Development of a plant for extraction of essential oil from leaves of eucalyptus tree

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***Abstract* – In this paper, a plant for the extraction of essential oil from leaves of eucalyptus tree was developed. The extraction plant is made up of a steam generation unit (boiler), stripping chamber, condenser (heat exchanger), decanter (settler), cooling water system and a pressurized gas burner as heat source. The condenser, decanter, steam generation unit, stripping chamber, control valves and the cooling water system were sized and selected in such a way that the plant will perform to specification. The steam generation unit was designed to contain 25 litres of water with dimension 0.35m diameter by 0.26m high. The condenser has 24 tubes (i.e. 12 tubes per pass), its size is 1m long by 0.215m shell diameter. The stripping chamber was designed to process a maximum of 10kg of the raw material per batch run and its size is 0.35m diameter by 0.45m high while the cooling water system was specified as 200 litres capacity with 0.5HP centrifugal pump to aid circulation of the cooling water. After the construction, the performance of the plant was evaluated and the following result was obtained: 18ml of eucalyptus oil only was realized at the end of the eighty – two (82) minutes batch run trial. The overall cost of producing the plant was One hundred and fifty thousand, three hundred and ten Naira only (N150, 310:00), which is affordable to many small and medium scale investors/entrepreneurs and local fabricators with small capital base considering the importance of the eucalyptus oil in Nigeria.**

***Index Terms* - essential oil, eucalyptus leaves, distillation**

I. INTRODUCTION

Essential oils are volatile oils, which occur in some trees. They occur in the leaves, blossoms, fruits, trunks, stems and/or roots of the bearing trees. However, very few of the great number of essential oil bearing species are being used for commercial production of the oils. Though they are called oils, they are quite distinct from the traditional vegetable oils, because they are very light, non – greasy, absorbed quickly into the skin and above all, very volatile [1]. A number of essential oils are exploited by chemical and allied industries as a source of specific compounds for subsequent transformation to a wide range of synthetic products such as aroma chemicals, flavours, vitamins and pesticides. They are also valuable in the manufacture of essential balms, medicated ointments, soaps, perfumes, shampoos and other cosmetics. Various methods exist for the recovery of essential oils, which include mechanical expression, effleurage, maceration, steam distillation, water distillation, water and steam distillation and supercritical fluid extraction. Most essential oils currently in use by cosmetic, food, perfumery and pharmaceutical industries in Nigeria are imported. Perhaps, this is due to the fact that there are virtually little or no local manufacturers of these all-important industrial intermediates in Nigeria. Therefore, for the aforementioned numerous uses of essential oils coupled with the high cost of their importation, significant increase in demand by chemical and allied industries and availability of abundant raw materials in Nigeria, there is the need to develop appropriate technology for local production of essential oils. This can assist in reducing the large amount of money being spent on the importation of these oils and if scaled-up to industrial level, it will also provide a base for essential oils exportation which could in turn make Nigeria improve its foreign exchange savings and earnings.

II. ESSENTIAL OILS

Essential oil is the volatile part of a tree that is largely responsible for its characteristic aroma. Essential oil trees are widely spread and occur even in remote geographical regions, but the tropical regions produce most of them. The trees grow in areas other than those in which they are indigenous, but often yield oils of different and inferior composition [2].

There are over 700 trees species that produce essential oils. Some of them are Eucalyptus, Lemongrass, Lemon, Peppermint, Lavender, Clove, Jasmine, Geranium, Orange, Rose, Spearmint and Winter green. Essential oils occur in different parts of their bearing trees. For instance, essential oil of Eucalyptus occurs in the leaves and the stems; for Spearmint, Winter green, Geranium and lemongrass occur in the leaves, for Clove in the bud, for Lemon and Orange in the peel while for Rose and

Jasmine occur in the flowers. There are major and minor constituents in essential oils, but the different percentages of each constituent give each oil its own unique characteristic [3, 4].

Most essential oils are only slightly soluble in water, but completely soluble in organic solvents such as benzene and alcohol. They have characteristic odours and are flammable [6]. However, the only type of essential oil of interest to this design is the Eucalyptus oil.

A. Eucalyptus Tree

Eucalyptus is a member of family of trees that has proven value in erosion control, land reclamation, shade/shelter and wind break. It is a fast growing source of wood, its oil can be used for cleaning and functions as a natural insecticide and it is sometimes used to drain swamps and thereby reduce the risk of malaria [5]. There are more than 500 species of eucalyptus and several of them were introduced to Nigeria but of all the species tried, only *Eucalyptus Camaldulensis, Eucalyptus Terticornis and Eucalyptus Saligana* are the most promising as plantation species in the Savannah area [6, 7]. These species are widely used in this area as shelterbelts, pulpwood and as house construction materials. Their use in agro-forestry for inter cropping is limited to the Savannah due to their tendency of inhibiting the growth of other trees in the vicinity. This disadvantage is believed to be the reason behind the refusal of small farmers to cultivate the tree despite the listed benefits. Hence, to reverse this ugly trend and make the tree more popular, there is the need to explore other potential uses of the species [5].

B. Eucalyptus oil

Eucalyptus oil has a cooling and deodorizing effect on the human body, cure for fever and malaria. For the respiratory track, it helps in curing coughs, bronchitis, asthma, throat infections and catarrhal conditions. It soothes inflammation and mucks. It is valuable in the manufacture of medicated ointments, soaps, perfumes, Robb, Mentholatum and other essential balms. It is also used to mask the natural odours of plastic, rubber and paint materials. In addition, the oil is used directly in fragrance and flavour applications [8]. Eucalyptus oil is also used in very small quantities in food supplements especially sweets, cough drops and decongestants. It also has insect repellent properties and is an active ingredient in some commercial mosquito repellents [9]

III. DESIGN OF THE PLANT

The extraction plant shown in Fig. 1 is made up of a steam generation unit (boiler), stripping chamber, condenser (heat exchanger), decanter (settler), cooling water system and a pressurized kerosene stove as heat source. The steam generation unit was designed as cylindrical tank with a conical top cover. It is to be fired by 2.5litres capacity pressurized kerosene stove. This unit is connected to the stripping chamber via a 19.05mm diameter galvanized pipe and a control valve is fitted in between to control the flow of steam from the unit to the stripping chamber. The stripping chamber, which is also cylindrical in shape with conical bottom and top covers, has two openings. The topmost opening is for charging the raw material, while the down opening is for discharging raw material after stripping. Both the steam generation unit and the stripping chamber were fully lagged with fiberglass to minimize the heat loss to the surrounding and enhance boiling and stripping efficiency. Top cover of the chamber is connected to the condenser through a 19.05mm diameter fully lagged galvanized pipe for the escape of steam from chamber to the condenser. The condenser is to condense the vapour coming from the chamber, which is basically a combination of water and traces of oil. Cooling water is introduced into the condenser to facilitate the condensation process inside the condenser. Whereas, the decanter is for the collection and separation of the condensate (i.e. oil from water). The overall size of the plant is 2.35m high by 1.6m wide by 0.5m deep.

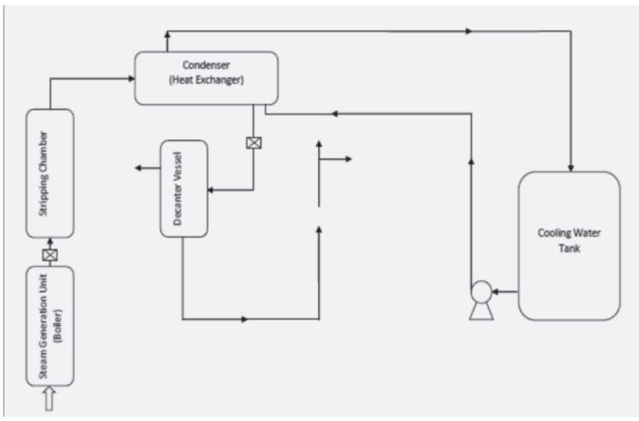

Fig.1: Schematic diagram of the extraction plant

A. Condenser (Heat Exchanger) Design

Condenser, otherwise known as heat exchanger is a device that facilitates heat transfer between two or more fluids at different temperatures [10, 11, 12, 13]. In this design, the condenser is to be used to condense the vapour, (which is a mixture of water and traces of oil) that will be coming from the stripping chamber. The design procedure used for the condenser design is as given below. Shell and tube type of heat exchanger was selected for this design, being the most widely available and most commonly used type of heat – transfer equipment in the chemical and allied industries [14, 15]. The prime objective in the design of a condenser is to determine the surface area required for the specified duty (rate of heat – transfer) using the temperature differences available. Detail design procedure of the condenser is given below:

Rate of heat transfer,

Q = $U_oA\Delta T_m$ = (steam rate) x (change in enthalpy)…(1)

Upon substituting the values, Q was found to be = 46.73kW.

Logarithmic Mean Temperature Difference,

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left[\frac{(T_1 - t_2)}{(T_2 - t_1)}\right]} = 40^oC \quad (2)$$

Dimensionless correction factors: Ratio of shell – side and tube – side fluid temperatures,

$$R = \frac{(T_1 - T_2)}{(t_2 - t_1)} = 3.33 \quad (3)$$

Measure of temperature efficiency of the exchanger,

$$S = \frac{(t_2 - t_1)}{(T_1 - t_1)} = 0.20 \quad (4)$$

True temperature difference,

$\Delta T_m = F_t \Delta T_{lm}$, (5)

which was found to be 37°C

Average value of heat transfer coefficient, U_{ass} was taken from the table as 1150W/m^{2o}C

Heat transfer area,

$$A = \frac{Q}{U_{ass}\,\Delta T_m} = 1.20m^2 \quad (6)$$

Area of one tube,

$$A_t = \pi dl = 0.0503\text{m}^2 \quad (7)$$

Number of tubes,

$$N_t = \frac{heat\ transfer\ area, A}{Area\ of\ one\ tube, A_t} = 24\text{ tubes} \quad (8)$$

Tube pitch for equilateral triangular tube arrangement, $P_t = 1.25d_o = 20mm$ (9)

Bundle diameter,

$$D_b = d_o\left(\frac{N_t}{K_1}\right)^{1/n_1} = 127mm \quad (10)$$

Shell diameter,

D_s = (bundle diameter, D_b) + (clearance) = 215mm (11)

Baffle spacing,

l_b = Shell diameter, D_s = 215mm (for condenser) (12)

Shell – side cross – flow area,

$$A_s = \frac{(P_t - d_o)D_s l_b}{P_t} = 9.25 \times 10^{-3}m^2 \quad (13)$$

Shell – side fluid flowrate,

$$W_s = \frac{Q}{C_p(t_1 - t_2)} = 0.75\text{kg/s} \quad (14)$$

Shell – side mass velocity,

$$G_s = \frac{W_s}{A_s} = 81.1\text{kg/s m}^2 \quad (15)$$

Shell – side linear velocity,

$$u_s = \frac{G_s}{\rho} = 8.13\text{x}10^{-2}\text{m/s} \quad (16)$$

Shell – side equivalent diameter,

$$d_e = \frac{1.10}{16}(P_t^2 - 0.917d_o^2) = 11.36 \times 10^{-3}m \quad (17)$$

Shell – side Reynolds Number,

$$R_e = \frac{G_s d_e}{\mu} = 1035\text{ (Laminar)} \quad (18)$$

Shell – side Prandtl Number,

$$P_r = \frac{C_p\mu}{k_f} = 6.1 \quad (19)$$

Shell – side heat transfer coefficient,

$$h_s = \frac{k_f}{d_e} j_h R_e P_r^{0.33} = 1.92\text{kW/m}^2\,{}^o\text{C} \quad (20)$$

Shell – side pressure drop,

$$\Delta P_s = 8j_f\left(\frac{D_s}{d_e}\right)\left(\frac{L}{l_b}\right) = 162\text{N/m}^2 \quad (21)$$

Tube – side mean water temperature,

$$t_w = \frac{t_1 + t_2}{2} = 33^oC \quad (22)$$

Number of tubes per pass $= \frac{N_t}{2} = 12\ tubes$ (23)

Tube – side cross flow area,

$$A_t = \frac{(P_t - d_i)D_b l_b}{P_t} = 8.19 \times 10^{-3}m^2 \quad (24)$$

Tube – side steam mass flowrate,

$$W_t = \frac{Q}{C_p(T_1 - T_2)} = 4.5 \times 10^{-1}kg/s \quad (25)$$

Tube – side fluid mass velocity,

$$G_t = \frac{W_t}{A_t} = 55kg/s\ m^2 \quad (26)$$

Tube – side linear velocity,

$$u_t = \frac{G_t}{\rho} = 0.06\text{m/s} \quad (27)$$

Tube – side Reynolds Number,

$$R_e = \frac{\rho u_t d_i}{\mu} = 1101 \quad (28)$$

Tube – side heat transfer coefficient,

$$h_i = \frac{k_f}{d_i} R_e^{0.8} P_r^{0.33} C = 477\text{W/m}^{2o}\text{C} \quad (29)$$

Tube – side pressure drop,

$$\Delta P_t = N_p\left[8j_f\left(L/d_i\right) + 2.5\right]\rho u_t^2/2 = 27.38\text{N/m}^2 \quad (30)$$

Overall (calculated) heat – transfer coefficient, U_o is;

$$1/U_o = 1/h_o + 1/h_{od} + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2k_w} + d_o/d_i \times 1/h_{id} + d_o/d_i \times 1/h_i = 296\text{W/m}^{2\text{o}}\text{C} \quad (31)$$

B. Design of the Stripping Chamber

The design of the stripping chamber basically involves the determination of chamber volume and height, which were determined from the simple geometric formulae as shown below. However, the diameter of the chamber used is 0.35m. The Assumed weight of raw material (eucalyptus leaves) to be charged into the chamber was taken as 10kg and density of the leaf was found to be 231kg/m^3.

Volume of the chamber,

$$V = \frac{mass\ of\ raw\ material\ (kg)}{density\ of\ raw\ material\ (kg/m^3)} = 0.0433m^3 \quad (32)$$

Chamber diameter, D (assumed) was 0.35m. Hence, *chamber height*, H was determined as:

$$H = \frac{4V}{\pi D^2} = 0.45m \quad (33)$$

C. Design of the Steam Generation Unit (Boiler)

The steam generation unit was designed to take 25 litres of water, as this quantity will be enough to exhaust the 10kg raw material charged into the stripping chamber [16]. If the diameter of the boiler is taken same as that of the stripping chamber, i.e. 0.35m; volume of water to be used is known and that density of water being 1000kg/m^3. This implies that mass of the water is 25kg. Thus, volume of the boiler (V) can be determined from the following relation:

$$V = \frac{mass\ of\ water\ (kg)}{density\ of\ water\ (kg/m^3)} = 0.025m^3 or\ 25litres \quad (34)$$

Take diameter, D was taken the same as that of the chamber = 0.35m. Then, height of the unit was determined from;

$$h = \frac{4V}{\pi D^2} = 0.26m \quad (35)$$

D. Design of the Decanter (Settler)

Separation of two liquid phases, immiscible or partially miscible liquids is a common requirement in the chemical process industries. For instance, in the unit operation of liquid – liquid extraction, the liquid contacting step must be followed by a separating stage. It is also frequently necessary to separate small quantities of entrained water from process streams [14, 15, 17]. The simplest form of equipment used to separate liquid phases is the gravity settling tank, the decanter and the type of decanter to be used for this process plant is the vertical, cylindrical decanter. The general approach taken in designing the decanter is as illustrated by [14, 15], while the summary of the design parameters and values are presented below. Some constants used in the decanter design such as density of dispersed phase (i.e. eucalyptus oil), r_d was found to be 823.16kg/m^3, that of the continuous (heavy) phase (i.e. water), r_c is 1000kg/m^3; acceleration due to gravity, g=9.81m/s^2 and viscosity of the continuous phase, μ_c is 1mNs/m^2. Then, diameter of the decanter vessel, d was taken the same as that of the boiler, which is 0.35m.

Interfacial area,

$$A_i = \pi r^2 = 0.1m^2 \quad (36)$$

The decanter vessel *height,*

$$h_v = 2d = 0.70m \quad (37)$$

Assumed droplet diameter, d_d used for the design was 150µm

Settling velocity of the dispersed phase droplets,

$$u_d = \frac{d_d^2 g(\rho_d - \rho_c)}{18\mu_c} = \frac{2.2mm}{s}(rising) \quad (38)$$

Residence time of droplets in the dispersion band,

$$t_r = \frac{h_v}{u_d} = 318\text{secs.}\ (\sim 5mins) \quad (39)$$

Velocity of oil phase,

$$u_{oil} = 20\%\ of\ u_d = 0.44\text{mm/s} \quad (40)$$

Entrained droplet size,

$$d_{drop.} = \left[\frac{u_{oil} 18\mu_c}{g(\rho_c - \rho_d)}\right]^{1/2} = 117\mu\text{m} \quad (41)$$

Height from datum to light liquid overflow,

$$Z_1 = 0.9h_v = 0.63\text{m} \quad (42)$$

Position of the interface (height from datum to interface),

$$Z_3 = 0.5h_v = 0.35\text{m} \quad (43)$$

Height from datum to heavy liquid overflow,

$$Z_2 = \frac{(Z_1 - Z_3)\rho_1}{\rho_2} + Z_3 = 0.58\text{m} \quad (44)$$

E. Design of the Cooling Water System

A cooling water reservoir is to be specified for the distillation plant for cooling the steam inside the condenser. The cooling water is to be recycled and be used for many batch runs to avoid wasting much water. A moderate reservoir of 200 litres capacity that would be sufficient to absorb the quantity of heat released by the steam in a batch run is selected for this design. This will serve as a heat sink [16]. A smaller rated centrifugal pump of 0.5HP is to be used for pumping cooling water from tank to the condenser. Specifications of the pump are as follows: Power, P = 0.37kW or 0.5HP; Maximum head, H_{max} = 35m; Speed, N = 2850rpm; Maximum volumetric flowrate, Q_{max} = 35l/min. or $5.83x10^{-4}m^3/s$ and voltage, V=220V (single phase).

IV. FABRICATION AND ASSEMBLY OF THE PLANT

The components of the plant designed such as steam generation unit, stripping chamber, condenser and support frame were fabricated and assembled to obtain the plant. An assembly of the fabricated plant is shown in Fig.2 below.

Fig.2 Assembly of the fabricated plant

V. TESTING OF THE PLANT

The procedure for testing the plant involves ensuring that the plant is in good condition and this could be initiated by closing all valves that are supposed. The boiler tank was filled with clean water and the stove was put on and the starting time was recorded. The leaves were prepared, weighed on a scale and charged into the stripping chamber. When the thermometer reading on the boiler reads 70°C, the control valve was opened slightly to allow steam pass through the stripping chamber. The effectiveness of the steam generation unit was monitored to ensure its ability to generate steam rapidly and that of the stripping chamber by its ability to strip the leaves effectively. The condenser vent were also monitored. When steam is observed, on the cooling water pump the condenser valve was opened and the condensate collected. The water on top of the condensate was drained thus leaving the oil in the separating funnel. The oil collected was put in a bottle and closed. The process above was repeated until no oil was observed in the condensate. The time from starting the stove to when no more oil drops was recorded as the maximum extraction time. The procedure was repeated for other batch runs, each time recording the maximum extraction time and the corresponding quantity of oil collected. The total time taken for the batches run per day and the corresponding quantities of oils collected were added to obtain the approximate output of the plant per the run hours which was based on the plant size and specifications. From the tests carried out, the plant extracted only 18ml of eucalyptus oil for 82 minutes run.

VI. COST ANALYSIS

Cost is a major factor that determines the materials to be used as well as the method of fabrication to be used in the manufacture of an item. Hence, it is very vital to ensure that the cost of the finished item is moderate and affordable. The total cost incurred in the cause of developing the designed extraction plant consist of material cost, labour cost and overhead cost. The overhead cost was taken as 20% of the total materials cost. The total cost incurred is:

$Total\ Production\ cost$ =(Labour cost + overhead cost + material cost) = $(11,950 + 115,300 + 23,060) = N150,310:00$

That is, One hundred and fifty thousand, three hundred and ten Naira only.

VII. CONCLUSION

The plant for extraction of eucalyptus oil from eucalyptus leaves was developed. The plant is relatively simple to operate and is capable of extracting essential oil locally from eucalyptus leaves. The cost of the plant is also affordable. When it was tested, the plant was able to extract 18ml of eucalyptus oil during the 82 minutes of operation. The test result shows that the production volume is small. This may be due to some problems encountered during the testing such as inconsistency of flame from the stove, steam leakages and using eucalyptus leaves that are not fresh i.e the ones that might have lost moisture. Based on the work conducted, it is recommended that planting of species of the eucalyptus trees other than *Eucalyptus Camaldulensis, Eucalyptus Terticornis and Eucalyptus Saligana,* that are capable of producing leaves even during dry season period should be encouraged by the government so as to sustain a year round production of these leaves for essential oil production.

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