DESIGN AND SIZING OF A HYDROCARBON VAPOUR RECOVERY UNIT AT PETROLEUM DEPOTS

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ABSTRACT

This paper presents a work on "The design and sizing of a hydrocarbon vapour recovery unit at petroleum depots". It intervenes in a context where most of the depots handling volatile hydrocarbons records evaporative losses during operations of various activities. In the case of an oil depot, the storage operation would result in the loss of the storage tanks and the losses by movement of the vapours concentrated outward when filling these tanks, during the loading operations the product turbulence and the loss of preloading vapours are recorded. The purpose of this paper is therefore to design and size a unit that will collect the vapours and regenerate them. To achieve this objective, the methodology adopted begins with the functional analysis of the vapour recovery unit. It has enabled a solution consisting in the aspiration of vapours from the loading stations using vacuum pumps and a piping system. The regeneration of these vapours by condensation with a refrigeration system and the dissociation by a liquid gas separator. The second stage consist of the sizing and the choice of the different components of the unit. This part allowed us to have a vacuum pump (Becker U 5.70 with 1.5 kW of power and 70 $m^3.h^{-1}$ of maximum suction flow), and a tube NPS 4 SCH 80 API 5 L grade B (100 mm nominal diameter and 2.11 mm thick). A refrigeration system of 19.250 kW of power and a liquid gas separator VIRON VVS-14K60L46. The unit thus designed will allow the recovery of at least 0.15% of product stored per year.

KEYWORD: Design, Gas-liquid Separator, Loading Station, Recovery unit, Sizing.

I. INTRODUCTION

Oil products are now the main source of energy in the world. They are not only the driving force behind the industrialization of a country but also an essential element in satisfying domestic needs. That is why each country is setting up oil depots with the aim of satisfying consumers by making oil products available in a rational and non-disruptive manner with sufficient quantity. To carry out this purpose, oil depots store petroleum products in storage tanks and distribute them in case of need by trucks and wagon tankers through the loading stations.

However, these depots record many evaporative loss during the loading and storage operations. These vapours cause financial loss, health problems for employees, safety of the facility, and degradation of the environment. To deal with these problems, it is therefore important to setup a hydrocarbon Vapour Recovery Unit (VRU) within the petroleum depot in order to avoid the emission of these vapours into the atmosphere. These recovered vapours can be valorised energetically or regenerated in order to obtain the initial product. The structure of the work includes the generalities on the different elements of recovery units which presents the different components of the VRU and their function, then the sizing methodology which presents the different steps followed for the sizing of the different elements of the VRU. Finally, the presentation of the results and discussion.

II. MATERIALS

1) The elements of the Vapour Recovery Unit (VRU)

The vapour recovery process requires several devices, the first is the refrigeration circuit which is used to condense vapours and is composed of four main elements namely; the evaporator which is the heat exchanger between the medium to be cooled and the refrigerant. The compressor aspires in the vapour at low pressure state and discharge in the same state and at high pressure the refrigerant flowing from the evaporator. The condenser is the heat exchanger that recovers the fluid from the compressor. The regulator regulates the flow of the refrigerant into the evaporator.

The second material is the gas-liquid separator (Gas scrubber) which is used to separate the liquid state from the gaseous state resulting from partial condensation of vapours. It is a horizontal or vertical cylinder or a spherical ball with several separation zones, such as the deflector which is use for primary separation, the plenum section is where the secondary separation takes place which uses gravitational separation, and the fog extractor is where the last filtration of the mixture takes place, here we observe the separation of the smallest drops of liquid.

The third material is the piping system used to convey the steam from the collection site to the recovery site. It consists of a vacuum pump used to suck the vapours to the separator from the collection area. The pipes are the main organ which serves as a conduit for transport connected by welds, the elbows allow the change of direction and the valves regulates the flow of vapours. The non-return valves allow the circulation of vapours in one direction, whilst the flanges connect the piping system to the equipment. The piping system is equipped with cathodic protection to combat corrosion.

The last material is the recovery tank that collects the recycled fluid for reuse.

2) Elements of the VRU solution in the depot

The solution adopted for the VRU is divided into two parts:

The Collection part

The collection at the Trucks Tankers Loading Station (TTCS) and Wagon Tankers Loading Station (WTLS) is carried out using the PVC hoses are provided with a suitable cover matching the shape of the vapour exhaust openings. The end of the piping system consists of two main components which are a valve faucet and a non-return valve.

The Regeneration part

This part is responsible for the recovery which consist of three (3) main elements, a refrigeration circuit, a separator and a recovery tank which is also connected to the collection section to foresee a possible evaporation of the regenerated product. The Fig. 1 below shows the block diagram of the VRU.

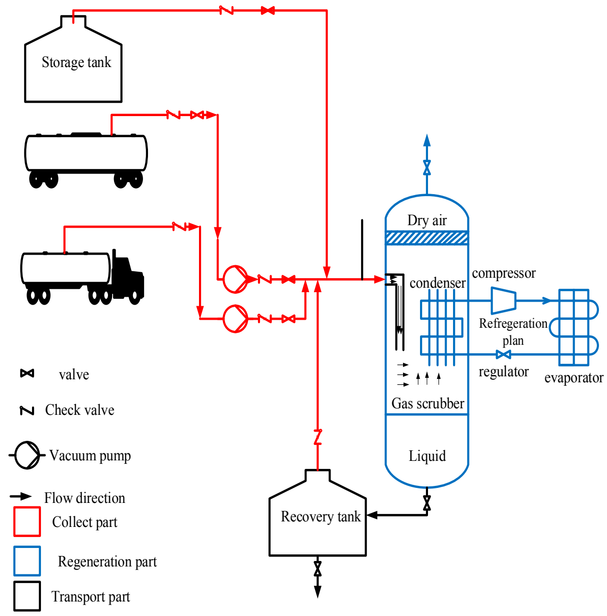

Figure 1: Block diagram of the VRU

III. SIZING METHOD

1) Quantitative Evaluation of Vapours

The sizing of a steam recovery unit begins by determining the mass or volume quantity of vapours to be treated which depends on their activities. In the case of an oil depot, the vapours are escaped during the operations of loading and storing the petroleum products. The studies carried out by (ADEME, 2005) give the following eqs. (1) to (3).

Emission during loading

Emission during loading is given by the eq. (1) below and depends on the mode of loading characterized by V_b , the type of product characterized by C_p and the contents of the tank before loading characterized by C_S :

$$E_g = 0.0045 \times C_S \times \left[C_P + V_b \times \frac{1 - C_P}{1 - C_S}\right] \times V \quad \ldots\ldots\ldots (1)$$

Whereas, C_P is the vapour concentration (%), C_S is the preloading concentration (%), V_b is the splash intensity, E_g is the emission quantity during loading (m^3) and V is the transferred volume (m^3).

Emission by Respiration

This emission is given by the eq. (2) below:

$$E_r = 7 \times 10^{-4} \times P_V \times M_{mol} \times D_t^{1.73} \times H^{0.51} \times C \quad \ldots (2)$$

Whereas, P_V is the saturated vapour pressure $(mbar)$, M_{mol} is the molar mass of the storage product (g/mol), D_t is the tank diameter (m), H is the tank height (m), C is the colour coefficient, and E_r is the emission by respiration (kg/an).

Emission by Movement

This emission is given by the eq. (3) below:

$$E_m = 4.11 \times 10^{-5} \times P_V \times M_{mol} \times V \quad \ldots\ldots\ldots\ldots \quad (3)$$

Whereas, E_m is the emission by movement(kg/an).

The amount of steam to be recovered is the sum of the three eqs. (1) to (3) seen above and it is given by the eq. (4) below:

$$Q = E_g + \frac{E_r + E_m}{\rho_p} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Whereas, Q is the quantity of recovered vapour(m^3), and ρ_p is the density of the storage product(kg/m^3).

2) Diameter of the Pipe and Vacuum Pump Calculation

The diameter of the pipe is determined by the eq. (5) below and deduced from the volume or mass relationship flow by setting a flow velocity of the fluid in the pipeline.

$$D = 2\sqrt{\frac{Q_m RT}{\pi P_v M_{vapour} v}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Whereas, Q_m is the mass flow(kg/s), v is the flow rate, M_{vapour} is the molar mass of vapour(kg/mol), P_v is the average vapour pressure(Pa), T is the service temperature(K), R is the perfect gas constant (8.314 $J.K^{-1}.mol^{-1}$) and D is the pipe diameter (m).

The power of the pump is determined by calculating the losses of regular and singular loads using the eq. (6) below:

$$J_{1\to2} = \frac{\lambda v^2 L}{2gD} + \frac{K}{2g}v^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Whereas, λ is the pipe resistance, g is the gravity constant(9.81 N/kg), L is the piping length(m), K is the coefficient of load loss and $J_{1\to2}$ is the loss of load(m).

The power of the vacuum pump is given by the eq. (7) below:

$$P_{vacuum\,pump} = gQ_m\left(\frac{P_{ref} - P_{asp}}{\rho_p g} + Z_2 - Z_1 + \frac{{v_{ref}}^2 - {v_{asp}}^2}{2g} + J_{1\to2}\right) \ldots\ldots\ldots (7)$$

Whereas, $P_{vacuum\,pump}$ is the power of the vacuum pump(W), P_{ref}, P_{asp} are the pump suction and discharge pressure(Pa), v_{ref}, v_{asp} are the suction and delivery speed (m/s) and Z_i is the height(m).

3) Sizing of the Pipe

The calculation of the piping is carried out in three (3) steps, the determination of the thickness, the calculation of the weld, and the calculation of cathodic protection.

Pipe Thickness determination

The calculation of the industrial piping is carried out in accordance with the industrial piping sizing Code (CODETI) of the (SCNT, 2006). After choosing the material for the tube, the minimum thickness is determined through the eq. (8) below.

$$e_p \geq \frac{P_p D_m}{2fz + P_p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Whereas, e_p is the thickness of the pipe(mm), D_m is the nominal diameter of the pipe(mm), f is the nominal strength of the pipe(MPa), z is the welding coefficient, P_p is the calculation pressure(MPa).

The determination of f and z passes through a succession of steps defined by the CODETI. The application of these steps by (KOUAMO Blondel, 2017) allowed hydrocarbons as a fluid that lead to the eq. (9), where z = 1.

$$f = \min\left(\frac{R_e}{1.6}, \frac{R_m}{2.7}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Whereas, R_e is the material elasticity limit (MPa) and R_m is the maximal strength(MPa).

The choice of the final thickness takes into account the thickness of the corrosion and control.

Weld calculation

The welding parameters are defined by (LONGEOT and JOURDAN, 1982) and are determined by the following eqs. (10) to (12).

The welding section is defined by the eq. (10) below.

$$SS = e_w^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Whereas, e_w is the thickness of the welded part (mm), and SS is the welding section (mm^2).

The delivery mass is defined by the eq. (11) below.

$$m_a = \rho_a.V_a.\frac{\phi}{\eta} = \rho_w.SS.L_{ij}.\frac{\phi}{\eta} \quad \ldots\ldots \quad (11)$$

Whereas, m_a is the mass of input metal(g), ρ_a is the density of input metal(g/cm^3), V_a is the volume of input metal(cm^3), L_{ij} is the weld length (mm), ϕ is the electrode performance, ρ_w is the density of the weld metal(g/cm^3), and η is the welding process performance.

The welding time is given by the eq. (12) below.

$$t_{arc} = \frac{m_a}{v_a} = \frac{m_a}{v_f m_f} \quad \ldots\ldots\ldots\ldots\ldots (12)$$

Whereas, t_{arc} is the time needed to achieve a welding(min), v_a is the consumption rate of the input metal and gas (g/min), v_f is the wire speed (m/min), m_f is the mass of a meter of electrode (g/m).

Cathodic Protection Calculation

The calculation of cathodic protection is given by (Alexandre MENNIER, 2006). The total current required to polarize the surface of the piping system is given by the eq. (13) below.

$$I_{tot} = I_s F_c S = \pi D_e L I_S F_c \quad \ldots\ldots\ldots\ldots (13)$$

Whereas, I_s is the surface density of current (A/m^2), D_e is the outside diameter of the pipe(m), I_{tot} is the total current intensity (A) and F_c is the degradation factor, L and S are the piping length$(m)$and section (m^2).

The maximum current per anode is given by the equation of DWIGTH i.e. eq. (14) below developed by (AFNOR, 2008). This standard recommends a difference of negative potential greater than or equal to -850 MV.

$$I_a = \frac{E}{\frac{0.005\delta}{\pi L_{anode}}\left[\ln\left(\frac{8L}{D_{anode}}\right) - 1\right]} \quad \dots\dots(14)$$

Whereas, E is the potential difference between metal and anode(V), δ is the resistivity of the anode$(\Omega.m)$, L_{anode} is the length of the anode(m), D_{anode} is the diameter of the anode(m), and I_a is the maximum current(A).

4) Sizing of the Gas Scrubber

The Souders-Brown relationship developed by (John CAMPBELL, 2015) determines the maximum velocity of vapour movement in the separator. This speed is given by the eq. (15) below.

$$V_{gas} = K_S\sqrt{\frac{\rho_L - \rho_g}{\rho_g}} \quad \dots\dots\dots\dots\dots\dots\dots (15)$$

Whereas, $\rho_L$is the liquid density to be extracted(kg/m^3), ρ_g is the gas density to be extracted(kg/m^3), K_S is the coefficient of Souders-Brown, V_{gas} is the minimum permissible steam (m/s).

This speed allows us to have the minimum input diameter of the separator through the flow relationship. This diameter is given by the eq. (16) below.

$$D_{emin} = \sqrt{\frac{4Q_v}{\pi F_G V_{gasmax}}} \quad \dots\dots\dots\dots\dots\dots\dots\dots (16)$$

Whereas, Q_v is the vapour volume flow(m^3/s), F_G is the fraction of available section, and V_{gasmax} is the maximum speed of the movement of vapours(m/s).

The diameter of the separator is obtained by adding 6 feet to the inlet diameter and the height is defined in accordance with the coefficient of Souders-Brown.

5) Sizing of the Refrigeration System

The sizing of the refrigeration circuit starts with the calculation of the refrigeration power. The choice of the refrigerant and the internal temperature of the chamber to be cooled which allows to determine the different pressures (low and high) and in the Mollier diagram, the refrigeration circuit is drawn and the characteristics are determined in their different points (temperature, pressure, enthalpy, etc.). The power of the different equipment is determined by the eq. (17) below.

$$P_e = \dot{m}\Delta h \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (17)$$

Whereas, P_e is the power of the equipment(W), Δh is the difference in enthalpy between two points (J) and $\dot{m}$ is the mass flow rate(kg/s).

This is the power of the main factor to be taken into account when choosing the equipment.

IV. RESULTS AND DISCUSSION

1) Quantitative Evaluation of Vapour

The application of the eqs. (1) to (4) allows us to have the annual losses recorded in Table 1 below.

Table 1: Annual lost of vapours

Products	Annual quantity (V)	E_m	$\frac{E_r + E_m}{\rho_s}$	Total lost (Q)
Super	578,732.222	347.239	1,262.068	1,609.307
Gasoil	741,352.413	74.135	443.652	517.787
kerosene	86,515.860	0.865	12.808	13.673
Jet A1	122,220.914	1.222	18.687	19.909

2) Diameter of the pipe and vacuum pump calculation

The Table 1. above provides an average mass flow of 43 kg/s. The eq. (5) allows us to have an internal diameter of 100 mm for the pipe.

This diameter is used to estimate the total load losses of 34 m for the collection portion using the eq. (6). The eq. (7) allows us to have a power of 1019 W for the vacuum pump. The Becker manufacturer's catalogue allows us to select the Becker U. 5.70 ATEX pump, the characteristics of which are recorded in Table 2 below.

Table 2: Characteristics of Becker U 5.70 vacuum pump

Designation	Flow (m^3/h)	Power (kW)	Motor power (kW)	Operating pressure (mPa)	Mass(kg)
Becker U 5.70	70	1.5	1.8	0.1-400	60.5

3) Sizing of the Pipe

Thickness of the Pipe

The eqs. (8) and (9) are used to obtain the characteristics of the tube and is recorded in Table 3 below.

Table 3: Characteristics of the pipe

Greatness	Value
Material	API 5L grade B
Nominal diameter	100 mm
Inlet diameter	110.08 mm
Outlet diameter	114.3 mm
Thickness	2.11 mm

Weld Parameters

The eqs. (10) to (12) allows us to have the parameters of the weld which is recorded in Table 4 below.

Table 4: Welding parameters

Welding parameters	Value
Entity of preparation	Welding on straight
Welding process	MAG
Welding section	5 mm^2
Input mass	15 g
Minimal time	1.5 min/weld

Cathodic Protection Parameters

The eqs. (13) and (14) allows us to have the parameters of the cathodic protection represented in Table 5 below.

Table 5: Parameter of Cathodic Protection

Parameter of Cathodic Protection	Value
Type of protection	Sacrificial anode
Type of anode	HOWAH MGMIC C145
Intensity of total current	0.2 A
Deliverable current	0.23 A
Life time	6.7 years
Number of anodes	5

4) Sizing of Gas Scrubber

The eqs. (15) and (16) allows us to have the parameters of the separator which is summarized in Table 6 below.

Table 6: Parameters of Gas Scrubber

Parameter of Gas Scrubber	Value
Designation	VIRON VVS-14K60L46
Type	Vertical
Inlet diameter	180 mm
Gas scrubber diameter	350 mm
Height	3000 mm
Thickness	4mm

5) Sizing of Refrigeration System

For a condensing temperature of 0°C and external of 30°C, an overheating and deheating of 5° C, the trace of the Mollier diagram and the eq. (17) allows us to determine the power of the equipment of the refrigeration circuit. The data is recorded in the Table 7 below.

Table 7: Summary of the Refrigeration Circuit Elements

Designation	Calculated Power (kW)	Real Power (kW)
Compressor Damfoss model MTZ564V	10.312	10.555
5 Evaporators FRIGA BOHN MR 270 R	18.36	19.250
Condenser TKE 352 A4	23.45	23.6
Regulator Danfoss TES 2 R404 A	Universal	universal

The operation of the isometric view of a hydrocarbon Vapour Recovery Unit (VRU) can be seen in Fig. 2 below. This unit will recover a minimum quantity of 2.160.676 litres on every 1.528.821.409 litres, which is 0.15% of the annual volume of diesel.

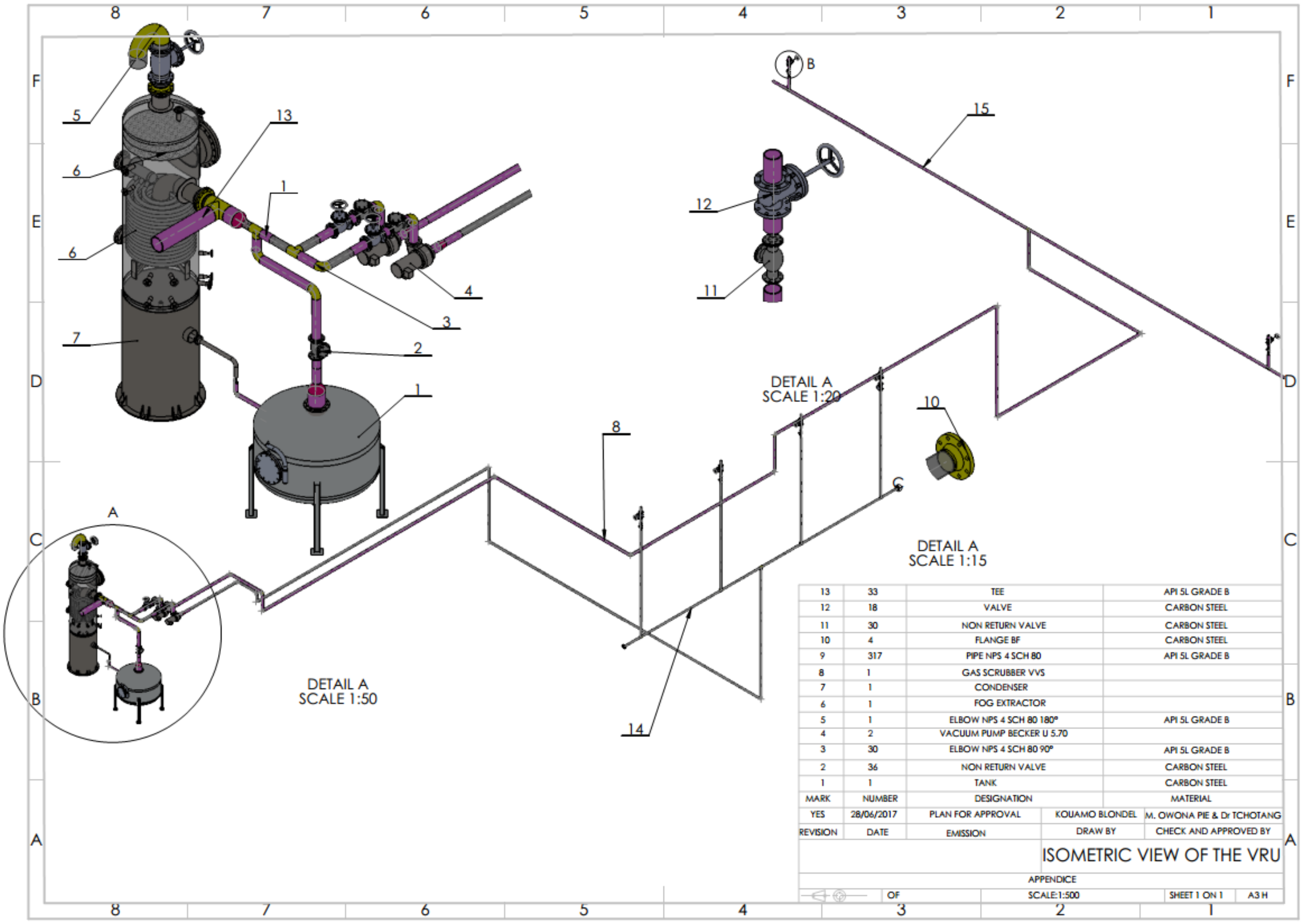

Figure 2: Isometric View of the VRU

V. CONCLUSION

This paper is focused on the design and sizing of a hydrocarbon vapour recovery unit at petroleum depots. The objective of this work was to conduct a detailed study aimed at proposing a vapour recovery unit to collect and regenerate the vapours thus making it possible to increase the productivity of the oil depots, limit the health risks of the operators, and the safety of the equipment and operators, and also to preserve the environment. To carry out this work, several steps were necessary to note and to have knowledge on the equipment surrounding recovery processes, carry out the functional analysis of the unit to be put in place in order to identify technological solutions, to size the chosen equipment and at the end choose the different equipment for the installation. This unit will recover a quantity of at least 0.15% of the annual volume of diesel.

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