

Re_{crit} is the critical Reynolds number above which deviation from the laminar flow regime will take place.

If flat plates (with front and rear contours) are used, then Re_{crit} is 850; if corrugated plates are used then Re_{crit} is 450.

$(d_{pp,max})_l$ and $(d_{pp,max})_h$ are the corresponding plate spacings.

If d_{pp} is too large to ensure laminar flow, select a smaller value for d_{pp}
(with $d_{pp} \leq d_{pp,max}$) and repeat steps 5a and 5b.

The calculated $d_{pp,max}$ values are an approximation, since $A_{f,net}$ is a function of the selected d_{pp}, so probably at least one iteration step is required.

If the above criteria still cannot be satisfied for $d_{pp} = d_{pp,min}$, then the minimum distance should be used for d_{pp}, accepting the deviation from laminar flow. Although turbulent flow in the plate pack will then affect separation, the separation will still be better than if no plate pack were used.

5d. Determine the angle θ of the plates with the horizontal plane (45° in non-fouling service and 60° in fouling service)

5e. Select the length of the plate pack, L_{pp}

For the length of the plate pack, L_{pp}, it is recommended that:

$L_{pp,max} = L_{set} - 0.65$ [m]

distance to calming plate and outlet nozzles 0.15 and 0.5 m respectively.

$L_{pp,min} = 0.3$ [m]

If L_{set} < 0.95 m, the above requirements cannot be met and compromises will be necessary.

5f. Calculate the separation performance of the plate pack

If the flow in the plate pack is laminar, the smallest droplet to be separated for both phases is given by the following relationships:

– heavy-phase droplet:

$$d_h = \sqrt{18 \eta_l v_{dh,set} / \{g(\rho_h - \rho_l)\}}$$ [m]

with $v_{dh,set} = v_{l,pp} d_{pp} / \{\cos\theta \, (L_{pp} - 8d_{pp})\}$ [m/s]

in which $v_{l,pp} = Q_l / (A_{f,net})_l$ [m/s]

– light-phase droplet:

$$d_l = \sqrt{18 \eta_h v_{dl,set} / \{g(\rho_h - \rho_l)\}}$$ [m]

with $v_{dl,set} = v_{h,pp} d_{pp} / \{\cos\theta \, (L_{pp} - 8d_{pp})\}$ [m/s]

in which $v_{h,pp} = Q_h / (A_{f,net})_h$ [m/s]

$v_{l,pp}$ and $v_{h,pp}$ are the axial velocities in the upper and lower separation part of the plate pack.

$v_{l,ax}$ and $v_{h,ax}$ are the axial velocities in the light and heavy liquid phase upstream of the plate pack.

The term $8d_{pp}$ in the expression for $v_{dh,set}$ and $v_{dl,set}$ is a correction for the non-laminar flow in the entrance of the plate pack.

Strictly speaking the correction is equal to 0.01xmax.(Re_l,Re_h)xd_{pp}, where Re_l and Re_h are the Reynolds numbers in the light-phase and heavy-phase part of the plate pack respectively, but in most cases the simple term $8d_{pp}$ is equal to or larger than the exact value (see also Appendix II).

If the calculated drop sizes are still too large, a larger L_{pp} has to be selected (if still allowed by the vessel geometry) and step 5f has to be repeated.

IV.1.3 Calculation example

An existing horizontal open two-phase settler has to be checked to establish whether it can separate oil and water properly under given process conditions.

If required, its separation performance has to be upgraded by the installation of internals.

Flow conditions are:

Oil: mass flow rate of 500 t/d with a density of 750 kg/m^3 and a dynamic viscosity of 0.5 mPa.s.

Water: mass flow rate of 320 t/d with a density of 990 kg/m^3 and a dynamic viscosity of 0.9 mPa.s.

- Design margin is 1.2
- No dispersion band expected in the oil/water interface
- Level control (based on water flow rate):
  3 minutes between high and low level (pre-alarms)
  1 minute between pre-alarm and trip

Further information:

- Vessel: diameter 1.5 m and T/T of 5 m (heads semi-elliptical with a ratio of 2:1)
- Nozzles: feed inlet is a top inlet located 0.25 m from the "left" vessel tangent line; distance of oil and water outlets from "right" vessel tangent line is 0.4 m; diameters of feed inlet, oil outlet and water outlet are 0.15, 0.15 and 0.10 m respectively
- Internals: only vortex breakers on the oil and water outlet are present

Check

To optimise the settling conditions, it is proposed to convert the vessel layout to the layout shown in the top part of Figure 3.1.

It is proposed to fit the feed nozzle with an elbowed pipe directed to the nearest vessel head and to install a double calming baffle (30 % NFA and 50 % NFA respectively), the second baffle to be located at 0.75 m (0.45 vessel diameter) from the “left” tangent line with a distance of 0.3 m (0.2 D_{ves} diameter) between the baffles. The distance from the vertical TL to the first baffle is taken slightly larger than the minimum (0.25 vessel diameter) to accommodate the inlet nozzle with sufficient clearance from left tangent line and baffle. This distance is 150+ ID_{nozzle}+ max(150, 0.5xID_{nozzle}) = 0.45 m.

This will result in an effective settling length to the nozzles of 5 - 0.4 - 0.75 = 3.85 m.

The distance between pre-alarm and trip level in each set is at least 0.1 m (no allowance for dispersion band necessary) and the distance between high and low IL is minimal 0.35 m. This results in a total control band of minimal 0.55 m.

As a starting point it is assumed that the control band has this minimum width of 0.55 m.

It should be located in the vessel so that in both the oil and the water layer proper bulk separation takes place i.e. all droplets larger than 150 μm diameter shall be removed.

Initially three locations of this control band in the vessel have been considered:

Position I: At the lowest location ($LZA(LL)_{int} = 0.2 * D_{ves}$ = 0.3 m)

Position II: In the centre ($A_l = A_h$)

Position III: At the highest location ($LZA(HH)_{int} = 0.8 * D_{ves}$ = 1.2 m)

For these three positions the various quantities (e.g. cross-sectional areas, velocities, cut-off diameters, control time and maximum allowable axial velocities) have been calculated according to the calculation scheme presented in Appendix IV.3.

They are listed in the following table.

Nozzle velocities (including design margin!) have also been calculated and listed.

In this table it has been indicated (by bold italic and border) where the various requirements for this type of separator are not satisfied (see Appendix IV.1.2).

location of control band			position I (low)	position II (medium)	position III (high)	position IV
limits of control band	$LZA(LL)_{int}$	(m)	0.300	0.475	0.650	0.380
	$LZA(HH)_{int}$	(m)	0.850	1.025	1.200	0.930
step 1	A_l	(m^2)	0.734	0.480	0.252	0.616
	A_h	(m^2)	0.252	0.480	0.734	0.352
	$v_{l,ax}$	(mm/s)	12.6	***19.3***	***36.8***	15.0
	$v_{h,ax}$	(mm/s)	***17.8***	9.3	6.1	12.8
step 2	L_{set}	(m)	3.85	3.85	3.85	3.85
step 3	$v_{dh,set}$	(mm/s)	2.1	2.4	2.9	2.2
	$v_{dl,set}$	(mm/s)	1.4	1.2	1.1	1.3
	d_h	(μm)	103	113	134	107
	d_l	(μm)	125	106	96	114
step 4	A_{con}	(m^2)	0.505	0.520	0.505	0.516
	ΔV_{hd}	(m^3)	0.143	0.152	0.143	0.149
	V_{con}	(m^3)	2.813	2.905	2.813	2.878
	t_{con,H_L}	(sec)	627	647	627	641
	t_{con,HH_H}	(sec)	186	177	155	184
	t_{con,L_LL}	(sec)	155	177	186	167
nozzle velocities	feed: v_{N1}	(m/s)	0.74	0.74	0.74	0.74
	oil out: v_{N3}	(m/s)	0.50	0.50	0.50	0.50
	water out: v_{N4}	(m/s)	0.55	0.55	0.55	0.55

The check of the settler leads to the following conclusions:

- The calculations show that for the low, medium and high control band position, adequate bulk separation takes place for both liquid phases (cut-off diameter smaller than 150 μm).
- However, the axial velocity in the light phase exceeds the upper limit of 0.015 m/s when the control band is in the medium or high position. The axial velocity in the heavy phase exceeds the limit of 0.015 m/s when the control band is in the low position. Therefore, for optimum settler performance, a control band position between the low and medium position should be selected.
  The table shows that if $LZA(LL)_{int}$ is at 0.38 m (position IV; 0.08 m above the low position) the velocity requirement for both phases has been satisfied.
- The available time for the various control bands is in all cases much more than the minimum requirements, so the selected width of the control band of 0.55 m is more than sufficient.
- The nozzle inlet and outlet velocities are well below the maximum of 1 m/s.

IV.1.4 Upgrading of the separation performance of the settler by installing of a plate pack

In this example it will be investigated to what extent the separation performance of the settler can be upgraded by installing a plate pack.

The layout of the separator fitted with a plate pack is shown in Figure 3.2.

Input

- The control band will be taken at position IV (see preceding table)
- Since the service is non-fouling, flat plates and a plate angle of 45º are selected.
- Selected plate thickness is 1 mm.
- Because flat plates have been opted for, the critical Reynolds number is 850.

The maximum space available for the plate pack is 3.85 - 0.65 = 3.2 m. However, in practice such a long plate pack will normally not be installed. Normally the length of a plate pack is in the range of 0.5 to 1.5 m.

- As a first choice, a plate pack length of 1 m has been selected.

If the calculated cut-off diameters are still not small enough then a longer plate pack could be considered.

- Because the service is non-fouling the minimum allowable plate spacing is 10 mm.

Further input:

- F_{pp} is 0.8
- F_{loss} is 0.9
- correction of effective plate pack length for turbulence in entrance: subtract 8 times the plate spacing.

In the following table the calculations (iterative procedure because $A_{f,net}$ is influenced by d_{pp}) are presented following the calculation scheme as outlined in Appendix IV.1.2.

selection of plate spacing			d_{pp} is 30 mm start value	d_{pp} is 13 mm 1st iteration	d_{pp} is 12 mm 2nd iteration
step 5a	$(A_{f,gross})_l$	(m^2)	0.493	0.493	0.493
	$(A_{f,gross})_h$	(m^2)	0.282	0.282	0.282
step 5b	$(A_{f,net})_l$	(m^2)	0.429	0.412	0.410
	$(A_{f,net})_h$	(m^2)	0.245	0.235	0.234
step 5c	$(d_{pp,max})_l$	(mm)	13.1	12.6	12.5
	$(d_{pp,max})_h$	(mm)	21.1	20.2	20.1
	check of d_{pp}		**too large** (turb.) go to step 5b with $d_{pp} \leq 13.1$ mm	**too large** (turb.) go to step 5b with $d_{pp} \leq 12.6$ mm	**OK** no turbulence; proceed with step 5d
step 5d	θ	(degrees) (input)			45
step 5e	L_{pp}	(m) (input)			1.00
step 5f	$v_{l,pp}$	(mm/s)			22.6
	$v_{dh,set}$	(mm/s)			0.42
	d_h	(μm)			40
	$v_{h,pp}$	(mm/s)			19.2
	$v_{dl,set}$	(mm/s)			0.36
	d_l	(μm)			50

The following conclusions can be drawn from above calculations:

- Installation of a plate pack in the settler gives a substantial improvement of the separation performance.
  Comparison of the corresponding two tables shows that with the selected plate pack layout for both phases the cut-off diameter will be reduced from about 110 μm to about 40 - 50 μm.
- Selection of a plate pack length of 1 m results in cut-off diameters close to the diameter that can be achieved with a plate pack in practice. It is therefore concluded that in this particular case it is not necessary to install a longer plate pack.
- Rather small plate spacing; could slightly be improved by relocating $LZA(LL)_{int}$ to 0.3 m.

APPENDIX V THREE-PHASE SETTLERS

V.1 CHECK OF AN EXISTING HORIZONTAL OPEN THREE-PHASE SETTLER FITTED WITH A BOOT

(See also main text (4.1.3) and Figure 4.1)

This procedure can also be used as the sizing procedure for a new settler starting with the specification of the vessel dimensions and the various level control heights.

The various steps taken in the procedure are described below.

V.1.1 Input

1. Diameter and tangent/tangent length of vessel and boot.
2. The volumetric flow rate and density of the gas and liquid phases and the dynamic viscosity of the liquid phases. Specification of design margin.
3. Control levels of both G/L and L/L interface.
4. Required minimum control times for G/L and L/L interface control.
5. The maximum allowable gas load factor, λ_{max}, in the gas cap above LZA(HH). With bulk separation: λ_{max} = 0.07 m/s.
6. Specification of foam allowance /or dispersion band.

   If a foaming system is present, normally a foam allowance of 250 mm is taken which has to be accommodated between LA(H) and LZA(HH).

   A settler with a boot is normally applied when the concentration of one of the phases is small, typically <5 %. For such applications a dispersion band is not expected.
7. Specification of slug size

V.1.2 Calculations

1. **Check of vessel dimensions with respect to de-gassing (if required)**

   $$D_{ves}*L_{ves} \geq \{4.5*10^7(Q_l + Q_h)\eta_l/(\rho_l - \rho_G)\}$$

2. **Check of vessel dimensions with respect to de-foaming (if required)**

   $$D_{ves}*L_{ves} \geq 7000(Q_l + Q_h)\{\eta_l/(\rho_l - \rho_G)\}^{0.27}$$

   The de-gassing and de-foaming criteria (also described in DEP 31.22.05.11-Gen.), are based here on the physical properties of the light liquid and the total liquid flow rate.

3. Check of selected G/L control levels

The following criteria shall be satisfied:

1. $LZA(HH)/D_{ves} \leq 0.8$
2. D_{ves} - $LZA(HH) \geq 0.3$
3. The gas gap area above LZA(HH), A_G, is expressed as:

   $$A_G \geq Q_G / \lambda_{max} \sqrt{\rho_G / (\rho_l - \rho_G)} \qquad [m^2]$$

   A_G follows directly from LZA(HH) and D_{ves} utilising the chord area - chord height relationships presented in Appendix VI.

4. The height of the various control bands shall have a minimum height (including, if required, foaming and slug accommodation allowances) as specified in Appendix X.
5. The ratio $LZA(LL)/D \geq 0.2$
6. LZA(LL)/(nozzle ID of the light phase outlet) ≥ 1
7. D – LZA(HH) ≥ 200 mm +2x(ID of the inlet nozzle). This distance is required to accommodate the inlet device.

4. Check of selected L/L control levels in the boot

The following criteria should be satisfied:

1. If trip levels are specified, LZA(HH)int - LA(H)int and LA(L)int - LZA(LL)int shall be at least equal to 100 mm. For the interface level a high level trip will not always be required.
2. The distance of the control band from the vessel bottom and from the boot bottom tangent should be at least 200 mm.

5. Calculation of the various control times of the L/L level control

From the flow rate of the heavy phase, Q_h, and boot diameter, D_{boot}, the downward liquid velocity in the boot, $v_{h,boot}$, is calculated:

$$v_{h,boot} = Q_h/(\pi/4 * D^2_{boot}) \qquad [m/s]$$

From this velocity and the specified control levels the associated control times of the heavy-phase liquid are calculated:

$$t_{HH\_H,h} = (LZA(HH)_{int} - LA(H)_{int})/ v_{h,boot} \qquad [sec]$$

$$t_{H\_L,h} = (LA(H)_{int} - LA(L)_{int})/ v_{h,boot} - V_{slug}/(Q_l + Q_h) \qquad [sec]$$

(assumption: the slug has the same ratio of light and heavy liquid phases as the regular feed)

$$t_{L\_LL,h} = (LA(L)_{int} - LZA(LL)_{int}) / v_{h,boot} \qquad [sec]$$

It has to be checked whether the calculated control times are at least equal to the specified minimum control times. If not, the control levels shall be adjusted.

In the case of a new vessel, of course D_{boot} and/ or L_{boot} can be adjusted.

6. Calculation of the various control times of the G/L level control

In a foaming system, first the foam allowance has to be subtracted from the value of LZA(HH) for proper calculation of the control time associated with the band between LZA(HH) and LA(H).

Subsequently the cross-sectional areas of the various control bands are calculated from the vessel diameter and the various control levels with the aid of the chord area - chord height relationships presented in Appendix VI.

Finally the various control times of the light-liquid phase are calculated with the following formulae:

$t_{HH\_H,l} = \{L_{ves} * A_{con,HH\_H} + 2\Delta V_{hd,HH\_H} - V_{foam}\} / \{Q_h + Q_l\}$ [s]

$t_{H\_L,l} = \{L_{ves} * A_{con,H\_L} + 2\Delta V_{hd,H\_L} - V_{slug}\} / \{Q_h + Q_l\}$ [s]

$t_{L\_LL,l} = \{L_{ves} * A_{con,L\_LL} + 2\Delta V_{hd,L\_LL}\} / \{Q_h + Q_l\}$ [s]

In the above formulae the **specified** rather than the calculated control times for the heavy phase have been taken into account.

The relationship for ΔV_{hd} as a function of its boundaries and the vessel diameter is also given in Appendix VI.

It has to be checked whether the calculated control times are at least equal to the specified minimum control times. If not, the control levels shall be adjusted.

In the case of a new vessel, of course D_{ves} and/ or L_{ves} can be adjusted.

7. Sizing of the compartments

- Inlet compartment

  This is the part of the vessel between the vessel tangent line closest to the feed inlet and the second calming baffle.

  recommended: $L_{in} = 0.45D$ [m]
  (L_{in} = 0.45 D for vessels with plate pack and one baffle).

- Outlet compartment

  This is the part of the vessel between the other vessel tangent line and the light phase outlet nozzle

  typically: $L_{out} = 0.25D$ [m]

- Settling compartment

  This is the intermediate part of the vessel. It contains the boot.

  $L_{set} = L_{ves} - L_{in} - L_{out}$ [m]

  Obviously, if L_{set} is very small, smaller values for L_{in} and L_{out} shall be selected.

8. Calculation of the smallest light-phase and smallest heavy-phase droplet which can still be separated

- Heavy-phase droplets in settling compartment

$$d_h = \sqrt{18\eta_l(v_{dh,set} + 0.05 v_{l,ax})/\{g(\rho_h - \rho_l)\}} \quad \text{[m]}$$

with $v_{dh,set} = Q_l/(L_{set} x D x 0.8)$ [m/s]
and $v_{l,ax} = (Q_l + Q_h) / A_l$ [m/s]

A_l is calculated from the vessel diameter D and NL, using the formulae given in Appendix VI.

It has to be checked that $v_{l,ax}$ does not exceed 0.015 m/s, because this may result in a larger value of d_h than is given by the above formula.

$v_{l,ax}$ can be decreased by selecting a higher NL.

- Light-phase droplets in boot

$$d_l = \sqrt{18\eta_h\ 1.05 v_{h,boot} / \{g(\rho_h - \rho_l)\}} \quad \text{[m]}$$

V.1.3 Calculation example

An existing three-phase separator with a boot has to be checked to establish whether it will still be able to perform adequate three-phase separation in a future flow scenario in which all the flow rates will be increased.

Future flow conditions are :

Gas: mass flow rate of 167 t/d with a density of 10 kg/m^3
Oil: mass flow rate of 410 t/d with a density of 750 kg/m^3 and a dynamic viscosity of 0.5 mPa.s
Water: mass flow rate of 20 t/d with a density of 990 kg/m^3 and a dynamic viscosity of 0.9 mPa.s

- Design margin is 1.2
- Only bulk G/L and L/L separation is required.
- Non-foaming feed but slugs up to 1 m^3 can be expected
- No dispersion band in the oil/water interface
- G/L and L/L level control:
  3 minutes between high and low level (pre-alarms)
  1 minute between pre-alarm and trip

The layout of the vessel is similar to the one shown in Figure 4.1.
The feed nozzle is fitted with an elbowed half-open pipe as is shown in the figure.
However, no calming baffle is present.

Further information

- Vessel: diameter 1.5 m and T/T of 4.2 m (heads semi-elliptical with a ratio of 2:1)
- Boot: diameter of 0.45 m and a length (to BTL) of 1.20 m
- Nozzles: diameters of feed inlet, gas outlet, oil outlet and water outlet are 0.20, 0.15, 0.10 and 0.05 m respectively; distance of oil outlet from "right" vessel tangent line is 0.40 m

Check

The first action is to propose a double perforated baffle (30 % and 50 % NFA respectively and a hole diameter of 12 mm), the second baffle to be located at a distance of 0.7 m (=0.45D_{ves}) from the "left" vessel tangent line to promote the dewatering of the oil.

It is assumed that most of the liquid ejected from the half-open pipe reaches the gas-liquid interface at a point upstream of the first baffle, which is located at 0.4 m from the “left” tangent line.

Attempts are made to meet all the requirements by appropriate selection of the various control levels.

As far as G/L separation is concerned, λ_{max} = 0.07 m/s, since there are no G/L internals and bulk separation is required (DEP 31.22.05.11-Gen.: Horizontal Knock-out Drum).

The normal procedure is to select LZA(HH) so that the G/L separation criterion is satisfied, also bearing in mind that D_{ves} - LZA(HH) ≥ 0.3 m and that LZA(HH)/D_{ves} ≤ 0.8 and maintaining a distance of at least 150 mm between inlet device and LZA(HH). The latter criterion implies that the gas cap should be minimum 2 times the feed nozzle diameter (bend radius 1½D assumed) + ~50 mm (above bend) + 150 mm (below inlet device).

The height of the perforated baffles shall be at least as high as LZA(HH).

In the following table the final choice of the various control levels is presented.

The nozzles have also been checked and the separation performance of the settler has been calculated following the calculation scheme as outlined in Appendix V.2.

check on de-gassing (step 1)	$D_{ves}*L_{ves}$ (m^2)	6.30	minimal requirement: 0.239 m^2	OK
check of chosen levels +	LZA(HH) (m) (≡ height of calming baffle)	0.90	LZA(HH)/D_{ves} =0.6 < 0.8 D_{ves} - LZA(HH) = 0.60 m > 0.3 m λ_G = 0.041 m/s < 0.07 m/s (λ_{max}) D_{ves} - LZA(HH)-0.15=0.45 ≥ 2*d_{N1}+0.05	OK OK OK OK
calculation of control times	LA(H) (m)	0.80	LZA(HH)-LA(H)=0.1 m (min.) t_{HH_H} = 91 sec >60 sec	OK OK
	LA(L) (m)	0.45	LA(H)-LA(L)= 0.35 m ≥ 0.35 m t_{H_L} = 184 sec > 180 sec	OK OK
(steps 3 to 6)	LZA(LL) (m)	0.35	LA(L)-LZA(LL)=0.1 m (min.) t_{L_LL} = 79 sec >60 sec LZA(LL) > 0.3 m (extended outlet) LZA(LL)/D_{ves} = 0.23 > 0.2 LZA(LL) > 0.15 + ID N3	OK OK OK OK OK
	$LZA(HH)_{int}$ (m)	-0.20	distance to vessel bottom 0.2 m	OK
	$LA(H)_{int}$ (m)	-0.31	$LZA(HH)_{int}$-$LA(H)_{int}$=0.1 m (min.) $t_{HH\_H,int}$ = 62 sec > 60 sec	OK OK
	$LA(L)_{int}$ (m)	-0.89	$LA(H)_{int}$-$LA(L)_{int}$= 0.58 m > 0.35 m $t_{H\_L,int}$ = 202 sec > 180 sec	OK OK
	$LZA(LL)_{int}$ (m)	-1.00	$LA(L)_{int}$-$LZA(LL)_{int}$=0.1 m (min.) $t_{L\_LL,int}$ = 62 sec >60 sec dist. to BTL boot 0.2 m	OK OK OK
step 7	L_{in} (m) L_{out} (m) L_{set} (m)	0.70 0.40 3.10		
step 8	$v_{l,ax}$ (mm/s) $v_{dh,set}$ (mm/s) d_h (µm) $v_{h,boot}$ (mm/s) d_l (µm)	11.3 2.0 100 1.8 113		OK
nozzle check	N1: $\rho_m v_m^2$ (Pa) N2: $\rho_G v_G^2$ (Pa) N3: v (m/s) N4: v (m/s)	1825 1547 0.92 0.13	$\rho_m v_m^2$ < 2100 Pa $\rho_G v_G^2$ < 4500 Pa v < 1 m/s v < 1 m/s	OK OK OK OK

The following conclusions can be drawn from the calculations:

- The de-gassing criterion has been met.
- The control levels have been properly selected.
- The requirements for proper G/L and L/L separation have also been satisfied:
  - At maximum gas flow and with the G/L interface at LZA(HH), the gas load factor is well below 0.07 m/s.
  - d_h and d_l are both well below 150 µm.

V.2. RETROFIT OPTION FOR EXISTING HORIZONTAL OPEN THREE-PHASE SETTLERS TO BE FITTED WITH A DOUBLE WEIR (INCLUDING PLATE PACK OPTION)

(See also main text (4.1.4) and (4.2) and Figures 4.4, 4.5 and 4.6)

This procedure can also be treated as the sizing procedure for a new settler starting with the specification of the vessel dimensions and the various level control heights.

The various steps taken in the procedure are described below.

V.2.1 Input

1. Diameter and tangent/tangent length of vessel.
2. Volumetric flow rate and density of the gas and liquid phases and dynamic viscosity of the liquid phases.

   If there are flow scenarios with different densities, all densities shall be considered.
3. Specification of LZA(HH). In the case of a settler with an overflow weir LZA(HH) is not a trip level in the real sense. It will be used here to indicate the maximum acceptable liquid level.
4. Specification of LZA(HH) and IL. (IL can be adjusted during the calculations).
5. The maximum allowable gas load factor, λ_{max}, in the gas cap above LZA(HH). In the case of bulk separation with no demisting internals: λ_{max} = 0.07 m/s.
6. The height of the passage underneath the water underflow weir (at least 0.2 m) and the distance between the water underflow and water overflow weir typically 0.2 m).
7. Collection compartments: required minimum control times.
8. Specification of foam allowance and/or dispersion band.
   In a foaming system, a foam allowance has to be accommodated between LZA(HH) and NL. Typical foaming allowance is 0.25 m.
   If a dispersion band is present, the distance between each pre-alarm and trip level has to be increased by half the width of the dispersion band.
   If a dispersion band is expected but its width cannot be reliably estimated using the formula given in Appendix I, 0.2 m should be taken as dispersion band width.
9. Specification of slug size for both liquid phases.

V.2.2 Calculations

1. Check of selected LZA(HH)

The following criteria shall be satisfied:

1. LZA(HH)/$D_{ves} \leq 0.8$
2. D_{ves} - LZA(HH) ≥ 0.3 m
3. D_{ves} - LZA(HH) ≥ 0.2 m + 2 x ID of the inlet nozzle
4. The area of the gas cap above LZA(HH), A_G, is expressed as

$$A_G \geq Q_G / \lambda_{max} \sqrt{\rho_G / (\rho_l - \rho_G)} \qquad [m^2]$$

A_G follows directly from LZA(HH) and D_{ves} utilising the chord area - chord height relationships presented in Appendix VI.

If the above criteria are not satisfied a smaller value has to be selected for LZA(HH).

2. Calculation of the elevation of the normal liquid level, NL

NL is the sum of the height of the light phase overflow weir and its weir crest. It follows directly from LZA(HH) by subtracting the specified distance between LZA(HH) and NL, ΔH_{HH_NL}

ΔH_{HH_NL} is typically 0.1 m for non-foaming and 0.35 m for foaming systems.

$$NL = LZA(HH) - \Delta H_{HH\_NL}$$

3. Calculation of the height of the weirs

The height of the light phase overflow weir follows directly from NL and the height of the weir crest on top of the weir, $h_{crest,l}$

$h_{ow,l} = NL - h_{crest,l}$ [m]

with $h_{crest,l} = 0.670\{Q_l^2/(D*NL-NL*NL)\}^{0.333}$ [m]

The height of the heavy liquid phase overflow weir is given by the following function of the light and heavy liquid densities (ρ_l and ρ_h respectively), NL, the liquid/liquid interface level, IL and the weir crest on top of the weir, $h_{crest,h}$:

$h_{ow,h} = IL + (NL-IL)\rho_l/\rho_h - h_{crest,h}$ [m]

with $h_{crest,h} = 0.670[Q_h^2/(D*\{IL+(NL-IL)\rho_l/\rho_h\} - \{IL+(NL-IL)\rho_l/\rho_h\}^2)]^{0.333}$ [m]

IL should be halfway between the top of the under flow passage, h_{up}, of the heavy phase front weir and the top of the light phase overflow weir.

that is: $IL = (h_{ow,l} + h_{up})/2$

The input value for IL can now be changed to this preferred value. It can also be kept at its original value, provided that the following requirements are satisfied:

- $(IL-0.5H_{db})/D_{ves} \geq 0.2$
- IL shall be at a distance of at least $0.5H_{db}$ + 0.2 m from either the lower rim of the heavy-phase under flow weir or from the upper rim of the light-phase overflow weir.

h_{up} has been specified in the input and is at least 0.2 m.

The height of the heavy phase front weir, $h_{fw,h}$ follows directly from LZA(HH).

$h_{fw,h} = LZA(HH) + 0.1$ [m]

If there are flow scenarios with different densities it shall be checked that the above requirements are met for all densities.

4. Calculation of the axial liquid velocities in the settling compartment and underflow passage

For a given IL, A_l (cross-sectional area between NL and (IL+0.5H_{db})) and A_h (cross-sectional area between (IL-0.5H_{db}) and vessel bottom) can now be calculated from the various levels with the aid of the formulae of Appendix VI.

Subsequently:

$v_{l,ax} = Q_l/A_l$ [m/s]

$v_{h,ax} = Q_h/A_h$ [m/s]

$v_{l,ax}$ and $v_{h,ax}$ should not exceed 0.015 m/s. Similarly, from the given central height of the passage underneath the water front weir, h_{up}, the velocity in the passage can be calculated.

$v_{up} = Q_h/A_{up}$ [m/s]

A_{up} also follows from the relationships given in Appendix VI, taking into account that only a part of the cross-sectional area below h_{up} is used for the underflow passage (50 % if the collection compartments have the same width).

5. Sizing of the compartments

- Inlet compartment

  $L_{in} = 0.45D$ [m]

This determines the location of the calming baffle.

- Collection compartments

  From the liquid flow rates, estimated slug sizes (if expected) and the specified control times it follows which volume has to be contained between the high and low level control in each collection compartment.

  For the calculations the slug (if any) has to be split up in a heavy-phase and a light-phase part.

  If split-up is not known, take as default:

  $V_{slug,l} = V_{slug} * Q_l/(Q_l + Q_h)$ [m^3]

  $V_{slug,h} = V_{slug} * Q_h/(Q_l + Q_h)$ [m^3]

  For the volume contained between the pre-alarm levels in each collection compartment is given by:

  $V_{H\_L,l} = Q_l * (t_{con,l})_{spec} + V_{slug,l}$ [m^3]

  $V_{H\_L,h} = Q_h * (t_{con,h})_{spec} + V_{slug,h}$ [m^3]

  From the specified high and low liquid levels in each collection compartment (which should be at a distance of 0.2 m from the top of the corresponding overflow weir and 0.2 m from the bottom of the vessel, respectively), the effective lengths of the light and heavy liquid phase collection compartments, $L_{coleff,l}$ and $L_{coleff,h}$ respectively, can be derived.

  First for each collection compartment the effective length is calculated (assuming the longitudinal compartment separation plate between the collection compartments is in the middle of the vessel (i.e. coinciding with the vessel axis)). In the calculation of this effective length the contribution of the vessel heads has been taken into account.

In the case of a large Q_l / Q_h ratio:

$L_{coleff,l} = (Q_l * (t_{con,l})_{spec} - \Delta V_{hd,l} + V_{slug,l})/A_{H\_L,l}$ [m]
$L_{coleff,h} = (Q_h * (t_{con,h})_{spec} + V_{slug,h})/A_{H\_L,h}$ [m]

In the case of a small Q_l/Q_h ratio:

$L_{coleff,l} = (Q_l * (t_{con,l})_{spec} + V_{slug,l})/A_{H\_L,l}$ [m]
$L_{coleff,h} = (Q_h * (t_{con,h})_{spec} - \Delta V_{hd,h} + V_{slug,h})/A_{H\_L,h}$ [m]
$L_{col} = (L_{coleff,h} + L_{coleff,l} + w_{ww})/2$ [m]

w_{ww} is the distance between the two water weirs.
w_{ww} is min. 0.2 m (for accessibility during installation).

$A_{H\_L,l}$ and $A_{H_L,h}$are the cross-sectional areas of the light and heavy liquid phases collection compartments respectively between LA(H) and LA(L) just downstream of the weirs. They are half of the corresponding vessel cross-sectional areas.

These areas and also ΔV_{hd} of the largest liquid collection compartment are calculated using the relationships presented in Appendix VI.

The length of the smallest collection compartment will then also determine the location of the transversal separation plate (i.e. plate perpendicular to the vessel axis) between the collection compartments.

6. Settling compartment

$L_{set} = L_{ves} - L_{in} - L_{col}$ [m]

Obviously, if L_{set} is very small, or even negative (!), smaller values for L_{in} and L_{col} shall be taken. Depending on the feed internal to be used, a smaller value for L_{in} could be selected. Also it may be possible to relax the control time requirements which will result in a smaller value of L_{col}

The smallest droplets which can be separated off are given by the following relationships:

- heavy-phase droplet:

  $d_h = \sqrt{18\eta_l(v_{dh,set} + 0.05 v_{l,ax})/\{g(\rho_h - \rho_l)\}}$ [m]
  with $v_{dh,set} \approx Q_l/(0.8 x D x L_{set})$ [m/s]

  It has to be checked that $v_{l,ax}$ does not exceed 0.015 m/s, because this may result in a larger value of d_h than is given by the above formula.

  $v_{l,ax}$ can be decreased by selecting a lower IL.

- light-phase droplet:

  $d_l = \sqrt{18\eta_h(v_{dl,set} + 0.05 v_{h,ax})/\{g(\rho_h - \rho_l)\}}$ [m]
  with $v_{dl,set} = \approx Q_h/(0.8 x D x L_{set})$ [m/s]

  It has to be checked that $v_{h,ax}$ does not exceed 0.015 m/s, because this may result in a larger value of d_l than is given by the above formula.

  $v_{h,ax}$ can be decreased by selecting a higher IL.

If the smallest droplets which can be separated off are still too large, the following actions could be considered in the following order:

a. Adjust IL, if the above limitation holds only for either the heavy or light phase.
Of course this will have consequences for the various weir heights and also possibly for L_{col}.
IL shall be at a distance of at least $0.5H_{db}$ + 0.2 m from either the lower rim of the heavy-phase under flow weir or from the upper rim of the light-phase overflow weir.

b. Install a plate pack in the settling compartment possibly in conjunction with an adjustment of IL.
In Appendix II rules and background are given for the sizing of a plate pack.
Below (under point 9) the major steps are given.

7. Check of vessel dimensions with respect to de-gassing (if required)

$$D_{ves}*(L_{in} + L_{set}) \geq \{4.5*10^7(Q_l + Q_h)\eta_l/(\rho_l - \rho_G)\}$$

8. Check of vessel dimensions with respect to de-foaming (if required)

$$D_{ves}*(L_{in} + L_{set}) \geq 7000(Q_l + Q_h)\{\eta_l/(\rho_l - \rho_G)\}^{0.27}$$

The de-gassing and de-foaming criteria (also described in DEP 31.22.05.11-Gen.) are based here on the physical properties of the light liquid and the total liquid flow rate.

In this type of settler the collection compartments have not been taken into account.

9. Installation of a plate pack in the settling compartment

The performance of the existing three-phase separator can be upgraded by installing a plate pack.

The plate pack to be installed will extend from vessel bottom to NL and its distance from the calming baffle of the inlet compartment is 150 mm.

Its performance as a function of the selected plate pack characteristics (plate spacing, angle between plates and horizontal plane and length of the plate pack) and of the flow conditions can be assessed by means of the following procedure:

9a. Determine the part of the gross frontal plate pack area, $A_{f,gross}$, which can be accommodated in the vessel cross-sectional area between NL and (IL+$0.5H_{db}$) and between (IL-$0.5H_{db}$) and vessel bottom respectively.

$(A_{f,gross})_l = F_{pp}A_l$ [m^2]
$(A_{f,gross})_h = F_{pp}A_h$ [m^2]

F_{pp} is assumed to be the same for both areas and is typically 0.8.

9b. Calculate the corresponding net free area, $A_{f,net}$, taking into account the plate thickness t_{pp}, a selected plate distance d_{pp} and the loss factor F_{loss}.

$(A_{f,net})_l = (A_{f,gross})_l*F_{loss}*d_{pp}/(t_{pp} + d_{pp})$ [m^2]
$(A_{f,net})_h = (A_{f,gross})_h*F_{loss}*d_{pp}/(t_{pp} + d_{pp})$ [m^2]

F_{loss} is typically in the range of 0.9 to 0.95 and t_{pp} is typically 1 mm.

9c. Check the selected d_{pp}.

The distance between the plates, d_{pp}, has to be selected so that it is sufficiently small to ensure laminar flow in the plate pack but it shall not be smaller than a given minimum distance, $d_{pp,min}$. This minimum distance is 10 mm for non-fouling conditions and 40 mm for fouling conditions.

Both the following criteria should be satisfied:

– for upper part of plate pack:
  $d_{pp,min} \leq d_{pp} \leq Re_{crit}\eta_l(A_{f,net})_l/(2\rho_l Q_l)$ [m]

– for lower part of plate pack:
  $d_{pp,min} \leq d_{pp} \leq Re_{crit}\eta_h(A_{f,net})_h/(2\rho_h Q_h)$ [m]

Re_{crit} is the critical Reynolds number above which the flow regime will no longer be laminar. If flat plates (with front and rear contours) are used, then Re_{crit} is 850; if corrugated plates are used then Re_{crit} is 450.

If d_{pp} is too large to ensure laminar flow, select a smaller value and repeat steps 9b and 9c.

If the above criteria still cannot be satisfied for $d_{pp} = d_{pp,min}$, then the minimum distance should be used for d_{pp}, accepting the deviation from laminar flow. Although turbulent flow in the plate pack will then affect the separation, the separation will still be better than if no plate pack were used.

9d. Determine the angle θ of the plates with the horizontal plane (45° in non-fouling service and 60° in fouling service).

9e. Select the length of the plate pack, L_{pp}

For the length of the plate pack, L_{pp}, it is recommended that:

$L_{pp,max} = L_{set} - 0.65$ [m]

(distance from calming plate and collection compartments 0.15 and 0.5 m, respectively)

$L_{pp,min} = 0.3$ [m]

If Lset < 0.95 m, the above requirements cannot be met and compromises will be necessary, for which the Principal should be consulted.

9f. Calculate the separation performance of the plate pack

If the flow in the plate pack is laminar, the smallest droplets to be separated for both phases are given by the following relationships:

– heavy-phase droplet:

$d_h = \sqrt{18\eta_l v_{dh,set} / \{g(\rho_h - \rho_l)\}}$ [m]

with $v_{dh,set} = v_{l,pp} d_{pp} / \{\cos\theta\ (L_{pp} - 8d_{pp})\}$ [m/s]

in which $v_{l,pp} = Q_l / (A_{f,net})_l$ [m/s]

– light-phase droplet:

$d_l = \sqrt{18\eta_h (v_{dl,set} / \{g(\rho_h - \rho_l)\}}$ [m]

with $v_{dl,set} = v_{h,pp} d_{pp} / \{\cos\theta\ (L_{pp} - 8d_{pp})\}$ [m/s]

in which $v_{h,pp} = Q_h / (A_{f,net})_h$ [m/s]

$v_{l,pp}$ and $v_{h,pp}$ are the axial velocities in the upper and lower separation part of the plate pack.

$v_{l,ax}$ and $v_{h,ax}$ are the axial velocities in the light and heavy liquid phase upstream of the plate pack.

The term $8d_{pp}$ in the expression for $v_{dh,set}$ and $v_{dl,set}$ is a correction for the non-laminar flow in the entrance of the plate pack (see also Appendix II).

If the calculated drop sizes are still too large, a larger L_{pp} has to be selected (if still allowed by the vessel geometry) and step 9f has to be repeated.

V.2.3 Calculation example

From an existing horizontal vessel with an ID 1.4 m and T/T of 4.3 m (semi-elliptical heads: ratio 2:1) and no internals it has to be checked whether it can be converted into a three-phase separator which can handle the following process conditions:

Oil: mass flow rate is 60 t/d with a density of 750 kg/m^3 and a dynamic viscosity of 0.5 mPa.s.

Water: mass flow rate is 410 t/d with a density of 990 kg/m^3 and a dynamic viscosity of 0.9 mPa.s.

Gas: mass flow rate is 2 t/d with a density of 0.2 kg/m^3.

- Clean service.
- Feed has no foaming tendency.
- Design margin is 1.2.
- There are no liquid slugs to be expected.
- Allowance has to be made for a dispersion band of 0.2 m in the oil/water interface.
- Only bulk separation is required.
  (If no G/L separation internals are used, then in gas cap above LZA(HH), λ_{max} = 0.07 m/s).
- Minimum control time for the two liquid phases is 180 s (between LA(H) and LA(L).
- The vessel shall also act as a sealing vessel (to preserve vacuum conditions in upstream equipment).
- Further, both the location and size of the various nozzles may be changed.

Selection of type of three-phase separator

In view of the large water/oil ratio it has been decided to convert the vessel into a three-phase separator with a weir arrangement, two calming baffles and collection compartments for the separated liquid phases as shown in the top part of Figure 4.5.

The required sealing function calls for a bottom feed inlet.

Further input

LZA(HH) = 1.1 m (in view of the small gas load, the height of the gas cap has been taken at its minimum value of 0.3 m)

IL = 0.6 m

h_{up} = 0.2 m

w_{ww} = 0.2 m

Calculations

Step1

The selected LZA(HH) is correct since :

$LZA(HH)/D_{ves} = 0.786 < 0.8$

$D_{ves} - LZA(HH) = 0.3$ m

$$A_G = 0.2419 \; > \; Q_G / \lambda_{max} \sqrt{\rho_G / (\rho_l \; - \; \rho_G)} = 0.0324 \qquad [m^2]$$

There is no inlet device in the gas cap so there are no additional constraints.

Step 2

Non-foaming system, therefore select NL = LZA(HH) - 0.10 = 1.00 m

Step 3

$h_{crest,l}$ = 9.8 mm
$h_{ow,l}$ = NL - $h_{crest,l}$ = 0.990 m

$h_{crest,h}$ = 28.2 mm
$h_{ow,h}$ = IL + (NL-IL)ρ_l/ρ_h - $h_{crest,h}$ = 0.875 m

NOTE The selected value for IL is very close to the preferred location of IL (($h_{ow,l}$ + h_{up})/2 = 0.595 m).

Further checks of IL:

(IL - 0.5 H_{db})/D_{ves} = 0.357 > 0.2 OK
($h_{ow,l}$ - (IL + 0.5H_{db}) = 0.290 > 0.2 m OK
IL - 0.5H_{db} - h_{up} = 0.300 > 0.2 m OK

Step 4

$v_{l,ax}$ = 2.7 mm/s < 15 mm/s OK
$v_{h,ax}$ = 11.7 mm/s < 15 mm/s OK
v_{up} = 85.3 mm/s is relatively high

If required, by increasing h_{up} up to 0.3 m (max. value, see step 3), then v_{up} can be brought down to 0.048 m/s

Step 5

Feed nozzle N1 sizing: velocity ≤ 1 m/s. Select a diameter of 0.45 m.

The first baffle would be located at 0.35 m (0.25 D) minimum, however 0.825 is taken to accommodate the feed nozzle with 150 mm clearance at the side of the tangent line and 0.5 x the inlet nozzle diameter at the side of the baffle. The location of the second baffle will be 0.2 x the vessel diameter = 0.28 m from the first baffle. This brings L_{in} to 1.105 m

It has been assumed that in both collection compartments LA(L) is at 0.2 m and LA(H) is 0.2 m below the rim of the corresponding overflow weir.

w_ww = 0.20 m
$L_{coleff,l}$ = 0.27 m
$L_{coleff,h}$ = 3.20 m
L_{col} = 1.84 m

The real lengths of the oil and water collection compartments are 0.27 and 1.64 m, respectively.

Step 6

L_{set} = L_{ves} - L_{in} - L_{col} = 1.055 m
$v_{dh,set}$ = 0.74 mm/s
d_h = 59 µm
$v_{l,ax}$ = 2.7 mm/s < 15 mm/s OK

Amended per Circular 17/08

$v_{dl,set}$ = 4.05 mm/s
d_l = 178 µm, slightly exceeds 150 µm (criterion for bulk separation)
$v_{h,ax}$ = 11.7 mm/s < 15 mm/s OK

Step 7

Check on de-gassing:

According to the criterion, the product $D_{ves} * (L_{in} + L_{set})$ shall be at least 0.206 m^2.

Since $D_{ves} * (L_{in} + L_{set})$ = 1.4 * 2.160 = 3.024 m^2 , proper de-gassing will take place.

Step 8:

Since there is no foaming tendency, check on de-foaming is not required.

Nozzle sizing (including design margin!)

- Feed nozzle N1: see step 5: 0.45 m.
- Gas outlet nozzle N2: $\rho_G v_G^2 \leq 4500$ Pa. Select a diameter of 0.05 m
- Oil outlet nozzle N3: velocity ≤ 1 m/s. Select a diameter of 0.05 m.
- Water outlet nozzle N4: velocity ≤ 1 m/s. Select a diameter of 0.1 m.

It can be concluded from the above calculations that the separator will perform well as far as the G/L separation and dewatering of the oil is concerned, but will be borderline as far as the de-oiling of the water is concerned.

Therefore it will be investigated to what extent the de-oiling performance of the settler can be upgraded by installing a plate pack in the settling compartment.

Upgrading of the separation performance by installing a plate pack

The layout of the separator fitted with a plate pack is shown in Figure 4.6. Only one calming baffle, with 20 % NFA, will be placed at 0.825 m from the tangent line.

Because of the clean service flat plates will be selected with an angle of 45° (thickness of 1 mm).

The start value for the plate spacing is 20 mm.

The maximum space available for the plate pack is 1.335 - 0.65 = 0.685 m

A length of 0.65 m has been selected.

Further input:

- F_{pp} is 0.8
- F_{loss} is 0.9
- correction of effective plate pack length for turbulence in entrance: subtract 8 times the plate spacing

In the following table the calculations are presented following the calculation scheme as outlined in Appendix V.2.2.

selection of plate spacing		d_{pp} is 20 mm start value
step 9a	$(A_{f,gross})_l$, m^2 $(A_{f,gross})_h$, m^2	0.325 0.395
step 9b	$(A_{f,net})_l$, m^2 $(A_{f,net})_h$, m^2	0.279 0.338
step 9c	$(d_{pp,max})_l$, mm $(d_{pp,max})_h$, mm check of d_{pp}	71 23 **OK** no turbulence proceed with step 9d
step 9d	θ, degrees (input)	45
step 9e	L_{pp}, m (input)	0.65
step 9f	$v_{l,pp}$, mm/s $v_{dh,set}$, mm/s d_h, µm $v_{h,pp}$, mm/s $v_{dl,set}$, mm/s d_l, µm	4.0 0.23 30 17.0 0.98 82

It can be concluded that installation of a plate pack will give a substantial improvement of de-oiling performance in particular.

The cut-off diameter of the oil droplets will be reduced from 205 to 82 µm.

V.3. SIZING OF A VERTICAL THREE-PHASE SETTLER WITH PLATE PACK

V.3.1 Calculation example

A three-phase separator has to be designed for the following flow conditions:

Gas: mass flow rate is 1600 t/d with a density of 2.6 kg/m^3
Oil: mass flow rate is 2100 t/d with a density of 750 kg/m^3 and a dynamic viscosity of 0.5 mPa.s
Water: mass flow rate is 200 t/d with a density of 990 kg/m^3 and a dynamic viscosity of 0.9 mPa.s

- Design margin is 1.1
- Both the G/L and L/L (in particular de-watering) separation has to be efficient (cut-off diameter of water droplets 50 μm)
- Clean service
- There is no foaming tendency
- Gas carry-under shall be avoided
- There is no dispersion band expected in the L/L interface
- There are no slugs to be expected
- Min. control time for G/L and L/L separation (between high and low level (or pre-alarm levels)) is 3 minutes
- Min. flow time between all pre-alarm and trip levels is 1 minute

In view of the high gas load, clean service and the requirement of efficient G/L and L/L separation the type of separator to be selected is a vertical separator fitted with a plate pack and a mist mat (see also Table 2.1).

Design

First the nozzles are sized according to Appendix VIII.

Subsequently the design of the vessel is carried out following the calculation scheme as outlined in (4.3).

Nozzles

N1: feed inlet (fitted with Schoepentoeter); nozzle diameter is 24”
$\rho_m v_m^2$ = 5228 Pa < 8000 Pa

N2: gas outlet; nozzle diameter is 20”
$\rho_G v_G^2$ = 4139 Pa < 4500 Pa

N3: oil outlet (fitted with vortex breaker); nozzle diameter is 10”
v = 0.69 m/s < 1 m/s
vortex breaker halfway between LZA(LL) and LZA(HH)$_{int}$

N4: water outlet (fitted with vortex breaker); nozzle diameter is 3”
v = 0.54 m/s < 1 m/s

Diameter

According to DEP 31.22.05.11-Gen, the maximum allowable gas load factor for a vertical wiremesh demister with the mist mat over the total cross-section of the separator, taking into account the specified flow conditions, is 0.101 m/s.

Round off to 0.10 m/s.

Therefore, to satisfy the gas handling criterion:	D ≥ 2.43 m
To satisfy the de-gassing criterion:	D ≥ 1.22 m
The gas handling determines D:	D = 2.45 m

Layout of the plate pack

Select a plate pack with the following characteristics:

- plate spacing is 20 mm
- plate angle is 45°
- plate thickness is 1 mm
  (small plate angle and plate spacing permitted because of clean service; for further background see Appendix II)

It has been assumed that:

- F_{loss}= 0.9
- critical plate pack Reynolds number is 850

The following values are calculated according to Appendix II, assuming that the Reynolds number is at its critical (maximum) value:

$(A_{f,net})_l$ = 2.571 m^2
$(A_{f,gross})_l$ = 3.00 m^2
$(A_{f,net})_h$ = 0.514 m^2
$(A_{f,gross})_h$ = 0.600 m^2

L_{pp} is determined by the dewatering requirement (d_h = 50 µm) → L_{pp} = 0.77 m
(A correction term of 8*d_{pp} has been included to compensate for the turbulence in the entry region).

Due to the small waterflow this plate pack length results also in an efficient de-oiling of the water: d_l = 40 µm.
From L_{pp} and D it follows that W_{pp} < 2.05 m
Take as initial value W_{pp} = 2.00 m

$H_l = (A_{f,gross})_l/W_{pp}$ = 1.5 m; H_l/W_{pp} = 0.50
$H_h = (A_{f,gross})_h/W_{pp}$ = 0.3 m (minimum); H_h/W_{pp} = 0.16

Both heights are larger than 0.3 m.

Therefore the initial choice of W_{pp} can be maintained.

Calculate T/T length of separator

$H_{contot} = Q_{h} * \Sigma t_{con} /(0.25\pi D^2) = 0.17$ m. Because this is smaller than the minimum span, it will default to 0.45 m (no high level trip).

$H_{pp} = H_l + H_h + H_{contot} = 2.25$ m

Following paragraph F in (4.3):

X_1 = 2.28 m (height required for G/L level control = 1 * 1.368 + 2 * 0.456)
X_2 = 0.15 m
X_3 = 0.62 m
X_4 = 0.60 m
X_5 = 0.10 m
X_6 = 0.37 m

$H = H_{pp} + X_1 + X_2 + X_3 + X_4 + X_5 + X_6 = 6.40$ m

Check location of nozzle N3

Distance between HIL and LZA(LL) is 1600 mm. Nozzle N3 is 200 mm, so the nozzle can be accommodated without further modifications.

V. 4. SIZING OF A HORIZONTAL THREE-PHASE PRODUCTION SEPARATOR

V.4.1 Calculation example

The design of production separators is usually complicated by the fact that the flowrate of gas, oil and water changes over time. In principle the separator sizing is to be based on the maximum gross liquids flowrate, However, oil is usually produced in the form of water in crude dispersions, and there is a maximum to the water concentration that can be dispersed. This is assumed to be 50 %. The rest of the water will already drop out in the flowlines upstream and will enter the separator as free water. The latter affects the sizing of the water handling compartment and the outlet water nozzle, but it does not add to the required separation volume.

The 'maximum gross liquid rate' scenario for the separator duty considered in this case study is as follows:

	Flowrate ton/d	**Density** kg/m^3	**Viscosity** mPa.s	**Flowrate** m^3/s [1)]
Gas	1020	9.6	–	1.60
Oil	7490	798	1.5	0.141
Water	1960	985	0.8	0.030

[1)] Including 30 % design margin

The maximum water cut considered is 18 %, so it can be assumed that all water will be dispersed.

Interpolating the table in Appendix I it can be established that the coefficients a and b corresponding to the prevailing viscosity (1.8 cS) are a =0.085 and b =0.048. The dispersion band expansion equation in Appendix I can then be used to establish the maximum allowable flux as a function of the selected dispersion band height, and the vessel size required to acommodate this:

H_{DB}	D_{vessel}, m	Q/A_{max}, mm/s	A_{nett}, m^2	A_{gross}, m^2	L_{vessel}, m
0.5	3.4	4.6	37.2	46.5	13.6
0.55	3.7	4.9	34.6	43.3	11.7
0.6	4.0	5.3	32.3	40.4	10.1

The allowable flux in its turn gives the area required. The area is to be increased by 25 % to 30 % to include the space required for the inlet and outlet compartment, and to allow for flow maldistribution. With some iteration it can be established that a vessel size of 3.6 m ID and 12 m TT length will be adequate.

The rest of the sizing in terms of nozzle sizes, control volumes and levels proceeds along the same lines as for other horizontal separators as explained in paragraph 4.1.4. The resulting design is shown in Fig. V.1.

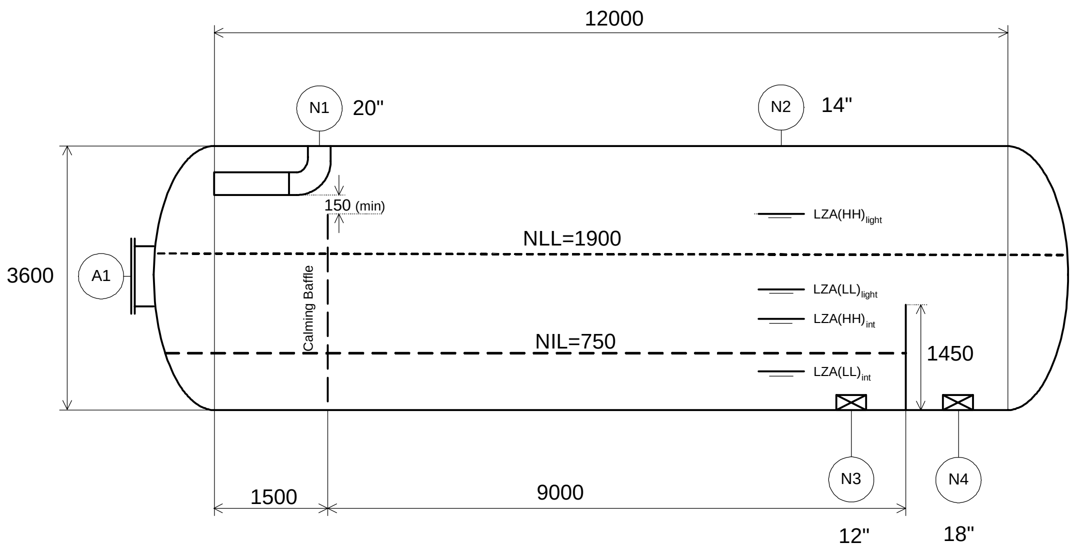
The gas load factor based on an LZA(HH) of 2450 mm is λ=0.061, so the gas cap is sufficiently large for gas handling.

It can be seen that there is sufficient space in between the Normal Interface Level and the level corresponding to the top of the weir to accommodate a dispersion band layer with a height of 0.50-0.55 m. It should be noted that this is the part of the separator where all the oil water separation takes place. This volume is not directly related to the overall liquids

residence time, which is often used as basis for separator sizing.

This also means that the correct positioning of the Interface Level is essential for good separation. In later field life when the oil production has declined and water cut is high the interface can be raised to improve the removal of oil from water. In this case the water outlet nozzle was made larger than required on the basis of the max gross liquids rates specified above. It has been designed on the basis of the maximum water flow expected, which does not coincide with the maximum gross liquids production.

Figure IV.1 Design of a production separator



APPENDIX VI VESSEL GEOMETRICAL RELATIONSHIPS

CROSS-SECTION: CHORD AREA AND CHORD HEIGHT

In the calculation procedures presented in Appendices IV and V for the sizing of horizontal two-phase and three-phase separators respectively, frequently the boundaries have to be determined of the horizontal zones occupied by the various phases, using as input the respective cross-sectional areas.

The reverse calculation (calculation of the respective cross-sectional areas from the respective lower and upper boundaries) is often required as well.

In this Appendix the relationships will be given which enables this type of calculations, both graphically and via equations.

Figure VI.1 shows schematically a cross-section of a horizontal three-phase separator with diameter D.

The position of the three phases, heavy and light liquid phase and gas phase respectively, have been indicated and have as cross-sectional area A_h, A_l and A_G respectively.

The heights of the boundary are h_0 (=0), h_1, h_2 and h_3 (=D) respectively.

For a more general representation the areas and heights are made dimensionless by dividing them by the vessel cross-sectional area and the vessel diameter respectively.

$A^*_h = A_h /(\pi D^2/4)$ $A^*_l = A_l /(\pi D^2/4)$ $A^*_G = A_G /(\pi D^2/4)$

$(A^*_G + A^*_l + A^*_h = 1)$

$h^*_0 = 0$ $h^*_1 = h_1/D$ $h^*_2 = h_2/D$ $h^*_3 =1$

A^*_h and A^*_G are now dimensionless chord areas with dimensionless chord heights, h^*_1 and $(1-h^*_2)$ respectively.

In Figure VI.2 the general relationship between a dimensionless chord area, A^* and its associated dimensionless chord height, h^*, is presented.

This graph gives directly the relationship between A^*_h and h^*_1 and between A^*_G and $(1-h^*_2)$. From this, taking into account the vessel diameter D, the relationship between the cross-sectional areas of the various phases and their boundaries in the vessel is obtained.

Relationships

Both h* and A* can be expressed in terms of φ (see also insert in Figure VI.2)

$A^* = 0.5*(\varphi - \sin\varphi)/\pi$ [–]

$h^* = 0.5*\{1 - \cos(\varphi/2)\}$ [–]

- **h* → A***

  Since h^* can also be expressed in terms of φ, A^* can be directly calculated from h^* via: $\varphi = 2*\arccos(1- 2*h/D)$ and subsequently $A^* = 0.5*(\varphi - \sin\varphi)/\pi$.

- **A* → h***

  Calculation of h* from A* requires iteration:

  The iteration formula is :

  $$\varphi_{i+1} = \varphi_i - (2*\pi*A^* - \varphi_i + \sin\varphi_i)/(\cos\varphi_i - 1)$$

  The start value for φ is not critical. Even the simple start $\varphi_0 = \pi$ always gives convergence. After convergence, h* follows then from:

  $$h^* = 0.5*\{1 - \cos(\varphi/2)\} \qquad [-]$$

Volume of vessel heads

The interface level control band of horizontal L/L separators will include a part of the vessel heads.

This may also be included in the G/L control band in the liquid collection compartments of three-phase separators.

The relationship for this volume, ΔV_{hd}, as a function of the vessel diameter D and its lower and upper boundaries, h_1 and h_2 respectively, is given below.

$$\Delta V_{hd} = \alpha\pi D^3\{0.75*(h^*_2 - h^*_1) - (h^*_2 - 0.5)^3 + (h^*_1 - 0.5)^3\}/6$$

h^*_1 and h^*_2 are the dimensionless lower and upper boundaries respectively and are defined as:

$$h^*_1 = h_1/D \qquad [-]$$
$$h^*_2 = h_2/D \qquad [-]$$

α is the ratio of the short to the long axis of the vessel head.

The most common semi-elliptical head has an α of 0.5.

In rare cases (at very high operating pressure, for instance) a semi-spherical head is specified: α =1.

Figure VI.1 Simplified cross-section of a horizontal three-phase separator with the position and cross-sectional areas of the three phases indicated

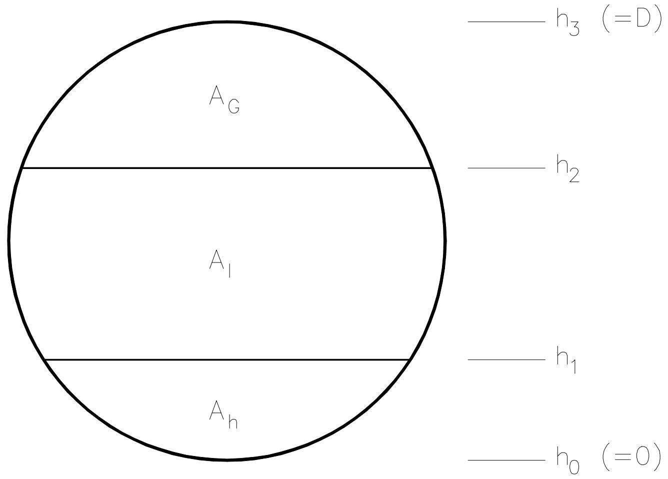
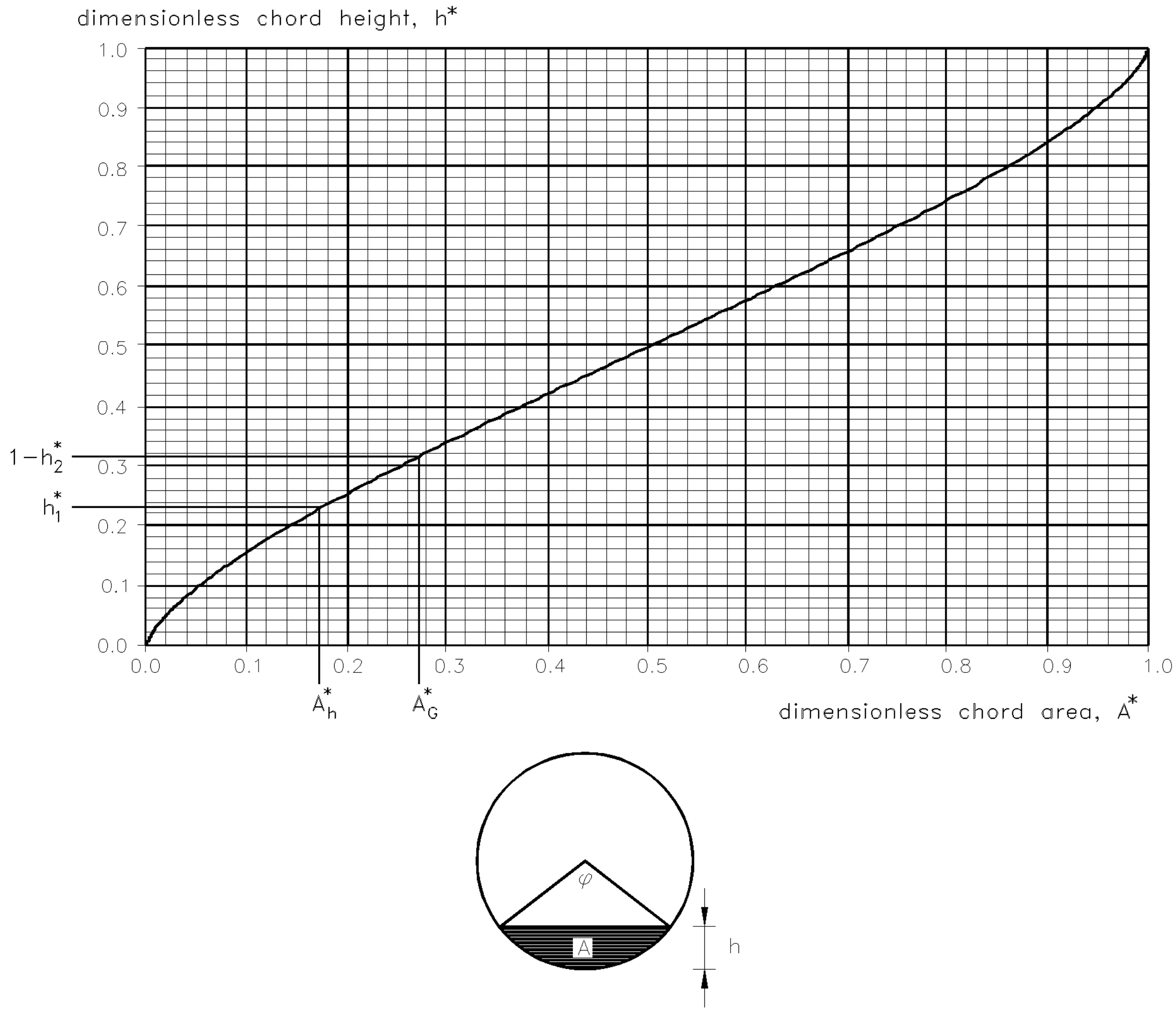


Figure VI.2 Relationship between the dimensionless chord area, A* and dimensionless chord length, H*, of a vessel cross-section



$A^* = A/A_{ves} = 0.5*(\varphi - \sin\varphi)/\pi$

$h^* = h/D = 0.5*\{1-\cos(\varphi/2)\}$

φ = 2 acos (1-2h/D)

APPENDIX VII NATURE OF THE FEED IN THREE-PHASE SEPARATORS

FLOW REGIME IN THE FEED PIPE

As in the case of a G/L separator, the feed entering a three-phase separator can be in the form of mist, stratified flow, slug flow, etc. depending on the flow rates and physical properties of the gas and liquid phases and on the feed pipe characteristics (diameter, length, vertical/horizontal).

If the liquid phases are assumed to be homogeneously mixed, they can be considered to be a single liquid phase and use can be made of available two-phase flow maps to characterise the G/L flow regime in the feed pipe.

Two flow maps are presented in Figure VII.1 and Figure VII.2. The first flow map gives the two-phase flow regimes in a horizontal pipe and the second one those in a vertical pipe (upflow).

Strictly, the flow maps are only applicable to very long pipes with equilibrium two-phase flow. However, if the feed pipe is longer than ten pipe diameters, the flow maps still give a fair indication of the prevailing flow regime for a given set of conditions.

The transition from one flow regime to another is relatively gradual, and the boundaries shown separating the different regimes should not be interpreted as sharp changes in flow pattern.

The flow maps are generalised by using as parameters the gas and liquid Froude numbers, based on the feed pipe velocity and diameter.

The advantage of this general representation is that the flow maps are then unaffected by variations in flow conditions, physical properties and feed pipe geometry. This means that the flow maps can be used for a wide range of flow conditions, physical properties and feed pipe diameters.

If it is still considered necessary to generate a flow map for a particular set of conditions, the Principal should be consulted.

The gas and liquid Froude numbers are defined as follows:

gas Froude number:

$$Fr_G = v_G \sqrt{\frac{\rho_G}{(\rho_L - \rho_G)\, gD}} \qquad [-]$$

liquid Froude number:

$$Fr_L = v_L \sqrt{\frac{\rho_L}{(\rho_L - \rho_G)\, gD}} \qquad [-]$$

In the above formulae v_G and v_L are the superficial gas and liquid velocity respectively in the feed pipe and d_{fp} is the inside diameter of the feed pipe.

$$v_G = \frac{Q_G}{\pi d_{fp}^2 / 4} \qquad [kg/m^3]$$

$$v_L = \frac{Q_l + Q_h}{\pi d_{fp}^2 / 4} \qquad [kg/m^3]$$

and the average liquid density ρ_L is defined as:

$$\rho_L = (Q_l\rho_l + Q_h\rho_h)/(Q_l + Q_h) \qquad [kg/m^3]$$

Within the stratified-wavy and annular flow regime it is possible that droplet formation will take place in the feed pipe, resulting in a mist when these droplets are entrained into the separator.

As a rough indication, the approximate size of the largest droplets, $d_{p,max}$, formed in the feed pipe with diameter d_{fp} is given by:

$$d_{p,max}/d_{fp} = 4.5\{\sigma/(\rho_G v^2_G d_{fp})\}^{0.6}(\rho_G/\rho_L)^{0.4}$$

The smallest drops will generally have a diameter five to ten times smaller than $d_{p,max}$.

NOTE Much smaller droplets can be formed if the multi-phase flow has passed a sudden and significant pressure reduction (e.g. a choke with a pressure drop of more than, say, 10 bar).

FOAMING TENDENCY

For foaming to occur it is necessary that gas bubbles are formed, and that the drainage of the liquid films surrounding the bubbles is retarded. Drainage of the films is slower in highly viscous liquids, but the chief causes of foaming are surface properties which are usually unpredictable. For this reason the foaming tendency is best judged on the basis of experience in similar cases. Laboratory tests may also give an indication of the foaminess of the system.

Examples of foaming systems are some crude oils, heavy residues and absorption and extraction solvents.

Foaming in the separator may lead to carry-over of liquid (when foam reaches the gas/liquid separation internal and/or the gas outlet) or to carry-under of gas. It will also upset the level control system.

It should be noted that foaming is more likely to be a problem at high liquid loads, when flow in the inlet pipe is in a frothing or intermittent flow regime.

Installating of G/L separation internals to combat foam is not normally very effective, with the exception of cyclones.

Foaming in the vessel is minimised by decreasing the downward liquid velocity, for instance by increasing the diameter of the separator vessel.

Sometimes an antifoam agent can be injected to suppress foaming.

FEEDS WITH SOLIDS AND WAX (fouling service)

Sand, rust, scale or other solids present in the feed will leave the separator together with the liquid. However, solids will also settle out in the separator and tend to accumulate. For this reason care should be taken with the location of instrument connections which could become plugged. Provision should be made for cleaning the separator during shutdowns, and if necessary during operation, by the installation of a liquid (water) spray and drain.

If solids are present in the feed, consideration should be given to reducing the inlet velocity and adding an "erosion allowance" of 1 - 2 mm extra material thickness to the inlet device (if fitted).

Wax in the feed will be deposited on any surfaces where the velocities and temperatures are low. Also, narrow openings will tend to become plugged.

Empty settlers should be used in fouling service. However, if L/L and/or G/L separation internals have to be used in order to fulfil high efficiency requirements, the selected internal should be insensitive to fouling (e.g. by using a vane pack instead of a mist mat for G/L separation or a plate pack with large plate angle or large plate spacing for L/L separation). If this is not possible, the internal shall be adequately protected by a pre-filter.

Figure VII.1 Two-phase flow map for horizontal feed pipes

Conditions:

$\rho_G = 8 \text{ kg/m}^3$ $\rho_L = 860 \text{ kg/m}^3$ $\sigma = 0.03$ N/m

$\eta_G = 1.2*10^{-5}$ Pa.s $\eta_L = 1.6*10^{-4}$ Pa.s $d_{fp} = 0.50$ m

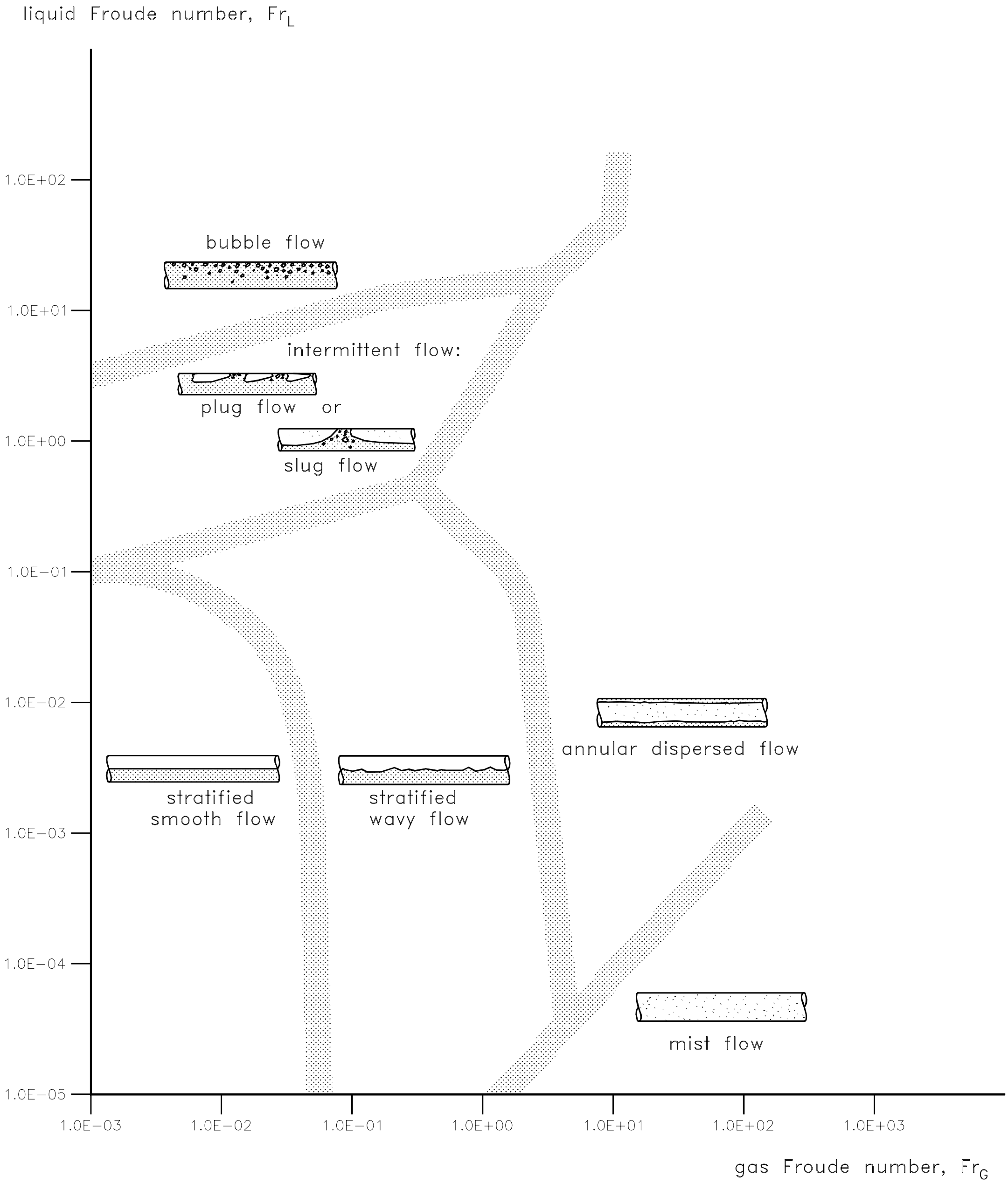
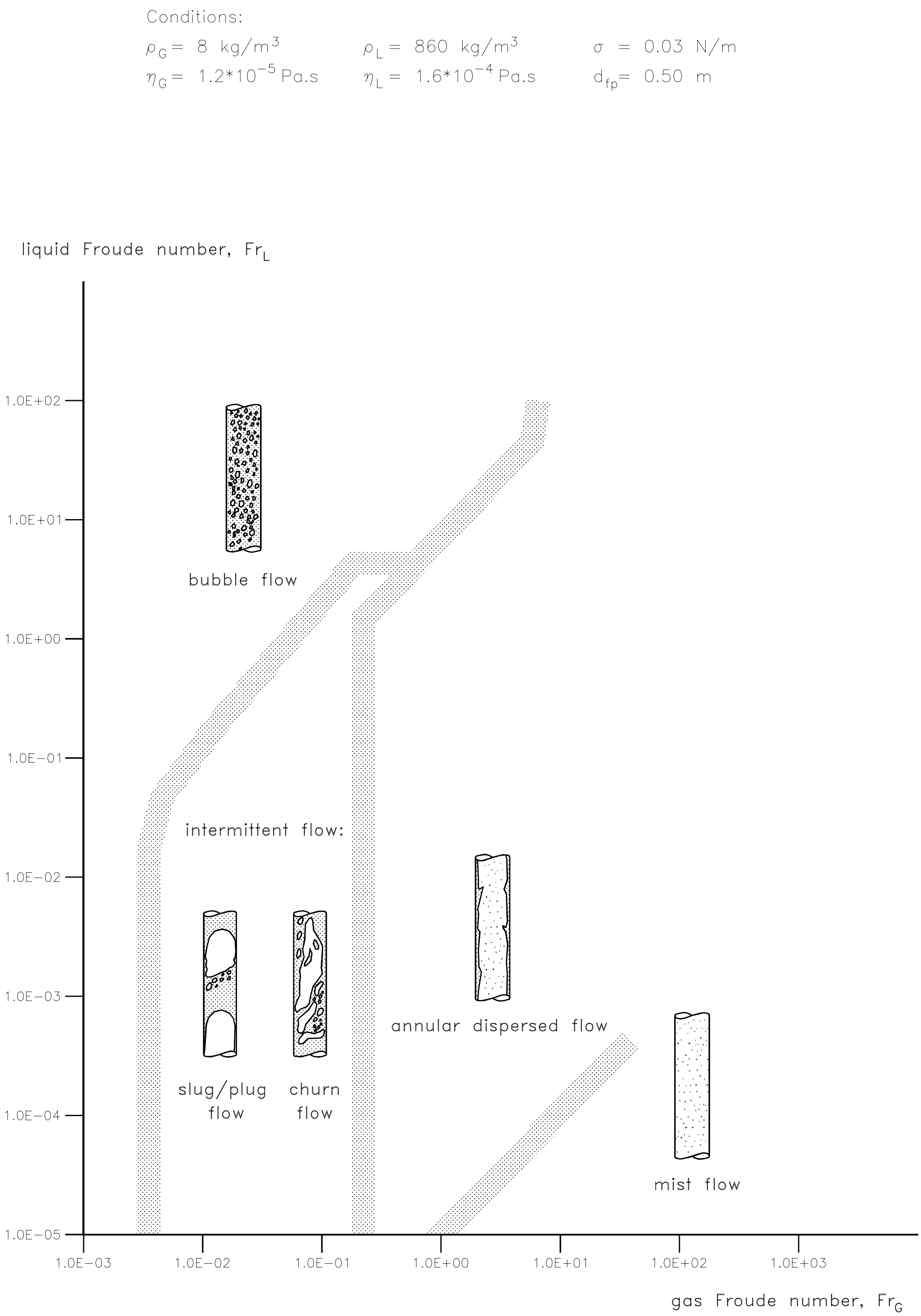


Figure VII.2 Two-phase flow map for vertical feed pipes (upflow)



APPENDIX VIII SIZING OF THE FEED AND OUTLET NOZZLES

The sizing of the nozzles shall normally be based on the **MAXIMUM** flow rates (i.e. **INCLUDING** the appropriate design margin (see Appendix IX)).

(If for some reason extra high design margins are required, the Principal should be consulted).

FEED INLET NOZZLE

- **In L/L separators:**

  The inner diameter of the feed inlet nozzle should be equal to the inner diameter of the inner piping but shall also be sufficiently large so that the total liquid velocity does not exceed 1 m/s.

  To promote even distribution of the feed flow into the separator, the feed nozzle should be equipped with a feed inlet device, such as an elbowed pipe or a slotted pipe (see also Figure 3.1 in (3.1) of the main text).

- **In G/L/L separators:**

  The inner diameter of the feed inlet nozzle should be equal to the inner diameter of the inner piping but shall also be sufficiently large to satisfy the relevant momentum criterion:

  – If **no** inlet device is used:

    $\rho_m v^2_{m,in} \leq 1400$ Pa

    where ρ_m is the mean density of the mixture in the feed pipe

    $\rho_m = (Q_l\rho_l + Q_h\rho_h + Q_G\rho_G)/(Q_l + Q_h + Q_G)$ [kg/m^3]

    and $v_{m,in}$ is the velocity of the mixture in the inlet nozzle

    $v_{m,in} = (Q_l + Q_h + Q_G)/(\pi\, d_1^2 / 4)$ [m/s]

  – If a **half-open pipe** is used as inlet device:

    $\rho_m v^2_{m,in} \leq 2100$ Pa

  – If a **Schoepentoeter** is used as inlet device:

    $\rho_m v^2_{m,in} \leq 8000$ Pa

GAS OUTLET NOZZLE

The diameter of the gas outlet nozzle should normally be taken as equal to that of the outlet pipe, but also the following criterion shall be satisfied:

$\rho_G v^2_{G,out} \leq 4500$ Pa

LIQUID OUTLET NOZZLE

The diameter of the liquid outlet nozzles shall be chosen so that the liquid velocity does not exceed 1 m/s. The minimum diameter is 50 mm (or 2 inch).

The nozzle shall be equipped with a vortex breaker in accordance with Standard Drawing S 10.010.

The vortex breaker shall be at least half a nozzle diameter away from the corresponding control level.

APPENDIX IX DESIGN MARGINS FOR SEPARATOR DESIGN

To determine the highest envisaged gas and liquid loads for vessel design, design margins (surge factors) are required:

The design margins should be supplied by the Principal.

Typical values are:

IN SIEP APPLICATIONS:

1.	**Offshore service**	**Design margin**
	Separator handling natural-flowing production from:	
	a. its own platform	1.2
	b. another platform or well jacket in shallow water	1.3
	c. another platform or well in deep water	1.4
	Separator handling gas lifted production from:	
	a. its own platform	1.4
	b. another platform or well jacket	1.5
2.	**Onshore service**	
	Separator handling natural-flowing production, or gas plant inlet separator in:	
	a. flat or low rolling country	1.2
	b. hilly country	1.3
	Separator handling gas lifted production in:	
	a. flat or low rolling country	1.4
	b. hilly country	1.5

IN APPLICATIONS OF SHELL GLOBAL SOLUTIONS AND SIC:

The design margin ranges typically from 1.15 to 1.25.

APPENDIX X LEVEL CONTROL

In Figure X.1 the control levels are indicated both for a G/L/L settler (right part of the figure) and for an L/L settler (left part of the figure).

Going from top to bottom the criteria for the various control levels are as follows:

G/L INTERFACE

For the control of the G/L interface the hold-up times of BOTH the light and heavy liquid phases shall be taken into account.

- **LZA(HH)** (high level trip of the G/L interface) is located at least 150 mm below the feed inlet device (and at least 0.05 vessel diameter in the case of a vertical three-phase separator fitted with a Schoepentoeter as feed inlet device).
  The gas compartment of the vessel above LZA(HH) shall be sufficiently large to allow proper G/L separation. The sizing of this gas compartment is dependent on the type of G/L/L separator and is addressed in the corresponding section of this DEP.
- **LA(H)** (high level pre-alarm of the G/L interface) is either at least 100 mm below LZA(HH) or, if required, located so that there is sufficient liquid hold-up time between the two levels for operator intervention (typically 60 seconds for action in the control room and 5 minutes for action outside the control room).
  If the liquid has a foaming tendency, the distance between LA(H) and LZA(HH) has to be increased by a further 250 mm.
- **LA(L)** (low level pre-alarm of the G/L interface) is either at least 350 mm below LA(H) or located so that there is sufficient liquid volume between the two levels for control purposes.

In Shell Global Solutions, the following general principles for hold-up times for control are applied:

- 1 minute on "short" circulation flows (i.e. back to inlet of vessel) PLUS
- 2 minutes on longer circulation flows (other upstream vessels within unit) PLUS
- 2 minutes on product to storage OR 3 minutes on product to other equipment/vessels OR 4 minutes on product to a furnace.

The hold-up times for control shall be specified separately for the light and heavy liquid phases.

If slugs are expected, they should be accommodated between NL and LA(H).

If the volume of the slug to be expected is not known, it is suggested that 2-5 seconds of flow with the maximum feed (gas + liquid) velocity and 100 % liquid filling of the pipe be taken as that volume.

In general the slug size is influenced by the layout of the upstream piping. In case of doubt the Principal should be consulted for an estimate of the slug size.

In practice the total volume to be provided between LA(L) and LA(H) is the sum of the required control volume and volume of the anticipated slug.

- **LZA(LL)** (low level trip of G/L interface)) is either at least 100 mm below LA(L) or, if required, located so that there is sufficient liquid hold-up time between the two levels for operator intervention (to be specified, but typically 60 seconds for action in the control room and 5 minutes for action outside the control room).
  This minimum distance is dependent of the type of G/L/L separator and is addressed in the corresponding section of this DEP.

L/L INTERFACE

The L/L interface should be positioned so that above and below this interface adequate L/L separation can take place.

For the control of the L/L interface the hold-up time of the heavy liquid phase ALONE has to be taken into account.

- **$LZA(HH)_{int}$** (high level trip of L/L interface). In horizontal L/L separators the distance of this level from the top of the vessel shall be at least 0.2 vessel diameter.
  In the boot of a horizontal open three-phase settler, it is typically located 200 mm below the bottom of the vessel.

- **$LA(H)_{int}$** (high level pre-alarm of L/L interface) is located either at least 100 mm below $LZA(HH)_{int}$ or, if required, so that there is sufficient liquid hold-up time between the two levels for operator intervention (typically 60 seconds for action in the control room and 5 minutes for action outside the control room).

  Quoted times are based on the flow rate of the heavy phase alone.
  If a dispersion band width is specified, the distance between $LZA(HH)_{int}$ and $LA(H)_{int}$ has to be extended by half the band width.
  If a dispersion band is expected but its width cannot be estimated by means of the formulae given in Appendix I, 0.2 m should be taken as dispersion band width.

- **$LA(L)_{int}$** (low level pre-alarm of L/L interface) is either at least 350 mm below $LA(H)_{int}$ or located so that there is sufficient liquid volume between these two levels for control purposes

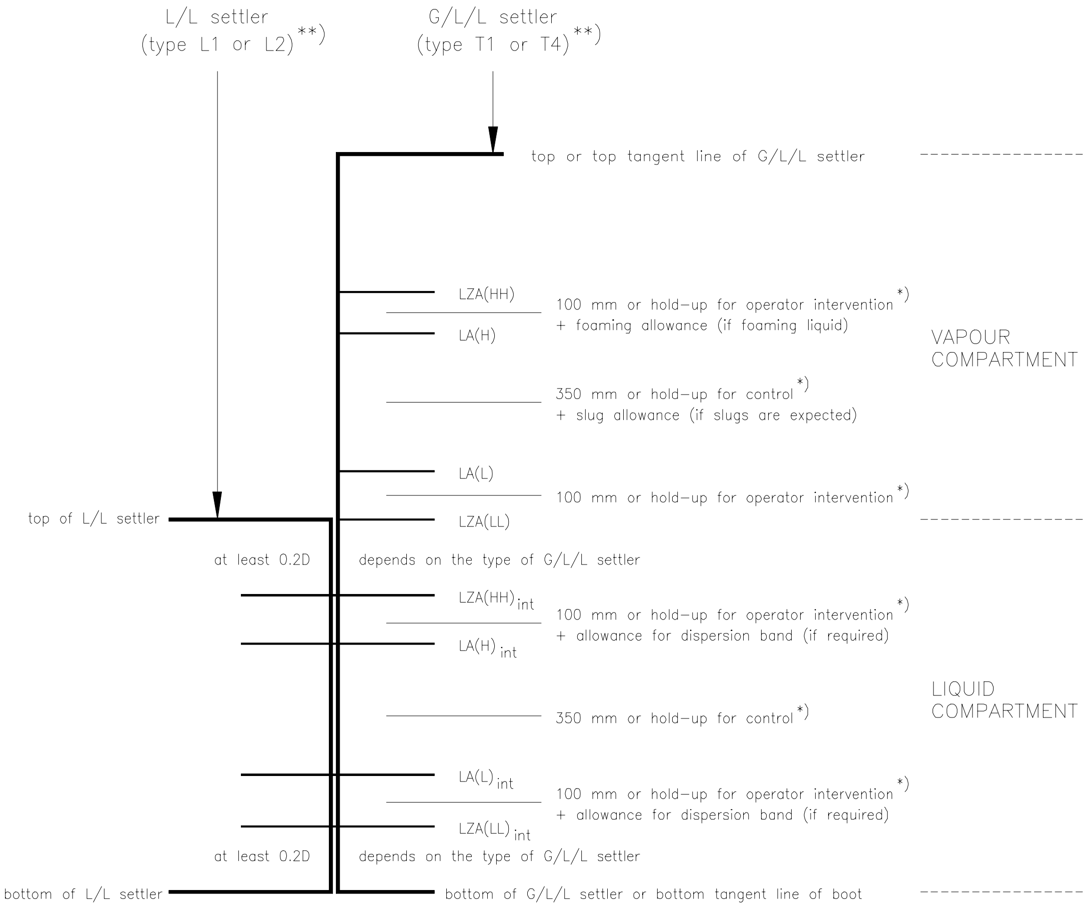
  In refinery applications the following general principles for hold-up times for control are applied:

  - 1 minute on "short" circulation flows (i.e. back to inlet of vessel) PLUS
  - 2 minutes on longer circulation flows (other upstream vessels within unit) PLUS
  - 2 minutes on product to storage OR 3 minutes on product to other equipment/vessels OR 4 minutes on product to a furnace.

- **$LZA(LL)_{int}$** (low level trip of L/L interface) is either at least 100 mm below $LA(L)_{int}$ or, if required, located so that there is sufficient liquid hold-up time between the two levels for operator intervention (to be specified, but typically 60 seconds for action in the control room and 5 minutes for action outside the control room). If a dispersion band width is specified, the distance between $LA(L)_{int}$ and $LZA(LL)_{int}$ has to be extended by half the band width.
  In horizontal L/L separators the distance of this level from the bottom of the vessel shall be at least 0.2 vessel diameter.
  In the boot of a horizontal open three-phase settler it is typically located 200 mm above the bottom tangent of the boot.

NOTE In practice not all the described control levels will always be installed.
For instance, under certain, non-critical circumstances it may be permissible not to install one or more level trips. If operator action to prevent a trip is not realistically possible, the pre-alarms should be eliminated.

Figure X.1 Control levels of G/L and L/L interfaces



*) whichever leads to the largest distance
**) see Table 2.1 in (2.)