Design and CFD Simulation of Knockout Drum

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Abstract:

Recently, the emission of black smoke over local area of Basra Oil Company from flare system represents a big problem facing the company and causing huge pollution in the surrounding environment. The main reason of emission black smoke is carryover of droplets of the rest hydrocarbons such as condensate and droplets of crude oil by gases which are came from degassing stations facility in the north Rumelia field, southern Iraq. In this study, a design methodology was developed for designing the knockout drum, and different design criteria were used in sizing and selecting the drum based on the specification of the inlet fluid mixture. Three designs of knockout drums with respect to the gas conditions were performed. The horizontal knockout drum with a diameter of 2.5 m and length of 5.5 m was simulated using a Computational Fluid Dynamics (CFD) model (ANSYS FLUENT 15.0). The CFD model predicted very well the two-phase flow behavior and proved the need for a vortex breaker at the liquid outlet. The CFD simulation revealed quantitatively that the design configuration of the knockout drum performed the separation of condensate droplets from natural gas with excellent efficiency.

Keywords: Konckout drum, CFD, simulation, flare emissions.

1. Introduction:

The flare system is commonly used by refineries, chemical plants and gas processing facilities around the world as an appropriate and safe way to deal with excess gas generated as part of the production or refining process [1].

The black smoke emission is one of most dangerous problems facing Basra Oil Company , the main reason is the flare system which burning an excessive amount of liquids and condensates [2]. The Rumalia oil field is located in south Iraq near the city of Basra. It runs down to the Kuwait border and is approximately 80 km wide. The production facilities are comprised of hundreds of production wells and 14 degassing stations (7 in North Rumaila and 7 in south Rumaila) for the collection, stabilization and export of the treated oil. The field has been developed since the 1950s and had declined to less than one million barrels of oil per day of production in recent years due to reservoir and /or facility limitations [3].

Degassing station DS-1 in the North Rumaila field was taken as an example to the black smoke emission at southern Iraq and how can to solve this problem. Degassing station DS-1 currently is located in close proximity to the company office and is consisted of eight trains (A, B, C, E, F, G, H, I), (A, B, & C) trains are divided into four stages separation while the other trains have three stage separators. Fig. 1is illustrating train A. Eight storage tanks are available inside DS-1, which are also connected to flare stacks and these flares face the same problem of black smock emissions [4]. Figure (2) is a Photograph show the Black smoke.

Fig. (1) Photograph of Train A of Degassing station DS-1[4]

Fig. (2) Photograph of Black smoke [2]

Knockout drum separators are essential compound in degassing station inside the oil productions field, which is located before the flare stack as the final separator system [5]. Since DS1station didn't has Knockout drum separator, and it suffer from unstable operating conditions and black smoke emission, from that it is suggested to add Knockout drum in this station. Where;

DS-1 trains A, first and second stages (1^{st} & 2^{nd}) are selected to put the new separator before flare as shown in the Figure (3).

The same technical procedures are done to third and fourth (3^{rd} & 4^{th}) stages, and for Tank flare which are suffer from the same problems.

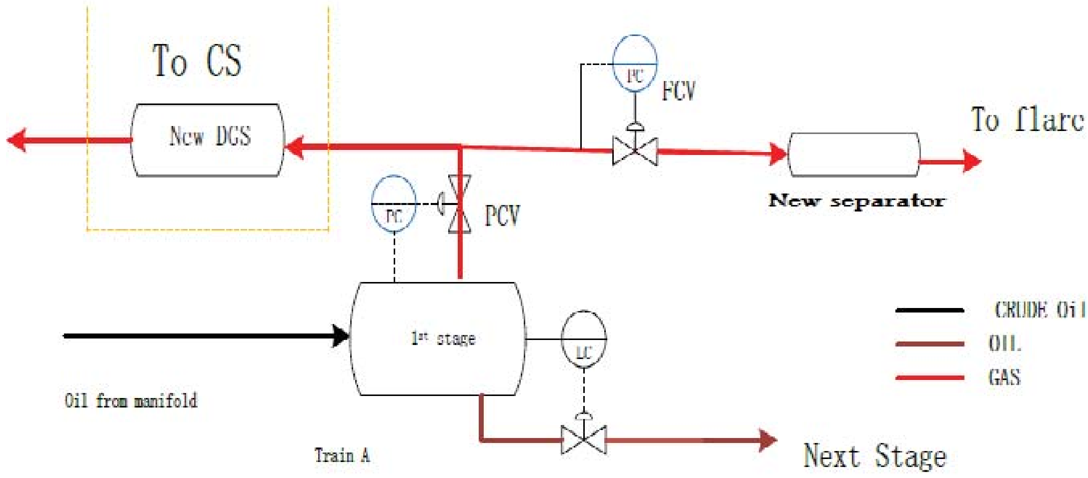


Fig. (3) Location of new separator before flare [2]

Schematic flow diagram of flare system is illustrating as shown in Figure (4).

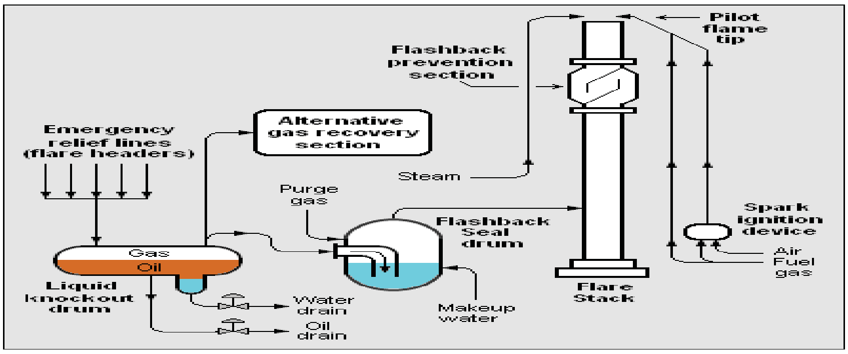


Fig. (4) Schematic flow diagram of an overall vertical, elevated flare stack system in an industrial plant [5].

Currently, DS-1 train A is consists of flare stacks only without Condensate handling System, and as results of that sometimes the liquid hydrocarbons which is carry over with gas is burning with flare lead to improper burning and creates the black smoke [4], So the first step to solve black smoke emission is design knock out drum as a separator according to design and operation conditions for DS-1 train A [7].

Knockout drum have been widely used to perform separation of condensate droplets from natural gas. Knock out drum is two phase separators (vapor-liquid) and it is oriented either vertically or horizontally. It should be chose from these two types which one is more economic [6]. These separators are design with or without mist eliminators and inlet diverters. Vapor liquid separator is accomplished in three stages. Primary stage by inlet diverter so that the momentum of the liquid content in the vapor phase grow up to large droplets as a result of impingement on the diverter and drop by gravity. Second stage is gravity separation, of droplets as the flow through the large volume of separator (disengagement volume). Final stage is the mist eliminator the part that smallest droplets are coalesced to form large droplets which will separate by gravity [8].

2. Design Methodology:

The design methodology that could be adopted for sizing the dimensions of the knockout drum is based on calculation of the allowable velocity for settling the liquid droplets. Specifically, the disengagement volume can be determined from the allowable velocity. Making a force balance on liquid settling out is to get the necessary relationship [9-13].

Stock equation $F_{vis} = 6\pi\mu R_p v_p$

Drag equation $F_{drag} = C_D \frac{1}{2} A \rho_v v_p^2$

Gravity-Buoyancy equation $F_g = (4/3) (\rho_L - \rho_v) g \pi R_p^3$

Since $F_{drag} >> F_{vis}$, therefore the balance the forces become:-

$(1/8) C_D \pi D_p^2 \rho_v v_p^2 = (4/3) (\rho_L - \rho_v) g \pi R_p^3$

Where C_D= drag Coefficient, D_p, R_p=droplet diameter, radius, ρ_L, ρ_v Liquid, vapor density, vp= droplet velocity.

So Terminal velocity for settling of heavier liquid droplets is

$$U_T = \sqrt{\frac{4gDp(\rho L - \rho v)}{3CD\rho v}}$$

The vertical velocity is less than Terminal velocity and set as 0.75 of it.

Sit $U_V=0.75\ U_T$

Terminal velocity equation rearranged to

$$U_T = K\sqrt{\frac{(\rho L - \rho v)}{\rho v}}$$

Where K is a function of droplet size and drag coefficient (which is a function of vessel size, vapor properties, vapor flow rate, and droplet size). The theoretical K is as follows:

$$K = \sqrt{\frac{4gDp}{3CD}}$$

Because of droplet diameter is hardly predict so K value is typically empirical. There are many literature and technical publications for calculation of K value (charts or empirical equations).

$K = 0.021 + 0.0325h, \quad 3 < h < 12,$

With a maximum value 0.4. This equation is for standard efficiency pads. For vertical or inclined pad installation position the values of K should be taken 2/3 of the horizontal ones.

Another equation may be used to calculate K

$K=-0.0073+(0.263/(x^{1.294}+0.573))$ $\quad 0.04<x<6$

Where x is a function of the weight flow rates and densities of the phases

$$x = \left(\frac{WL}{Wv}\right)\sqrt{\frac{\rho v}{\rho L}}$$

Or another empirical equation

$K = EXP(A+Blnx+C(lnx)^2+D(lnx)^3+E(lnx)^4$

$$x = \left(\frac{WL}{Wv}\right)\sqrt{\frac{\rho v}{\rho L}}$$

A=-1.877478, B=-0.81458, C=-0.187074, D=-0.014523, E=-0.001015

And from vapor volumetric flow rate and vapor velocity, vessel inside diameter is calculated by:

$$D=\sqrt{\frac{4*Q_V}{\pi*U_V}}$$

Calculation of hold up volume from hold up time which is chosen from literatures

$V_H=T_HQ_L$

Simply V_S surge volume is calculated by (even T_s is chosen from literatures):

$V_S=T_SQ_L$

Then the calculation of the height of low liquid level by

$H_{LLL} = 0.5D+7$

And the Height of normal and high liquid level by the equation:

$$H_{NLL}=\frac{V_H}{\frac{\pi}{4}D^2}$$

$$H_{HLL}=\frac{V_S}{\frac{\pi}{4}D^2}$$

From that the Liquid depth is $H_{LLL}+H_{NLL}+ \quad H_{HLL}$

H_F=12+d_N

Where H_F is the high from H_{HLL} to the center inlet line (d_N) which is calculated by the equations:

$$d_N=\sqrt{\frac{4*Q_m}{\pi*60\,/\sqrt{e_m}}}$$

Where:

Q_m =Q_L+Q_V

ρ_m=ρ_Lx+ρ_V(1-x)

$$x=\frac{Q_L}{Q_{L+}Q_V}$$

The calculation of vapor space is done as follow:

H_D= 24+1/2 d_N

Add 0.5 ft for mist eliminator pad and 1 ft from the top of mist eliminator to the top of vessel head (H_w) to the height to get the total vessel height as:

H_T=H_{LLL}+H_{NLL}+H_{HLL}+H_F+H_D+H_W

The above equations are used for vertical knockout drum.

If L/D > 5 so it should be used horizontal drum

For horizontal design, it will use the same first equations until surge volume equation.

Then estimate of L/D, and calculate vessel diameter from equations:

$$D=\left(\frac{4(V_H+V_S)}{\pi(0.6)(\frac{L}{D})}\right)^{1/3}$$

Then total cross sectional are:

$$A_T=\frac{\pi}{4}D^2$$

Low liquid level is calculated by:

$H_{LLL} = 0.5D + 7$

Then obtain of $\frac{Alll}{A_T}$

$$\frac{Alll}{A_T} = \frac{a+b(\frac{Hlll}{D})+c(\frac{Hlll}{D})2+d(\frac{Hlll}{D})3+e(\frac{Hlll)4}{D}}{1+f\frac{Hlll}{D}+g\left(\frac{Hlll}{D}\right)2+h(\frac{Hlll}{D})3+j\left(\frac{Hlll}{D}\right)4}$$

Where: A = 4.756, b =0.175, c =5.66, d =-4.916, e = -0.145, f = 3.924 , g = -5.359, h = 4.018, j = -1.802

Using the same above equation to calculate $\frac{A_v}{A_T}$

From $\frac{H_v}{D}$, Where: H_v = 0.2 D ,and then obtain A_v that used to get vessel length

$$L = \frac{V_H + V_s}{A_T - A_v - A_{lll}}$$

For Calculate the minimum length for vapor –liquid disengagement by the procedure

$$\emptyset = \frac{Q_v}{Av}$$

$$\mathrm{UAV} = \frac{\mathrm{Q_V}}{\mathrm{A_v}}$$

$L_{min} = U_{AV} * \emptyset$

Where $\emptyset$ = liquid dropout time, U_{AV} = actual vapor velocity

Know compare between L and L_{min}

If L < Lmin then set $L=L_{min}$

$L \ll L_{min}$ increase H_v and repeat calculation from its equation

$L > L_{min}$ the design is acceptable

$L \gg L_{min}$ decrase H_v and repeat calculation from its equation

After that it should be check the new $\frac{L}{D}$

If $\frac{L}{D} > 6.0$ then increase D and repeat the calculation from its equation

$\frac{L}{D} < 1.5$ then decrease D and repeat the calculation from its equation

Wall thickness, surface area and approximate knockout drum weight is calculated by :

Shell thickness (ts) = $\frac{P*D}{2SE-1.2\ P} + t_c$

Elliptical head thickness (t_H)= $\frac{P*D}{2SE-0.2\ P} + t_c$

Where D = diameter (in), S = allowable stress, E = joint Efficiency, t_c = corrosion allowance (in), shell surface area $A_s = \pi DL$

Elliptical head surface area $A_{H} =$ 1.09 D^2

Approximate knockout drum weight W = $(\rho s)\ (\frac{t_s}{12})(As + 2A_H)$

Finally calculate normal liquid level height $H_{Nll}$and high liquid level heigh from this equation.

$$A_{Nll} = A_{lll} + \frac{V_H}{L}$$

$$\frac{A_{Nll}}{D} = \frac{a + b\frac{A_{Nll}}{A_T} + c(\frac{A_{Nll}}{A_T})2 + d(\frac{A_{Nll}}{A_T})3 + e\left(\frac{A_{Nll}}{A_T}\right)4}{1 + f\frac{A_{Nll}}{A_T} + g\left(\frac{A_{Nll}}{A_T}\right)2 + h(\frac{A_{Nll}}{A_T})3 + j\left(\frac{A_{Nll}}{A_T}\right)4}$$

Where:

a=0.0015, b=3.299, c=24.354, d=-36.999, e= 9.893, f = 26.787, g =-22.924, h=-14.845, j=10.5296

And $H_{Hll} = D - H_v$

3. Design Results:

I- Knockout drum relating to first and second stages of Degassing station DS-1as shown in Table (1).

Table (1) Operating conditions and design results of 1 & 2 stages

Name	results	Units
Gas flow rate (Q_v)	7638.9	ft^3/min
Gas density (ρ_V)	0.069	Ib/min
Liquid flow rate (Q_L)	15.27	Ft^3/min
Liquid density (ρ_L)	49.94	Ib/ft^3
Operation pressure	3	bar
Design pressure	9	bar
Operation temperature	55	C^0
Design temperature	-10 -100	C^0
Internal diameter (ID)	2.5	m
Length (L)	5.5	m
Diameter of inlet pipe (d_n)	20	in
Diameter of outlet gas pipe (d_g)	20	in
Diameter of inlet liquid pipe (d_L)	6	in
Hight of low liquid level (H_{LLL})	0.375	m
Hight of normal liquid level (H_{NLL})	o.75	m
Hight of high liquid level (H_{HLL})	1.125	m
Sheel thickness	0.5	in
Head thickness	0.5	in
Material	Carbon steel +internal coated of Epoxy ceramic	

II- Knockout drum relating to third and fourth stage of Degassing station DS-1 as shown in Table (2).

Table (2) Operating conditions and design results for 3 & 4 stages

Name	results	Units
Gas flow rate (Q_v)	833.3	ft^3/min
Gas density (f_V)	0.109	Ib/min
Liquid flow rate (Q_L)	1.66	Ft^3/min
Liquid density (f_L)	49.4	Ib/ft^3
Operation pressure	1.5	bar
Design pressure	6	bar
Operation temperature	53	C^0
Design temperature	-10 -100	C^0
Internal diameter (ID)	1.2	m
Length (L)	3	m
Diameter of inlet pipe (d_n)	6.5	in
Diameter of outlet gas pipe (d_g)	6.5	in
Diameter of inlet liquid pipe (d_L)	3	in
Hight of low liquid level (H_{LLL})	0.16	m
Hight of normal liquid level (H_{NLL})	o.325	m
Hight of high liquid level (H_{HLL})	0.5	m
Sheel thickness	0.25	in
Head thickness	0.25	in
Material	Carbon steel +internal coated of Epoxy ceramic	

III- Knockout drum relating to the tank of Degassing station DS-1 as shown in Table (3).

Table (3) Operating conditions and design results for tank

Name	results	Units
Gas flow rate (Q_v)	555.5	ft^3/min
Gas density (f_V)	0.089	Lb/min
Liquid flow rate (Q_L)	1.11	Ft^3/min
Liquid density (f_L)	49.9	Lb/ft^3
Operation pressure	0.5	bar
Design pressure	5	bar
Operation temperature	51	c^0
Design temperature	-10 -100	c^0
Internal diameter (ID)	1	m
Length (L)	2.6	m
Diameter of inlet pipe (d_n)	4	in
Diameter of outlet gas pipe (d_g)	4	in
Diameter of inlet liquid pipe (d_L)	2	in
Hight of low liquid level (H_{LLL})	0.15	m
Hight of normal liquid level (H_{NLL})	o.3	m
Hight of high liquid level (H_{HLL})	0.45	m
Sheel thickness	0.2	in
Head thickness	0.2	in
Material	Carbon steel +internal coated of Epoxy ceramic	

4. CFD Simulation:

Predictions of multiphase flow behavior can be performed using sophisticated Computational Fluid Dynamics (CFD) software packages such as ANSYS- Fluent, which is one from CFD programs and it is a numerical program for solving continuity and momentum equations. The horizontal knockout drum with a diameter of 2.5 m and length of 5.5 m designed for separation of condensate droplets from natural gas feed of 11,000,000 ft3/day was considered as case study to simulate the gas-liquid flow field within the knockout drum using a two dimensional transient CFD model. A sketch of the knockout drum is shown in Figure (5). The CFD model was based on a two-phase flow Reynolds-Average Navier-Stokes equations (RANS), closed via the RNG $k-\varepsilon$ turbulence model, continuity equation, Transit, with interaction between droplets and gas (flotation and gravity), at the boundary conditions, the above flow rate, with zero velocity at the wall, the pressure 9 bar, with atmospheric outlet pressure. Fig. 6 shows snapshots of contours of gas volume fraction at different times, where red color shows that the volume fraction of gas is 1.0, whereas blue color indicates the regions where volume fraction of gas is 0 (i.e., volume fraction of condensate is 1.0). By considering the overall flow structure of present case as unsteady flow, it is shown that the knockout out performed separation of condensates droplets from gas completely. The volume fraction of condensate at gas outlet is 0.0. It is also clearly shown the stages of gas funnel formation at the interface of phases and the penetration of gas towards the liquid outlet. Therefore, it is very necessary to install a vortex breaker at the liquid outlet.

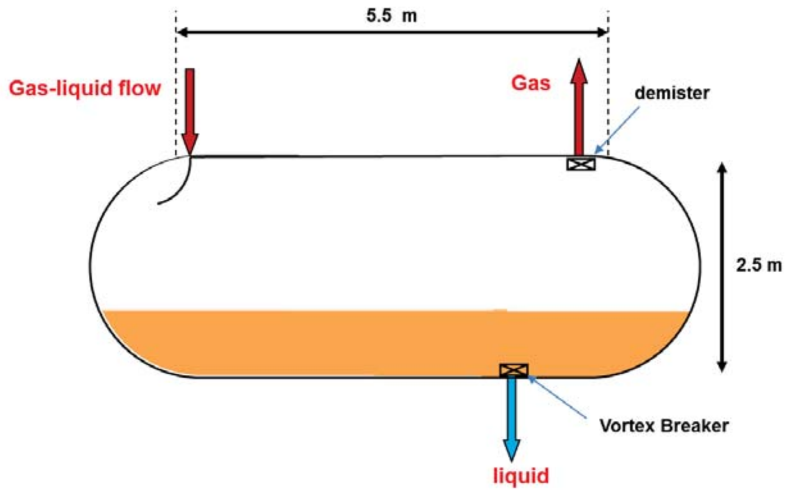
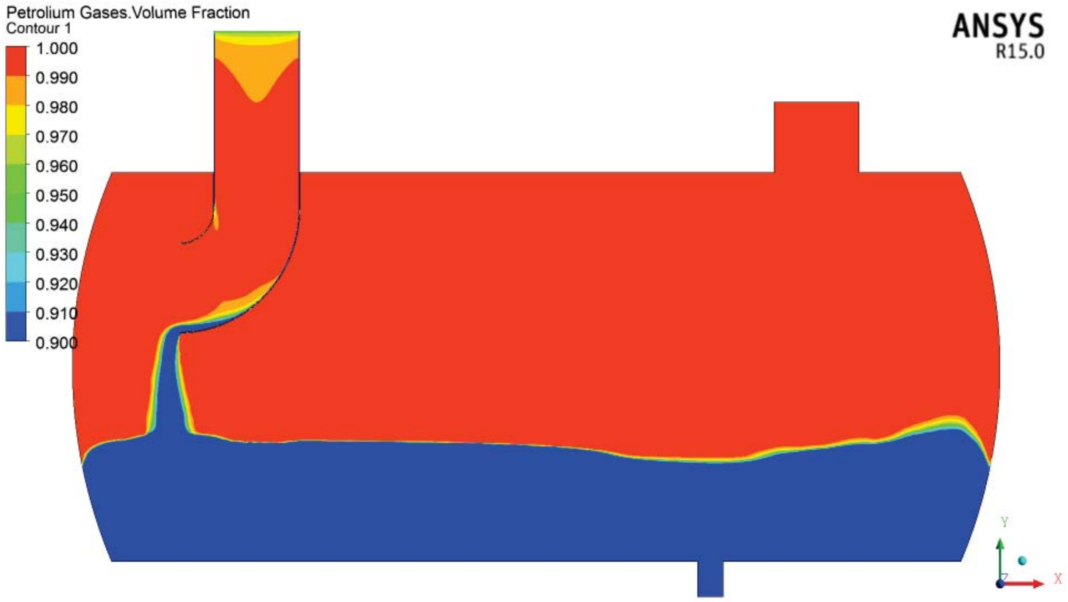
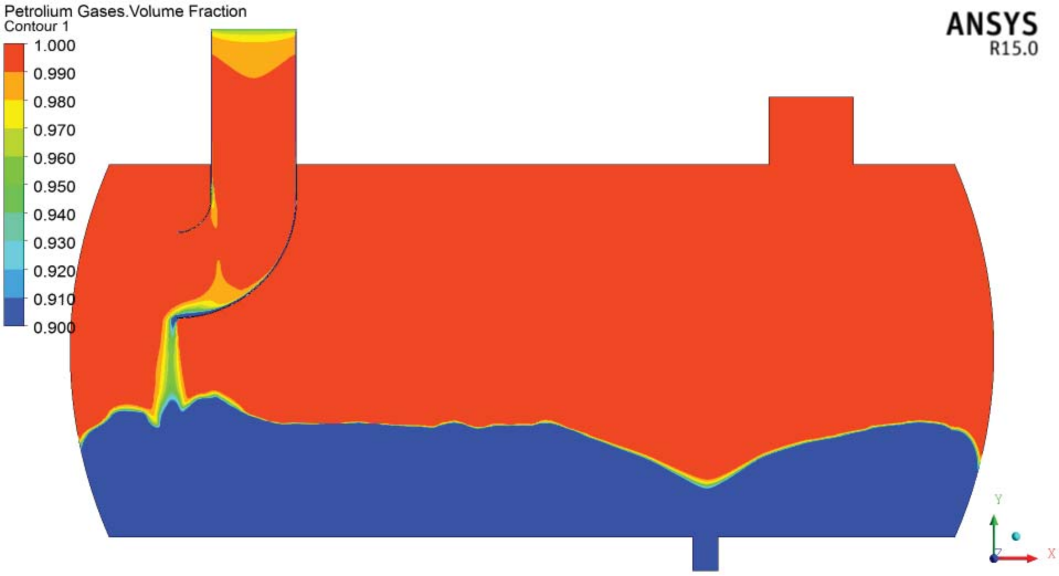


Fig. (5) Knockout drum sketch

Note: The figure is attached with more details in separate word program because it is landscape orientation paper layout



(A)


Petrolium Gases.Volume Fraction
Contour 1
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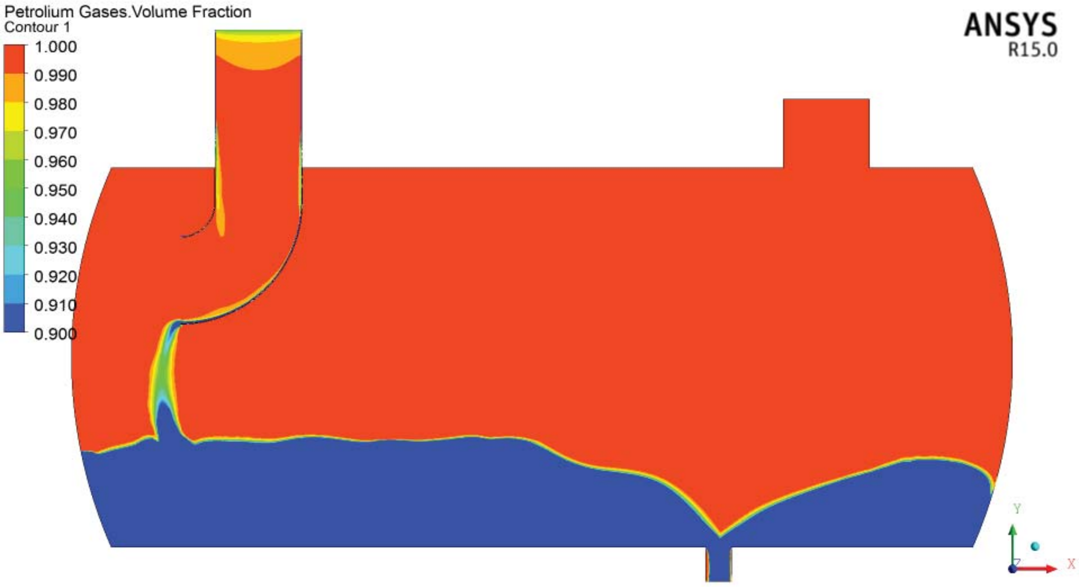
Petrolium Gases.Volume Fraction
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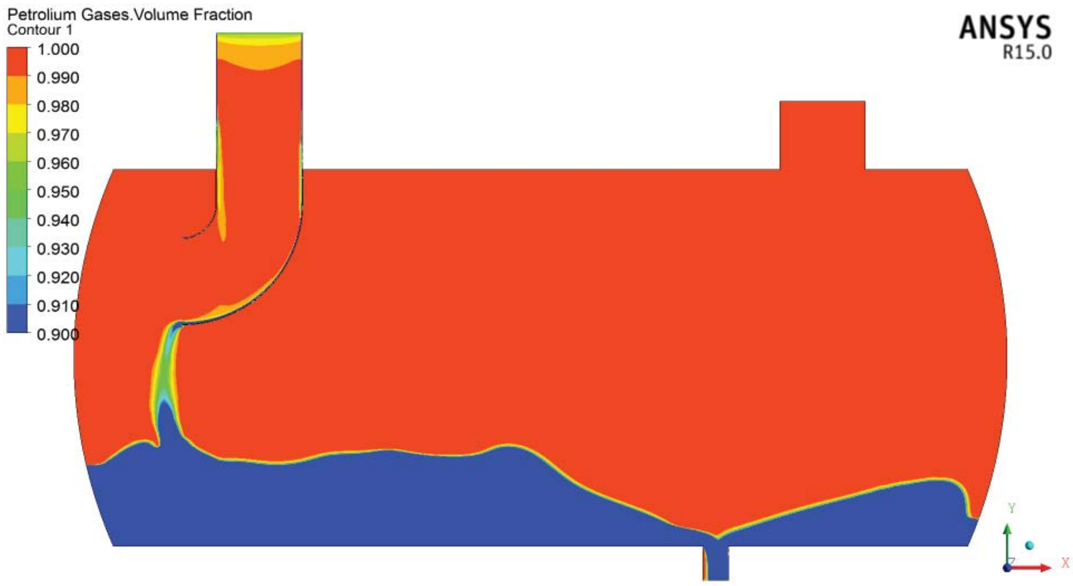

(D)

Fig. (6) Snapshots of volume fraction contours of gases at different time intervals.

5. Conclusions:

A design method was developed for the knockout drum. Design equations were properly integrated into a rigorous design method, which was backed up by a CFD simulation model. Analysis of CFD simulation quantitatively revealed that the dimensions of knockout drum were sufficient to separate condensate droplets from gas completely. A vortex breaker must be installed at the liquid outlet to avoid entrainment of gases in the liquid stream.

Nomenclature:

A_T = total cross sectional area

A_s = shell surface area

A_H = Elliptical head surface area

C_D= drag Coefficient,

D = vessel inside diameter

D_p, R_p=droplet diameter, radius,

d_N center inlet line

E = joint Efficiency,

H_{HLL} H_{NLL} H_{LLL} High, Normal, Low liquid level

H_D = vapor space

Q_L Q_V Q_m Liquid, vapor, mixture volumetric flowrate.

S = allowable stress,

t_c = corrosion allowance (in),

ts = Shell thickness

t_H =Elliptical head thickness

U_T = Terminal velocity

U_v = vertical velocity

V_H Hold up volume

V_S Surge volume

vp= droplet velocity

W_L, W_v Liquid, vapor weight flow rates

W = Approximate knockout drum weight

ρ_L, ρ_v Liquid, vapor density,

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