Cleaner Production by Using Recent Type of Reactor in Chemical Reactions

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ABSTRACT

Cleaner production is a pollution preventive, company-specific environmental protection initiative which intends to minimize waste and emissions and maximize product output. It is also reduces energy consumption and global warming. Improvement of organization and technology helps to reduce or suggest better choices in use of materials and energy and to avoid waste, waste water generation and gaseous emissions. The recently developed novel design of two rectors like jet loop rectors and gas induction rectors with new reactions will provide cleaner production. Jet loop reactor (JLR) utilizes kinetic energy of a high velocity liquid jet to entrain the gas phase and creats a fine dispersion of two phases thus having very high efficiency in gas dispersions resulting in high mass transfer rates. Gas Induction type Reactor uses the self induction principle for impellers providing vigorous gas-liquid mixing with substantial increase in gas-liquid interfacial area of contact and enhances gas- liquid mass transfer rate. JLR shows excellent performance in process of bio filtration where pretreatment of waste pretreatment of waste gases is necessary to ensure the stable operation of biofilter. JLR also found to be suitable method in high rate aerobic treatment of brewery waste waters. Gas induction reactors shows high efficiency for the removal of industrial wastes and have reliable operational stability at low investment and operating cost in processes of hydrogenation and sulphonation in dyes industries. Thus JLR and Gas induction reactor prove to be potential candidate for cleaner productions.

This paper also provides novel design of both the reactors for process of hydrogenation of edible oil. Design correlations and resulting data are presented in tabular form and design of any of these rectors can be done using this table.

Key words: jet loop, gas induction, spiral baffle jacket, mass transfer coefficient, hydrogenation Corresponding author. E-mail : jalpa6019@gmail.com , sbthakore@yahnoo.co.in, Tel : 9428044179

1. Introduction

Gas-liquid reactions are frequently encountered in chemical, biochemical, pharmaceutical and polymer processing industries[1]. In gas-liquid operations, a gas must be effectively and efficiently contacted with the liquid to provide mass transfer[2]. Agitated tank is one type of the most common and important reactor widely used for gas-liquid heterogeneous reactions in the chemical industry. It provides many characteristic performances such as good mixing effect, better mass and heat transfers, etc[3,4]. However, the interaction between turbines and baffles requires high power consumption. Furthermore, the recovery of the unreacted gas injected through the process liquid from the bottom of the tank is complicated in the conventional agitated tanks. This problem is commonly solved by linking tanks in series or by using a compressor to recirculate the unreacted gas back to the process liquid. Both of these two methods are complex processes and may need additional accessory equipment and increase the operational costs.

For improvements of conventional agitated tanks, gas-inducing impellers may be used as an advanced method for gas-liquid contacting in stirred tank reactors[5]. As the impeller rotates, the liquid phase is accelerated over the surface of the contoured impeller blades, resulting in the formation of a reduced pressure region. This reduced pressure region on the blade surface is connected to the reactor headspace, via a gas inlet on the shaft above the liquid level, hollow shaft and blades, and an outlet orifice on each blade (Figure 2). The pressure difference between the blade surface and the headspace produces a gas induction effect. The magnitude of this driving force depends on the impeller speed and the radial position of the orifice; gas induction commences when the pressure at the orifice falls to the headspace pressure, i.e. when the static head of liquid above the orifice has been overcome. The speed at which this occurs is known as the critical impeller speed [6].

Thus gas-inducing reactors provide an advantage over conventional agitated stirred tank reactors for a number of industrially important gas-liquid unit operations. Potential applications of these reactors are in the fine chemicals industry for reactions where external recycling of the headspace gas would be hazardous, e.g. for hydrogenations or chlorinations etc [7].

Jet loop reactors are increasingly being used in gas-liquid systems in place of sparged vessels and bubble columns because of their high mass transfer performance, well defined flow pattern, better dispersing effects and relatively low power requirements. The majority of investigations reported on jet-propelled loop reactors concern with a central draft tube and a two fluid nozzle installed at the bottom of the reactor [8,9]. This type of arrangement is disadvantageous when the reactor is used as a slurry reactor, or in processes involving sparingly soluble gas, due to the blockage of the nozzle and a lower residence time of the gaseous phase [10].

These difficulties in the design led to the development of a new jet propelled loop reactor where the gas is introduced from the top of the reactor through a tube arranged in the centre of the liquid nozzle, which is referred as down flow jet loop reactor [11,12]. The gas phase residence time can be increased considerably in the down flow reactor when the gas is introduced from the top of the reactor into a liquid flowing cocurrently downwards so that the bubbles are forced to move in a direction opposite to their buoyancy. The heterogeneous reactions requiring high conversion of the gas phase reactants and processes that require high ratios of liquid to gas throughput like waste water treatment can be favorably contacted in a down flow jet loop reactor[11].

The objective of the present study is to gain a better understanding of the mechanism of gas induction and gas loop reactors such that an improved and general design for gas-inducing impellers and jet ejectors can be developed. The influence of operational variables and design parameters affecting overall volumetric mass transfer coefficient were also investigated.

2. Jet Loop Reactor (JLR)

Jet Reactor is a new and most versatile design of reactor (Figure 1) which can be used to achieve excellent gas – liquid mixing among all gas-liquid Contactors and it is a type of loop Reactor. In the field of chemical, biochemical, and reaction engineering Jet Loop Reactor (JLR) is widely used because of their high efficiency in gas dispersion resulting in high mass transfer rates.

2.1 Principle

The principle in this reactor type is the utilization of the kinetic energy of a high velocity liquid jet to entrain the gas phase and to create a fine dispersion of the two phases. The circulation flow caused by hydrodynamic jet drive and hydro-mechanical liquid is very important in conducting reaction [1].

2.2 Working Characteristics

According to the jet ejector position, the reactor can be operated in both down flow and up flow regimes. The Jet Loop Reactor shown in Figure 1 consists of an ejector, which discharges into a vessel; the liquid is circulated through the system via an external loop & gas is introduced from the top of the reactor. When the gas-liquid flow leaves the ejector a secondary dispersion of gas bubbles is obtained in the bulk fluid of the vessel. The mass transfer occurs in the Jet Loop Reactor (JLR) via three ways.

1. Liquid is supplied to the reactor system via a nozzle and consequently gas is sucked into the suction chamber**.**
2**.** In the throat a so-called mixing shock occurs causing an intensive mixing of the two phases.
3. Mass transfer then takes place in the diffuser section.

The existence of the gas and liquid circulation loops provides perfect mixing in both phases. In addition, an external heat exchanger can be suitably inserted into the liquid circulation loop, eliminating thus the disadvantages of internal coils installation. Gas recirculation ensures complete gas utilization. Hence, the JLR can be operated at large values of gas throughput, providing large intensity interfacial area, without losses of the active component or requirements for installation of a circulation compressor. The complete gas utilization eliminates the problems of safety control on the off gas streams, and moreover, the gas circulation loop circumvents the problem of the removal of undesired volatile components from the gas phase. The liquid circulation mode and high degree of macro scale turbulence in the reactor vessel provide favorable conditions for catalyst suspension, which may be one of the critical issues in large-scale stirred-tank reactors.

Due to the operating principle and construction, the JLR exhibits numerous favorable features regarding their process application as well as design and scale-up. A high intensity interfacial area and a high mass transfer in the reactor occurred from the dispersion behaviour. The JLR is thus particularly suitable for fast reactions in which the liquid phase mass transfer is the reaction-limiting step of the process.

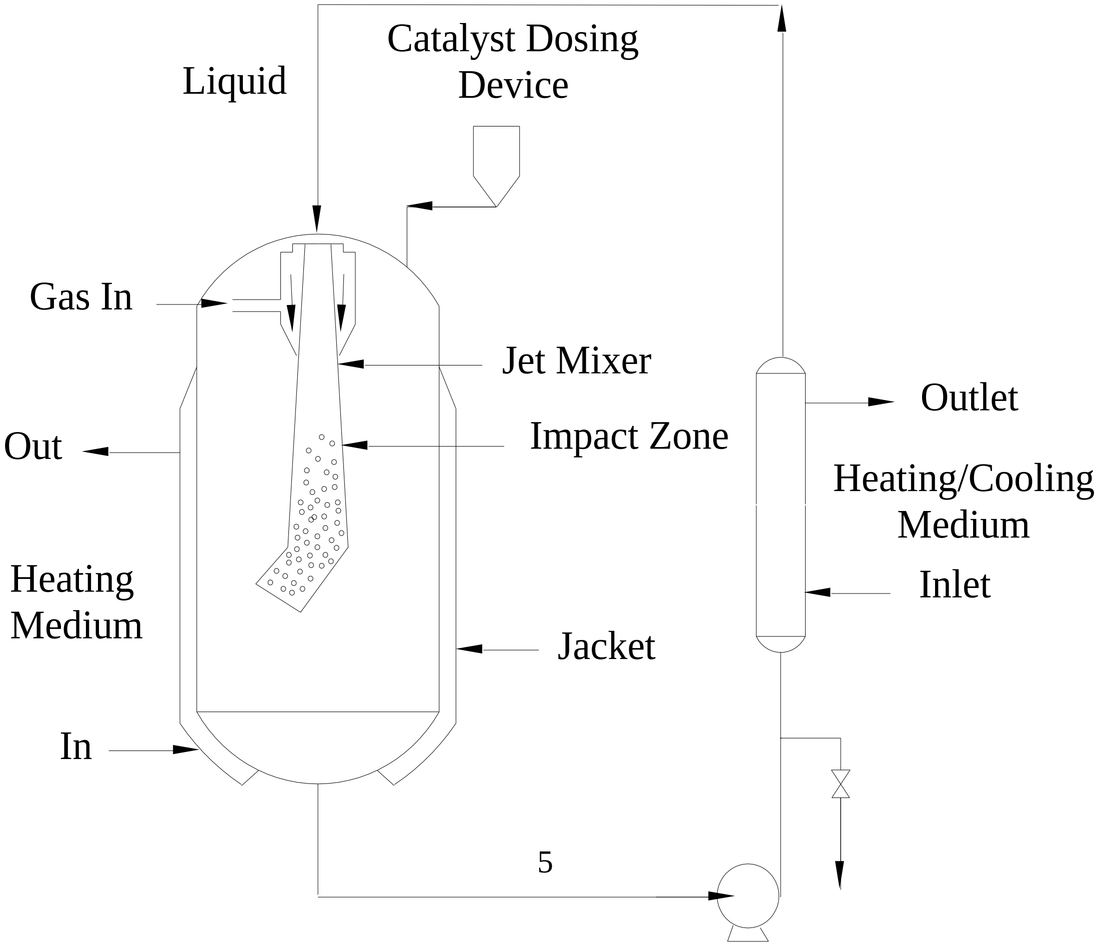


Figure 1 Jet Loop Reactor[1]

2.3 Advantages

1. Jet Loop reactor (JLR) promotes a faster reaction rate by exerting its higher mass transfer rate & mixing intensity as compare to continuous stirred tank reactor (CSTR). Absence of moving parts in jet loop reactors eliminates the sealing problems and allows easier operation at elevated pressure.
2. Length to diameter ratio of jet reactor is higher than same of agitated vessel, thus it requires less cost particularly for high pressure reactions.The external heat exchanger (instead of internal coil or jacket) can be built as needed and can have accurate temperature control even if the reactor is operated with reduced working volumes [13].
3. The maximum power input per unit volume is often a limiting factor, especially for large reactors with an agitator. Since there is no agitator in the jet reactor, this limitation does not exist. The circulation pump can provide very high power per m^3 of working volumes if it is required to achieve the desired mass transfer rate.

2.4 Disadvantages

Greater power consumption than other alternatives; and high attrition of suspending catalysts, if present. High installation & operating cost.

2.5 Applications

Jet Loop Reactor gives excellent performance on a faster reaction scheme such as the fully saturated hydrogenation process in palm oil refinery, hydrogenation, alkylation, carbonylation, oxidation, halogenations, animation, phosgenation, etc. reactions.

3. Gas Induction type Reactor

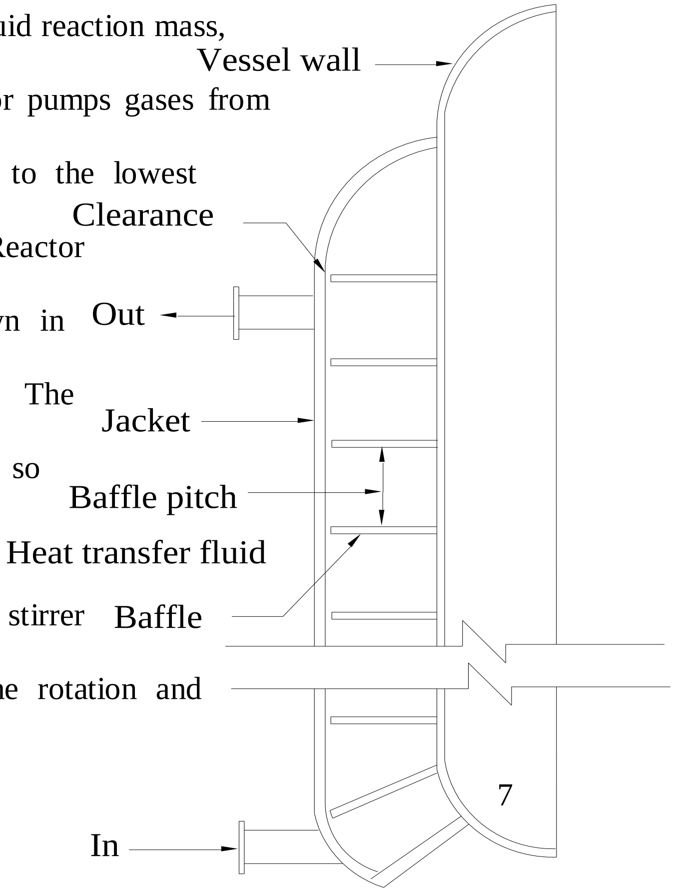
Gas itself creates the axial currents. Hence for the gas – liquid reaction system suitable agitator is that which creates the current in tangential and radial directions. Gas induction type hollow agitator is new innovation for Gas-liquid reaction application.

3.1 Principle

Gas Induction type reactor uses the self induction principle for impellers. The agitator operates on the principle of water jet ejector. The suction so generated blows the stirrer edges during the rotation and hence gas enters through windows and discharges from the bottom of impeller to liquid pool. Gas bubbles react with liquid as they rise. For efficient gas-liquid mixing the unreacted gas from the gas space is drawn back into liquid [1].

3.2 Working characteristics

A Gas Induction Reactor (Figure 3) offers a radial change from this conventional approach. Instead of churning the liquid reaction mass, a hollow agitator pumps gases from the head space to the lowest part of the Reactor vessel, as shown in the Figure 2. The suction so generated bellows the stirrer edges during the rotation and



hence gas through windows and discharges from the bottom of the impeller to liquid pool. A specially designed impeller vigorously disperses the gas bubble and creates a mixture akin to a boiling liquid. Gas bubbles react with liquid as they rise (Figure 2). Unreacted gas is re-induced into the liquid through windows. Recirculation is important because bubbling of gas only once through the liquid does not use it up completely [5].

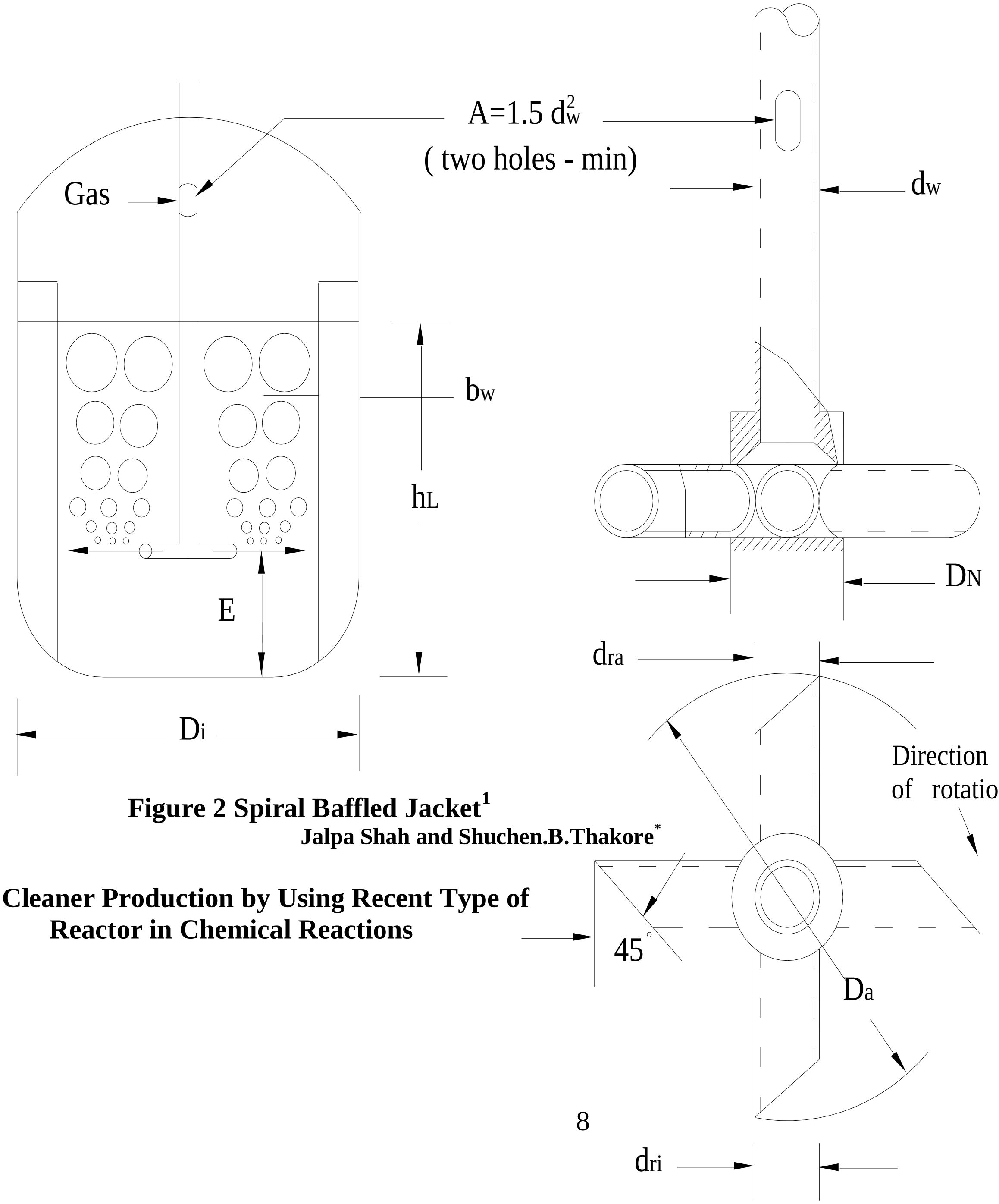


Figure 2 Spiral Baffled Jacket[1]

Figure 3 Gas Induction Type Reactor[1]

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3.3 Advantages

The self-aspiration agitator of a Gas-induction reactor has a highly efficient design, which leads to the following advantages.

1. It provides vigorous gas liquid mixing and complete utilization of solute in gas phase.
2. It substantially increases gas-liquid interfacial area of contact and enhances gas- liquid mass transfer rate. High rates of heat transfer coefficient – more than 500 kcal/h-m^2 °C. The high values of heat transfer coefficient have been achieved by the optimization of flow pattern near the heat transfer surface [14].
3. It reduces reaction time considerably for the gas–liquid reaction in which overall reaction rate is governed by rate of mass transfer. It also reduced bath times and minimal side reactions.
4. It provides very high vessel side (inside) coefficient which approaches a boiling coefficient. It gives excellent bath-to-bath repeatability and reaction time required is less compare to other convectional reactors.
5. The higher efficiency of the reactor can be advantageously used by reducing reactor volume (less capital cost) or reducing temperature, pressure, power consumption and catalyst loading. It is also the best choice for the gas-liquid reaction with suspended solid catalyst [1,2].

3.4 Disadvantages

High installation & operating cost.

3.5 Applications

It is widely used for catalytic hydrogenation reaction. Oxidation using pure oxygen or air. Manufacture of terpthalic acid, dimethyl terepthalate, adipic acid, acetic acid, acetic anhydride, phenol, hydrogen peroxide, benzoic acid and substituted benzoic acids, benzaldehyde and substituted benzaldehydes, etc. Alkylation using olefins Reductive alkylation’s. Carbonylation and carbozylation reactions. Ammonolysis and Ozonolysis, Hydroformylation. Wastewater treatment using aerobic biological Hydro metallurgical operations [1].

3.6 Spiral baffle jacket for gas induction reactor.

Recent development in jacket design is use of spiral baffle jacket (Figure 3). In case of exothermic reaction involving corrosive system cooling medium like cooling water or oil is circulated through the jacket. In such case plane jacket gives very poor heat transfer coefficient hence other types of jacket half coil jackets are well preferred for such cases. The plug flow characteristics of a half coil jacket permits faster displacement of the heat transfer fluid in the jacket and also avoids the problem of non uniform heating or cooling between the side walls and bottom dish. This is desirable for good temperature control[1].

Recent development for such application is spiral baffle jacket. In this type of jacket the spiral jacket decreases the flow area and increases turbulence in the flow of cooling medium and thereby increases heat transfer coefficient. Spiral baffle also acts as a stiffening ring and increases the resistance of shell to withstand the external pressure.

4. Design Calculation

4.1 Problem

Hydrogenation of edible oil is carried out to produce “Vanaspati” (hydrogen fat) in presence of nickel catalyst in batch reactor. In the standard age old process, edible oil in hydrogenated at about 2 bar g and 160 – 170 °C in 8 to 10 hours (excluding heating/Cooling). During this period, iodine value of the mass is reduced from 128 to 68. Final mass has a melting (Slip) point of 39 °C. The batch reactor has a jacket for heating the initial charge with circulating hot oil. Cooling requirements are met by passing cooling water in internal coils.

In a newly developed Jet Reactor, is planned to complete the reaction in 5 hours by improving mass transfer in the reactor and cooling the mass in external heat exchanger, thereby maintaining near isothermal conditions. Soyabean oil, having iodine value (IV) of 128 is to be hydrogenated in the jet reactor at 5 bar g and 165 °C. Initially the charge is heated from 30 – 140 °C with circulating hot oil in external heat exchanger, Hydrogen is introduced in hot soybean oil and pressure is maintained in the reactor at 5 bar g. Reaction is exothermic and the temperature of mass increases. Cold oil flow in the external heat exchanger controls the temperature at 165 °C as per the requirements; IV reduction is desired up to 68 when the reaction is considered over.

For the same hydrogenation of edible oil Gas Induction Type Stirrer and Spiral jacket is to be designed with the same duty. About 200 kg catalysts (1 to 2 µm particle size) is used with 10 t soybean oil. Spiral baffled jacket is to be used for heat transfer instead of plane jacket[1].

Input data for design calculation.

1) Charge = 10 t soybean oil with 128 IV

2) Average molar mass of soyabean oil = 278.0.

3) Average chain length of fatty acids = 17.78.

4) Product specifications: 68 IV, 39°C melting point.

   Assume linear drop of IV in 5 hours.

5) Average exothermic heat of reaction = 7.1 KJ/ (Kg IV reduction).

6) Hydrogen feed rate = 110 to 125 Nm^3/h.

7) Thermic fluid or oil is used as both, heating medium in starting of reaction and cooling medium in running of reaction.

8) Cooling water is available at 2 bar g and 32°C. A rise of 5°C is permitted. Cooling water is used for cooling the oil from 80°C to 70°C in oil cooler (HE-2) of oil cycle.

SR No.	Properties	Soyabean oil or Hardened fat	Circulating oil (Thermic fluid)
1	Density, kg/L	0.825	0.71
2	Specific heat, kJ/(kg·°C)	2.56	2.95
3	Viscosity, mPa.s	2.0	0.5
4	Thermal conductivity , W/(m.°C)	0.16	0.1

Table A Properties of Edible Oil (Tube side) and Circulating Oil (Shell side).

4.2 Design Calculation

Design equations with results for both Jet Loop reactor and Gas Induction Type Reactor are shown in Table B [1, 15,17-22] and Table C[1, 15,17-22]

4.2.1 Jet Loop Reactor

SR No.	Properties	Jet Loop Reactor (JGR)	
		Design Equations	**Results**
1.	Volume of liquid inside the reactor (m^3)	$V_L = \frac{\pi}{4} D_i^2 h_L$ + inside Volume of bottom head $h_L = 1.5 D_i$	12.12
2	Heat duty required (kW)	$\phi_C = m C_P \Delta T$	236.67
3	Tube side flow area (m^2)	$a_t = \frac{Nt}{N_P} \times \frac{\pi}{4} d_i^2$	0.01314
4	Tube side mass velocity (kg/m^2·s)	$G_t = \frac{m}{a_t}$	1237.5
5	Tube side velocity (m/s) and shell side velocity (m/min)	$u_t = \frac{G_t}{\rho}$	1.5
6	Tube side Reynold's Number and Shell side Reynold's no.	$\mathrm{Re}_t = \frac{d_t G_t}{\mu}$	13673.14
7	Tube side Prandlt Number and Shell side prandlt no.	$P_r = \frac{C_P \mu}{\kappa}$	32
8	Tube side Heat transfer coefficient (W/m^2·°C) and Shell side h.t. coefficient	$\frac{h_i d_i}{k_f} = 0.023\ R_e^{0.8}\ P_r^{0.33} \left(\frac{\mu}{\mu_W}\right)^{0.14}$	1063.87
9	Shell side flow area (m^2) and Heat transfer area available	$a_S = \frac{P_t - d_0}{p_t} \times D_S \times B_S$	0.00762
10	Shell side mass velocity (kg/m^2·s)	$G_S = \frac{m}{a_S}$	1052.89

11	Shell side velocity (m/s)) and jacket side velocity (m/s)	$u_S = \frac{G_S}{\rho_S}$	1.483
12	Shell side equivalent diameter (mm)	$d_e = \frac{1.1}{d_0}\left(P_t^2 - 0.907 d_0{}^2\right)$	18.3147
13	Shell side Reynold’s Number and jacket side Reynold’s no.	$R_e = \frac{d_e G_S}{\mu}$	38,566.7
14	Shell side Prandlt Number and jacket side prandlt no.	$P_r = \frac{C_P \mu}{\kappa}$	14.75
15	Shell side heat transfer coefficient (W/m^2·°C) and Jacket side h.t. coefficient	$\frac{h_0 d_e}{k} = 0.36 R_e{}^{0.55} p_r{}^{0.33}\left(\frac{\mu}{\mu_W}\right)^{0.14}$	1590.82
16	Overall heat transfer coefficient (W/m^2·°C)	$\frac{1}{U_0} =$ $\frac{1}{h_0} + \frac{1}{h_{0d}} + \frac{d_0 \ln(d_0/d_i)}{2k_W} + \frac{d_0}{d_i}\frac{1}{h_{id}} + \frac{d_0}{d_i}\frac{1}{h_i}$	416.5
17	Tube side Pressure drop (kPa)	$\Delta P_t = N_P(8 j_f (L/di)\left(\frac{\mu}{\mu_W}\right)^{-0.14} + 2.5)\frac{\rho u_t{}^2}{2}$	6.856
18	Tube side Pressure drop (kPa)	$\Delta P_t = 8J_f\left(\frac{D_S}{d_e}\right)\left(\frac{L}{B_S}\right)\frac{\rho u_S{}^2}{2}\left(\frac{\mu}{\mu_W}\right)^{-0.14}$	70

Table B Design Calculation of Jet Loop Reactor

4.2.2 Gas Induction type Reactor

SR No.	Properties	Gas Induction type Reactor	
		Design Equations	**Results**
1.	Volume of liquid inside the reactor (m^3)	$V_L = \frac{\pi}{4} D_i{}^2 h_L$ + inside Volume of bottom head $h_L = D_i$	14.084

2	Heat duty required (kW)	$\phi_C = mC_L\Delta T$	236.67
3	Tube side flow area (m^2)	—	
4	Tube side mass velocity (kg/m^2·s)	—	
5	Tube side velocity (m/s) and shell side velocity (m/min)	$V = \pi\ D_a\, n$ $D_a = \frac{D_S}{3}$	300
6	Tube side Reynold's Number and Shell side Reynold's no.	$\mathrm{Re} = \frac{ND_a{}^2\rho}{\mu}$	552093
7	Tube side Prandlt Number and Shell side prandlt no.	$P_r = \frac{C_P\mu}{\kappa}$	32
8	Tube side Heat transfer coefficient (W/m^2·°C) and Shell side h.t. coefficient	$\frac{h_i d_i}{k} = 0.023\ R_e^{2/3}\ P_r^{1/3}$ $\left(\frac{\mu}{\mu_W}\right)^{0.14}$	504.91
9	Shell side flow area (m^2) and Heat transfer area available	$A_{av} = \pi\ d_0\ h_L$	20
10	Shell side mass velocity (kg/m^2·s)	—	
11	Shell side velocity (m/s)) and jacket side velocity (m/s)	$\upsilon = \frac{(m'/\rho)}{PW}$	0.9
12	Shell side equivalent diameter (mm)	$D_e = 4\ W$	300
13	Shell side Reynold's Number and jacket side Reynold's no.	$\mathrm{Re} = \frac{D_e\upsilon\rho}{\mu}$	383400
14	Shell side Prandlt Number and jacket side prandlt no.	$P_r = \frac{C_P\mu}{\kappa}$	14.75
15	Shell side heat transfer coefficient (W/m^2·°C) and Jacket side h.t. coefficient	$\frac{h_j D_e}{k} = 0.027\ R_e^{0.8} P_r^{0.33}$ $\left[\left(\frac{\mu}{\mu_W}\right)^{0.14}\left(1+3.5\left(\frac{D_e}{D_j}\right)\right)\right]$	902.14

Table B Design Calculation of Gas Induction type Reactor.

List of symbols

V_L = Volume of the liquid inside the reactor (m^3).
D_i = Inside diameter of reactor (m)
h_L = Height of liquid inside the shell of reactor (m)
ϕ_C = Heat duty required (kW)
m_0 = Circulation rate (kW)
C_L, C_P = Specific heat of fluid (kJ/kg · °C)
ΔT = Temperature difference (°C)
a_t = Tube side flow area (m^2)
A_{av} = Shell side available heat transfer area (m^2)
G_t, G_S = Tube side, Shell side mass velocity ($kg/m^2 \cdot s$)
u_t, u_S = Tube side, Shell side velocity (m/s)
R_e, R_{et} = Reynold's number, Tube side Reynold's number.
P_r = Prandtl number
μ = Liquid viscosity (mPa·s)
ρ, ρ_L = Density of fluid (kg/m^3)
k = Liquid thermal conductivity (W/m·°C)
k_W = Thermal conductivity of tube wall material (W/m·°C)
μ_w = Viscosity of water ((mPa·s))
d_0 = Inside diameter of tube (m)
d_0 = Outside diameter of tube (m)
D_S = Shell diameter (m)
B_S = Baffle spacing (mm)
P_t = Tube pitch (mm)
p = Pitch of Baffle spiral (m)
W = Width of jacket (m)
m' = Effective mass flow rate through spiral (kg/s)
$\dot{m}$ = Actual mass flow rate through spiral jacket (kg/s)
d_e = Shell side equivalent diameter (m)
D_j = mean diameter of jacket (m)
D_{j0} = Outside diameter of jacket (m)
D_{ji} = Inside diameter of jacket (m)
D_a = Diameter of agitator (m)
D_S = Shell inside diameter (m)
V = Tip velocity of agitator (m/min)
h_i = Tube side heat transfer coefficient ($W/m^2 \cdot °C$)
h_0 = Shell side heat transfer coefficient ($W/m^2 \cdot °C$)
h_{id} = fouling coefficient for tube side fluid ($W/m^2 \cdot °C$)

h_{0d} = fouling coefficient for shell side fluid (W/m^{2}·°C)
h_{j} = Jacket side heat transfer coefficient (W/m^{2}·°C)
U_{0} = Overall heat transfer coefficient based on outside area of tubes (W/m^{2}·°C)
L = Tube length (m)
N_{P} = Number of tube side passes
N_{t} = Number of tubes
j_{f} = Friction factor
ΔP_{S} = Shell side pressure drop
ΔP_{t} = Shell side pressure drop

5. Conclusion

Jet Loop Reactor (JLR) & Gas Induction type Reactors has been the focus of a significant research effort devoted to provide novel design. These reactors aided in vigorous Gas-Liquid mixing and promote a faster reaction rate by exerting its higher mass transfer rate & mixing intensity as compare to conventional reactors. These novel reactors resolve the problems due to non-ideal mixing, negligible gas-liquid interfacial areas, as well as low heat and mass transfer coefficients thus giving satisfactory performances. Considering the economics and novel design, these reactors is thought to be an attractive technology in future applications.

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