Gas/Liquids Separators—Part 3
Quantifying Separation Performance

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In this third article of a three-part series, the results of selected gas/liquid separation case studies/sensitivities are presented to show the effects of key separator selection/sizing decision parameters, fluid properties, and operational parameters. The results are generated from an Excel spreadsheet model, which incorporates the equations/methods outlined in Part 1 and 2 of this series published in 2013 August and October *Oil and Gas Facilities* issues, respectively. The Excel Solver add-in is used to find the optimum separator size, in this case defined as the lowest-weight vessel that satisfies the specified separation performance requirements as well as any applicable constraints.

Part 1 of the series in August provided a general discussion of separation equipment classification, as well as existing limitations to methods used for quantifying separator performance. Part 2 in October discussed methods for improved quantification of operating performances of the gas gravity separation, the mist extraction, and the liquid gravity separation sections of gas/liquid separators.

Parts 1 and 2 presented the equations and methods that can be used to improve the quantification of gas/liquid separation performance compared with traditional techniques. The key aspects of the recommended methodology include quantification of the following:

1. The amount of gas (liquid) entrained in the form of droplets (bubbles)
2. The size distribution of the entrained droplets (bubbles)
3. The continuous phase (gas or liquid) velocities
4. Droplet (bubble) separation performance based on 1–3 above and the geometry of the separator

The purpose of the articles is to present a more rigorous approach to gas/liquid separator design and rating that more accurately reflects the physics involved. The traditional K_s/residence-time approach is inadequate for anything but the smallest/simplest separator applications.

The expanding use of computational fluid dynamics (CFD) for separator design purposes has been useful, but does not readily lend itself to the needs of the majority of facilities engineers faced with separator design and operational issues. CFD is expected to be an excellent tool for refining several of the calculations presented in this series of articles. The spreadsheet used to generate the results contained in this article, while complex from a calculational point of view, is quite user friendly.

The spreadsheet will be made available for public use in the near future. To be notified of its availability, please contact the author's company's website at www.jmcampbell.com/separatorOGF.

Definition of Base Case Parameters

The main assumptions and parameters used in the Excel spreadsheet to generate the results discussed in this article are as follows:

The fluid properties are assumed as 35°API crude oil; 0.7 SG gas; 100°F operating temperature, and 1,000 psig operating pressure.

Various correlations are incorporated into the spreadsheet to obtain the following fluid properties: gas compressibility factor, gas in solution, dead oil viscosity, live oil viscosity, and liquid surface tension.

Table 1 shows the constraints of horizontal and vertical separators relevant to the spreadsheet.

Vessel weight is estimated using the *American Society of Mechanical Engineers' Boiler and Pressure Vessel Code* Section VIII equations to calculate shell and head thickness based on the parameters in **Table 2.**

Vessel design pressure is set at 110% of the operating pressure. Nozzle weights, including manway(s) are estimated from a look-up table based on the nozzle size and American National Standards Institute class rating. The weight of the vessel internals is estimated based on the types and sizes of the internals, such as inlet devices (Table 3), mist extractors (Tables 4 through 6), and perforated plates.

Vertical Scrubber Base Case

The following assumptions and parameters define the vertical scrubber base case that will be used as the reference point for the case studies/sensitivities to be discussed in this article.

- Vertical orientation
- 100 MMscf/D, 10 bbl/MMscf
- 1,000 psig, 100°F
- Design factor=1.15
- Slug size = 1 second
- Half-pipe inlet device
- Standard mesh pad
- No perforated plates for flow straightening

TABLE 1—SEPARATOR CONSTRAINTS		
Constraint	**Vertical Separator**	**Horizontal Separator**
Maximum separator length, ft	80.00	
Maximum separator outside diameter, ft	20.00	
Maximum length/diameter	10.0	
Minimum length/diameter	1.5	2.5
Minimum distance between HLSD and inlet device, ft	Depends on inlet device (see **Table 3**)	ID≤6=0.5 ID>6=1.0
Minimum distance between HLSD and mist extractor, ft	N/A	ID≤6=0.75 ID>6=1.0
Minimum distance between inlet device and mist extractor, ft	Depends on inlet device (see Table 3) (minimum=1.5 ft)	N/A
Minimum distance for control volume (LLA–HLA), ft	ID≤6=1.17 ID>6=1.5	
Minimum holdup time for control volume (LLA–HLA), minutes	2	
Minimum distance between alarm and shutdown, ft	ID≤6=0.5 ID>6=0.75	
Minimum time between alarm and shutdown, minutes	0.75	
Minimum distance between BTL/BV and LLSD, ft	ID≤6=0.5 ID>6=1.0	
Maximum plug flow Souders-Brown sizing coefficient in gas gravity separation section, K_s, ft/sec	0.5	0.75
Re-entrainment, ft/sec	N/A	$V_r < V_{r,\,max}$
Maximum HLSD/D_i	N/A	Depends on mist extractor type (see **Tables 4 through 6**)

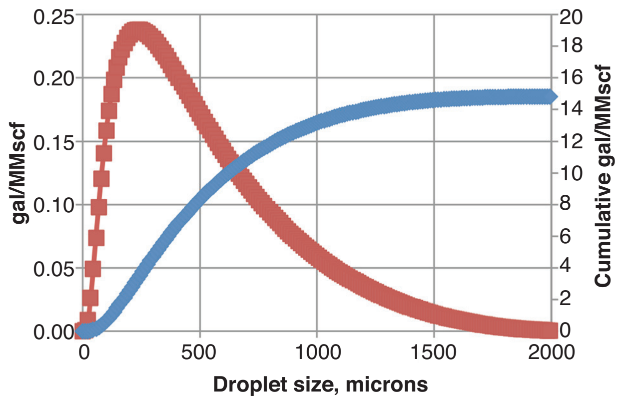

Fig. 1—Feed-pipe entrainment.

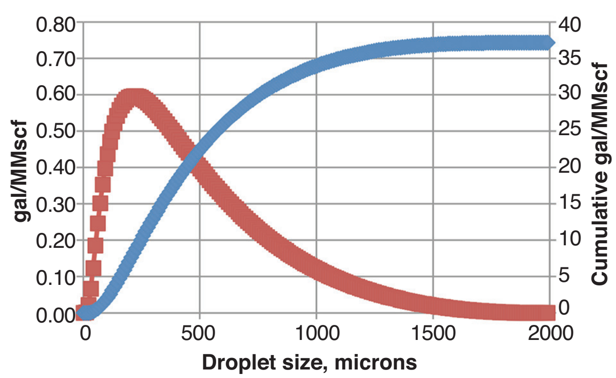

Fig. 2—Droplet size downstream of inlet device.

TABLE 2—ESTIMATES OF VESSEL WEIGHT	
Parameter	**Value**
S, allowable stress, psi	20,000
Joint efficiency, *E*	1.00
Corrosion allowance, in.	0.125
Steel density, lb/ft^3	489

The separation specifications are allowable liquid of up to 0.1 gal/MMscf in separated gas, and allowable free gas of up to 2% v/v in separated oil. The operational requirements, such as times between alarm and shutdown, are defined by the separator constraints shown in Table 1.

Base Case Results

The results are shown in **Tables 7 through 11** and **Figs. 1 through 4.** Droplet size distributions of liquid in gas at different locations are shown in Figs. 1 through 4.

The vessel diameter is dominated by gas-handling requirements and is dictated by the type of mist extractor selected, in this case a standard mesh pad. This is typical for low liquid load applications. Vessel diameter is significantly larger than would be calculated assuming uniform plug flow. The estimated degree of gas-flow maldistribution is indicated by the value

TABLE 3—TYPES OF INLET DEVICES				
Type of Inlet	**ρV^2 Limit, lb/ft-sec^2**	**Minimum Distance Between HLSD and Inlet Device (Vertical), Fraction of Vessel ID**	**Inlet Device Height, Fraction of Inlet Nozzle Nominal Diameter**	**Minimum Distance From Inlet Device to Mist Extractor (Vertical), Fraction of Vessel ID**
No inlet device	700	0.4	1.0	0.6
Diverter/splash plate	950	0.4	1.5	0.5
Half-open pipe	1,400	0.3	1.0	0.45
Multivane (Schoepentoeter/ Evenflow)	4,000	0.2	1.1	0.3
Cyclonic	10,000	0.2*	1.1	0.45
*Cyclonic inlets are partially submerged below the normal liquid level (NLL).				

TABLE 4—MESH PADS

Description	Density, lb/ft^3	Percent Voidage	Wire Diameter, in.	Surface Area, ft^2/ft^3	Thick-ness, ft	Nominal Design K_s, V/H	Maximum HLSD/D_i	Minimum Gas-Space Height, ft
High-capacity wire mesh	7	0.986	0.011	65	0.5	0.38	0.75	1.5
Standard wire mesh	9	0.982	0.011	85	0.5	0.35	0.75	1.5
High-efficiency wire mesh: 0.011	12	0.976	0.011	115	0.5	0.35	0.75	1.5
High-efficiency wire mesh: 0.006	12	0.976	0.006	200	0.5	0.25	0.75	1.5

Note: Many of the above parameters are adjustable by the user.

TABLE 5—VANE PACKS

Description	Vane Spacing, in.	Vane Angle, degrees	Number of Bends	Thickness, ft	Nominal Design K_s, V/H	Maximum HLSD/D_i	Minimum Gas-Space Height, ft
Simple vane design	0.5	45	6	0.7	0.50	0.65	2.0
High-performance vane design: single pocket	0.5	45	6	0.7	0.80	0.65	2.0
High-performance vane design: double pocket	0.5	45	6	0.7	1.00	0.65	2.0

Note: Many of the above parameters are adjustable by the user.

TABLE 6—AXIAL CYCLONES

Description	Cyclone Nominal Diameter, in.	Cyclone Spacing, Distance Between Centerlines, $\times D$	Length, in.	Inlet Swirl Angle, degrees	Nominal Design K_s (Based on Bundle Face Area)	Maximum HLSD/D_i	Minimum Gas-Space Height, ft
2-in. axial-flow cyclone	2	1.75	10	45	1.10	0.65	2.0
3-in. axial flow cyclone	3	1.75	15	45	1.30	0.65	2.0

Note: Many of the above parameters are adjustable by the user.

TABLE 7—SEPARATION PERFORMANCE			
Parameter	**Design**	**Actual**	**Comments**
Liquid carry-over in separated gas, gal/MMscf	0.10	0.00	Primary specification
Free gas in separated oil, volume%	2.0%	0.3%	Primary specification
Separable gas bubble size from oil, microns	500	72	Secondary requirement
Corrected oil-residence time (NLL), minutes	2.00	9.49	Secondary requirement
Entrainment fraction in feed pipe		3.1%	
Entrainment in feed pipe, gal/MMscf		14.8	
Inlet device separation efficiency		92.2%	
Entrained liquid exiting inlet device, gal/MMscf		37.2	
Plug flow Souders-Brown sizing coefficient in gas gravity separation section, K_s	0.50	0.18	Constraint
Adjusted effective average gas velocity variation factor in gas gravity separation section, V_{actual}/V_{plug}, F		1.52	
Souders-Brown sizing coefficient in gas gravity separation section adjusted for actual velocity, K_s		0.27	
Separable oil droplet size from gas in gas gravity separation section, microns		274	
Gas gravity separation section droplet removal efficiency		69.9%	
Liquid content of gas to primary mist extractor, gal/MMscf		11.2	
Liquid content of gas to primary mist extractor, gal/min/ft^2		0.03	
Primary mist extractor K_s (actual velocity), ft/sec	0.27	0.27	Constraint
Primary mist extractor separation efficiency		100.00%	
Liquid content of gas to secondary mist extractor, gal/MMscf		N/A	
Secondary mist extractor K_s (actual velocity), ft/sec		N/A	
Secondary mist extractor separation efficiency		N/A	

TABLE 8—CALCULATED VESSEL DIMENSIONS	
Outside diameter, ft	6.5
Inside diameter, ft	6.1
Length s/s, ft	11.5
Length/diameter	1.76
Wall thickness, in.	2.21
Dry weight, lb	28,533

TABLE 9—NOZZLES

Nozzles	Size, in.	Inlet Flow Pattern
Inlet nozzle	16	Slug
Gas outlet nozzle	12	—
Oil outlet nozzle	2	—

TABLE 10—LEVELS	
HLSD, ft	4.01
HLA, ft	3.26
NLL, ft	2.50
LLA, ft	1.75
LLSD, ft	1.00

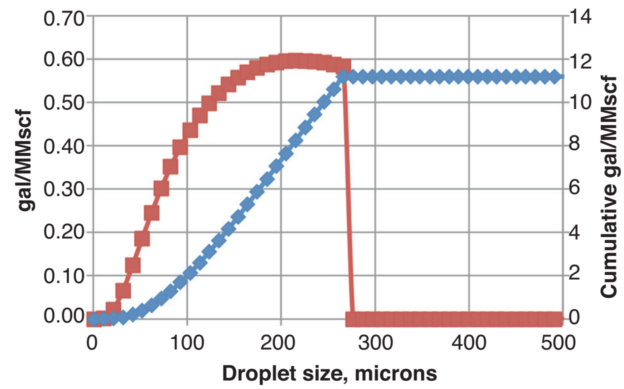

Fig. 3—Droplet size at outlet of gas gravity separation section/inlet to primary mist extractor.

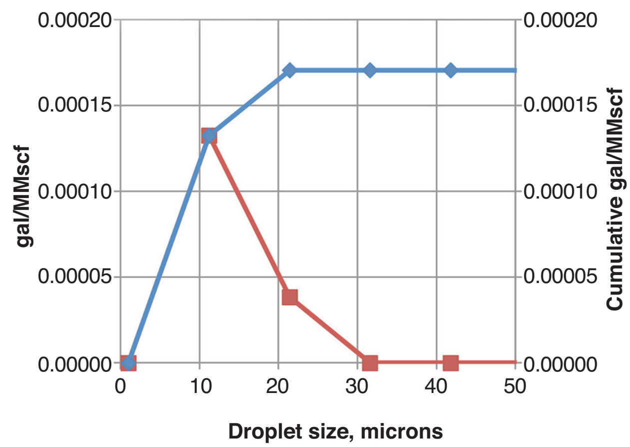

Fig. 4—Droplet size downstream of primary mist extractor.

of F=1.52 in Table 7, the ratio of the actual effective velocity/plug flow velocity (see Fig. 11 in Part 1 of the series). A lower F value, indicating a more uniform flow, could be achieved by using a higher-performance inlet device or a perforated plate, which would reduce the vessel diameter.

As far as liquid handling is concerned, the separator easily achieves the specification of 2.0% free gas in oil, and the liquid levels (alarm and shutdown points) are dictated by the minimum distance constraints. Even the assumed 1-second slug size is accommodated in the control volume (LLA→HLA) using the minimum spacing, although just barely.

The half-pipe inlet has a relatively low ρV^2 limit, which results in lower feed-pipe velocities, low entrainment (3.1% of feed liquid, 14.8 gal/MMscf), and relatively large liquid droplet sizes.

The Effect of Inlet Liquid Content

Figs. 5 and 6 show the effects of the inlet liquid content while other parameters remain the same as in the base case.

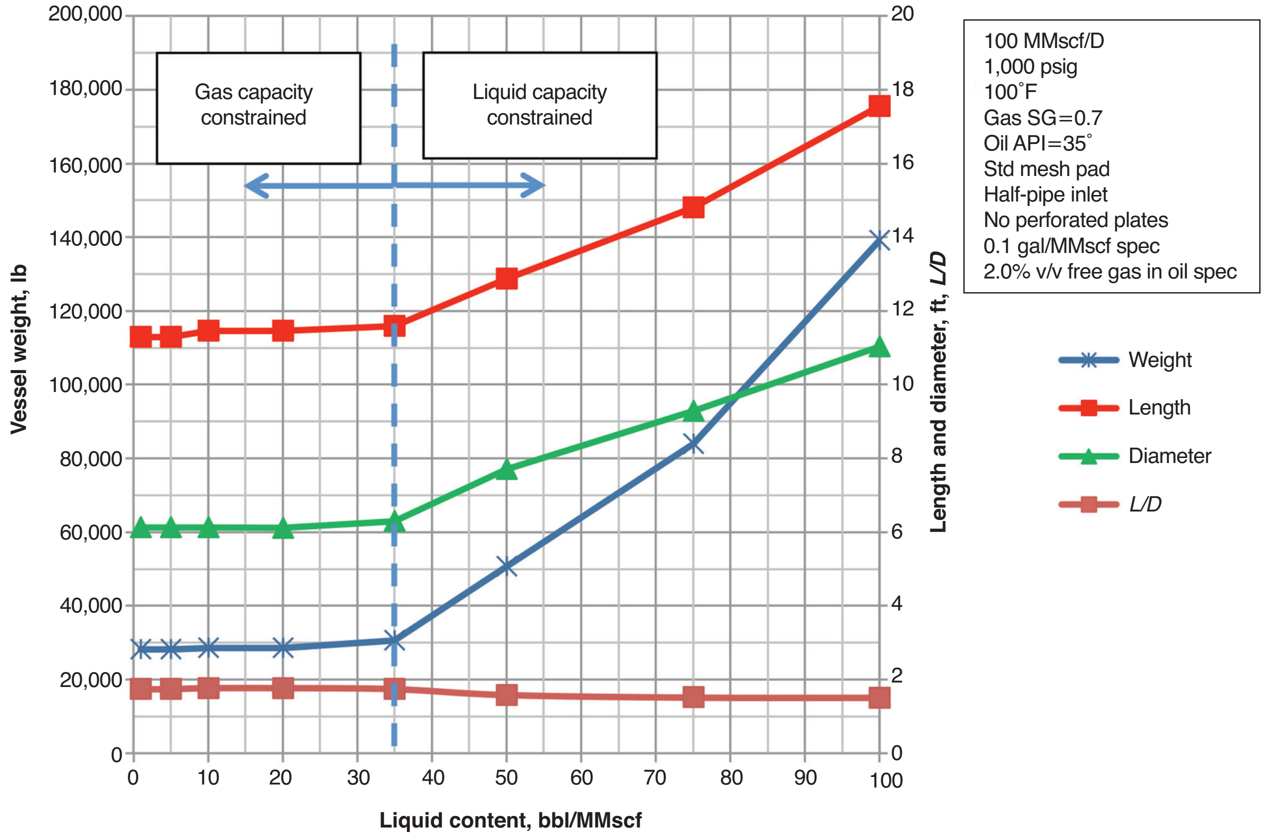

Fig. 5—Vertical separator size and weight vs. the inlet liquid content.

Up to approximately 25 bbl/MMscf inlet liquid, the separator size remains constant. The diameter is dictated by gas-handling capacity via the mist extractor K_s value (K_s=0.27/ft/sec). As for the base case, the mist extractor area and vessel diameter are larger than would be required, based on the assumption of uniform plug flow.

At more than approximately 25 bbl/MMscf inlet liquid, the separator diameter begins to increase. This is necessary to limit the downward oil velocity to satisfy the specification of 2.0% v/v free gas in oil (Fig. 6).

Note that with respect to degassing performance, residence time is a fairly meaningless criterion for a vertical separator. It is the effective liquid velocity that matters. As the separator diameter increases to handle more liquid, the gas-handling capacity of the separator becomes increasingly underutilized, indicated by the declining value of K_s in Fig. 6. Even with the increasing liquid content over the range shown, the liquid levels are still set by the minimum distance constraints for the liquid level alarm and shutdown points.

TABLE 11—VOLUME, TIME, AND DISTANCE BETWEEN LEVELS

Levels	Volume, ft^3	Distance, ft	Time, sec	Time, min
HLA—HLSD	22	0.75	260	4.34
LLA—HLA	44	1.51	524	8.74
LLA—LLSD	22	0.75	260	4.34

A higher-capacity mist extractor (higher K_s) would result in a smaller diameter, lower-weight vessel, but the 2.0% v/v free gas in oil specification would be reached at a lower inlet liquid content, because of the higher downward oil velocities associated with the reduced diameter.

The Effect of the Feed-Pipe Size

Fig. 7 shows the effect of the feed-pipe size while other parameters remain the same as in the base case.

In this case, the separator dimensions are fixed at those obtained for the base case design (ID=6.1 ft, length=11.5 ft). The feed-pipe size is varied to determine the effect on separation performance, or rating calculations.

While the amount of liquid entrained at feed-pipe conditions increases with decreasing feed-pipe size below the design size of 16 in., the amount of entrainment exiting the inlet device and reaching the mist extractor increases much more significantly. This is mainly caused by the increased entrainment, increased droplet shearing, and reduced separation efficiency of the half-pipe inlet device because of excessive ρV^2 values associated with the smaller feed-pipe sizes (see Fig. 9 in Part 1 of the series).

The difference in entrainment loads between the "exit from inlet device" and "inlet to mist extractor" curves in Fig. 7 reflects the separation performance of the gas gravity separation section part of the separator.

The amount of free gas in oil was unchanged at 0.3% v/v for all feed-pipe sizes.

The Effect of the Inlet Device

Fig. 8 shows the effect of the inlet device on vertical scrubber weight while other parameters remain the same as in the base case.

The main effect of inlet device type on diameter relates to gas flow distribution as reflected by the *F* factor. The selected inlet device also affects vessel length/height via the minimum distance requirements as outlined in Table 3.

Fig. 8 shows a slight increase in vessel size for the cyclonic inlet. Inspection of the spreadsheet calculations shows that if the feed pipe is sized for the limiting ρV^2 value

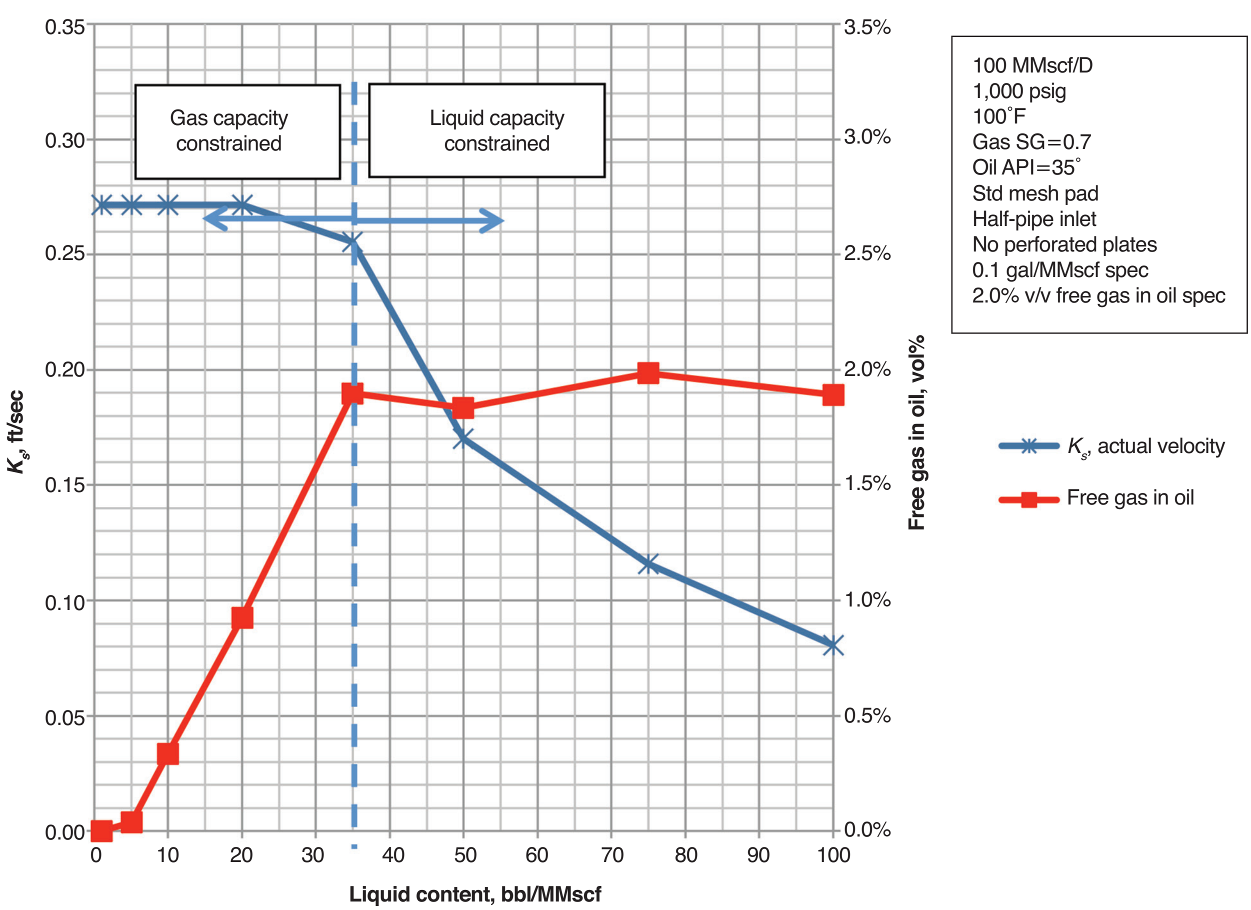

Fig. 6—Vertical separator gas handling (K_s) and oil degassing performance vs. the inlet liquid content.

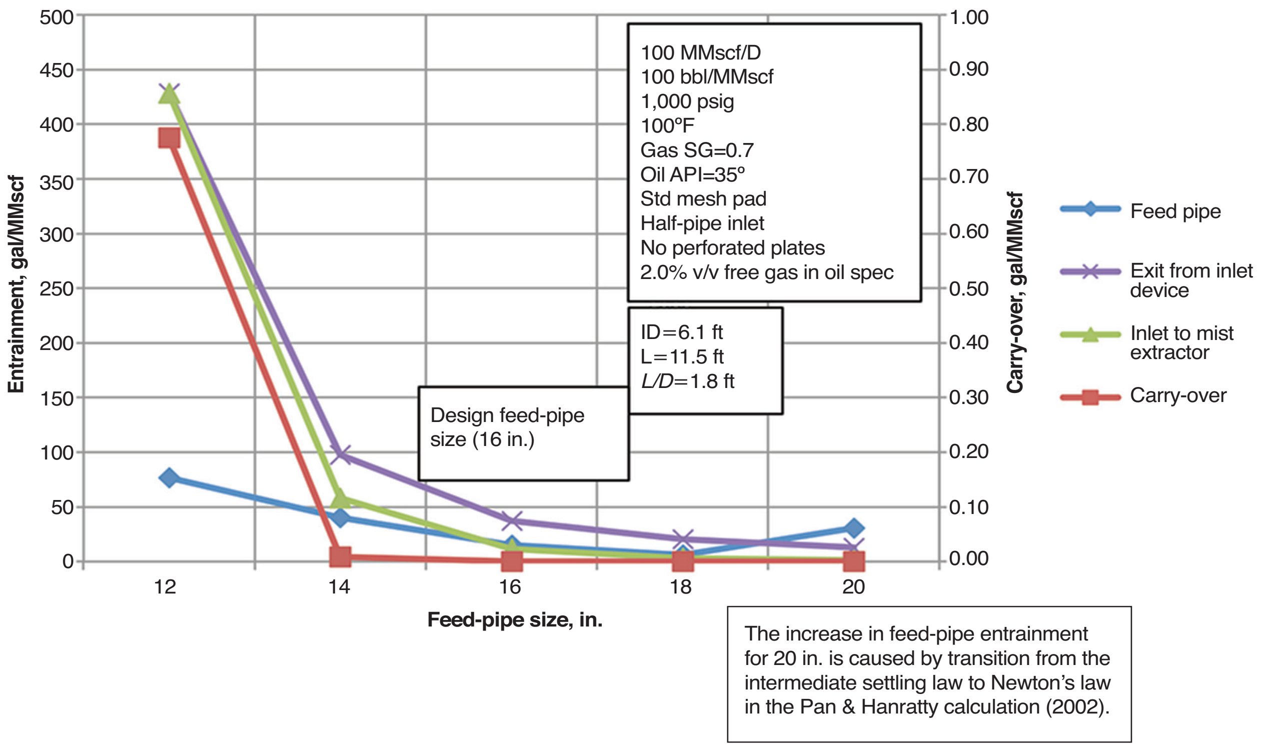

Fig. 7—The effect of the feed-pipe size on entrainment and carry-over.

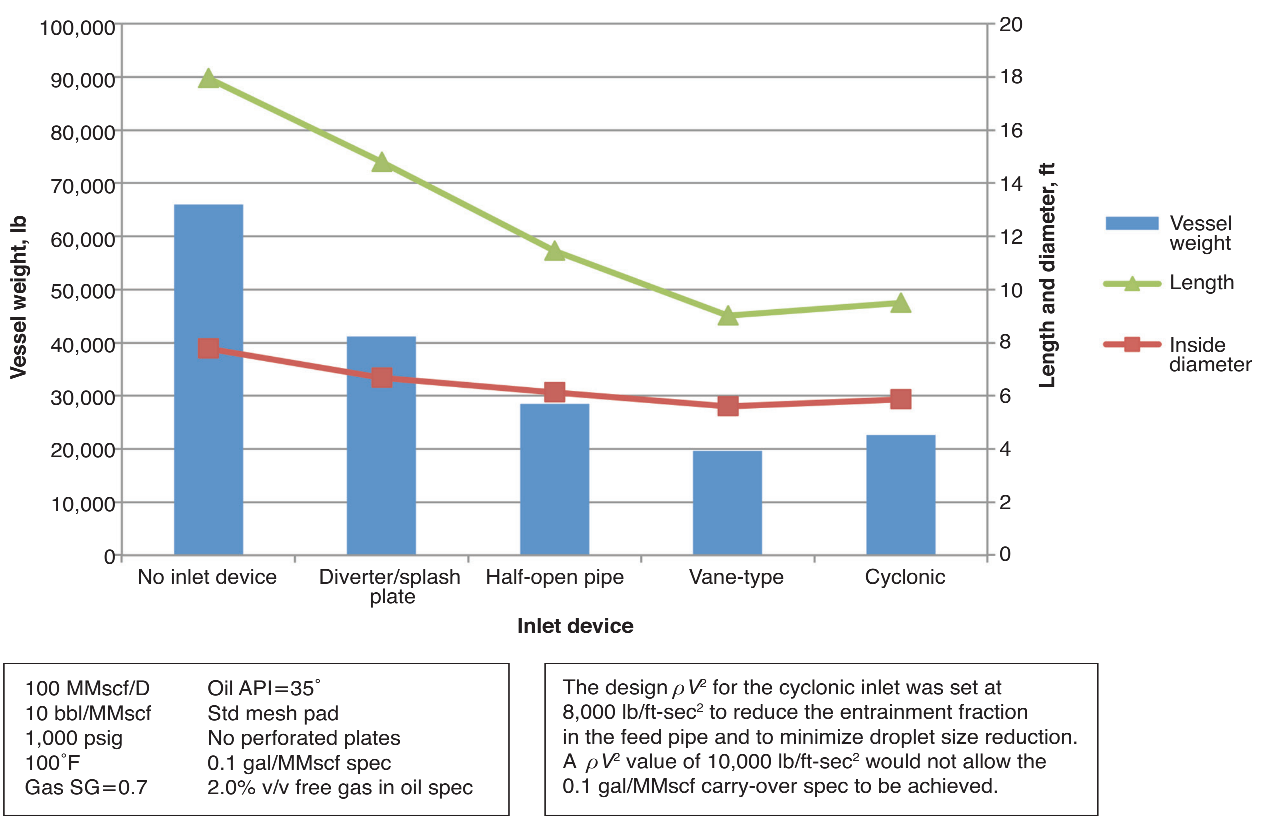

Fig. 8—The effect of the inlet device on the vertical scrubber weight.

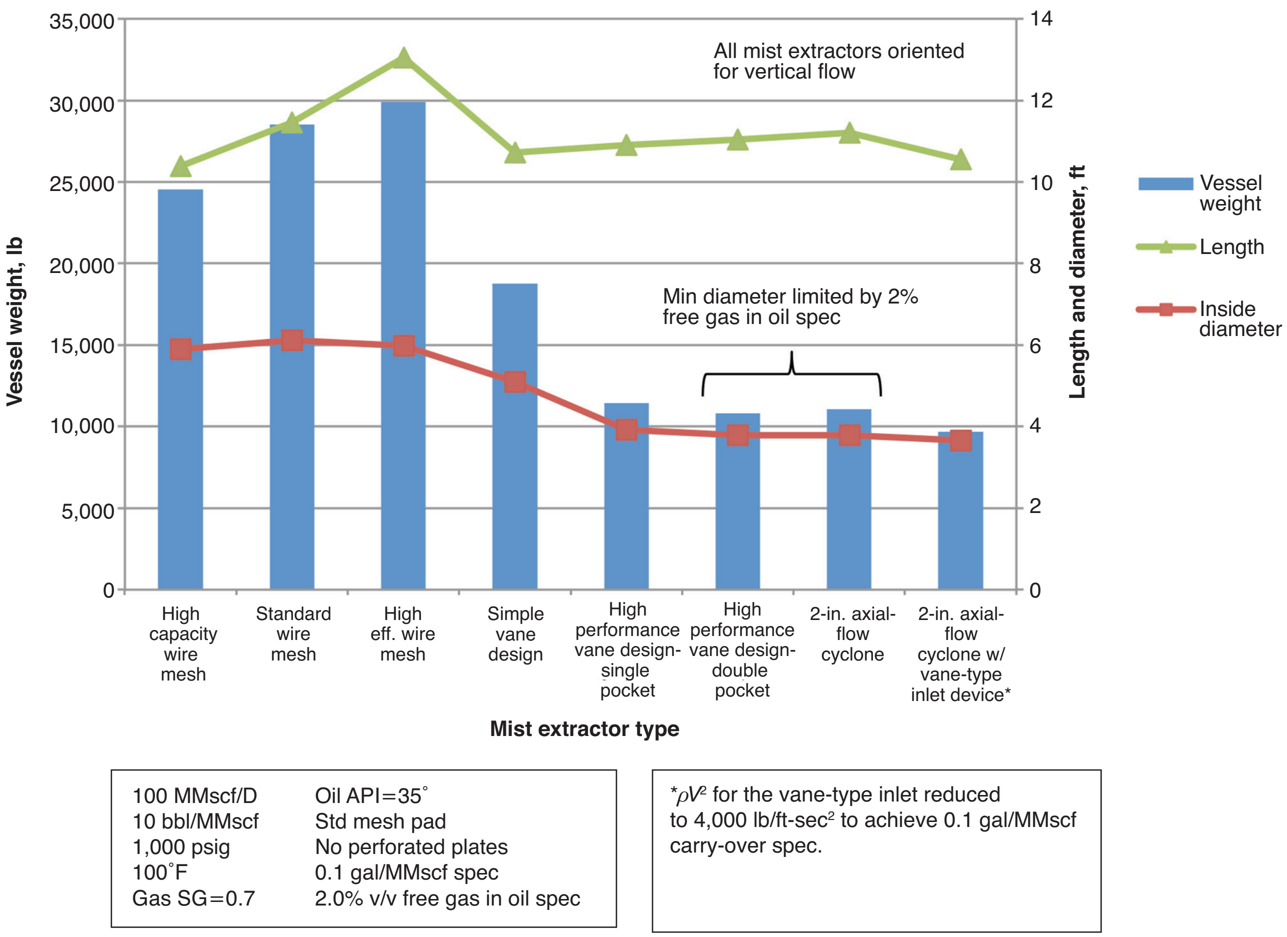

Fig. 9—The effect of mist extractor type on the vertical scrubber size and weight.

of 10,000 lb/ft-sec^2 typically specified for a cyclonic inlet, the liquid entrainment fraction in the feed pipe is high, and the entrainment droplet size distribution is shifted to smaller sizes.

Even though the cyclonic inlet is estimated to achieve good liquid-separation efficiency at these conditions, the amount of unseparated liquid and its size distribution overwhelms the mist extractor such that it cannot achieve the 0.1 gal/MMscf specification. Therefore, it is necessary to reduce the design feed-pipe/inlet device ρV^2 value. In Table 3, it has been assumed that the cyclonic inlet also has a larger inlet device–mist extractor distance requirement than the vane-type inlet.

A standard cyclonic inlet device would not typically be expected to be particularly good with respect to flow distribution. In Part 1, Fig. 11, the curve for the cyclonic inlet device assumes it is equipped with mixers on the fluid outlets to substantially remove spin from the fluids and thereby improve flow distribution. If the cyclonic inlet is not equipped with these outlet mixers, flow distribution can be expected to be poor, and a perforated plate would be necessary to improve flow distribution.

The amount of free gas in oil was <0.4% v/v for all inlet devices.

The Effect of Mist Extractor Type on the Vertical Scrubber

Figs. 9 and 10 show the effects of mist extractor types while other parameters remain the same as in the base case.

For the low liquid loading base case conditions, vessel diameter is essentially a function of the mist extractor K_s value. The higher-capacity mist extractors allow higher gas velocities and, therefore, smaller diameters for a given gas flow rate.

As can be seen in Fig. 10, the high-performance double pocket vane and 2-in. axial–flow cyclone cases are actually constrained by the 2% free gas in separated oil spec. The 2-in. axial-flow cyclone with vane-type inlet case is constrained by the maximum vessel plug flow K_s value of K_s= 0.5 ft/sec limitation (Table 1).

While this may seem to be a conservative assumption that negates the potential capacity advantages of high-

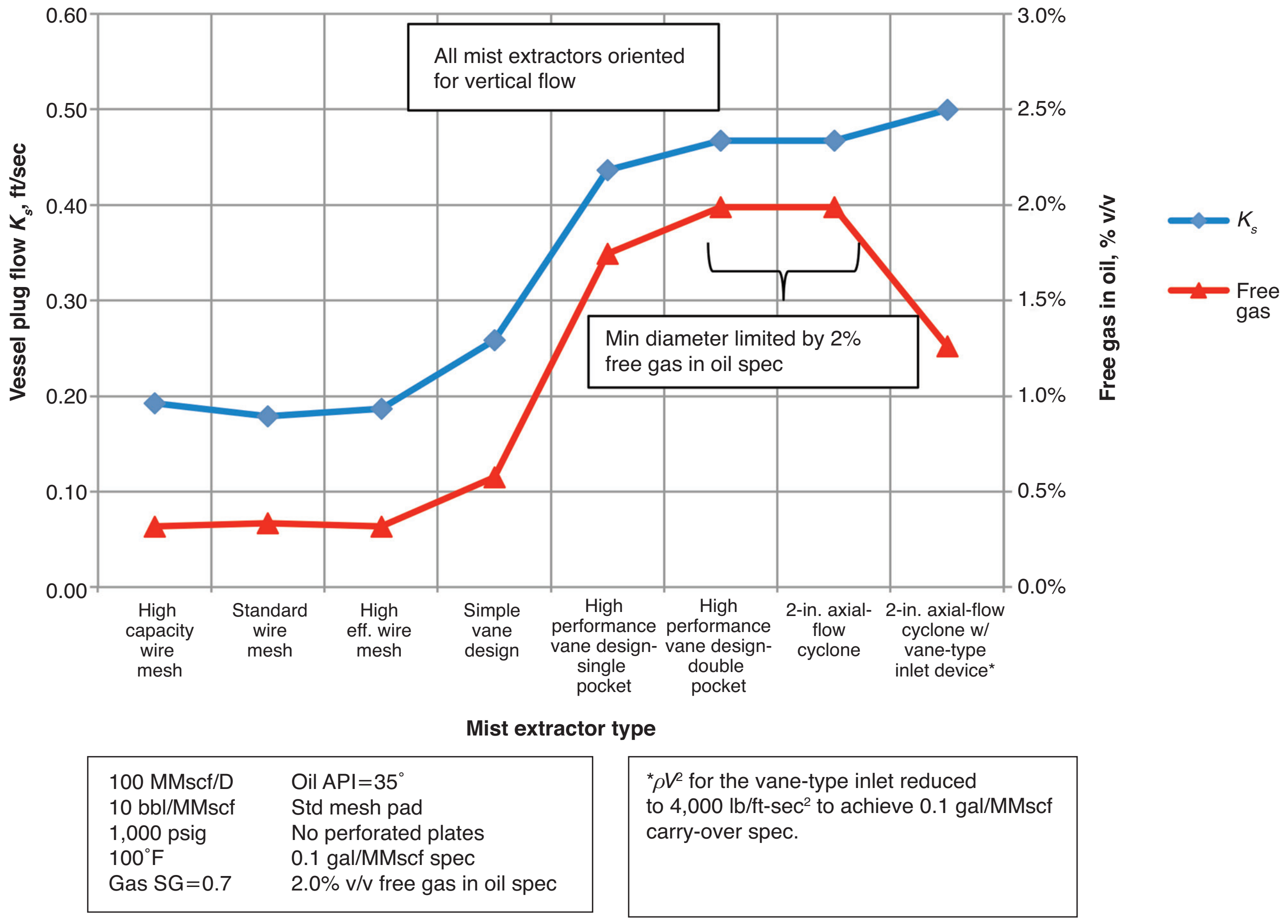

Fig. 10—The effect of mist extractor type on gas handling and liquid degassing performance.

performance vane and cyclone demister designs, there is evidence from the field that this conservatism is warranted. This view may change as more data become available and vessel internals are improved further.

In this case, even though the vessel diameter went down slightly, the amount of free gas in the separated oil decreased. This is explained by the better flow distribution of the gas and liquid phases achieved by the vane-type inlet compared to the half-pipe inlet.

The Effect of Liquid Content on Horizontal Separator Sizing

Figs. 11 through 13 show the effect of the liquid content in horizontal separators while other parameters remain the same as in the base case.

The diameter remains constant at approximately 5.0 ft over the investigated range of inlet liquid content. For these conditions, the diameter is set by two dimensional constraints: 1) the minimum distances between alarm and shutdown levels for the liquid, and 2) the vertical gas-space height required to accommodate the mist extractor and the required minimum space between HLSD and the bottom of the mist extractor. The gas capacity of the gas gravity separation section is acceptably below the K_s= 0.75 ft/sec plug flow constraint across the range of inlet liquid contents (Fig. 12).

The actual K_s value decreases slowly with increasing inlet liquid content as the separator length increases to accommodate the higher liquid loads. The reason the actual K_s value is decreasing for constant gas flow and constant cross-sectional area of the gas gravity separation section is because of the improvement of the gas velocity profile with increasing L/D_i, as shown in Part 1, Fig. 11. Across the range of inlet liquid contents evaluated, the HLSD point is at 53% of the vessel inside diameter. This may seem high for relatively low inlet liquid contents, but is mainly the result of the assumed minimum spacing criteria for liquid level alarm and shutdown points, combined with the high operating pressure that reduces the cross-sectional area required for gas handling.

The constant vessel length of approximately 13.4 ft for low liquid loads is set by the minimum L/D constraint of 2.5. This length is not dictated by the separation requirements

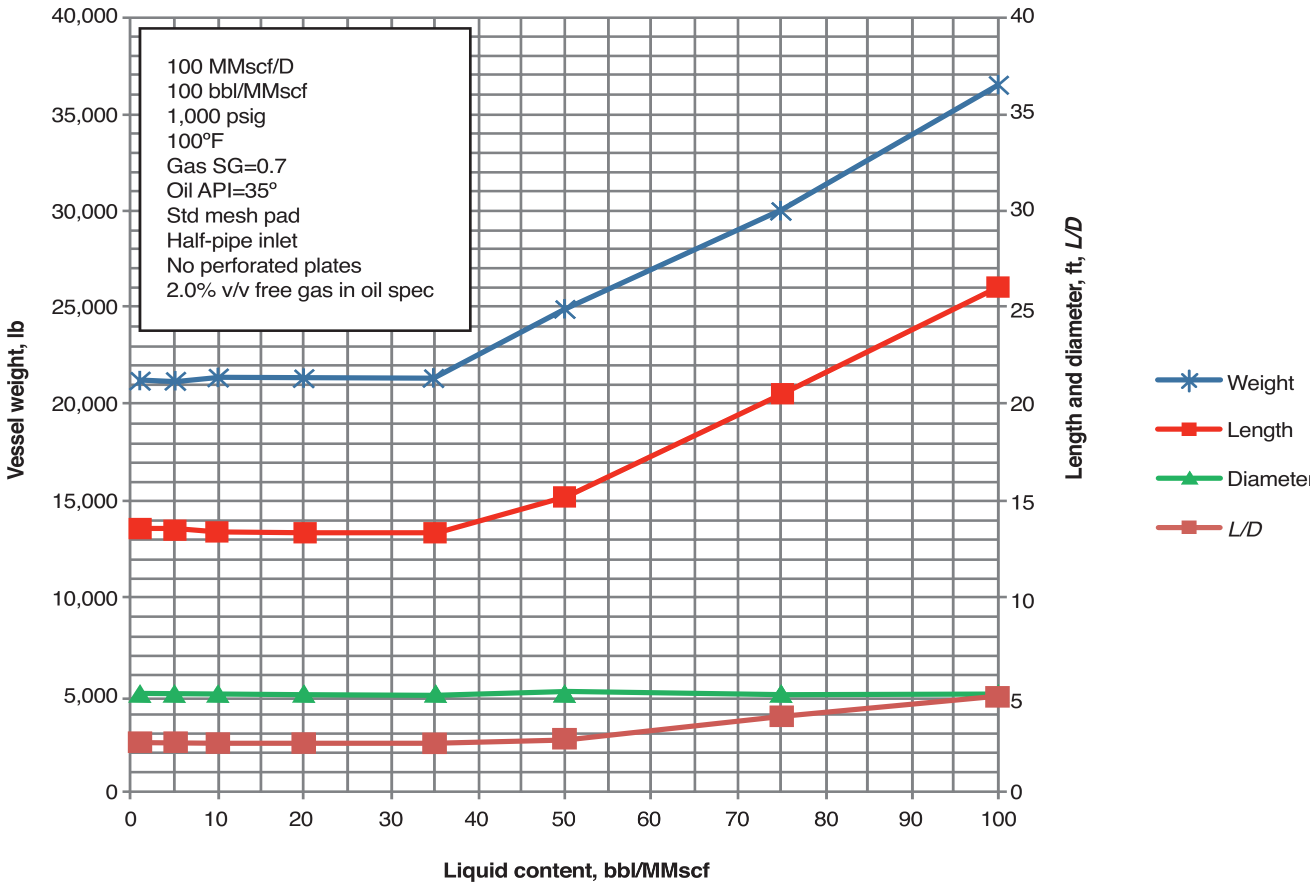

Fig. 11—The horizontal separator size and weight vs. inlet liquid content.

of either the gas or liquid phases. As inlet liquid content increases to more than 35 bbl/MMscf, the separator length also increases.

This is a lower-cost (weight) means of handling the increased liquid volumes than increasing diameter would be to satisfy the "time between level" constraints, which would override the minimum distances between liquid level alarm/shutdown points that are controlling at lower liquid loads.

As shown in Fig. 12, the horizontal separator can easily achieve the 2.0% free gas in outlet oil spec across the range of inlet liquid contents evaluated, which reflect gas-dominated conditions. This situation changes for higher liquid loads and lower gas/liquid ratios, in which cases the separator size is primarily dictated by liquid-handling requirements. In no case did the horizontal separator exceed the re-entrainment constraint caused by excessively high gas velocities across the liquid surface.

Fig. 13 compares the calculated weights for both the vertical and horizontal orientations over the range of inlet liquid contents. The horizontal vessel is lighter than the vertical vessel in all cases, even at the lowest inlet liquid contents. However, the vertical vessel would be lighter than the horizontal over much of the inlet liquid content range evaluated, if it was equipped with a higher-capacity vane type or axial cyclone demister. The horizontal would show less benefit from these mist extractors, mainly because of the liquid-level requirements, gas-space height needed to accommodate the mist extractor, and the $K_s = 0.75$ ft/sec plug flow constraint assumed for the gas gravity separation section.

Conclusions

A sampling of results from a new gas/liquid separator sizing/rating methodology has been presented. The results have been generated from an Excel spreadsheet that uses an optimization algorithm to determine the "optimum" vessel size, given a set of separation performance requirements and constraints.

The methodology not only provides a more quantitative basis for analyzing separator design and operation than traditional methods, it also provides significant insight into the interactions and sensitivities of the numerous variables, parameters, and design decisions involved. While further work is needed in certain areas, it is anticipated that that this tool and the underlying

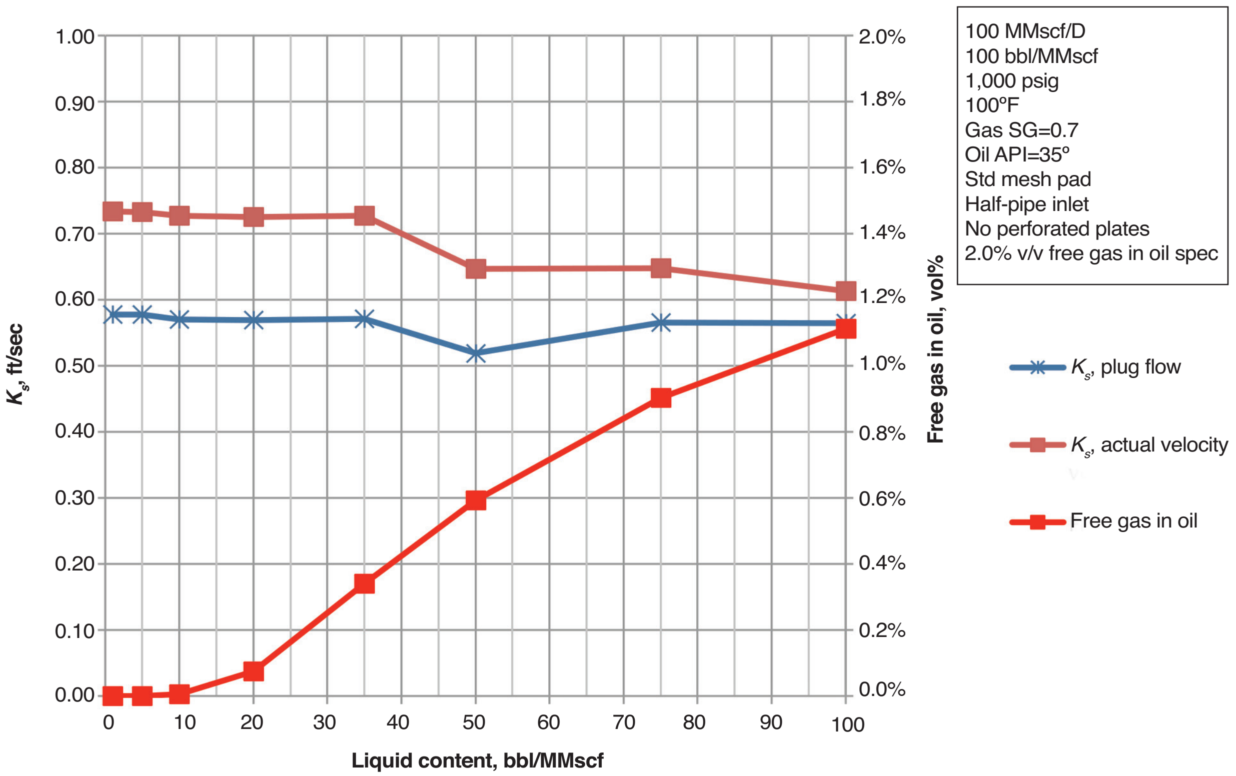

Fig. 12—Horizontal separator gas handling (K_s) and oil degassing performance vs. inlet liquid content.

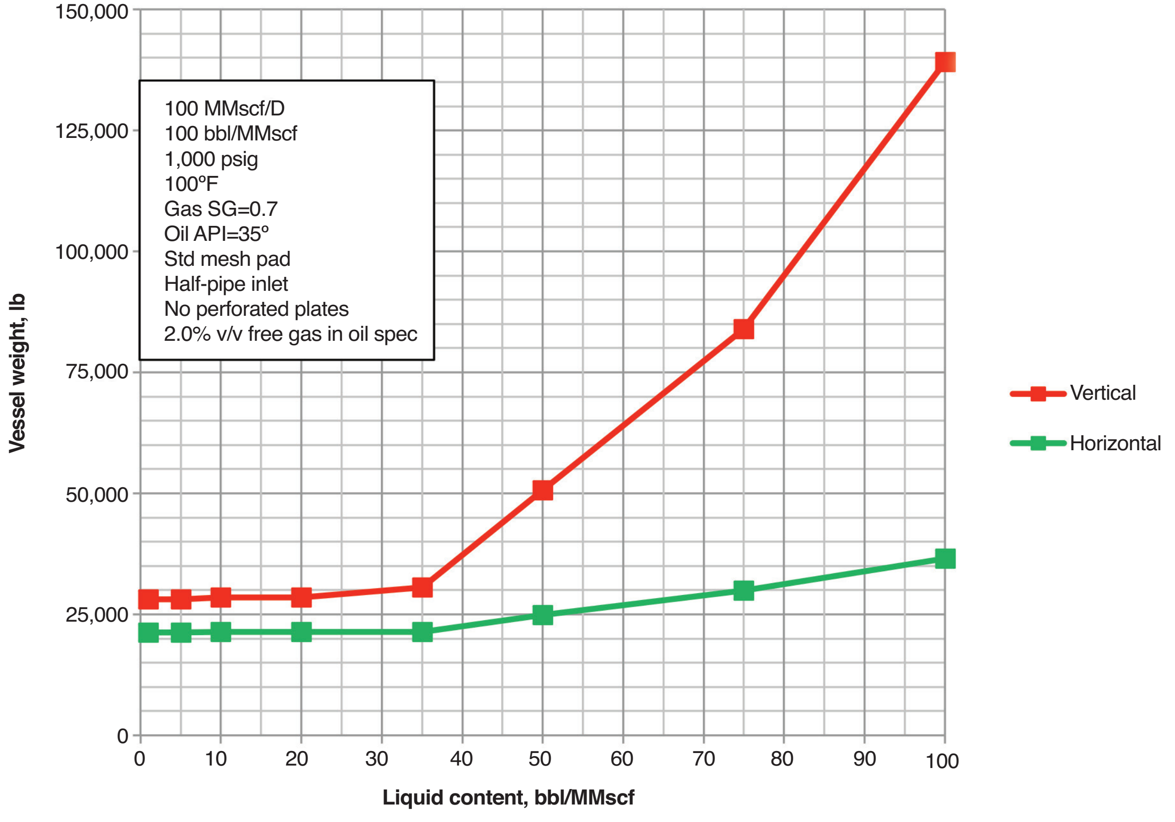

Fig. 13—The effect of vessel weight on liquid content in horizontal and vertical separators.

methodology will advance the oil and gas industry's capability in the field of gas/liquid separation. OGF

Nomenclature

ρV^2 = Inlet momentum value
ID = Inside diameter
D_i = Inside diameter
s/s = Seam-to-seam
HLSD = High-level shutdown
LLSD = Low-level shutdown
HLA = High-level alarm
LLA = Low-level alarm
BTL/BV = Bottom tangent line/bottom of vessel
V_r = Difference between gas- and liquid-phase horizontal velocities

For Further Reading

Grødal, E.O. and Realff, M.J. Optimal Design of Two- and Three-Phase Separators: A Mathematical Programming Formulation, SPE 56645.

Pan, L. and Hanratty, T.J. 2002. **Correlation of Entrainment for Annular Flow in Horizontal Pipes.** *Int. J. Multiphase Flow* **28** (3): 385–408.

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