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Energy Consumption in Hydrogenation Plant

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ABSTRACT

Fatty acid part of triglycerides having double bonds is susceptible to attack by atmospheric oxygen, resulting in rancid odor, which is not acceptable to consumers. Unsaturated fatty acid molecules having 2 - 4 double bonds (unsaturated) are hydrogenated fully to convert the double bonds into single bonds (saturation). Hydrogenation of C18 unsaturated fatty acids give stearic acid which has large number of industrial applications. In today's world, fatty acids are hydrogenated using supported nickel metal as most appropriate catalyst to remove the unsaturation and nickel catalyst offers comparatively higher "performance / price" ratio. Hydrogenation is the process of addition of hydrogen gas to the double bonds by reaction with hydrogen for conversion of unsaturated fatty acids to saturated fatty acids in presence of nickel catalyst. Compromising on quality cannot reduce cost and hence the most appropriate area for cutting cost is the energy bill. The major draw for all companies working on conserving energy in their plants is the reduction in production costs leading to an out and out profit gain, with minimal investment. In this work heat recovery system, steam consumption, hydrogen gas consumption and energy consumption were studied.

Keywords: Hydrogenation, Hydrogen, Nickel Catalyst, Jomel, Energy

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INTRODUCTION

In hydrogenation, that is saturation of the double bond has in fact taken place, the net liberation of energy for a drop of one unit in iodine value is sufficient to raise the temperature of the oil close to 1.7°C ; depending on the specific heat of the oil, the exothermic heat of reaction has been computed as 1.7 Btu/lb or 0.942 k.cal/kg per unit drop in iodine value. This liberation of heat has very important implications for the design of hydrogenation autoclaves [1].

Oil partially hydrogenated to a certain degree of unsaturation, as measured by its iodine value, will therefore show wide variations in its composition & physical properties, depending upon which of the many possible reactions predominated. The technology of hydrogenation is concerned with the control of these reactions in order to achieve certain characteristics in this product.

The overall rate at which hydrogenation takes place, the composition, characteristics of the final product depends upon the type of catalyst used, the catalyst concentration in the oil, the hydrogen gas pressure, the temperature of the reaction, and the degree of hydrogen gas dispersion [2].

The most important factor perhaps is the type of catalyst used. Finely divided nickel metal catalysts are commonly used in commercial hydrogenation.

The accepted theory is that the reaction takes place on the surface of the catalyst where the oil & gas molecules are adsorbed & brought into close contact. It is understandable therefore that any condition which affects the catalyst surface or which controls the supply of gas to the catalyst surface will in turn affect the course & the rate of the reaction.

It is generally concluded that the selectivity of the reaction is favored by low temperature, high catalyst concentration, high temperature and low degree of gas dispersion in the oil. It should be realized that the theoretical aspects of hydrogenation are not very well established and that in practice hydrogenation is as much an art as it is a science [3].

Reaction Variables

Pressure

Reaction rate increases with increasing pressure up to a maximum of approximately 500 psig (34 atm). Increasing the pressure above 500 psig has little or no effect on additional increase in reaction rate. In a controlled laboratory hydrogenation reaction using distilled tallow fatty acid, constant catalyst concentration, and isothermal temperatures, increasing the pressure from 50 psig to 150 psig resulted in a 50% decrease in product IV at equal times.

Increasing the pressure to 300 psig resulted in an additional 37% decrease in product IV. However, increasing the pressure to 500 psig resulted in only an additional 7.5 % decrease in product IV. It therefore appears that a pressure in the range of 300 to 400 psig (20 to 27 atm) is the ideal range for fatty acid hydrogenations when considering solely improvements caused by pressure [4].

Temperature

Increasing temperature increases the reaction rate up to a maximum, above which there may be a negative effect. The optimum temperature varies depending on the type of fatty acid, its purity, or the degree of saturation required; however, it is normally in the range 149 to 205°C (300 to 400°F). Above the optimum temperature, degradation products may come into effect, thereby slowing the reaction rate due to catalyst blinding or pore blockage.

When the temperature of hydrogenation is increased, several parameters affecting the observed hydrogenation rate occur. Increasing the temperature increases the hydrogen solubility in the oil and lowers the viscosity of the fatty acid, thus increasing the effective agitation rate. With the increased solubility of the hydrogen in the oil and the greater effective agitation rate, a faster reaction can occur on the catalyst surface since hydrogen is more readily available to the catalyst [5].

Agitation

Increasing reactor agitation increases reaction rate. When an agitation rate of 900 to 1000 rpm was obtained, the increase seemed to level off; subsequent increases above the 1000 rpm level had little or no additional effect on the reaction rate. The effective agitation rates in industrial reactors are generally nowhere near the 900 to 1000 optimum rpm obtained in laboratory studies. Normally, because of equipment restraints, commercial reactor agitation cannot be increased to ideal levels [6].

Catalyst Loading

Increasing catalyst loading increases reaction rate. There would appear to be a maximum due to the fact that during the course of fatty acid hydrogenations, utilizing extremely large amounts of catalyst would cause a rapid decrease in hydrogen concentration in the fatty acid. If this did occur in isolated areas of the reactor, the dehydrogenation of the reaction could become the predominant driving force until additional hydrogen was introduced into the deficient area. This is exemplified in the hydrogenation of castor oil, where the use of either too much catalyst or too active a catalyst can lead to dehydrogenation of the hydroxyl group to a ketone rather than hydrogenation of the double bonds [7].

Catalyst Addition

In addition to the variables noted above, a factor sometimes overlooked is the time of catalyst addition. Ideally, the catalyst should be added to the reactor after the fatty acid is

near the reactor temperature; and then hydrogen should be added immediately after catalyst introduction in order to start the reaction.

Prolonged exposure of a nickel catalyst to hot fatty acid can cause catalyst deactivation from impurities or degradation of the feed. The hot fatty acid can also dissolve nickel off the catalyst support, thus rendering a specific amount of nickel inactive for the hydrogenation reaction. Again, ideally, a catalyst should be added to the reactor dry (unslurried) to prevent both the deactivation and the dissolving of the catalyst [8].

Feedstock Quality

The levels of inhibitors in the feed may have to be lowered. Otherwise, the catalyst concentration may be prohibitively high, time of hydrogenation exceedingly long or final quality of the hydrogenated oil poor.

A typical split fatty acid may require 6 to 8h to lower the IV 40 units using 0.06% nickel; while the same fatty acid, which has been distilled, would undergo a unit decrease of 50 to 55 IV in 2h using the same 0.06% nickel. Therefore, inhibitor reduction is utmost importance for the hydrogenation of fatty acids.

Some of the impurities in feed stocks that affect the rate of hydrogenation are moisture, sulfur, halides, polyethylene, and phosphorous. Other intrinsic properties of the feed, such as hindered bonds, branch chain, and substituted fatty acids, may require special processing, special reaction conditions, or special catalysts [9].

EXPERIMENTAL

Charging

- Fatty acids to be hydrogenated are first taken to drier through low temperature heat exchanger.
- In low temperature heat exchanger these fatty acids are heated by taking heat from hydrogenated fatty acids of the penultimate batch.
- Dryer is operated under vacuum and the moisture is removed from the fatty acids.
- The dried fatty acids are sent to feed tank through high temperature heat exchanger.
- In high temperature heat exchanger fatty acids are further heated by taking heat from the hydrogenated fatty acids (penultimate batch) coming from discharge vessel.
- This process is continued till the required level of feed is received in feed tank sufficient for one batch.
- Feed tank is also kept under vacuum.
- From feed tank the batch of material is taken to autoclave (charging).
- After getting sufficient level in autoclave, agitation is to be started.

Catalyst Dosing

- After getting the required temperature in the autoclave catalyst is dosed to start the reaction with hydrogen gas. For that required amount of catalyst is taken in catalyst mixer and made into slurry by taking the material from the autoclave. Then the slurry is charged to autoclave [10].

Gassing

- After completion of the dosing of catalyst hydrogen gas is supplied to autoclave.
- Due to this unsaturated fatty acids are converted to saturated fatty acids and this is being an exothermic reaction heat is generated and the temperature of the autoclave increases.
- The temperature of the autoclave materials is maintained under 200⁰C by passing hot water through coils of autoclave if required.
- This gassing is continued till required iodine value is achieved.

Discharging

- After getting the required IV value (after sampling) hydrogen gas is stopped to autoclave and the contents are released to discharge vessel (discharging).
- After discharging is completed the autoclave would be ready for the next batch.

Cooling

- Now the hydrogenated fatty acids from the discharge vessel are transferred to cooler through high temperature heat exchanger and then to low temperature heat exchanger. Simultaneously fatty acids to be hydrogenated are started from storage tank to feed tank.
- Due to the heat exchange between HCFA and CFA hydrogenated fatty acids are cooled to 90⁰C.
- In cooler these fatty acids are further cooled if required by circulating cooling water in cooler.
- Carbon is added to cooler at 85⁰C.

Filtration

- Pressure leaf filter is used for removal of the catalyst and carbon.
- Material is taken to cloudy tank and filter aid is added. This material is circulated through PLF to form a coating on the leaves.
- After completing this coating the hydrogenated fatty acids from the cooler are sent to PLF.
- The clear filtrate is collected in filtered oil tank [11].



RESULTS AND DISCUSSION

Calculation of plant capacity for different batches

Observation: Batch -1

Material: CPSCFA + PFADCFA

Grade: Jomel<2

Iodine value: 1.7

- Feed taken to feed tank through high temperature heat exchanger and low temperature heat exchanger: 6:20 am to 8:00 am
- Feed tank to autoclave at 148⁰C: 9:20 am to 9:28 am
- Agitation starting and ending time: 9:28 am to 11:25 am
- Catalyst adding time: 9:30 am to 9:35 am
- Gassing time (starting and ending): 9:35 am to 11:05 am
- Sampling time: 11:30 am to 12:00 noon
- HCFA discharging time from autoclave to discharge vessel: 12:05 pm to 12:15 pm
- HCFA is taken to cooler from discharge vessel through high and low temperature heat exchangers: 12:55 pm to 2:25 pm
- Carbon adding time: 1:45 pm
- Filtration starting and ending time: 2:30 pm to 3:15 pm

Note: Total time taken for Batch-1 is given in Table 1

Batch Size: 11tons

In 2hr 48 min the HCFA production is 11tons

In 24 hrs the HCFA production is: Plant Capacity = $24 \times 11 / 2\text{hr } 48\text{min} = 94.28 \text{ tons/day}$

Observation: Batch-2

Material: CPSCFA + PFADCFA

Grade: Jomel<2

Iodine Value: 1.56

- Feed taken to feed tank through high and low temperature heat exchangers: 9:35 am to 11:00 am
- Feed taken to autoclave: 12:15 pm to 12:22 pm
- Agitation starting and ending time: 12:25 pm to 2:30 pm
- Catalyst adding time: 12:25 pm to 12:30 pm
- Gassing time: 12:30 pm to 1:44 pm
- Sampling given time: 2:30 pm
- HCFA discharged to discharge vessel from autoclave: 3:05 pm to 3:15 pm
- HCFA is taken to cooler through high and low temperature heat exchangers: 3:30 pm to 5:05 pm
- Carbon adding time; 4:50 pm
- Filtration starting and ending time: 5:10 pm to 5:46 pm



Note: Total time taken for Batch-2 is given in Table 2

Batch Size: 11tons

In 02hr 57 min the HCFA production is 11tons

In 24 hrs the HCFA production is: Plant Capacity = $24 \times 11 / 2\text{hr } 57\text{min} = 89.49$ tons/day

Observation: Batch-3

Material: CPSCFA + PFADCFA

Grade: Jomel<2

Iodine value: 1.7

- Feed taken to feed tank from storage tanks through high and low temperature heat exchangers and dryer starting and ending times: 9:52 am to 11:17 am
- Initial temperature of the material: 70⁰C
- Low temperature heat exchanger inlet temperature: 70⁰C
- Low temperature heat exchanger outlet temperature: 110⁰C ($\pm 2^0$ C)
- Dryer temperature: 110⁰C ($\pm 2^0$ C)
- High temperature heat exchanger inlet temperature: 110⁰C ($\pm 2^0$ C)
- High temperature heat exchanger outlet temperature: 148⁰C ($\pm 2^0$ C)
- Feed tank temperature: 150⁰C ($\pm 2^0$ C)
- Feed charging from feed tank to autoclave at 145⁰C: 12:23 pm to 12:31 pm
- Temperature after feeding: 151⁰C
- Agitation starting and ending time: 12:31 pm and 2:28 pm
- Gassing time: 12:34 pm to 1:50 pm
- Catalyst adding time: 12:31 pm to 12:34 pm
- Tempered water circulation time: 1:05 pm to 1:15 pm
- Temperature dropped: 200⁰C to 182⁰C
- Sampling time: 2:28 pm
- HCFA discharged from autoclave to discharge vessel: 3:10 pm to 3:15 pm
- HCFA is taken to cooler from discharge vessel through high and low temperature heat exchanger: 3:40 pm to 5:00 pm
- High temperature heat exchanger inlet temperature: 180⁰C
- High temperature heat exchanger outlet temperature: 145 to 150⁰C
- Low temperature heat exchanger inlet temperature: 145 to 150⁰C
- Low temperature heat exchanger outlet temperature: 95 to 98⁰C
- Cooler temperature: 85⁰C
- Cooling water is given to cooler: 4:20 pm to 5:05 pm
- Filtration starting and ending time: 5:05 pm to 5:25 pm

Note: Total time taken for Batch-3 is given in Table 3

Batch Size: 11tons

In 02hr 57 min the HCFA production is 11tons

In 24 hrs the HCFA production is: Plant Capacity = $24 \times 11 / 2\text{hr } 57\text{min} = 89.49$ tons/day

Note: Time taken and plant capacities of different batches is given in Table 4



Power Consumption per Batch

Note: Pump power details is given in Table 5

Total power per ton = 135.366 kW / 11 tons = 12.306 kW/ m.t

Initial=134.99294; Final=135.12925

Grade= 9

Initial iodine value=54; Final iodine value=4.6

Power consumption=final – initial (pan room)=133.12925-134.99294=0.13631 consumption

Total KW = consumption × 1000 = 136.31 kW

= 136.31 kW / 11 tons = 12.39 kW/ m.t

Hydrogen Gas Consumption for Hydrogenation

1 unit iodine value drops for one m.t required gas is 0.93m³ (gas effective 1.1m³)

1 unit iodine value drops raising temperature is 1.7⁰C (temp. efficiency 1.5⁰C)

Material = CPSCFA + PFADCFA

Initial IV = 39; Final IV = 1.7; Dropping IV = 37.3

Temperature = 37.3×1.5 = 55.9⁰C

Initial temperature AC = 148⁰C

Total = 203.9⁰C

0.93×11×37.3 = 381.5m³ of gas is required to drop the 37.3 units for one batch

Heat Recovery

In hydrogenation plant, heat is recovered from hydrogenated fatty acids to heat the incoming batch. This reduces the steam consumption in the plant.

Note: Observed data for Heat Exchanger-1 is given in Table 6

Heat given by the cold fatty acid:

$$Q = m C_p \Delta T = 10,000 \times 0.5 \times 44 = 2,20,000$$

Heat given by the hot fluid:

$$Q = m C_p \Delta T = 10,000 \times 0.52 \times 55 = 2,86,000$$

Note: Observed data for Heat Exchanger-2 is given in Table 7

Heat given by the cold fatty acid:

$$Q = m C_p \Delta T = 10,000 \times 0.6 \times 38 = 2,28,000$$

Heat given by the hot fluid:

$$Q = m C_p \Delta T = 10,000 \times 0.62 \times 35 = 2,17,000$$

Note: Heat load of Heat Exchangers is given in Table 8

Steam Consumption

The hydrogenation plant is designed to get full heat recovery by installing two spiral heat exchangers. The required temperature is 150°C which is achieved during the heat recovery. Hence no further heating is required and no steam consumption.

However, first two batches are to be heated as hydrogenated fatty acids are only available from 3rd batch onwards. So, steam is required to heat the first two batches to reaction temperature.

Calculation of steam consumption:

Quantity of batch = 10,000kg

Inlet temperature = 65°C

Outlet temperature = 90°C

Heat required = $m C_p \Delta T$

This material is heated by steam, which loses its latent heat to heat the batch.

Steam Consumption = Heat load / Latent heat

Latent heat of steam at 15kg/cm² = 463.1

Steam consumption = 8000/463.1 = 17.274 kg of steam.

The above result is approximately equal to zero. So the steam consumption is limited or zero.

Table 1: Total time taken for Batch-1

S.No.	Description	Time		Time Taken
		From	To	
1	Charging	9:20	9:28	08min
2	Drying	-	-	-
3	Catalyst Mixing	9:30	9:35	05min
4	Gassing	9:35	12:00	2hr 25min
5	Discharging	12:05	12:15	10min
Total				2hr 48min

Table 2: Total time taken for Batch-2

S.No.	Description	Time		Time Taken
		From	To	
1	Charging	12:15	12:22	07min
2	Drying	-	-	-
3	Catalyst Mixing	12:25	12:30	05min
4	Gassing	12:30	03:05	2hr 35min
5	Discharging	03:05	03:15	10min
Total				2hr 57min

Table 3: Total time taken for Batch-3

S.No.	Description	Time		Time Taken
		From	To	
1	Charging	12:23	12:31	08min
2	Drying	12:18	12:23	05min
3	Catalyst Mixing	12:31	12:34	03min
4	Gassing	12:34	03:10	2hr 36min
5	Discharging	03:10	03:15	05min
Total				2hr 57min

Table 4: Time taken and plant capacities of different batches

Batch	Material	Grade	Time Taken	Tons/Day
1	CPSCFA + PFADCFA	Jomel<2	2hr 48min	94.28
2	CPSCFA + PFADCFA	Jomel<2	2hr 57min	89.49
3	CPSCFA + PFADCFA	Jomel<2	2hr 57min	89.49

Table 5: Pump power details

S. No.	Pump Type	Motor Rating, kW/hr	Working Time, min	Total kW
1	Magnetic Drive	30	120	60
2	Vacuum Pump	11	180	33
3	Drier Pump	2.2	90	3.3
4	Discharge Vessel Pump	2.2	90	3.3
5	Filter Feed Pump	7.5	40	5
6	Direct Water Pump	5.5	180	16.5
7	Filter Oil Transfer Pump	3.7	60	3.7
8	Feed Tank Circulation	3.7	120	7.4
9	Tempered Water Pump	5.5	10	0.916
10	Feed Transfer Pump	1.5	90	2.25
Total per batch				135.366

Table 6: Observed data for Heat Exchanger-1

Description	Units	Type of Fluid	
		Cold Fluid	Hot Fluid
Material	Kg	CFA	HCFA
Inlet Temperature	$^{\circ}\text{C}$	65	140
Outlet Temperature	$^{\circ}\text{C}$	109	85
Specific Heat	Kcal/kg $^{\circ}\text{C}$	0.5	0.52
Quantity/Batch	Kg	10,000	10,000

Table 7: Observed data for Heat Exchanger-2

Description	Units	Type of Fluid	
		Cold Fluid	Hot Fluid
Material	Kg	CFA	HCFA
Inlet Temperature	$^{\circ}\text{C}$	108	175
Outlet Temperature	$^{\circ}\text{C}$	146	130
Specific Heat	Kcal/kg $^{\circ}\text{C}$	0.6	0.62
Quantity/Batch	Kg	10,000	10,000

Table 8: Heat load of Heat Exchangers

Equipment	Heat Load (Kcal)
Heat Exchanger – 1	2, 20, 000
Heat Exchanger – 2	2, 28, 000
Total	8000

CONCLUSIONS

- Hydrogenation uses flammable gas (hydrogen), hence electrical equipment is to be designed for flame proof.
- The heat generated by the exothermic reaction is effectively used to heat the contents of the incoming material thereby requires no additional heating.

- Gas induction reactor which is being used in hydrogenation plant has the advantages of vigorous gas liquid mixing, thorough suspension of catalyst, reduced batch time, minimum side reaction and excellent batch to batch repeatability.

Scope for Future Work

- Hydrogenation is extensively used in edible industry for manufacture of vanaspati. This is very much essential to produce toilet soap and stearic acid at inedible industry.
- In hydrogenation catalyst is the costly ingredient so the process design and autoclave design should aim to decrease the catalyst consumption. Here there is a good scope for improvements and a study can be taken up to see the catalyst consumption by increasing the pressure up to 19 kg/cm².
- The steam consumption is already achieved zero so the scope is limited.

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