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Influence of Flow Characteristics on the Design of Two-Phase Horizontal Separators

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ABSTRACT - Flouid streams produced from petroleum reservoirs reach surface as complicated mixtures consisting of multi-phase gas, oil, and water. Depending on the quantity of each phase, separators should be designed and installed to handle the mixture and separate it into pure phases for further treatment of each phase. Separators design follows calculations of sequential concepts that lead to determination of the optimum size (internal diameter and length) that provide efficient separation process at lowest cost. In this paper, the influence of flow characteristics has been studied using published calculation models. Because these models are performed through multi-step and iterated calculations which are time consuming, an algorithm and computational program has been developed to facilitate the analysis at this stage and serve as a robust computational tool for future work. Using the computational tool, the analysis results indicate significant influence of flow characteristics and separation conditions on separators design.

Keywords: *Settlement Velocity, Slenderness Ratio, Seam-To-Seam Length, Separator Sizing, Two-Phase Flow Separators.*

المستخلص- عادة ما تصل الموائع المنتجة من المكامن النفطية إلى السطح في شكل مزيج معقد يحتوي على عدة أطوار (غاز و نفط, و ماء). إعتماداً على الكمية المنتجة لكل طور, يجب تصميم وتركيب فواصل لمعالجة المزيج وتحويله إلى اطوار نقية من النفط والغاز والماء. عملية التصميم تتبع حسابات لمفاهيم متعاقبة تنتهي لتحديد الحجم الامثل (القطر الداخلي والطول) الذي ينتج عنه عملية فصل فعال بأقل تكلفة. في هذه الورقة تم تحليل تأثير مختلف الخواص الجريانية وظروف الفصل على اختيار الفاصل الافقي لفصل الطورين بإستعمال نماذج رياضية منشورة مسبقاً. ن لأن هذه الحسابات متتابعة ومكررة و تحتاج لزمن طويل لاكمالها فقد تم تطوير أداة حاسوبية لكي تستعمل لتصميم الفواصل ذات الطورين والثلاثة اطوار بصورة سريعة و صحيحة. بإستعمال الاداة الحاسوبية اتضح التأثير الملحوظ للخواص الجريانية وظروف التشغيل على إختيار الفاصل الامثل.

INTRODUCTION

Crude oils are produced from reservoirs in a form of multi-phase multi-component mixtures consisting of oil, water, gas, and other contaminants. The produced fluids in their initially produced form are, therefore, subjected to step-by-step treatment processes to convert them to final products that meet requirements. One of the important treatment processes is the separation of oil, water, and gas. This step is normally achieved by applying different theory based on the type of processed crude and interaction between the phases of the stream (Worley and Laurence, 1956). The initial separation in almost all streams is achieved following the gravity difference theory which depends mainly on the density difference between oil, water, and gas.

Oil/water separators were developed around 1960 by Royal Dutch Shell Company in cooperation with the Pielkenrood-Vinitex

Company (Water Smart Environmental Inc., 2000). The efforts of the two companies result in manufacturing the so called Corrugated Plate Separators (CPS) which were used in removing oil from water in oil production rigs, treating refineries, and chemical plants wastewater (Water Smart Environmental Inc., 2000). In petroleum production, there are different shapes of separators. The use of the appropriate shape depends on many factors such as the number of phases of the processed stream, crude properties, and separation conditions. M. Steven Worley and Lawton l. Laurence (1956) discussed the different separator shapes used in petroleum industry.

They introduced meaningful information about the separators components, separation mechanisms, and factors influencing the separation efficiency. With regards to gravity separation, Keller, Jr. (1975) proposed a method for treating mixtures of oil, water, and solids. His method can be used for oils with API gravity ranges from 11 to 70. Rehm and Shaughnessy (1983) proposed the so-called Performax Matrix Plate Coalescence, which is an improved gravity separator of the gunbarrel. Aymong (1988) designed a separator for treatment of waste water. His separator is containing a tank consists of corrugated coalescence plates, diffusion blades, vanes at the inlet, and horizontal baffles.

This design greatly enhances the separation by reducing turbulence. Inoue (1996) developed an apparatus suitable for separation of heavily polluted oil-water mixed liquids or mixed liquids of high viscosity oil and water. The apparatus consists of a top-opened separator tank divided into two sections one is for oil- water and the other is for water. The polluted oil-water mixture is fed to the separator tank from another (source) tank. Separation is assisted by applying electric field on the mixture fed into the separator. Subsequent developed apparatus by Kenawy and Kandil (1998), who developed Cross Flow Pack (CFP) separator that uses centripetal and gravity forces for oil-water separation and Ronan et al. (2000), who developed a separator uses coalescing filter technology are also considered of great contribution to the gravity separation.

A great contribution in oil separation has been introduced by Ken Arnolds and Maurice Stewart (89). They proposed a set of derived equations for application to size and select two-phase (Arnolds and Stewart 89) and three-phase (Arnolds and Stewart 89) separators. Their two papers were then emerged with other materials in a book covering all aspects of oil separation and treatment Arnold (Arnold and Stewart 1998), (Arnold and Stewart 1999)· Svrcek and Monnery (1993) have introduced the basic of two phase separators design and provided a step-by-step design procedure. Viska Mulyandasari (2011) at KLM Technology Group has prepared engineering design guidelines for separators sizing and selection. He introduced different methods used to separate two-phase and multi-phase heterogeneous mixtures. He also outlined the design consideration, criteria, and requirements for different separators.

In this paper, a predictive computational tool for sizing separator has been developed and used to analyze different parameters affecting the optimum size of separators. Although the tool can be used to size vertical and horizontal separators handling two-phase and multiphase streams, the discussion in this paper is limited to two-phase horizontal separators. The objective of this paper is to analyze the effect of flow parameters and separation conditions on selection of the optimum separator size.

THEORY AND METHODOLOGY

The model shown in Figure 1 of a two-phase (liquid-gas) separator can be used to describe the theory based on which separation occurs. The unprocessed stream enters the separator through the stream inlet (1) with very high velocity and, most probably, turbulent flow. Once the stream passes the inlet it impacts the inlet diverter (2) which causes the initial separation of gas pebbles from liquid phase. Any separated bubble should pass the distance between the inlet diverter (2) and the mist extractor (5). This distance is known as the effective length. Before gas reaches the mist extractor, all liquid droplets are desired to be settled down towards the liquid collection section (3). Liquid droplets are subject to two forces, the buoyant force due to gravity which assists settling of the droplet and drag force due to droplet movement with gas. The terminal (settlement) velocity of a liquid droplet can be obtained by balancing these two forces.

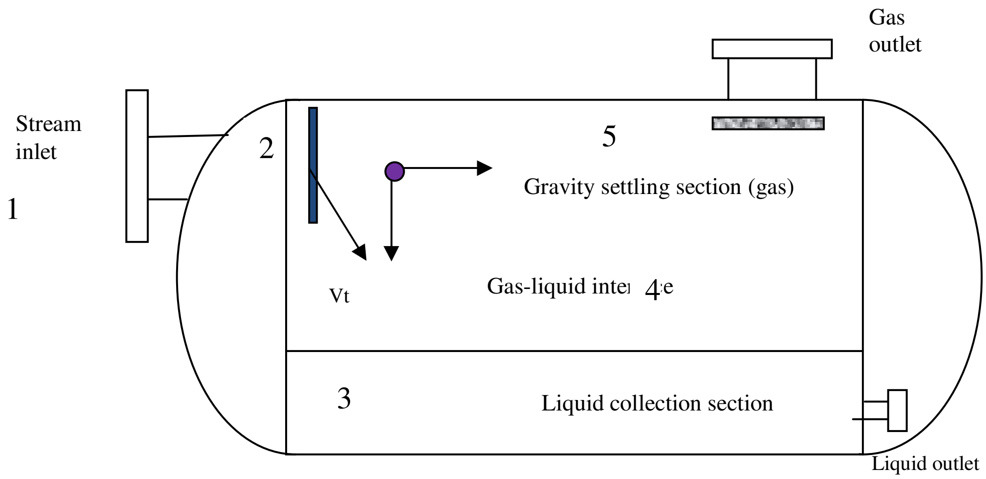

Figure 1: The main dimension parameters and direction of velocities in a horizontal separator

The settlement velocity can be obtained by equating the force of gravity on the droplet (negative buoyant force) with the drag force due to gas movement. i.e.

$$F_B = (\rho_l - \rho_g)V_d g = C_d A_d \rho_g \left(\frac{V_s^2}{2}\right) = F_D \qquad (1)$$

where: F_B: the negative buoyant force, lb_f (N) F_D: the drag force, lb_f (N), V_d: the droplet volume, ft^3 (m^3), $V_d = \pi D_d^3/6$

A_d: the droplet cross-sectional area, ft^2 (m^2), $A_d = \frac{\pi D_d^2}{4}$

Assuming a laminar flow (Stokes law) and substituting for V_d, A_d, and C_D, the settlement velocity can be obtained by the following equation:

$$V_t = \frac{C(SG_l - SG_g)D_d^2}{\mu} \qquad (2)$$

where C is a constant depending on the unit, SG is the specific gravity and the subscript l and g are denoting liquid and gas, respectively. It should be noted that the specific gravity of gas in equation 2 is relative to water not to air. This value can be calculated from the specific gravity relative to air SG_{ga} as follows: $SG_g = 0.0012 SG_{ga}$.

Equation 2 is derived assuming laminar flow which is not the case during stream flow to the separator. The produced stream always enters separators at high flow rate which makes flow regime turn to turbulent flow (non-Stokes flow). In turbulence flow, settlement velocity is a function in drag coefficient which itself is a function in Reynolds number (and hence flow velocity). An initial value of settlement velocity is, therefore, assumed (which is normally taken as the settlement velocity at Stokes laminar flow) and iteration method is applied to reach an acceptable value of settlement velocity. The Determined terminal velocity can be used to size a separator using the models derived by Arnolds and Stewarts (Arnold and Stewart 1998). These models have been derived based on the following two assumptions:

a) Half-full liquid (50% liquid)
b) Liquid droplets diameters of 140 microns are to be settled down (less than 140 microns can be separated by mist extractor without fear of over floading)

The key factor for selection of the optimum separator size is the slenderness ratio. The slenderness ratio (defined as the ratio of the separator length to its diameter) should not exceed a specified value to avoid the liquid re-entrainment in the gas phase. For horizontal two-phase separators, Arnolds and Stewart propose a slenderness ratio value between 3 and 5 (Arnold and Stewart 1998). Attaining the slenderness ratio is not an easy task, it needs performing many steps in advance.

To calculate separator length, the effective length should be determined. The effective length depends on whether the separator operates under liquid capacity constraint or gas capacity constraint, which is identified according to liquid and gas flow rate. The effective length for liquid capacity constraint and gas capacity constraint is calculated from the following equations (Arnold and Stewart 1998): Liquid capacity constraint:

$$L_{eff} = C_1 \frac{TZQ_g}{Pd}\left[\left[\frac{\rho_l - \rho_g}{\rho_g}\right]\frac{d_m}{CD}\right]^{1/2} \quad (3)$$

Gas capacity constraint:

$$L_{eff} = \frac{C_2 t_r Q_l}{d^2} \quad (4)$$

where: L_{eff}: the effective length, m (ft) and T: Separation temperature, $^{\circ}$k (R)

P: Separation Pressure, kPa (psia), d: Separator internal diameter, mm (ft), Q_g: Gas flow rate, scmh (MMscfd) and Z: Gas compressibility. C_1 and C_2: Constants depend on the used units. For SI unit, C_1=34.5 and C_2=42441. For field units C_1=420 and C_2=1.4286.

In the current work, the algorithm shown in Figure 2 has been employed to select the optimum separator size at different flow properties and separation conditions.

RESULTS AND DISCUSSIONS

The Computational Tool

A robust, easy, flexible computational program with user-friendly graphical interface has been developed to serve as a tool for sizing separators. The graphical user interface of the computational tool is shown in Figure 3. From this form a user can navigates to other forms according to the task the user performs. Currently, the program is capable to perform the following tasks:

a. Performing flash calculation for multi-components hydrocarbons.
b. Sizing two-phase horizontal separators
c. Sizing three-phase horizontal separators
d. Sizing two-phase vertical separators
e. Sizing three-phase vertical separators

The input data to the program required for sizing separators includes flow parameters and separation conditions. Separate input data forms are available for horizontal separators and vertical separators as shown in Figure 4. The input data form is navigated to from the main graphical user interface.

The output from the program is obtained after one-click process. The user can get the settlement velocity and the whole iteration process. The main beneficial output is a table showing the calculated separator dimensional parameters from which the user can select the optimum dimension based on the slenderness ratio. This is the separator with the least internal diameter with no re-entrainment of liquid droplets. An example of the output is shown in Figure 5.

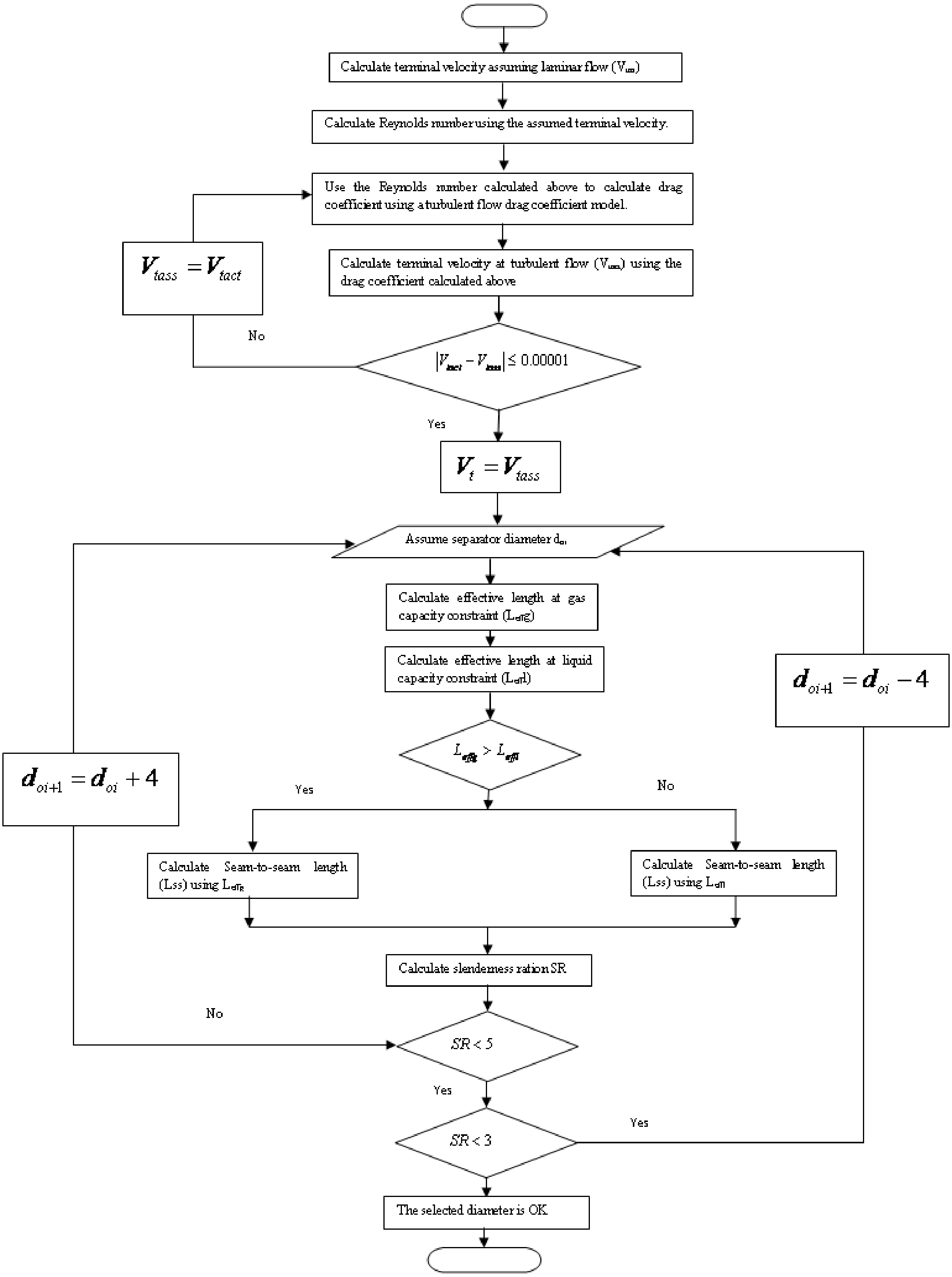

Figure 2: Algorithm for calculation of settlement velocity and selection of the optimum size.

Figure 3: The graphical user interface of the program

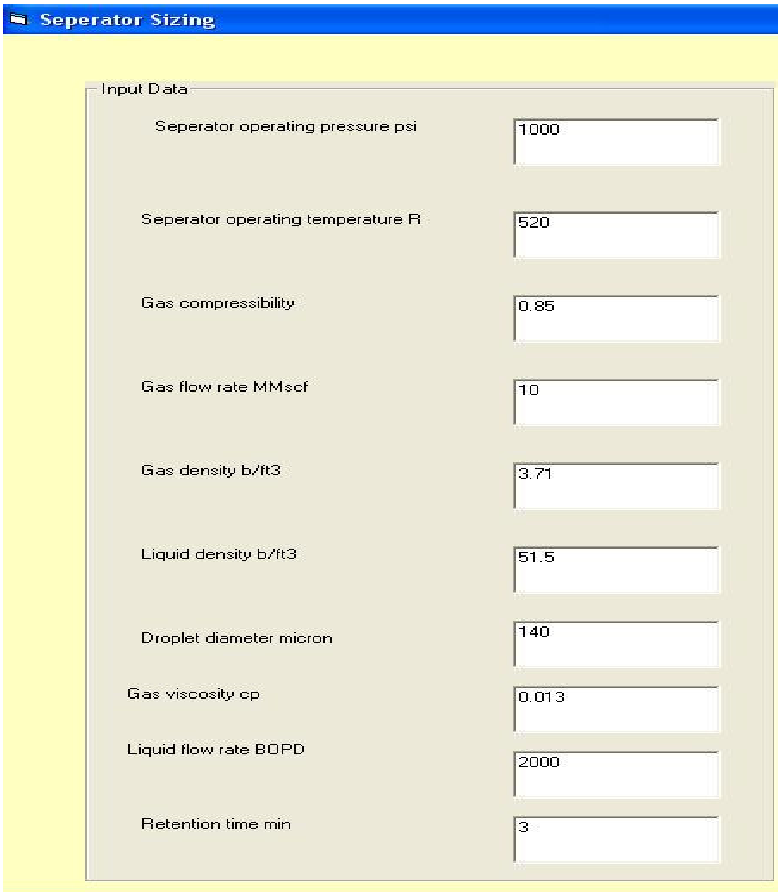

Figure 4: The input data form

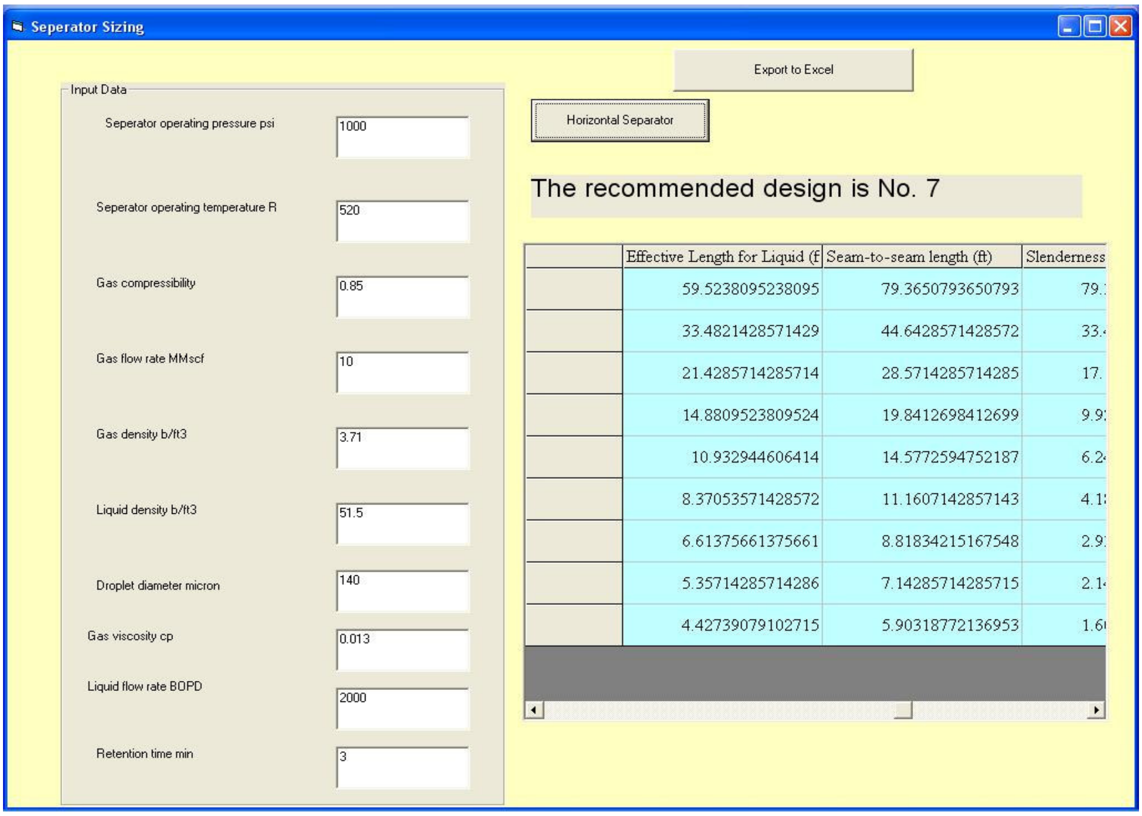

Figure 5: An example of output from the predictive tool

Variation of any flow parameter or separation condition will affect the selection of separator size. In this paper we will analyze the effect of flow characteristics and separation conditions on sizing two-phase horizontal separators. The results discussed in this paper are obtained at input data shown in Table 1.

Table 1: Calculation input data

Parameter	Value/Unit
Operating pressure	1000 psia
Operating temperature	520 R
Gas compressibility	0.85
Gas flow rate	10 MMSCF
Gas density	3.71 b/ft^3
Liquid density	51.5 b/ft^3
Droplet diameter	140 Micron
Gas viscosity	0.013 cp
Retention time	3 minute

Effect of flow characteristics

In this section we will analyze the effect of flow characteristics on sizing two-phase horizontal separators.

Effect of liquid flow rate

At flow rate of 1000 bbl/day the output is shown in Table 2. From the table two diameters (24 inch and 28 inch) fall within the safe operating limit (slenderness ratio between 3 and 5). Either diameter guarantees no-entrainment will take place. The smaller diameter, however, is more economically attractive.

The output at oil flow rate 500, 1000, 1500 and 2000 bbl/day is shown in Table 3. The result indicates that higher oil flow rate requires larger diameter to prevent the liquid re-entrainment in the gas phase. The result is graphically shown in Figure 6. This can be considered as a typical trend of variation of the optimum diameter with liquid flow rate.

Table 2: The dimensional parameters at oil flow rate of 1000 bbl/day

Internal Diameter (Inch)	Effective Length for Gas (ft)	Effective Length for Liquid (ft)	Seam-to-seam length (ft)	Slenderness ratio
12	1.65111	29.7619	39.68254	39.68254
16	1.238333	16.74107	22.32143	16.74107
20	0.990666	10.71429	14.28571	8.571429
24	0.825555	7.440476	9.920635	4.960317
28	0.707619	5.466472	7.28863	3.123698
32	0.619166	4.185268	5.580357	2.092634
36	0.55037	3.306878	4.409171	1.469724
40	0.495333	2.678571	3.571429	1.071429
44	0.450303	2.213695	2.951594	0.80498

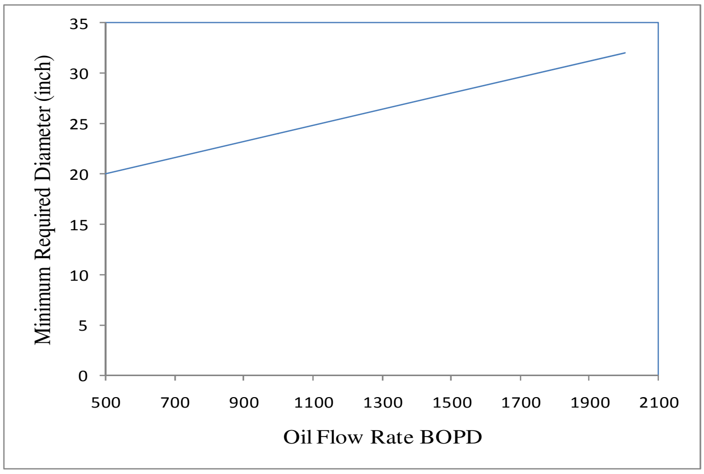

Figure 6: The variation of internal diameter with oil flow rate

Table 3: the variation of sized internal diameter with oil flow rate

Internal Diameter (Inch)	Effective Length for Gas (ft)	Effective Length for Liquid (ft)	Seam-to-seam length (ft)	Slenderness ratio @ flow rate BOPD			
				500	1000	1500	2000
12	16.5111	14.88095	19.84127	19.84127	39.68254	59.52381	79.36507
16	12.38333	8.370536	11.16071	8.370536	16.74107	25.11161	33.48214
20	9.90666	5.357143	7.142857	4.285714	8.571429	12.85714	17.14285
24	8.25555	3.720238	4.960317	2.480159	4.960317	7.440476	9.920634
28	7.076186	2.733236	3.644315	1.561849	3.123698	4.685548	6.247396
32	6.191663	2.092634	2.790179	1.046317	2.092634	3.138951	4.185267
36	5.5037	1.653439	2.204586	0.734862	1.469724	2.204586	2.939447
40	4.95333	1.339286	1.785714	0.535714	1.071429	1.607143	2.142857
44	4.503027	1.106848	1.475797	0.40249	0.80498	1.20747	1.609960

Effect of Gas flow rate

From Table 4, at gas flow rate at 50 MMscfd, slenderness ratio is higher than 5 for all diameters below 28 inch. Increase of gas flow rate always results in increase of required diameter as long as the separator operates under gas capacity constraint. The variation of the minimum required diameters with gas flow rate is shown in Figure 7.

Effect of liquid density

Liquid density is affected by quality of oil and the water volume fraction (water cut). Based on these two factors, liquid density can vary from low liquid density for light hydrocarbons with low water cut to high liquid density for heavy oil with high water cut. The maximum density, however, does not exceed 63 lb/ft^3 (estimated density of 99.9% water cut).

Table 5 indicates that the increase of liquid density decreases the slenderness ratio but it will not affect the choice of separators. For all densities, minimum internal diameter of 20 inch can be selected. At density of 40 lb/ft^3 it is better to select 24 inch because the slenderness ratio at 20 inch is very close to the recommended upper limit of slenderness ratio.

Table 4: Effect of gas flow rate on the optimum separator diameter

ID (inch)	Leff-Gas (ft)	Leff-liquid (ft)	Seam-to-seam length	Slenderness ratio at different gas flow rate (MMscfd)				
For gas flow rate of 50 MMscfd				50	75	100	15	150
12	16.511	0.595	17.511	17.511	25.767	34.022	42.278	50.533
16	12.383	0.335	13.716	10.287	14.931	19.575	24.218	28.862
20	9.907	0.214	11.574	6.944	9.916	12.888	15.86	18.832
24	8.256	0.149	10.256	5.128	7.192	9.256	11.32	13.384
28	7.076	0.109	9.409	4.032	5.549	7.065	8.581	10.098
32	6.192	0.084	8.859	3.322	4.483	5.644	6.805	7.966
36	5.504	0.066	8.504	2.835	3.752	4.669	5.586	6.504
40	4.953	0.054	8.286	2.486	3.229	3.972	4.715	5.458
44	4.503	0.044	8.17	2.228	2.842	3.456	4.07	4.684

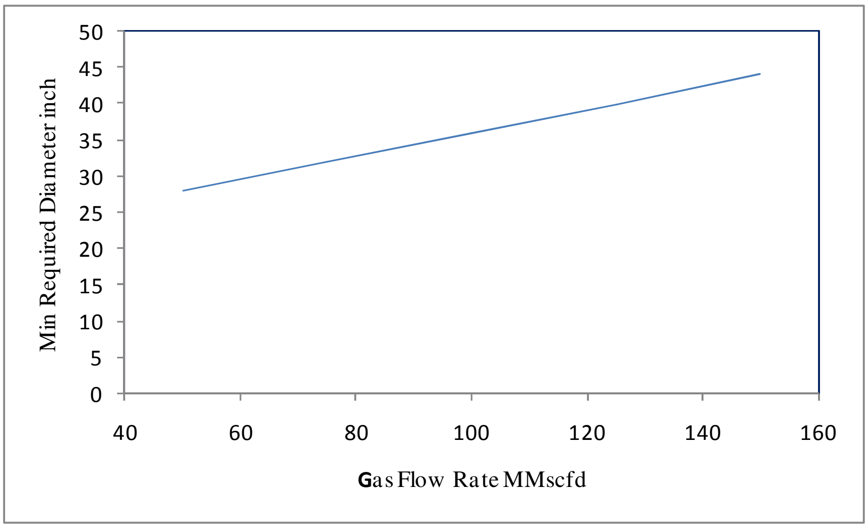

Figure 7: Variation of the optimum diameter with gas flow rate

Table 5: Variation of the optimum diameter with density

ID (inch)	Leff-Gas (ft)	Leff-liquid (ft)	Seam-to-seam length	Slenderness ratio at different liquid density (b/ft3)				
For liquid density of 40 lb/ft^3				40	45	50	55	60
12	11.0824	59.52381	79.36508	79.36508	79.36508	10.51124	9.922812	9.423097
16	8.311798	33.48214	9.645131	7.233848	6.746976	6.350072	6.019082	5.737992
20	6.649438	21.42857	8.316105	4.989663	4.678064	4.424046	4.212212	4.032315
24	5.541199	14.88095	7.541199	3.770599	3.554211	3.37781	3.230703	3.105774
28	4.749599	10.93294	7.082932	3.035542	2.876564	2.746962	2.638884	2.547099
32	4.155899	8.370536	11.16071	4.185268	4.185268	4.185268	4.185268	4.185268
36	3.694132	6.613757	8.818342	2.939447	2.939447	2.939447	2.939447	2.939447
40	3.324719	5.357143	7.142857	2.142857	2.142857	2.142857	2.142857	2.142857
44	3.022472	4.427391	5.903188	1.60996	1.60996	1.60996	1.60996	1.60996

Table 6: Effect of gas compressibility of the optimum size

ID (inch)	Leff-Gas (ft)	Leff-liquid (ft)	Seam-to-seam length	Slenderness ratio at different gas compressibility				
For gas compressibility of 0.85				0.6	0.7	0.8	0.9	1
12	3.618466	59.52381	79.36508	7.692109	8.80746	9.922812	79.36508	79.36508
16	2.71385	33.48214	44.64286	4.764311	5.391696	6.019082	6.646467	7.273852
20	2.17108	21.42857	28.57143	3.409159	3.810686	4.212212	4.613739	5.015265
24	1.809233	14.88095	19.84127	2.673027	2.951865	3.230703	3.509541	3.788379
28	1.550771	10.93294	14.57726	2.229163	2.434023	2.638884	2.843744	3.048605
32	1.356925	8.370536	11.16071	4.185268	4.185268	4.185268	4.185268	4.185268
36	1.206155	6.613757	8.818342	2.939447	2.939447	2.939447	2.939447	2.939447
40	1.08554	5.357143	7.142857	2.142857	2.142857	2.142857	2.142857	2.142857
44	0.986854	4.427391	5.903188	1.60996	1.60996	1.60996	1.60996	1.60996

Effect of gas compressibility

Higher compressibility gases require larger diameter to separate as shown in Table 6. Higher compressibility factor always leads to increase of slenderness ratio. In this result, the effect of increase is, however, insignificant, for gas compressibility factor within the range of 0.7-0.9. At any gas compressibility value falling within this range, separator diameter of 20 inch can be selected.

Separation Conditions

In this section, the effect of separation conditions on sizing separators is discussed. Separation conditions include separation pressure, separation temperature, and retention time. In this paper, un-heated separators are analyzed. Heated separators fall under oil heaters category which is normally used to treat pure oil comes from initial separation processes. The effect of temperature is, therefore, not been considered in this section.

Separator's pressure

The variation of separator's operating pressure will lead to the variation of the required diameter if, and only if, the separator is operating under gas capacity constraint (i.e. at high gas flow rate and/or low liquid flow rate). Table 7 shows the variation of the required diameter with operating pressure using the input data listed in Table 1 except that the gas flow rate and liquid flow rate are changed to 100 MMscfd and 20 BOPD, respectively (to guarantee gas capacity constraint). From Table 7, the required minimum diameter decreases with the increase of separation pressure. Form this result it can be concluded that when stage separation is applied larger diameter are required for low pressure separation. Suppose that three-stage separation is applied under the same condition of the input data used in this calculation, if the produced stream enters the first stage at pressure of 4000 psi and then goes to the subsequent intermediate and low stage separation at 2000 psi and 1000 psi, respectively; the selected sizes of the high pressure stage separator, intermediate pressure stage separator, and low pressure stage separator should be 24 inch, 32 inch, and 36 inch, respectively. If lower pressure separator is used, it is recommended to decrease gas flow rate to be able to use a low cost (small diameter) separator.

Retention time

Retention time affects separator sizing only if the calculation is based on liquid capacity constraint (high liquid flow rate and/or low gas flow rate). Under this condition, increasing retention time will increase the effective length for a selected diameter which leads to larger seam-to-seam length. This will turn in increasing the slenderness ratio, and hence, larger diameter is required to avoid liquid re-entrainment. Table 8 shows the variation of the minimum required diameter with retention time. The trend is shown more clearly in Figure 8.

Table 7: Variation of the optimum separator diameter with separation pressure

ID (inch)	Leff-Gas (ft)	Leff-liquid (ft)	Seam-to-seam length	Slenderness ratio at different separation pressures				
For separation pressure of 1000 psia				1000	2000	3000	4000	5000
12	33.022	0.595	34.022	34.022	17.511	12.007	9.256	7.604
16	24.767	0.335	26.1	19.575	10.287	7.192	5.644	4.714
20	19.813	0.214	21.48	12.888	6.944	4.963	3.972	3.378
24	16.511	0.149	18.511	9.256	5.128	3.752	3.064	2.651
28	14.152	0.109	16.485	7.065	4.032	3.021	2.516	2.213
32	12.383	0.084	15.05	5.644	3.322	2.548	2.161	1.929
36	11.007	0.066	14.007	4.669	2.835	2.223	1.917	1.734
40	9.907	0.054	13.24	3.972	2.486	1.99	1.743	1.594
44	9.006	0.044	12.673	3.456	2.228	1.819	1.614	1.491

Table 8: Effect of retention time on the optimum diameter

ID (inch)	Leff-Gas (ft)	Leff-liquid (ft)	Seam-to-seam length	Slenderness ratio at different retention time (minutes)				
For retention time of 1 minute				1	3	5	7	9
12	3.302	19.841	26.455	26.455	79.36508	132.2751	185.185	238.095
16	2.477	11.161	14.881	11.161	33.48214	55.80357	78.125	100.446
20	1.981	7.143	9.524	5.714	17.14286	28.57143	40	51.429
24	1.651	4.96	6.613	3.306	9.920635	16.53439	23.148	29.762
28	1.415	3.644	4.859	2.082	6.247397	10.41233	14.577	18.742
32	1.238	2.79	3.72	1.395	4.185268	6.975446	9.765	12.556
36	1.101	2.205	2.94	0.98	2.939447	4.899079	6.859	8.818
40	0.991	1.786	2.381	0.714	2.142857	2.142857	5	6.428
44	0.901	1.476	1.968	0.537	1.60996	1.60996	3.757	4.83

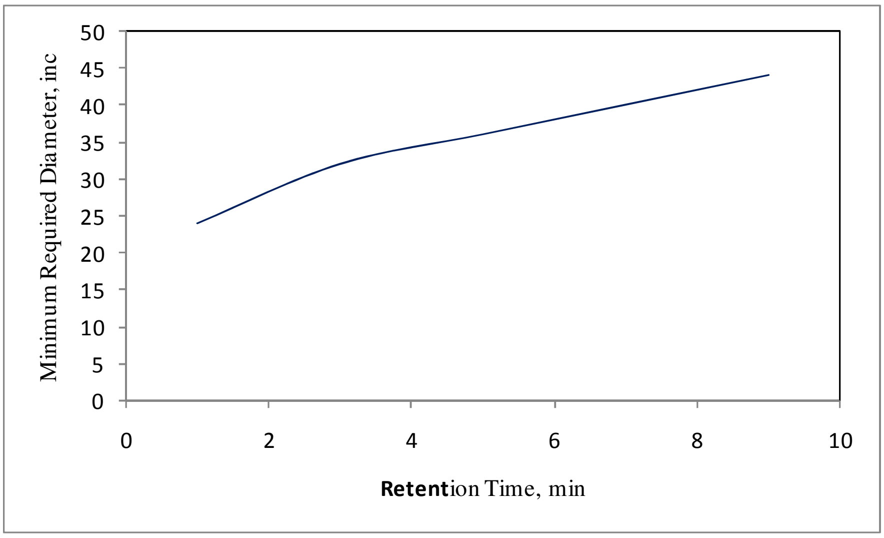

Table 8: Variation separator optimum diameter with retention time

CONCLUSIONS

A predictive computational tool has been developed for sizing different types of oil processing separators. In this paper, the computational tool has been used to analyze the effect of different parameters related to flow and separation condition. From the analysis, the following conclusions are pointed out:

1. Higher oil flow rate requires larger diameter to prevent the liquid re-entrainment in the gas phase
2. Increase of gas flow rate always results in increase of required diameter as long as the separator operates under gas capacity constraint.
3. Increase of liquid density decreases the slenderness ratio but it will not affect the choice of separators.
4. Higher compressibility gases require larger diameter to separate.
5. The required minimum diameter decreases with the increase of separation pressure. Form this result it can be concluded that when stage separation is applied larger diameter are required for low pressure separation.
6. Increasing retention time will increase the effective length for a selected diameter which leads to larger seam-to-seam length. This will turn in increasing the slenderness ratio, and hence, larger diameter is required to avoid liquid re-entrainment.

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