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Development of counter-current gas-liquid packed tower absorption apparatus: a pilot-plant-scale-project innovation

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Abstract

Various engineering equipment makers/developers developed the packed absorption column at the pilot plant scale, by approaching it from engineering design drawings. This report described the development of a pilot-plant-scale-packed absorption tower, by innovative-copy approach which entailed gas absorber development, from the images recorded by digital camera and processed/enlarged by computer. Spurred by the massive Naira devaluation (96% from 1985 to 2008), which made the cost of importing equivalent equipment very prohibitive for the education budget, this innovative-copy approach, exploited the existence of the pilot plant-scale absorber in developing a modified and retrofitted version for the purpose of providing Nigerian-made teaching equipment for engineering students. This paper reported the various stages of gas absorber development, entailing the production of working sketches from the images recorded by digital camera, components' fabrication, equipment assembly, fitting of auxiliaries and piping, and, wiring and leak testing of the apparatus after completion. Of course, this innovative copy approach, ensured rapid prototyping of the gas absorber, because it short cut the engineering efforts, and time consumption required, for undertaking engineering design. It is hoped that the innovative-copy approach will redefine the way Nigerian tertiary institutions of learning acquire teaching apparatus.

Keywords: Packed absorption column; Pilot-plant scale; Engineering-design drawing; Innovative-copy approach; Rapid prototyping; Massive Naira devaluation

1. Introduction

The introduction in 1985 of the economic reform package dubbed the Structural Adjustment Programme (SAP) brought about a market-driven foreign exchange mechanism. Unfortunately the foreign exchange market has caused a colossal devaluation of the national currency the Naira. For example, during the inception of SAP in 1985, the average parallel market exchange rate was N3.7900 per US$1.0 (CBN, 1999). Presently, Business Vanguard (2008) reports that the average exchange rate is N116.81 per US$1.0. The result of this economic reform is that the market driven foreign exchange market has devaluated the Naira by 96.76 percent for the period, 1985 – 2008.

This massive devaluation of the Naira has impacted negatively on the education budget. For instance, the cost of importing engineering teaching and research equipment has become progressively prohibited for educational institutions from the SAP era to date. Subsequently, the education budget has over the years become grossly insufficient in catering for the equipmentation needs of institutions of learning. This is the challenge that calls for inward-looking innovations.

Interestingly, the availability of fund from the Direct Teaching and Learning Cost (DTLC) source, and the technical capacity of the Scientific Equipment Development Institute (SEDI), provided the bed rock for taking up the challenge head-on. To this end, an in country development of packed tower adsorption apparatus at the pilot plant scale was undertaken by using locally available resources.

The packed tower absorber is a process engineering equipment that is frequently used to remove one component

Notation

d_p	Effective diameter of packing particle, m, or diameter of a sphere with same surface-to-volume ratio as packing particle. $d_p = 6(1-\varepsilon)/a_p$ where a_p is the surface area of packing per unit of packed-tower volume, (m^2/m^3.)
G	Superficial gas mass velocity per unit cross-sectional area of empty tower kg/m^{2}s
G_m	Molar gas flow rate per unit cross-sectional area (kmol/m^{2}s)
g_c	Conversion constant, (4.18 x 10^8 *(lb mass)(ft)/(lb force)(sq hr)* or 9.806kg$_m$.m/kg$_f$-s^2)
H_{OG}	Height of an overall gas-phase transfer unit (m)
H_{OL}	Height of an overall liquid-phase transfer unit (m)
h	Packed height (m)
L	Superficial liquid mass velocity per unit cross-sectional area of empty tower (kg/m^{2}s)
L_m	Molar liquid flow rate per unit cross-sectional area (kmol/m^{2}s)
N_{OG}	Number of overall gas-phase transfer unit -
N_{OL}	Number of an overall liquid-phase transfer unit -
ΔP	Pressure drop (N/m)
R_m	Values obtained from the ordinate of Fig. 6.26 in Treybal, 1968, p.160 -
X_1	Mole fraction of the solute in the liquid at the bottom of the column -
X_2	Mole fraction of the solute in the liquid at the top Of the column -
Y_1	Mole fraction of the solute in the gas at the bottom of the column -
Y_2	Mole fraction of the solute in the gas at the top of the column -
ρ_G	Density of gas (kg/m^3)
ρ_L	Density of liquid (kg/m^3)
ρ_w	Density of water (kg/m^3)
μ_G	Absolute viscosity of gas (kg/ms)
μ_L	Viscosity of liquid (kg/ms)
γ	Constant with value dependent on packing size and type (see Table 4 of Peters & Timmerhaus, 1981, p.756).
Φ	Constant with value dependent on packing size and type (see Table 4 of Peters & Timmerhaus, 1981, p.756) -
ε	Fractional void volume in bed, m^3 void/m^3 of packed-tower volume

of a gas mixture. An example is the scrubbing of sulphur dioxide gas from SO_2-air stream. The opposite of an absorber is a stripper which is a process engineering equipment that is applied in transferring the volatile parts from a liquid mixture to a gas.

The major objectives of developing a counter-current flow packed tower absorber are:

- Experimental determination of pressure drop (ΔP) in the packed absorption column for both dry air operation (single-phase flow) and irrigated operation (two-phase flow).
- Experimental study of the phenomenon of loading and flooding in a counter current flow packed tower absorption apparatus.
- Experimental determination of the packing factor for the ¼ inch Raschig rings.

2. Review of literature

The two approaches available to the authors for the development of the gas absorber at the pilot-plant scale are the design approach and the innovative-copy approach.

2.1. Design approach to gas absorber development

According to Peters and Timmerhaus (1981) the design of a packed tower requires consideration of mechanical factors such as pressure drop, flow capacities and foundation load; plus the factors that influence the effectiveness of contact between the fluid phases. Some of the design equations for the mentioned parameter will be considered as follows:

Perry and Green (1997) expresses that a material balance equation giving the relationship between the compositions of the gas and liquid streams at any point in the column is simply:

$$G_M\left(Y_1 - Y_2\right) = L_M\left(X_1 - X_2\right) \qquad (1)$$

where the symbols of the equation are defined in the notation.

Leva has correlated experimental data to obtain the following empirical equation for estimating pressure in packed beds under preloading conditions with simultaneous counter flow of liquid and gas (Peters and Timmerhaus, 1981):

$$\frac{\Delta P}{h} = \gamma(10)^{\Phi L/\rho_L}\frac{G^2}{\rho} \qquad (2)$$

where the symbols of the equation are defined in the notation.

The following equation by Ergun can be used to estimate pressure drop caused by the flow of a gas through dry packings (Peters and Timmerhaus,1981).

$$\frac{\Delta P}{h} = \frac{1-\varepsilon}{\varepsilon^3} \frac{G^2}{d_p g_c \rho_G}\left[\frac{150(1-\varepsilon)\mu_G}{d_p G} + 1.75\right] \qquad (3)$$

where the symbols of the equation are defined in the Notation Section.

Sinnott (1999) gives the height of transfer unit (Z) to be:

$$Z = H_{OG} N_{OG} \qquad (4a)$$

or

$$Z = H_{OL} N_{OL} \qquad (4b)$$

where the symbol are defined in the Notation Section.

The diameter of a packed tower is usually designed by choosing the material flow quantities at the bottom conditions. The liquid gas flow parameter, F_{LG} at the bottom condition is adapted from Treybal (1968) as:

$$F_{LG} = \frac{L_1}{G_1}\sqrt{\frac{\rho_G}{\rho_L}} \qquad (5)$$

F_{LG} is the abscissa of Fig. 6.26 (Treybal, 1968). If the ordinate of Fig. 6.26 in Treybal (1968) becomes R_m, then at flooding rate of 60%, G can be adapted from Treybal (1968) to be:

$$G_{\text{at flooding}} = \left(\frac{R_m g_c \rho_G \rho_L}{C_f \mu_L^{0.1}} \frac{\rho_L}{\rho_w}\right)(0.60) \qquad (6)$$

where the symbol are defined in the notation.

The tower cross section, A_t adapted from Treybal (1968) becomes:

$$A_t = \frac{G_1}{G_{\text{at flooding}}} \qquad (7)$$

Finally the tower diameter, D_t becomes:

$$D_t = \sqrt{\frac{4A_t}{\pi}} \qquad (8)$$

Nonetheless, Perry and Green (1997) writes that perhaps the most important variables and parameters to be considered in the design of the absorption system are those that are most difficult to describe accurately by mathematical expression.

2.2. Innovative-copy approach to gas absorber development

The innovative-copy approach exploited the existence of packed absorption tower in the Pilot-Plant Laboratory of the Institute of Management and Technology (IMT), Enugu, in developing a similar prototype for the Department of Chemical Engineering, Nnamdi Azikiwe University (NAU), Awka. The IMT packed absorption tower was imported from the UK's Corning Glass Works, the maker of chemical process systems and engineering teaching equipment.

Because of unavailability of design drawings, digital camera was employed as innovative tools. The digital camera computer hardware and application exploited for capturing the design features of the Corning absorber owned by the IMT, Enugu. While the computer was used for exposing the details and dimensions of the absorber structure.

For purpose of material costs curtailment and the usage of locally-available materials, innovative modifications were made on some features and materials, of the copied designs. This innovation extended to the materials selection and specifications for the main components of the absorber as would be explained in the materials and methods' section.

2.3. Description of existing equipment

The existing gas absorber consists of a 3inches (76.2mm) glass-column section filled to a height of 5feet(1.524m) with 1/4 inch (6.35mm) Raschig rings. A Raschig ring is simply a hollow cylinder that has an outer diameter equal to its height. The 5 feet height of Raschig-rings packing is held by a ½ inch (12.7mm) thick packing support plate made of glass with staggered perforations. The perforations on the packing-support plate are smaller than the outer diameter of the Raschig rings (1/4 inch) to prevent the escape of Raschig rings through the perforation.

Tappings are provided below the packing-support plate and above the top of the packing for connection to a 24 inches manometer to enable the pressure drop (ΔP) across the packed section to be measured. The manometric liquid is water and the pressure unit is inches Wg (water gauge).

The liquid and gas streams are designed to flow counter currently past each other to obtain the greatest absorption rate. Liquid is delivered to the top of the packed section via a 1.8942 to 18.942 cm^3/sec rotameter. Air or gas is delivered to the bottom of the packed column through a 3.14632 to 31.4632cm^3/sec rotameter. Adjustments to the air/gas and liquid flow rates can be made by the needle-control valves (type RV) fitted to the discharge side of the two rotameters.

After contact with the air/gas in the packed column, the liquid leaves via the 2ft (0.609m) liquid seal provided. The function of the seal is to prevent air/gas from leaving the tower at the bottom. The maximum supply gas pressure which can be used with this tower is limited by the height of the liquid seal, in this case 24 inches WG.

All the components of the packed absorption tower, namely, the packed column, the manometer, the two rotameters and the liquid seal are fitted on to a scaffold structure that houses and support them. The scaffold is built with a 2 inches (50.8mm) diameter pipe.

3. Materials and methods

The development of the gas absorber was undertaken at two project sites, namely the workshops of the Scientific Equipment Development Institute (SEDI), Enugu, and Chemical Engineering Laboratory, Nnamdi Azikiwe University (NAU), Awka. The development process entailed the production of working sketches, fabrication of components, assemblying of equipment, fitting of auxiliaries and piping, and wiring of the apparatus. All of these processes resulted in a compact unit captioned Packed Tower Absorption Apparatus, as would be elaborated in the following subsections.

3.1. Production of working sketches

With high definition application software, the details of the gas absorber photographs recorded with digital camera were exposed with high-resolution images. Dimensioned sketches of the gas-absorber components, namely the packed column, Raschig-ring packings, packing-support plate, water seal, liquid rotameter, air/gas rotameter and scaffold structure were produced from the high-resolution images.

3.2. Fabrication of components

The steel componets such as scaffold and rotameters were constructed in the Machine and Fabrication Workshops of SEDI, Enugu, while the glass components like water seal, Raschig-ring packings and packed column were made in the Glass Blowing Workshop of SEDI, Enugu. Every material used in the fabrication of the gas-absorber components has underlying reasons for their consideration and selection. Table 1 shows the various gas-absorber components, the materials used in fabricating them and the rationale for the choice of materials used in their fabrication. With the selected and specified materials(Table 1) the gas-absorber components were produced.

Thus the glass water seal and the Raschig-ring packings were products of the Glass Blowing Workshop SEDI, Enugu. The 3inch diameter glass column was purchased and 8mm diameter pressure tappings were fused onto it in the Glass Blowing Workshop. The air/gas rotameter, the liquid rotameter, the scaffold, the packing-support plate were produced in the Machine and Fabrication Workshop of SEDI, Enugu.

3.3. Equipment assembly

The finished components were transported to Chemical Engineering Laboratory, NAU, Awka, where the scaffold/support structure was erected/fitted and the gas-absorber components were assembled on and within the scaffold structure. Figure 1 shows the photograph of the gas-absorber after the assembly.

3.4. Fitting of auxiliaries and piping

Table 2 shows the auxiliaries selected and purchased, their capacity/technical specifications, the reasons for their selection/general properties and their various purchase costs. Also Table 3 displays the plumbing materials, their specifications, the justification for their selection and their purchase costs. By fitting the auxiliaries selected and utilizing the plumbing materials in Table 3, the pump and tank were piped to deliver liquid to the top of the packed tower and return it back to the tank after flowing through the Raschig-ring packings. While the air compressor was piped to supply air to the bottom of the packed tower and discharges to the atmosphere after air-liquid contacting in the packed tower.

3.5. Wiring and leak-testing of the apparatus

Table 4 displays the electrical materials chosen for wiring of the apparatus, their specifications, reason for their choice and their purchase cost. The fitting of the selected switches and connecting them with the appropriate wires to the liquid pump, air compressor and mains supply resulted in the completion of the apparatus.

Figure 2 shows the photograph of the Packed Tower Absorption Apparatus after completion. also, Fig. 3 is the schematic diagram showing the main features of the Packed Tower Absorption Apparatus and their flow directions/ flow sequences. The total material cost for the fitting of auxiliaries, piping and wiring is ₦ 53,780.00. (See Tables 2, 3 and 4).

The Packed Tower Absorption Apparatus was leak-tasted by switching on the centrifugal pump and rotary compressor and observing the flows through the liquid and air pipings. The identified leaks in the liquid-flow channel and the air-flow ducts were sealed with tangil gum and super glue. The apparatus is thus ready for experimental trials.

4. Discussion

In comparing the design and innovative-copy approaches to developing the gas absorber presented in this report, it could be said that the innovative-copy approach may be a rapid approach to prototyping pilot-plant-scale gas absorber. This is because the innovative-copy approach skipped the design stage which could have incurred some costs in terms of monetary expenses, time consumed and efforts applied in executing the engineering design. It should be remembered that engineering design may be cumbersome in calculations/predictions of design data, and production of design drawings.

Despite these difficulties, undertaking an engineering design may offer some benefits such as academic excitement and intellectual fulfillment. However, for this project, the innovative-copy approach which exploited the existence of Corning packed absorption tower at the IMT, Enugu, has proved to be a short-cut approach to developing packed tower absorption apparatus.

5. Conclusions

The development of packed tower absorption apparatus, at the pilot-plant scale, by innovative-copy approach, which exploited copying the existing engineering design, and modifying it for cost reduction and materials' availability, was successful. The packed tower absorption apparatus is ready for experimental trials.

Therefore, it is recommended that experimental trials be carried out for the purpose of accomplishing the following experimental objectives, namely:

(a) Determination of the packing factor for ¼' inch Raschig rings in a packed tower.
(b) Investigation of pressure drop for dry air-flow and irrigated operations in a packed tower.
(c) Study of loading and flooding of a packed tower.

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Table 1
Materials selected for gas absorber components

Absorber component	Material specification	Reason for selection/general properties
Absorption Column	Glass of 3in (76.2mm) diameter by 5ft (1.524m) height with thin wall.	Glass allows visual observation of liquid-gas continuous contacting. However the thin-wall glass can withstand atmospheric operation and can carry the weight of glass packings.
Packing Material	¼ in (6.35mm) Raschig rings made of borosilicate glass	a)Rasching ring provide a large surface area for intimate/contact between gas and liquid b) They have an open structure that accounts for low resistance to gas flow c) They promote uniform liquid distribution on the packing surface d) They promote uniform gas flow across the column cross-section
Packing support plate	½ in (12.7mm) thickness by 3 in (76.2mm) diameter Teflon with staggered perforations	a) Teflon is fairly sturdy/tough and can carry the weight of wet packings b) The perforation allows free passage of gas and liquid, so that local flooding is avoided.
Liquid distributor	3 in (76.2mm) diameter PVC shower rose	a) Shower rose ensures a uniform and adequate liquid spray on the column cross-section. b) The spray liquid relies on gravity flow throughout the height of the column.
Liquid seal	2 ft (0.6096m) high by 1.5 in (38.1mm) diameter U-tube made of borosilicate glass	The seal prevents gas from escaping from the bottom of the tower. Water will be used because of its cheapness.
Manometer	8mm diameter borosilicate glass forged into a U-tube of 24 in (609.9mm) height.	This enables pressure drop to be measured from the tappings provided below the packing support plate and above the top of the Rasching ring packings. The tappings are connected by flexible hose to the limbs of the monometer.
Manometric tube	8mm diameter transparent tubing.	Transparent tubing is cheaper than its equivalent copper or stainless steel ducts.

Manometric liquid	Water	a) Water is cheaper than mercury or any other manometric fluid b) The density of water is 13 times less than the density of equivalent mercury; 1000 kg/m^3 ≅ 13, 600 kg/m^3.
Liquid Rotameter	Glass tube transparently calibrated for the range of 1.8942-18.942 cm^3/s and housing a brass float and needle control valve.	a) The transparency allows visual observation and read-out of the float displacement and the measurement scale. b) The needle valve enhances fine control of liquid flow rate.
Air Rotameter	Glass tube transparently graduated for the range of 3.14632 to 31.4632 cm^3/s and also harbouring a brass and a needle control valve.	The transparency enables visual observation and measurement of the level of float suspension by gas stream. The needle valve improves fine control of air flow rate.
Scaffold/Rig	1½ inch (38.1mm) diameter steel pipe.	Steel pipe is sturdy and can carry both the absorber components and the human user.

Table 2
Selected packed tower auxiliaries

Auxiliary	Capacity/Specification	Reason for selection/General Properties	Purchase Cost (₦)
Centrifugal pump Make: Marquis	1 horse power (hp) delivering 20-80 liters/min and rated at 220 Volts, 50 Hz single phase power supply.	a) Centrifugal pump ensures continuous liquid supply and minimizes pulsations during delivery, at any flow rate. b) The capacity of the pump is sufficient to flood the packed tower during investigation of flooding phenomenon.	₦ 6000
Rotary Compressor	7.5 hp output rated at 380-415 Volts, 50 Hz for 3 phase power supply	a) The capacity ensures the adequacy of air supply needed to maintain continuous gas-liquid contacting in the packed column b) The capacity ensures that appreciable pressure differential is obtainable form the differential manometer c) The rotary compressor with discharge at the top ensures that oil is not entrained in the compressed air supply.	₦28, 000
Liquid Tank	100-liter PVC (Polyvinyl chloride) cylindrico-vertical tank	a) The tank capacity is enough to ensure fluctuationless liquid supply to the pump, rotameter and packed column, at any flow rate b) The material of construction PVC is resistant to corrosion and ensures rust control c) The material of construction PVC is inert to liquid solvents used for gas absorption.	₦1, 800
		Total	₦35,800

Table 3
Selected plumbing fittings for piping of the absorption apparatus

Fitting	Specification	Reason for selection/ General Properties	Quantity	Unit Cost (₦)	Purchase Cost (₦)
PVC pipe	1 inch (25.4mm) diameter	PVC is resistant to corrosion and ensures that rust is controlled	1 length	2, 800	2, 800
PVC ball valve	1 inch (25.4mm) diameter	Same as above	4	200	800
PVC union connector	1 inch (25.4mm) diameter	Same as above	4	150	600
PVC elbow	1 inch (25.4mm) diameter	Same as above	6	80	480
PVC backnut	1 inch (25.4mm) diameter	Same as above	2	100	200
PVC bushing	1 inch (25.4mm) diameter	Same as above	2	150	300
PVC T-connector	1 inch (25.4mm) diameter	Same as above	1	100	100
Flexible pipe connector made of rubber	½ inch x ¼ inch flow diameter reduction	Same as above	4	150	600
Tangit gum		Tangit gum bonds with PVC firmly and ensures that seals are air tight	2 tins	350	700
			Total		₦6580

Table 4
Selected electrical fittings for wiring of the absorption apparatus

Fitting	Specification	Reason for selection/ General Properties	Quantity	Unit Cost (₦)	Purchase Cost (₦)
Crabtree 3-phase switch	Rated at 60 Amps, 415 Volts, 50 Hz with circuit breaker.	1) Compatible with 7.5 hp air compressor. 2) Contains circuit breaker for compressor protection.	1	4, 500	4,500
1 gang 1 way flush switch with pilot lamp	Rated at 6 Amp, 250 Volts single phase power supply.	1) Compatible with 1 hp centrifugal pump. 2) Indicator lamp signals power presence	1	500	500
Federal Electric 3-phase switch	Rated at 125 Amps 415 Volts, 50 Hz 3-phase power supply.	Mains supply control switch that governs power supply to compressor and pump.		2,500	2, 500
Wire	25 mm^2 4-core flex for 3-phase compressor.	Wiring of 7.5 hp air compressor.	6 yards	400	2,400
Wire	15 mm^2 3-core flex for single-phase pump wiring.	Wiring of 1 hp centrifugal pump	6 yards	250	1, 500
				Total	₦11,400

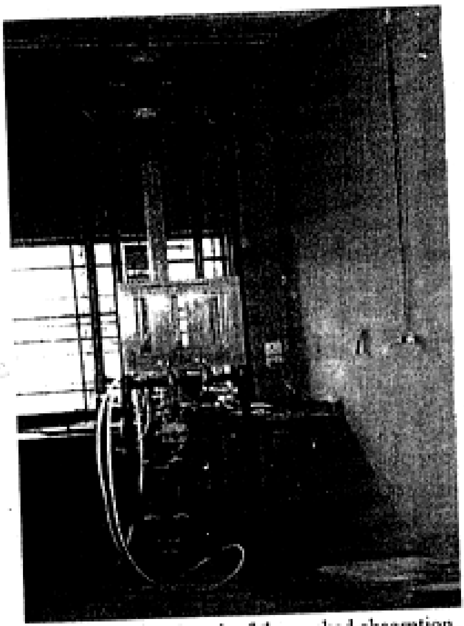

Fig. 1. The photograph of the packed absorption tower after the assembly.

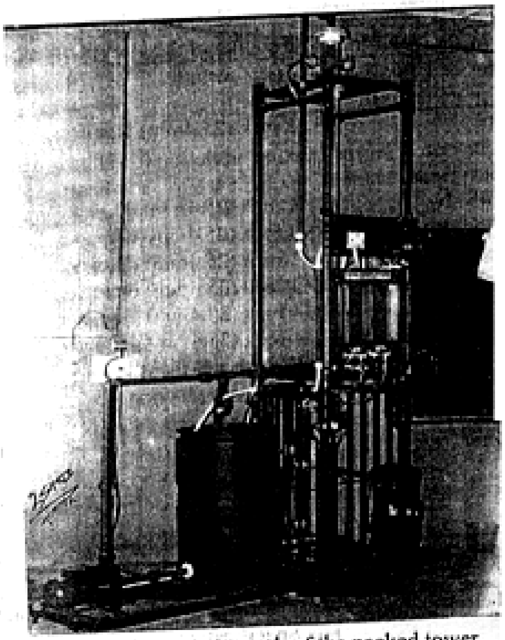

Fig. 2. The photograph of the packed tower Absorption apparatus after completion.

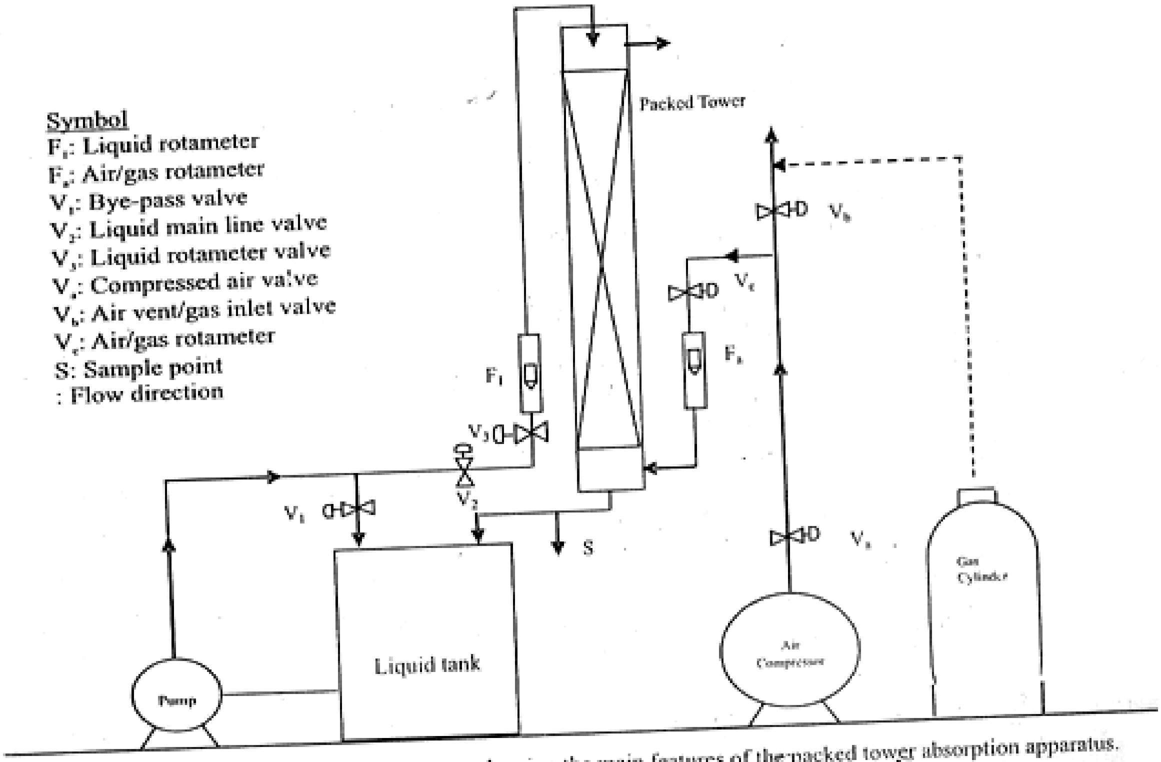

Fig. 3. The schematic diagram showing the main features of the packed tower absorption apparatus.

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