Parametric Approach for the Optimal Design of Knockout Drums

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In this paper, the optimal design of two-phase horizontal knockout drums is addressed. An optimization model is developed that predicts separator performance subject to nonlinear design constraints. The proposed model gives rise to a nonconvex, nonlinear problem that often causes convergence difficulties for standard local optimization techniques. We propose an optimal solution procedure based on a search parametric approach. Extensive numerical simulations on a case study are used to illustrate the proposed heuristic procedure that yields to a minimal cost design of knockout drums. Results of in-depth analysis aimed to characterize liquid−gas separation in horizontal knockout drums are also presented.

1. Introduction

Knockout drums are a main component in pressure-relief systems in industries. Pressure-relief systems in refineries are used to control vapors and liquids that are released by pressure-relieving devices and blowdowns. A typical closed pressure-release and flare system device includes the following: (a) relief valves and lines from process units for collection of discharges, (b) knockout drums that are used to separate vapors or gas and liquids, including seals and/or purge gas for flashback protection, (c) a flare and igniter system that combusts vapors when discharging directly to the atmosphere is not permitted.[1−3]

Knockout drum and flare systems need to be precisely designed, since equipment failures could result in economic loss to business, environmental contamination, and health and safety risks in the event of excessive overpressure. Therefore, the proper relief effluent handling equipment design is required. In this paper, the optimal design of two-phase horizontal-oriented knockout drums for oil industry applications is addressed. Horizontal-oriented knockout drums are often more economical when large liquid storage is desired and the vapor flow is high. In offshore applications, refineries, and petrochemical industries, knockout drums are designed to effectively remove hydrocarbon liquids from the main flare relief gas to prevent the possibility of liquid carryover and “flaming rain” from the flare tip. Knockout drums are classified as “two phase” if they separate gas from the total liquid stream and “three phase” if they also separate the liquid stream into its crude oil and water components.

The design of knockout drums typically is based on manual trial-and-error procedures with widespread table lookups that require the expert application of many rules-of-thumb.[2,4,5] Such knockout drum design methods provide limited tools for the designer because of the nature of multivariable manual trial-and-error procedures. Approaches based on simple force balance and correlations for drag force on a spherical droplet have been also reported.[6−15] Anaya et al.[13] have addressed the knockout drum design via a systematic design procedure for a two-phase knockout drum. The authors developed a heuristic algorithm to search out model convergence on the basis of the economical ratio of minimum length as a function of diameter.

In this paper, a parametric optimization approach to search minimizing the separator vessel manufacturing cost is proposed. The main concept behind the proposed procedure is based on the successive solution of a nonlinear programming (NLP) model.[16] It is shown that the proposed design procedure allows the robust solution for the optimal design of knockout drums under a variety of different scenarios. The optimization model and its heuristic solution algorithm are applied to determine the optimal horizontal knockout drum design for a nominal set of design parameters. The problem is constrained by a set of fluid dynamic and mechanical relationships formulated from the gravity-settling theory. The application of the parametric optimization procedure is illustrated through the solution of a case study. Also performed is an in-depth analysis aimed to characterize liquid−gas separation in horizontal knockout drum.

The paper is organized as follows. For the sake of clarity in presentation, we briefly discuss fundamentals in separator design theory in Section 2. In Section 3, the optimization model, model constraints, and objective function are presented. The parametric approach is discussed in Section 4. In Section 5, an illustrative example of a typical knockout drum for oil industry applications is presented, followed by the application of the proposed parametric approach for the optimal design. Finally, conclusions are presented in Section 6.

2. Foundations in Separator Design Theory

In this section, the basics of settling theory are reviewed. The settling theory is the standard method to size knockout drums.[6−15]

2.1. Settling Theory. Knockout drum sizing based on settling theory considers that the phase change is nearly complete as the fluid enters the separator. To apply settling theory in knockout drums design, it is assumed that the droplets act as spherical particles and that they will settle in a continuous phase due to the gravity forces. Whenever relative motion exists between a particle and a surrounding fluid, the fluid will exert a drag force upon the particle. The motion mechanism to separate the droplets assumed that a liquid in a gas or vapor flow is acted on by three main forces: gravity (directed downward), buoyancy (opposite to the gravity force), and drag

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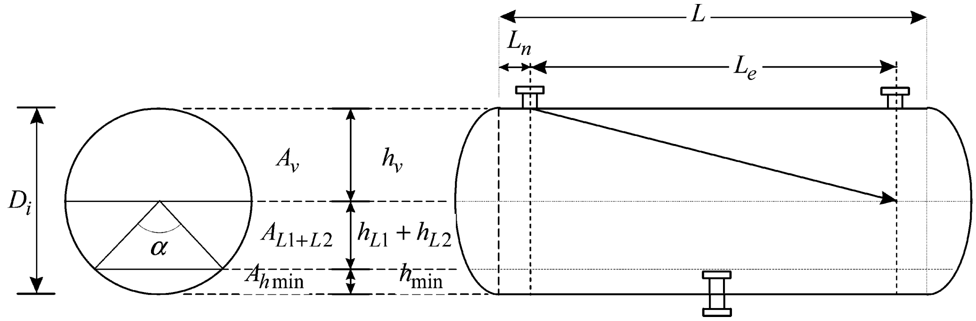

Figure 1. Critical settling path in knockout drum.

(opposite to the direction of droplet velocity) forces. The resultant of these forces causes acceleration a and motion in the direction of the net force F. An objective of design is to size the knockout drum such that the drag and buoyancy forces succumb to the gravity force, causing the droplet to disengage. The force balance on an average liquid droplet can be established by the application of Newton's law,

$$F = ma \tag{1}$$

where the vectors F and a are functions of time t, and m is the mass of the droplet.[15,17] The magnitudes of the gravity, buoyancy, and drag forces, respectively, are defined as follows:

$$F_G = \rho_l V_p g \tag{2}$$

$$F_B = \rho_v V_p g \tag{3}$$

$$F_D = \frac{C A_p \rho_v u^2}{2 g_c} \tag{4}$$

where A_p is the area of the particle projected on a plane normal to the direction of motion, F_D is the drag or resistance to motion of the body in fluid, u is the relative velocity between the particle and the main body of fluid, ρ is the density of the surrounding fluid, g_c is the acceleration due to gravity, and C is the dimensionless friction factor or drag coefficient.[15] The friction factor C, from a smooth sphere, can be calculated with the following relationship,[18,19]

$$C = \frac{24}{Re_p} + \frac{6}{1 + \sqrt{Re_p}} + 0.24 \tag{5}$$

where Re_p is the droplet Reynolds number, which is given by $Re_p = d_p \rho u/\mu$, where μ is the vapor viscosity (Stokes' Law), and the characteristic length is the droplet diameter. Settling theory considers the velocities of the phases through the separator and the settling velocity of the droplets.

2.2. Terminal Velocity. Terminal velocity is defined as the velocity at which the vertical component of the drag force exactly counteracts the net gravity force (force resulting from the gravity force downward and the buoyancy force upward). The motion mechanism for separating oil droplets in continuous gas phase, the force balance, and the acceleration on the body are zero, such that the body falls at a constant velocity.[2,4,10,15] The dropout velocity of a spherical particle of diameter d_p in a stream, relative to the vapor flow in the vertical direction, is given by

$$U_c = 1.15\sqrt{\frac{g d_p (\rho_l - \rho_v)}{\rho_v C}} \tag{6}$$

where ρ_l and ρ_v are the densities of the liquid and vapor at operating conditions, respectively. The friction factor C for both laminar and turbulent flow can be plotted and calculated by a function of bubble or drop Reynolds number by means of determination of the $C(Re)^2$ factor,[2]

$$C(Re)^2 = (0.13 \times 10^8)\rho_v d_p^{\,3}(\rho_l - \rho_v)/\mu^2 \tag{7}$$

and the friction factor can be computed by[13]

$$C = 78.241[C(Re)^2]^{-2.921} \tag{8}$$

Equations 6−8 determine the free settling velocity.

2.3. Critical Droplet Trajectories. The droplet terminal velocity must be less than the droplet velocity. The critical settling path in a two-phase separator is that, if the droplet is settled furthest away from its destination level, equal or larger sized particles, having initially equal or shorter traveling paths, will also reach their destination level (see Figure 1). Thus, in order to settle all 100 micron and larger particles, droplets must travel from the top of the separator through the gas phase before they escape into the gas phase. The critical settling path for a liquid droplet is related to the normal liquid level.[4,5,13] Two-phase separation should take place at any time when the levels are between low and high levels.[10,13] The critical settling path is, therefore, related to the maximum travel distance at the gravity settling section during flow operations (Figure 1). The continuous phases will change their flow directions in the end section, and no effective gravity settling can be expected. Knockout drum are used to prevent large slugs of liquid from entering the flare, such that the gas section must be designed so that most of the liquid droplets will settle and a relatively liquid-free gas will flow out of the knockout drum to be burned in the flare.

2.4. Drop Size. The liquid compartment in a knockout drum is designed based on the critical settling velocity of a certain size gas. Liquid particles will separate when the residence time of the vapor is greater than the time required to travel the available vertical height at the dropout velocity of the liquid particles. The vertical gas velocity must be sufficiently low to permit that the liquid droplets fall.[15,18,19] The separator design is fairly sensitive to the selected diameters of the settled droplets, such that the liquid section must be designed so that most of the gas will leave the knockout drum, and flares must be designed to handle small-sized liquid droplets. The allowable vertical velocity is based on separating droplets 100−600 μm in diameter.[2,8,9,13]

3. Formulation of the Optimization Model of the Knockout Drum Design Problem

The optimization model of the knockout drum design (KD) is outlined and discussed in the context of horizontal-oriented separators. For convenience, we have classified the constraints into four categories, namely, capacity, geometrical, transportation, and mechanical design constraints.

3.1. Gas Capacity Constraint. The vapor velocity is a function of the liquid level. The design of flowrate gas capacity in a two-phase knockout drum is based on oil droplet gravity settling in vertical height

$$Q_v = \alpha U_v A_t \tag{9}$$

where α is the ratio of vapor cross-sectional area above the liquid to total cross-sectional area of the vessel A_t and U_v is the velocity of N vapor passes. A design problem is to have sufficiently low vapor velocity to give enough time for liquid particles to settle out before the vapor leaves the vessel. Droplet trajectories are perpendicular to the gas velocity direction (see Figure 1). The travel time in vertical height for the gas through the settling section and the settling time for an oil droplet are given as

$$t_v = \frac{L_e}{U_v} \tag{10}$$

$$t_d = \frac{h_v}{U_c} \tag{11}$$

where L_e is the minimum cylindrical length of the knockout drum and h_v is the vertical space for the vapor flow. U_c is calculated from the requirement of a zero net force in the vertical height. In order that the droplet separation occurs, the next condition is required to complete the settling of an oil droplet of a certain particle size

$$t_v \geq t_d \tag{12}$$

Equations 10−12 lead to

$$L_e \geq h_v \frac{U_v}{U_c} \tag{13}$$

Equation 13 can be written in terms of the average volumetric flow rate and the cross-sectional area as

$$L_e \geq \frac{h_v}{\alpha A_t} \frac{Q_v}{U_c} \tag{14}$$

3.2. Liquid Capacity Constraint. The design of liquid capacity in the knockout drum is based on the gravity settling of liquid droplets. The liquid storage capacity should be estimated to design a knockout drum from the operation analysis of process plants, and it is necessary to determine the drum size required for the liquid entrainment separation. We can consider that the liquid volume, V_L, may result from (a) condensate holdup for 20−30 min that is separated during a vapor release contingency V_{L1} or (b) slope and drain volume V_{L2}. A horizontal vessel with an inside diameter, D_i, will be assumed.[2,6] This gives the following total cross-sectional area, A_t

$$A_t = \pi D_i^2/4 \tag{15}$$

A knockout drum normally should be sized for vapor−liquid separation at the maximum flow rate, when streams from process plants are released by pressure-relieving devices and blowdowns. From typical dimensions of horizontal-oriented knockout drums shown in Figure 1, the following relationships can be established,

$$V_L = L_e(A_t(1 - \alpha) - A_{hmin}) \tag{16}$$

$$V_{hmin} = L_e A_{hmin} \tag{17}$$

where A_{hmin} is the cross-sectional area for the minimum level of liquids and V_{hmin} is the volume for the minimum level of liquids. The cross-sectional area for the vapor flow A_v is given by

$$A_v = A_t - A_L - A_{hmin} \tag{18}$$

The vertical depth for the level of liquids is given by $h_L = h_{L1} + h_{L2}$, where h_{L1} is the vertical depth of slopes and drains and h_{L2} is the vertical depth of accumulated condensed liquids. The remaining vertical space for the vapor flow is named h_v. The inside drum diameter is calculated with the following equation,

$$D_i = h_v + h_L + h_{min} \tag{19}$$

and the cross-sectional area for minimum level of liquids is given by

$$A_{hmin} = \frac{D_i^2}{4}\left(\tan^{-1}\frac{X}{[1 - X^2]^{0.5}} + 1.573\right) - \left(\frac{D_i}{2} - h_{min}\right)(D_i h_{min} - h_{min}^2)^{0.5} \tag{20}$$

where

$$X = \frac{(D_i/2) - h_{min}}{D_i/2} \tag{21}$$

and h_{min} is the minimum height from the bottom of separator that reduces the volume available in the knockout drum.

3.3. *L*/*D* Ratio. Because an infinite set of separator lengths and diameters yields to feasible design, the structural design relationship L/D, defined as the relation of the ratio of the length to the diameter of the knockout drum, should be specified. It is common to determine the ratio based on plot restrictions, experience, and economic considerations.[2,8,9,13,20,21] Heinze,[20] Gerunda,[21] and Arnold and Steward[8,9] reported that L/D ratios of the order of 2−5 are commonly used in practice. Svrcek and Monnery[4] constrain their design to L/D ratios between 1.5 and 6. The L/D ratio considered in this paper is given by eqs 22 and 23, but it can be modified easily for any given L/D ratio.

$$L \leq 3D \tag{22}$$

$$L \geq 2.7D \tag{23}$$

3.4. Inlet and Outlet Nozzles Design. Minimum nozzle diameters for vapor (d_{nv}) and liquid (d_{no}) oil can be calculated with

$$L_n \geq 2(d_{nv} + d_{no}) \tag{24}$$

and the minimum nozzle size is given by

$$d_n \geq 0.161\sqrt{Q\rho^{0.5}} \tag{25}$$

where Q is the volumetric rate; eqs 24 and 25 are given in SI units, i.e., the coefficient has the following units: $m^{-0.25}s^{0.5}/$

$kg^{0.25}$. The liquid outlet is mounted with a vortex breaker,[11] which is designed according to the suggestions by Patterson,[22] of being twice the size of the inner diameter of the nozzles.

3.5. Transportation Constraints. Knockout drums dimensions, diameter, and length can be restricted by the separator size and/or service. For large shop-fabricated separators, diameter and length are usually limited because of over-the-road or rail transportation clearance restrictions. Thus, because of handling and transportation constraints, knockout drums have practical upper overall size limits given by

$$L \geq L_e + L_n + 2L_h + 2t_c \tag{26}$$

where t_c is the corrosion allowance and the chosen elliptical heads give $L_h = D_i/4$ and the following constraints

$$D \geq D_i + 2t_c \tag{27}$$

$$0 \leq D \leq 4.5 \tag{28}$$

$$0 \leq L \leq 20 \tag{29}$$

3.6. Mechanical Design Constraints. Vessel shells must be designed for the most severe conditions of coincident pressure and temperature expected in normal operation. The typical internal pressure of knockout drums in operation is nearly 1 atm. Vessels or their parts subject to thinning by corrosion, erosion, or mechanical abrasion have a provision made for the desired life of the vessel with a suitable increase in the thickness of the material determined by the design formulas.[11,23] The design equation for vessel shells under an internal pressure of 1.055 kg_f/cm^2 or greater, subject to circumferential stress, is

$$t_{cs} \geq \frac{P_D D_i}{2SE - 1.2P_D} + t_c \tag{30}$$

where t_{cs} is the minimum wall thickness of the cylindrical section, P_D is the design pressure, S is the maximum allowable stress value in tension, and E is the joint efficiency. The design pressure is used to determine the minimum permissible thickness of the various components of a pressure vessel such as the shell, heads, etc. The joint efficiency E ranges from 0.6 to 1 for 100% of X-rayed joints. The basic principle of radiographic examination of metallic objects is the same as in any other form of radiography such as medical radiography. Holes, voids, and discontinuities decrease the attenuation of the X-ray and produce greater exposure on the film or darker areas on the negative film.[24,25] The corrosion allowance, t_c, typically ranges from 1.5 to 3.2 mm. For vessels subject to internal pressure p only, the design pressure can be obtained by adding 2 bar or increasing 10% of the operating pressure, whichever is greater,[20]

$$p_D \geq \max(p + 200\,000, 1.1p) \tag{31}$$

The ASME[26] code approves the use of several different designs of heads on pressure vessels. Elliptical heads (2:1) provide an economic design with respect to material utilization because the ASME code determines that the overall vessel wall thickness should be the larger of the cylindrical section and head. The thicknesses of ellipsoidal heads are obtained with

$$t_{eh} \geq \frac{p_D D_i}{2SE - 0.2p_D} + t_c \tag{32}$$

This is less than the wall thickness of the cylindrical section. Depending on the application, the most commonly used materials of construction for welded pressure separators are carbon or low-alloy steel.

3.7. Objective Function. The objective function is the minimization of the manufacturing cost of knockout drums, which depends of the separator dimensions, diameter, and length. Another possible objective function could be the minimization of the surface area of the knockout drum; however, such an objective function may not result in minimum weight or the lower material cost. The objective cost function, denoted as C_{mkd},[25] can be formuled as[27]

$$C_{mkd} = t_{cs} F_c \rho_s [\pi D_m L + 2F_a F_h D_m^2] \tag{33}$$

where F_a is the factor determining the surface area of the vessel head from the squared vessel diameter, F_c is the manufacture cost factor per unit mass of a vessel head compared with the manufacturing cost of the vessel shell, F_h is the ratio of the manufacture cost per unit mass of a vessel head compared with the manufacturing cost of the vessel shell, ρ_s is the steel density, and D_m is the mean knockout drum diameter, which is defined as

$$D_m = \sqrt{\frac{D_i^2 + (D_i + 2t_{cs})^2}{2}} \tag{34}$$

Thus, the nonlinear objective function involves a manufacturing separator drum cost function, manufacturing cost factors, and the diameter and length of the knockout drum.

3.8. Bounds. In addition to the above-discussed constraints, the system also contains some nonnegative bounds for which the optimization model must account. The bounds are given from eqs 35−44.

$$0 \leq A_T \leq \frac{\pi}{4} D^2 \tag{35}$$

$$0 \leq A_{hmin} \leq A_v, A_L \leq A_T \tag{36}$$

$$0 \leq h_v, h_L \leq D_i \tag{37}$$

$$0 \leq D \leq 4.5 \tag{38}$$

$$0 \leq D_i \leq D_m \leq D \tag{39}$$

$$0 \leq L_e \leq L \leq 20 \tag{40}$$

$$1.5 \leq t_c \leq 3.2 \tag{41}$$

$$0 \leq t_v \leq t_v^U; \quad 0 \leq t_d \leq t_d^U \tag{42}$$

$$0 \leq U_v \leq U_v^U; \quad 0 \leq f \leq f^U; \quad f = \left(\frac{U_v}{U_c}\right) \tag{43}$$

$$0 \leq \alpha \leq 1 \tag{44}$$

3.9. Vapor Passes. The choice of two-pass flow into the knockout drum is optional. Indeed, we have two cases: (i) a horizontal drum with the vapor entering at each end on the horizontal axis and the outlet at the center of the knockout drum or (ii) a horizontal drum with the vapor entering in the center and leaving at each end on the horizontal axis of the knockout drum. A two-pass flow horizontal drum is more economical when minimum liquid storage is exhibited and the vapor flow is high, and the vertical gas velocity is sufficiently low to permit the liquid dropout to fall.[2,4,10,13,21,25] The velocity of two-pass flow vapor passes N is determined with

$$U_v = \frac{Q_v}{N\alpha A_t} \tag{45}$$

and the drum length required is determined with

$$L_e = N t_v U_v \tag{46}$$

The normal calculation for minimum nozzle size is given with one-half of the flow rate (eq 25).

3.10. Optimization Model. The optimization problem model of the knockout drum can be summarized as the minimization of the objective cost function (eq 33), subject to the fixed free settling velocity (eqs 6−8), the minimum nozzle dimensions (eqs 24 and 25), the design pressure (eq 31), the gas capacity constraints (eqs 9 and 14), the liquid capacity constraints (eqs 15−21), the transportation constraints (eqs 26−29), the mechanical design constraints (eqs 30−32), the fixed mean diameter (eq 34), and the bounds (eqs 35−44).

4. Parametric Approach for the Optimal Design of Knockout Drums

The optimization problem is addressed with a NLP model formulation based on the use of the volumetric capacity that is determined by the shell length and liquid depth. The gas capacity of a horizontal separator is proportional to the cross-sectional area of the vessel available for gas flow. The liquid capacity of a horizontal separator depends on the volumetric liquid settling capacity and the accumulation section of the separator. In this section, the model reduction is presented and the parametric approach is briefly discussed.

4.1. Model Reduction. The major difficulty in the optimization of the formulated model arises from bilinearities in eqs 9, 14, 16, and 17 and the objective function (eq 33). These bilinear terms may give rise to local minima and cause convergence difficulties. The procedure for obtaining the model reduction consists of fixing the basic variable α involved in the nonconvex terms (eqs 9, 14, and 16) in the KD. The other two design variables (L_e and D) must satisfy the structural relationship of L_e/D.[2,8,9,13,20,21] The variable $\alpha = A_v/A_t$ specifies the fraction of the total area A_t that should be have the sufficiently low vapor velocity to give the liquid particles enough time to settle out before the vapor leaves the vessel. The reduction of the number of complicating terms and variables is important for the systematic exploration of the design region associated with feasible designs of knockout drums. This model reduction scheme gives rise to the nonlinear program model KD-α, suggesting a parametric approach for conducting a systematic search to determine the optimal design of relief separators.

4.2. Solution Approach. The solution approach objective is to obtain the minimal cost of the NLP model. The procedure is based on the successive solutions of NLP models described in the previous sections. The method uses the KD-α model to generate good initial points for the KD model. The solution approach for the optimal knockout drum design is basically carried out by solving the KD model from a collection of starting points, systematically generated through the solution of a set of NLP problems that are defined by assigning different fixed values to α in the KD-α model. For example, once eqs 9, 14, and 16 have been utilized in the reduction scheme to generate the KD model for the optimization of a knockout drum exhibiting a variable cross-sectional fraction area, α remains as a complicating variable in the bilinear terms of the model, such that the KD model turns out to be a structured mathematical programming model. The solution approach for the knockout drums design reduces the number of design variables, hence reducing the search space. The solution strategy is then given as follows:

• Initialization:

1. Set $C^*_{mkd} = \infty$, $\alpha^* = \infty$.

2. Set $\alpha = 0$ and specify the size of the search step, $\Delta\alpha = 0$.

• Stage 1: (KD-α) model search

3. Solve NLP model (KD-α) with $\alpha = 0$. If the model (KD-α) is infeasible, then go to step 8.

4. If the optimal solution of the model (KD-α) presents an objective function value $C^*_{mkd,KD-\alpha} < C^*_{mkd}$, then set $C^*_{mkd} = C^*_{mkd,KD-\alpha}$ and $\alpha^* = \alpha$.

• Stage 2: (KD) model search

5. Solve NLP model (KD) from the optimal solution of model (KD-α).

6. If the optimal solution of the model presents an objective function value $C^*_{mkd,KD} < C^*_{mkd}$, with an associated optimal vapor cross-sectional area fraction value $\hat{\alpha}$, then set $C^*_{mkd} = C^*_{mkd,KD}$ and $\alpha^* = \alpha$.

7. Set $\alpha = \alpha + \Delta\alpha$. If $\alpha \leq 1$, then go to step 2.

• Ending step

8. If $C^*_{mkd} = \infty$, then it is probably that, if $\Delta\alpha$ is sufficiently small, the KD-α model is infeasible. Otherwise, the best-determined separator design exhibits an optimal vapor cross-sectional area fraction of α and a total separator cost equal to C^*_{mkd}.

Thus, the methodology adopted to generate a set of values of design variables (α, L_e, and D) can be obtained that gives the minimum total separator cost. The result of the solution strategy provides evidence that the optimization can lead to either the optimality or an infeasible design by solving a single problem, for each set of design variables.

5. Case Study

In this section, the optimization model derived in Sections 2 and 3 and the parametric approach presented in Section 4 is used for solving a case study reported in the literature.[2] GAMS[27] has been used as the equation modeling system, and GAMS/CONOPT[27] has been used as the NLP solver. The purpose is the minimization of manufacturing costs of a knockout drum for a single relief contingency. Equilibrium data and physical parameter values are shown in Tables 1and 2, respectively. The inlet two-phase separator operates at 13.8 kPa gauge and 149 °C. The sample calculations have been limited to the simplest design. Total flow rate, one-pass flow, and 1.89 m^3 of liquid storage for miscellaneous draining from the units are chosen.

Table 1. Equilibrium Data for Problem Design—Relief Contingency

total flow	25.2 kg/s
liquid flow	3.9 kg/s
vapor flow	21.3 kg/s
liquid density	496.6 kg/m^3
vapor density	2.9 kg/m^3
oil droplets diameter	300 microns
viscosity of the vapor	0.01 cp

Table 2. Physical Constants—Data for Design

E	1.0	h_{min}	0.1524 m
F_a	1.09	S	950 × 10^5 Pa
F_c	5.0 $/kg	T_c	0.0032 m
F_h	3.0	ρ_s	7850 kg/m^3

Table 3. Overall Solution for a Half-Filled Liquid Separator (Size of Knockout Drum)

areas (m^2)		diam. (m)		heights (m)		lengths (m)		vol. (m^3)	
A_t	6.162	D	2.808	h_v	1.388	L	8.423	V_l	16.026
A_v	3.048	DI	2.80	h_l	1.260	L_e	5.379	V_{hmin}	0.7256
A_l	2.98	D_m	2.8075	h_{hmin}	0.152	L_h	0.700		
A_{hmin}	0.135					L_n	1.637		

Table 4. Additional Optimal Results for a Half-Filled Liquid Separator

L/D	3	U_v/U_c	3.86
T_v	2.23 s	T_{cs}	0.0064 m
U_v	2.4 m/s	P_d	2.13×10^5 Pa
U_c	0.622 m/s		

5.1. Optimal Knockout Drum Manufacturing Cost and Dimensions for a Half-Filled Separator. For a half-filled liquid separator (i.e., $\alpha = 0.5$), Tables 3 and 4 summarize the results obtained with the proposed parametric approach. The minimum manufacturing cost is \$$31.4 \times 10^3$. The design diameter and length of the knockout drum are 2.808 and 8.423 m, respectively. For the case study, the heuristic procedure solution times are ~0.016 s.

The design of a knockout drum is typically governed by a number of constraints. Some of the geometrical constraints are minimum diameter and length, the structural relationship L/D, and the vapor cross-sectional area fraction α. In this work, the proposed heuristic parametric solution approach is used for determining a robust solution for the design problem under a variety of different scenarios of vapor cross-sectional area fraction α. Some recommendations about the distance for separation above the liquid level have been proposed in the literature. It has been suggested that the maximum liquid level should not be below that of a half-filled liquid separator.[21]

5.2. Effect of Design Parameters for a Constant Droplet Diameter. A number of results can be derived from model KD for the optimization of a knockout drum separator. In the following, analysis results of the effect of some design parameters of the knockout drum for a constant droplet diameter (300 microns) are presented.

5.2.1. Effect of the Variation of α on the Minimum Cost and the Vapor Velocity. Minimum cost and vapor velocity curves can be generated as a function of vapor cross-sectional area (α) and L/D ratios for liquid−vapor separation. Figure 2 shows the minimum separator cost and vapor velocity curves as a function of vapor cross-sectional area fractions α and L/D ratio for liquid−vapor separation generated with the proposed parametric approach. The feasible design space and optimal design are depicted from the manufacturing cost curve and the vapor velocity curve. The vapor velocity curve reveals that a decrease in cross-sectional area fractions leads to an increase in the vapor velocity when the diameter of the particle is constant (300 microns). The increased vapor velocity reduces the residence time of the droplet; thus, the distance that the droplet will fall during the residence time decreases. On the other hand, the minimum separator cost curve reveals that feasible designs that minimize the total cost can be found between 0.037 and 0.69 values of α for L/D ratios between 2.7 and 3. The manufacturing total cost curve defined the feasible design space to represent optimal designs where a set of knockout drum sizes fulfill the design requirements. Thus, every point in this feasible region corresponds to a unique optimal design that satisfies all the constraints. Then, it should be noted that a point on the curves in Figure 2 represents the minimum total cost and the best knockout drum designs in terms of the corresponding α. For instance, dotted vertical and horizontal lines touching the

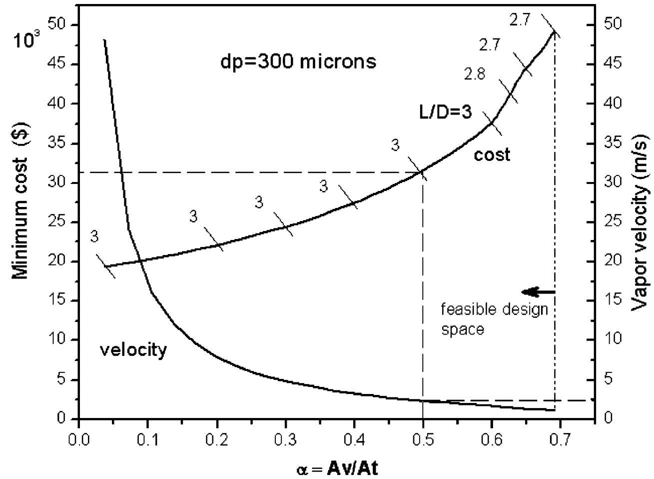

Figure 2. Minimum cost and vapor velocity curves as a function of α and L/D ratios.

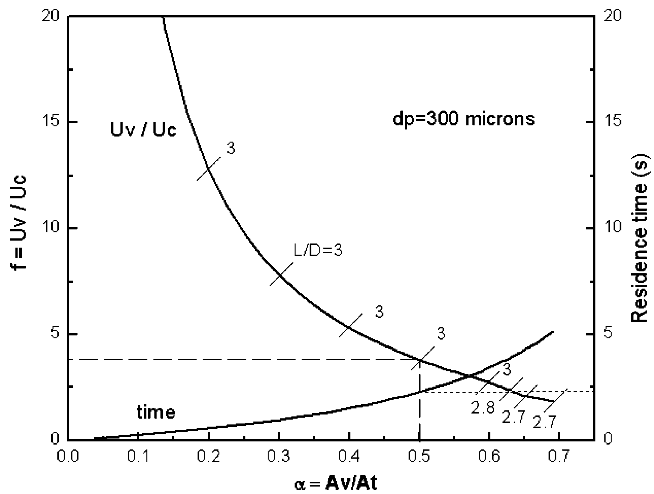

Figure 3. Ratio of vapor velocity to settling velocity f and residence time as a function of α and L/D ratios.

generated curves shown the optimal solution for $\alpha = 0.5$, where the vapor velocity is equal to 2.4 m/s and the residence time of the vapor is equal to 2.23 s. The lowest value for cost can be found for $\alpha = 0.037$, but one must be careful with vapor velocity and residence time constraints.

5.2.2. Effect of the Variation of α on the Ratio of Vapor Velocity to Settling Velocity and the Residence Time. It is important to emphasize that the geometry of the separator and the height of the vapor will determine whether the droplet is separated. As the height of the liquid is increased, the vapor flow area A_v decreases. The decreased area A_v leads to an increase in the vapor velocity, reducing the residence time of the droplet, which in turn decreases the distance that the droplet falls. Therefore, the selection of a particular knockout drum design should strongly take into consideration the vapor residence time and the recommended ratio of vapor velocity to settling velocity $f = U_v/U_c$. Vapor velocity is a function of the liquid level for a fixed volume flow of gas through the separator, and the critical settling velocity is a function of droplet diameter.

Curves of the ratio of vapor velocity to settling velocity f and residence time as a function of vapor cross-sectional area fractions α and L/D ratios are presented in Figure 3. A point on the curve of the ratio f implies that two of the variables, f and α, are specified. Thus, each point on that curve yields a unique optimal design. In the literature, it has been reported that the ratio f should not exceed the value of $f = 1.15$.[21] On

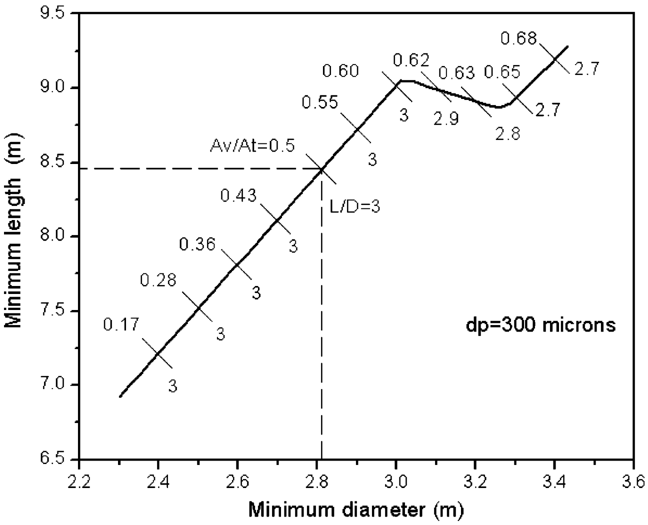

Figure 4. Minimum length as a function of diameter and as a function of α and *L/D* ratios.

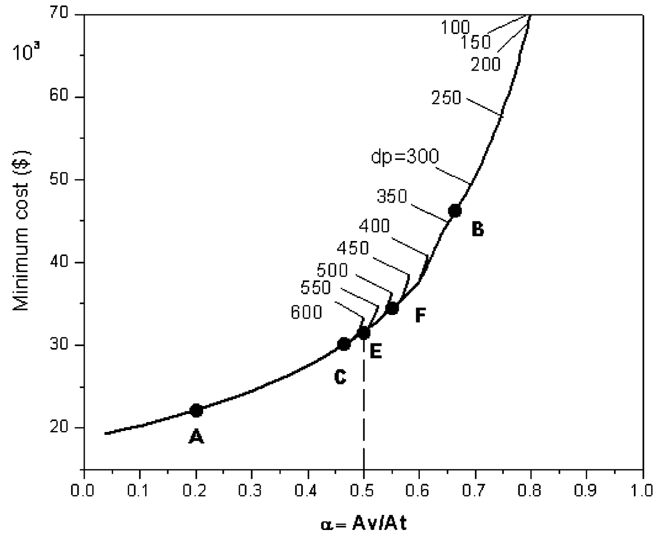

Figure 5. Minimum cost as a function of α and droplet diameter.

the other hand, Wu[10] suggested that the design vapor velocity for a separating vessel should be between 75% and 90% of the settling velocity, i.e., values of *f* between 1.75 and 1.90. However, in the literature, a knockout drum design problem involving 300 microns of particle diameter with higher values of the ratio of vapor velocity to settling velocity has been reported.[2] These values are accounted for $f = 5.5-10.6$, and they are associated with liquid dropout times of 1.45 and 0.98 s, respectively.

It can be seen from Figure 3 that the knockout drum design that minimizes the cost depends heavily on the ratio *f* and the residence time. Adequate residence time is required to accomplish the degree of separation of gas from oil. Liquid must be held in the knockout drum for a certain time to reach the gas−liquid equilibrium under working pressure. The results in Figure 3 show that feasible designs that minimize the ratio *f* can be found at values of $\alpha = 0.05-0.69$ for *L/D* ratios between 2.7 and 3. For instance, for $\alpha = 0.5$, *f* is equal to 3.82 and the residence time of vapor is equal to 2.27 s. Taking advantage of physical forces in the produced stream to achieve good separation, horizontal separators are operated half full of liquid to maximize the gas−liquid interface area. The design must provide sufficient retention time to allow the liquid to reach equilibrium. Thus, because of possible practical implications, the most suitable knockout drum size should be selected according to particular constraints, and the final selection must be made according to the lowest manufacturing cost.

5.2.3. Effect of the Minimum Diameter on the Minimum Length. The diameter of the knockout drum and the height of the liquid will determine whether the droplet is separated. To establish the size and design of a knockout drum, the designer must first determine the operational conditions for which maximum flow rate may be required. Reasonable care should be taken in establishing various possible contingencies for the suitable sizing. Figure 4 shows the minimum length for the best designs obtained for minimum inner diameter of the knockout drum, under different settings of α and *L/D* ratios, keeping the diameter of the particle constant at 300 microns. Figure 4 implicitly exhibits that, as the height of the liquid increases, the required distance or α for separation of the droplet decreases; as a consequence, the length and diameter of the knockout drum decrease in the same way. On the other hand, the vapor velocity is increased. The distance for separation is the diameter of the vessel minus the height of the liquid or the distance above the liquid level.

Figure 4 is also helpful to evaluate the convenience of a cylindrical length with respect to possible changes in α. For instance, if the base case with $\alpha = 0.5$ is considered as a reference, then Figure 4 indicates that any decrease in α would place the design problem deeper into the region in which an optimal design with low cost prevails over an optimal design with a complete knockout drum size. On the other hand, a small decrease in α will prevent the advantage of the best design with low cost because of a sudden increase of vapor velocity (see also Figures 2 and 3).

5.3. Effect of Droplet Diameter on Design Parameters. The purpose of the gas separation section is the gas condition that will flow out of the knockout drum to be further burned in the flare. As an extension of the cost performance proposed in Figure 2, let us consider the effect of different diameters of particles on the minimum manufacturing cost, α, the ratio *f*, and the residence time, as well as the minimum diameter of the best designs of knockout drums.

5.3.1. Effect of the Variation of α on Minimum Cost. Figure 5 presents the optimal cost derived with the proposed parametric approach, under different settings of α and particle diameters. Figure 5 reveals that, as the height of liquid increases, the required vapor cross-sectional area fractions for separation of the droplet decrease; as a consequence, the manufacturing cost increases to separate smaller particles. It should be noted that the minimum manufacturing cost of the proposed solution approach remains invariable for different droplet diameters at the same vapor cross-sectional area fraction.

Gas flows over the inlet nozzle and then horizontally through the gravity settling section above the liquid. As gas flows trough this section, small drops of liquid are separated by gravity and fall in the gas−liquid interface.

5.3.2. Effect of the Variation of α on the Ratio of Vapor Velocity to Settling Velocity and the Residence Time. The study of ratio *f* and residence time curves as a function of α and the droplet diameter is presented in Figure 6. The importance of using the ratio *f* to design robust knockout drums has been stressed.[10,13] The velocity curves shown the same tendency for 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, and 600 droplet diameters. For a given design problem involving a particular size of particle diameter, higher values of ratio *f*

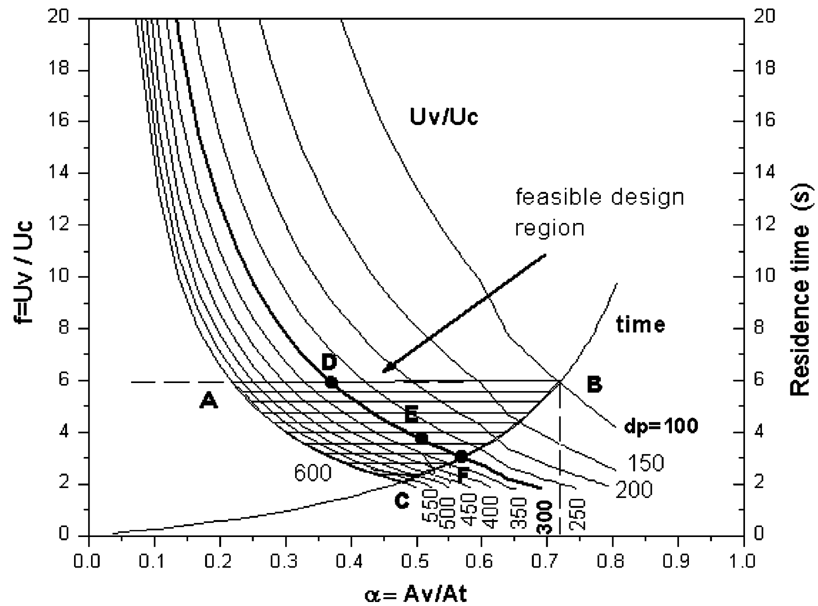

Figure 6. Knockout drum feasible design region.

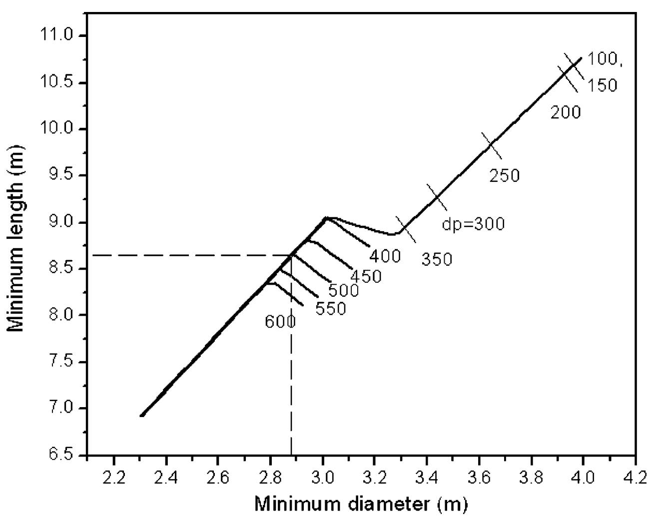

Figure 7. Minimum length as a function of minimum diameter and droplet diameter.

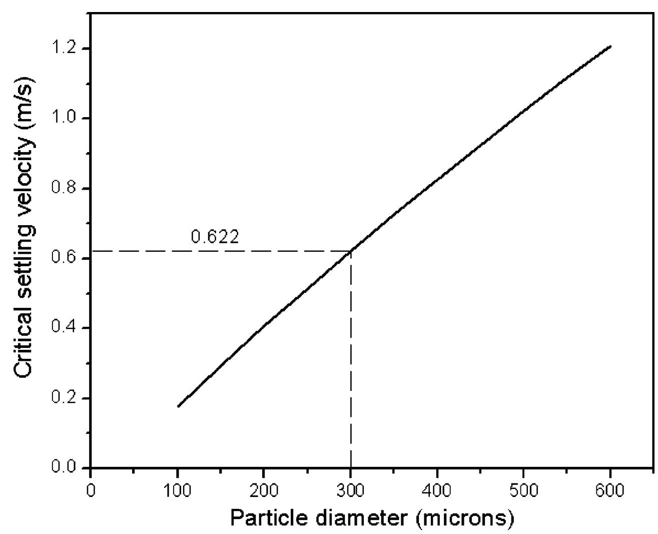

Figure 8. Critical settling velocity for different droplet diameters.

decrease the capacity to store liquids; as a consequence, the vapor residence time and the vapor cross-sectional area decrease in the same way. The curves on Figure 6 represent the optimal solution of the programming problem obtained by fixing α in model KD. Therefore, the highest point of each of the curves is associated with more expensive knockout drum designs. The region of feasible designs in Figure 6 is discussed in Section 5.4.

5.3.3. Effect of the Minimum Diameter on the Minimum Length. The study of the minimum length as a function of diameter can be studied rigorously and systematically with the proposed design approach. Figure 7 presents plots of the minimum length of the knockout drum obtained for different values of droplet diameters, where the gas capacity conditions are satisfied, allowing the liquid drops to fall from the phase gas to the liquid volume as the gas travels through the effective length of the vessel. It can be seen from the minimum length curve in Figure 7 that, when the diameter of the particle decreases, then higher length and diameter of the knockout drum will be required.

5.3.4. Critical Settling Velocity. Figure 8 presents the results obtained with the proposed parametric optimization for the settling critical velocity as a function of particle diameter. The concept of terminal velocity is associated as the velocity at which the vertical component of the drag force exactly neutralizes the net gravity force for spherical particles. The net force and the acceleration on the body is zero and the particle falls at a constant velocity. The solid line in Figure 8 represents the critical settling velocity required by the best separator designs in terms of the diameter of particle. For the case study with $\alpha = 0.5$, the critical settling velocity is equal to 0.623 m/s for a 300 particle diameter. In general, the critical settling velocity takes higher values when the particle diameter is increasing.

5.4. Region of Feasible Designs. The results previously discussed show that knockout drum feasible designs that minimize the total cost can be found between 0.037 and 0.806 values of α, *L/D* ratios between 2.7 and 3, and for 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, and 600 dropout diameters (Figures 2 and 5). Similar results can be seen in Figures 3 and 6 for separator feasible designs as a function of the ratio of vapor velocity to settling velocity. The minimum length as a function of the minimum diameter can be seen in Figures 4 and 7, and the critical settling velocity can be seen in Figure 8. In general, a point on the solid lines represents an optimal total cost and the best knockout drum designs in terms

Table 5. Optimal Solution for a 300 μm Dropout Diameter (Size of Knockout Drum)

areas (m^2)		diam (m)		heights (m)		lengths (m)		vol (m^3)	
A_t	5.372	D	2.621	h_v	0.824	L	7.865	V_l	16.026
A_v	1.981	DI	2.615	h_l	1.638	L_e	4.914	V_{hmin}	0.6378
A_l	3.261	D_m	2.621	h_{hmin}	0.152	L_h	0.654		
A_{hmin}	0.135					L_n	1.637		

Table 6. Additional Results for a 300 μm Dropout Diameter

L/D	3	U_v/U_c	5.961
T_v	1.32 s	T_{cs}	0.0061 m
U_v	3.707 m/s	P_d	2.13×10^5 Pa
U_c	0.622 m/s		

of the corresponding vapor cross-sectional area fraction, α. It should be noted that the solid lines define a feasible design space that represents optimal designs where a set of knockout drum sizes fulfills the design requirements. Consequently, every point in this feasible region corresponds to a unique optimal design that satisfies all the constraints.

The plot of f and α defines a region of feasible designs as discussed before (see Figure 6). It is important to emphasize that the dropout residence time of the proposed solution approach remains constant for different droplet diameters at the same α. The separator manufacturing cost increases dramatically below the curve of dropout residence time, as consequence of increases in α in the two-phase separator. It should be noted that the manufacturing cost increases considerably from \$50 (10^3) to \$70 (10^3) when α changes from 0.7 to 0.8, with respect to previous intervals on the horizontal axis (see Figure 5).

The upper limits of the ratio f and α on the f versus α plot (Figure 6) define a region design area (ABCA) for 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, and 600 dropout diameters. The maximum ratio of f versus α (f^{max} and α^{max}) represents limits to the ability of expensive knockout drum designs. Then, upper and lower bounds can be defined as

$$0 \le f \le f^{max} \le f^{U} \tag{47}$$

$$0 \le \alpha \le \alpha^{max} \le 1 \tag{48}$$

Thus, bounds 47 and 48 reduce the region of feasible designs (shaded in Figure 6) based on economical constraints. Upper points lying on f^{max} at the horizontal line (AB) in the region design specifies the best knockout drum design associated with the corresponding point on the plane of the α limits.

On the basis of the results previously presented, the point defining the minimum manufacturing knockout drum cost for several dropout diameters can be easily determined. For instance, point D in Figure 6, at coordinates (0.3687, 5.9612), represents the best design for the base case proposed, which corresponds to a value of \$26.471 (10^3) for minimum total manufacturing knockout drum cost. The corresponding values of DI and L are 2.6217 and 7.8651, respectively, which are read from Figure 4. The manufacturing cost difference with respect to the base case for a half-filled liquid separator is \$4.93 (10^3) of savings. The points E and F in Figure 6 represent the half-filled liquid separator design and the worst economical allowable separator design, respectively. In Figure 5, the feasible design region limits are also reported with points ABCDEF.

The final calculations with 300 μm of dropout diameter for determining the final vessel length and diameter are as reported in Tables 5 and 6. The complete design solutions for the case study using the KD model are presented in Tables 2−6 and Figures 2−8. The parametric approach proposed for the optimal design of separators can be conveniently apply to larger problems, reducing the number of degrees of freedom and, consequently, the design search space.

6. Conclusions

In this paper, we presented an optimization procedure to conduct a systematic search for the optimal design of two-phase knockout drums for Oil industry applications. The objective function is the minimization of separator vessel manufacturing cost. The model proposed and its parametric solution algorithm determine the optimal horizontal-oriented knockout drum design for a nominal set of design parameters. The optimum design is obtained through a parametric search approach over the design variables implemented in an automated model. The solution approach for a knockout drum design reduces the number of design variables, which reduces the search space. The feasible design space to represent optimal designs where a set of knockout drum sizes fulfill the design requirements has been developed for a case study for relief contingency. The application of the proposed parametric approach for the three-phase problem is under development and will be reported elsewhere.

Nomenclature

Physical Constants

g = acceleration due to gravity, 9.81 m/s^2

Parameters

C = drag coefficient
$C(Re)^2$ = droplet Reynolds's factor
d_p = particle diameter, m
E = joint efficiency, dimensionless
F_a = factor for determining surface area of a vessel head from vessel diameter squared (=1.09 for 2:1 elliptical heads), dimensionless
F_c = cost factor per unit mass to manufacture a vessel head compared with that of vessel shell, \$/Kg
F_h = ratio of cost per unit mass to manufacture a vessel head compared with that of vessel shell (usually 1.5 to 4.0), dimensionless
h_{min} = minimum height from bottom of separator, normally 0.1524 m
N = vapor passes
p = internal pressure, Pa
P_D = design pressure, Pa
Q = volumetric rate, m^3/s
Re = Reynolds number
S = maximum allowable stress value, Pa
t_c = corrosion allowance, m (ft)
t_{he} = wall thickness of elliptical (2:1) heads, m
T = temperature, °C
U_c = dropout velocity, m/s
V_{L1} = volume for slops and drains, m^3
V_{L2} = volume for accumulated condensed liquids, m^3
V_L = volume for accumulated liquids, m^3
ρ_l = liquid density at operating conditions, kg/m^3
ρ_v = vapor density at operating conditions, kg/m^3
ρ_s = steel density, kg/m^3
μ = vapor viscosity, cP

Positive, Continuous Variables

A_t = total cross-sectional area, m^2
A_L = cross-sectional area for liquid, m^2
A_{L1} = cross-sectional area for slops and drains, m^2

A_{L2} = cross-sectional area for accumulated condensed liquids, m^2
A_{hmin} = cross-sectional area for minimum level of liquids, m^2
A_v = cross-sectional area for the vapor flow, m^2
D_m = mean knockout drum diameter, m
D_i = inner knockout drum diameter, m
D = knockout drum diameter, m
h_L = depth for level of liquids, m
h_{L1} = depth of slops and drains, m
h_{L2} = depth of accumulated condensed liquids, m
h_v = vertical space for the vapor flow, m
L = cylindrical length of knockout drum, m
L_e = minimum cylindrical length of knockout drum, m
t_{cs} = minimum wall thickness of the cylindrical section, m
t_v = residence time of the gas or vapor, s
t_d = liquid dropout time particles, s
U_v = velocity of N vapor passes, m/s
V_{hmin} = volume for minimum level of liquids, m^3
α = vapor cross-sectional area fraction

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