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0.75MMTPA CAPACITY REACTOR AND HEAT EXCHANGER DESIGN FOR MANUFACTURING VG20 BITUMEN

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ABSTRACT

Bituminous materials are porous and waterproofing membranes used for construction, roofing, waterproofing and other applications. Bitumen is a viscous liquid soluble in trichloroethylene. They are four methods of manufacture bitumen by atmospheric distillation, vacuum distillation, air blowing and solvent refining. Rheological control is required for the production of bitumen in a given area The air blowing process using Biturox technology grants a maximum flexibility in crude selection. Hence quality bitumen can be produced from a wide range of crudes and refinery feedstock efficiently by downstream process. Here we are designing a VG20 bitumen reactor and heat exchanger for a capacity of 0.75MMTPA

INTRODUCTION

Bitumen is one of the oldest engineering materials known to mankind dating back to about 3800 BC. The comparatively recent expansion of highways has resulted in the use of bitumen in large quantities. In 2024, the world demand is estimated to reach around 119.5 million metric tons of bitumen, which is a rise of 4.1% when compared to average demand of previous years (Freedonia, 2021). Since 1854, when the first bitumen roadway was laid in Paris, paving products have accounted for most of the bitumen produced. At present 73 percent with the remaining 10 percent finding application in miscellaneous products such as tiles, floor coverings, pints, insulation, rust preventatives, and bituminized paper products.

LITERATURE REVIEW

- **Bitumen – Composition and Structure**

Bitumen is outlined as a viscous liquid, or a solid, consisting basically of hydrocarbons and their derivatives, that is soluble in trichloro ethylene and is well non-volatile and softens step-by-step once heated. It's black or brown in shade and possesses waterproofing and adhesive properties. Bitumen regarded as a complex mixture of high molecular weight hydrocarbons. A more specific statement concerning chemical composition is difficult because of the extremely large number of compounds occurring in bitumen make chemical analysis exceedingly complicated which includes oxygen, sulphur, and nitrogen, The oxygen present in form of carbonyl, carboxylic, and hydroxyl compounds; nitrogen is present as porphyrins and porphyrin metal complexes; while sulphur, as well as some of the nitrogen and oxygen, appears in heterocyclic rings. Also, the existence of nickel, vanadium, and traces of other metals in bitumen has been reported.

Bitumen is a thermoplastic material. It softens while heated and hardens on cooling. Within positive temperature range, bitumen is Visco-elastic. It famous the mechanical traits of viscous flow and elastic deformation

Constituent	Wt.% (percentage of weight)
Saturates + Aromatics	50-60
Resins	25
Asphaltenes	20

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Saturates and aromatics are the fraction with the lower molecular weight ranging from 300 to 2000. The hydrogen-carbon ratio is higher than asphaltenes or resins.

Aromatics oils consist mainly of carbon, hydrogen, and sulphur with a minor amount of nitrogen and sulphur with a molecular weight of 500 to 900. The compounds have mainly aromatic rings or naphthenic-aromatic nuclei with a side chain.

Saturated oils consist mainly of long chain saturated hydrocarbons with some branched chain compounds, cyclic paraffins. Molecular weight in the range of 500 to 1000.

Resins are composed of heterogenous polar compounds with a small percentage of oxygen, nitrogen, sulphur and metals. The molecular weight is 800 to 2000. Resins have higher hydrogen-carbon ratio compared to asphaltenes.

The asphaltene molecule has a core condensed aromatic rings and aliphatic side chain. Asphaltene molecule typically composed of 10 or more fused and naphthenic rings with a significant number of alkyl side chains. The molecular weight of asphaltene lies in the range of 2000 to 5000.

- **Bitumen production**

Crude oil is first processed in crude oil distillation unit (CDU) where it is heated up around 350 – 400°C depending on the type of crude oil after removing impurities such as sodium and magnesium salts, water and other sediments. Crude oil is then fractionated in a distillation column where lighter fractions such as liquefied petroleum gas (LPG), naphtha, kerosene and diesel are separated. The products are routed to respective storage locations after cooling to atmospheric temperature. Remaining heavier portion of the crude oil further distilled under vacuum in a Vacuum Distillation Unit (VDU) to separate vacuum gas oil (VGO) and vacuum residue (VR) as major fractions. VR and VDU are then routed to a biturox unit to produce oxidized bitumen or to a VIs-Breaker Unit (VBU) to produce furnace oil (BPCL 2006).

- **An overview of bitumen air-blowing technology**

Bitumen is frequently processed chemically to modify its physical properties. The most widely used process was first patented by E.J.DeSraedt in 1881. He found out that oxidation of bitumen resulted in a product which had a greater tenacity and was less brittle and less liable to be affected by air or water (Douglas, 1964). The present practice is to blow asphalt at a temperature of 260-272°C at a rate of 30-170 cubic feet air per minute per ton of bitumen for a period of 1 to 4 hours. The reaction carried out industrially either batch or continuous processes. Based on the trend to stiffer bitumen grades with excellent fatigue properties. The modern bitumen production requires chemical conversion in addition to distillation.

The biturox air blowing technology improves the thermal susceptibility, resulting in a softer grade at low temperatures and harder one at high temperatures. The feed composition is processed gently to preserve the valuable resin components under elevated pressure (Porner,2009). The polarity of the aromatic components is increased, minimising the risk of local overheating and coke build up. Internal reactor allows exact temperature control. The fully automated process in a constant and homogenous finished product quality. The technology is efficient, controllable and safe (Porner, 2009).

DESIGN

- **Material and Energy Balances**

1. Material balance for Bitumen blowing reactor

The gross chemical reaction for the asphalt blowing process might be described as follows (John, 1954).

$$Ar + O_2 + inerts \longrightarrow Aox + Lx + CO_2 + H_2O + O_2 + inerts$$

Ar = Asphalt charge stock

Aox = composite air blown asphalt product not removed

Lx = the complete condensed product removed overhead minus CO_2, H_2O, and other gases.

<u>Assumptions:</u>

Basis – 1 hour operation

Consider pseudo-components in air blown bitumen as follows:

C_5H_{10} = 11 %

C_6H_6 = 11 %

$C_{12}H_{26}$ = 11 %

$(C_2H_5)_2CO$ = 6.66 %

$C_2H_5COC_3H_7$ = 6.67 %

$C_5H_{11}COOH$ = 6.67 %

C_6H_5OH = 8.33 %

$C_6H_{10}O_3$ = 8.33 %

$C_2H_5COOC_2H_5$ = 11 %

$(C_2H_5)_2O$ = 8.34 %

C_2H_6 = 11 %

Off gases contain only CO_2, O_2, N_2 and H_2O (or water vapour).

Oxygen supplied is 4 % excess of the theoretical requirement [5].

Chemical Reactions:

1. Dehydrogenation of Aliphatic Bond to Form an Olefin

$C_5H_{12} + 0.5\ O_2 \rightarrow C_5H_{10} + H_2O$

2. Aromatization of Naphthenic Ring to Aromatic Ring

$C_6H_{12} + 1.5\ O_2 \rightarrow C_6H_6 + 3\ H_2O$

3. Direct Carbon-Carbon Bond Formation

$2\ C_6H_{14} + 0.5\ O_2 \rightarrow C_{12}H_{26} + H_2O$

4. Ketone on side chain

$C_5H_{12} + O_2 \rightarrow (C_2H_5)_2CO + H_2O$

5. Ketone with naphthenic ring rupture

$C_6H_{12} + 0.5\ O_2 \rightarrow C_2H_5COC_3H_7$

6. Carboxylic acid

$C_6H_{12} + O_2 \rightarrow C_5H_{11}COOH$

7. Hydroxyl group

$C_6H_6 + 0.5\ O_2 \rightarrow C_6H_5OH$

8. Anhydride

$2\ C_3H_8 + 2\ O_2 \rightarrow C_6H_{10}O_3 + H_2O$

9. Ester

$C_3H_8 + C_2H_6 + 2\ O_2 \rightarrow C_2H_5COO\ C_2H_5 + 2\ H_2O$

10. Ether

$2\ C_2H_6 + O_2 \rightarrow (C_2H_5)_2O + H_2O$

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11. Decarboxylation

$C_2H_5COOH \rightarrow C_2H_6 + CO_2$

Conversion of weight % to mole % for composition of air blown bitumen

Component	Weight %	Mole%
C5H10	11	12.05
C6H6	11	10.81
C12H26	11	4.96
(C2H5)2CO	6.66	5.94
C2H5COC3H7	6.67	5.11
C5H11COOH	6.67	4.41
C6H5OH	8.33	6.79
C6H10O3	8.33	4.91
C2H5COOC2H5	11	8.27
(C2H5)2O	8.34	8.64
C2H6	11	28.11

Amount of air blown bitumen to be produced = 750000 tons/annum = 1216.85 kmol/h From the chemical reactions mentioned above, components production rate as well as consumption rate can be calculated. It is therefore summarised in the table below

Material balance summary for air blowing reactor

Component	Feed stream (kmol/hr)	Product stream (kmol/hr)
C5H12	218.91	0
C6H12	247.38	0
C6H14	120.68	0
C6H6	82.61	131.54
C3H8	220.13	0
C2H6	310.89	342.05
C2H5COOH	342.05	0
O2	962.02	0
N2	3619.03	3619.03
C5H10	146.63	0
C12H26	0	60.34
(C2H5)2CO	0	72.28
C2H5COC3H7	0	62.18
C5H11COOH	0	53.66
C6H5OH	0	82.61
C6H10O3	0	59.75
C2H5COOC2H5	0	100.63
(C2H5)2O	0	105.13
H2O (vapor)	0	1040.13
CO2	0	342.05
Total	**6270.33**	

- **Energy balance for blown bitumen cooler**

The blown bitumen cooler unit facilitates the transfer of heat from the hot blown bitumen (VG20 grade) to the vacuum residue. Thus, bitumen is cooled to the temperature required for storage conditions. In the cooler, the vacuum residue is heated from 120^{o}C to 210^{o}C. The energy required for this is obtained from the bitumen stream. The principle of energy balance is used to find out the amount of energy required.

Temperature:

Bitumen VG20 in, T_{hi} = 270°C

Bitumen VG20 out, T_{ho} = 185°C

Vacuum Residue, T_{ci} = 120° C

Vacuum residue, T_{co} = 210°C

Bitumen VG 20 flow rate (m_h) = 25.912 kg/s

Vacuum residue flow rate (m_c) =26.19 kg/s

Specific heat of bitumen VG20 (Cp_h) = 2356 J/kg K

Specific heat of vacuum residue (Cp_c) = 2178 J/kg K

$Q\text{-}Q_c = Q_h$

Q_h = mh Cp_h ΔT = 25.912 x 2356 x (270 – 185) = 5189137.12 J/s

Q_c = 26.19 x 2178 x (210 – 120) = 5133763.8 J/s

- **Equipment Design**

Design of Bitumen Blowing Reactor

Bitumen blowing reactor is a continuous stirred tank reactor (Harry, 2003). It is assumed that reaction takes place only in the reactor and it is a constant density system.

Reactor volume = 49.63m^3

Minium diameter of reactor = 2.5m

Minimum height of reactor = 11.8m

1. **Design of agitator**

Design summary for agitator

Diameter of an agitator (impeller)	500mm
Shaft diameter	60mm
Agitator speed	123rpm
Stress on impeller blades	36.93 N/mm^2
Hub diameter	120mm
Hub length	150mm
Key length	100mm
Width of key	2mm
Dimensions of key	6mm*6mm*100mm

2. **Mechanical design**

2.1. Shell Thickness:

Shell thickness calculated from IS:2002-1962 Grade 2B

Outer shell thickness = 1.008<1.5; It is a thin-walled vessel

2.2. Thickness of Head:

Assuming an elliptical head,

Thickness of head was calculated as 10mm

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2.3. Design of tall vessel:

Diameter of vessel	2520 mm
Height of vessel	11800 mm
Height of support	4200 mm
Shell Thickness of the vessel	10 mm
Thickness of Elliptical Head	10 mm

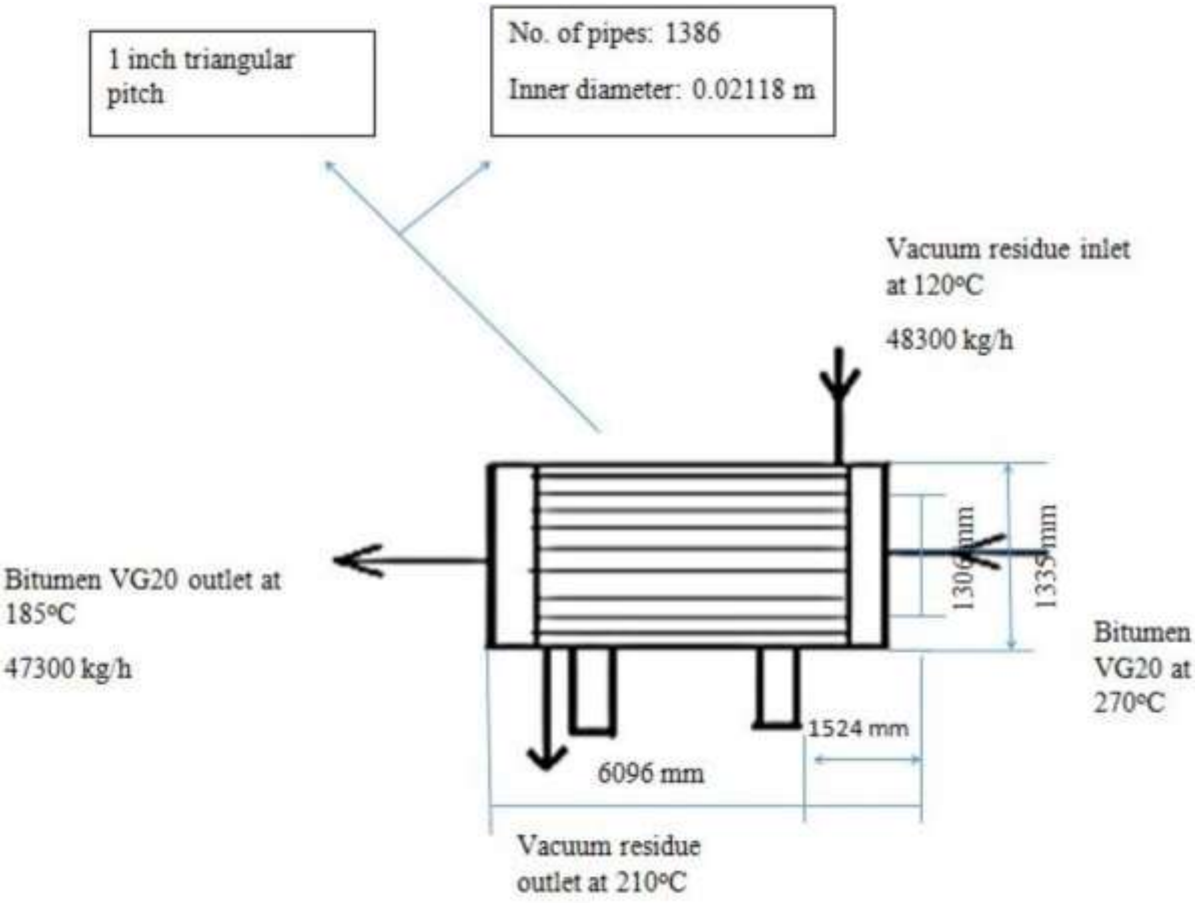
2.4. Skirt Support

Diameter of skirt	2520 mm
Height of skirt	4200 mm
Thickness of skirt	56 mm
Thickness of bearing plate	28 mm
Number of bolts	60

Design of Bitumen VG20 Heat Exchanger

1. **Process Design**

This section is about the design of bitumen heat exchanger which is used to cool the VG20 coming out of the reactor as the product (Seader, 2004).



CONCLUSION

A complete plant study of existing bitumen plant of 0.35 MMTPA was undertaken. The production of 0.75 MMTPA bitumen VG20 has been described in this report. The design of major equipment involved in the plant that include bitumen blowing reactor, heat exchanger for cooling the product have been done. The various factors that involved like the amount of raw materials, energy requirement have also been estimated. As a future scope other factor such as investment and break-even analysis can be estimated to ensure that it can be a highly profitable venture and a sure prospect for a new investment.

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