

Increased Productivity in Hydrogenation of Edible Fats and Oils

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Fatty-acid chains in triglycerides of fats and oils from natural sources typically contain up to three double bonds. These double bonds are partly or fully saturated by hydrogenation in the refining process. The purpose of hydrogenation, in addition to the adjustment of the melting range, is the increased long-time stability of the oil or fat.

The productivity and selectivity of the hardening process are determined by the four parameters as indicated in Table 1.

(i) Productivity

Productivity is defined as ton of converted oil per volume of reactor and per time. Higher productivities lead to more throughput (lower operating cost/ton) or to smaller equipment for the same output (lower investment cost). Catalyst consumption and catalyst cost also contribute to the productivity. The following article describes an improved gassing system that promotes shorter hydrogenation times, less catalyst consumption, and hence increased productivity.

(ii) Selectivity

For some products (like baking fats), oils are hydrogenated to a fully saturated state. In many other cases, control over the extent and nature of saturation is critical to achieve a desired physiological and chemical behavior. Therefore, the quality of an oil or fat is directly influenced by the selectivity of the hydrogenation process.

Table 1
Parameters for Selectivity and Productivity

Parameter	Selectivity	Productivity
High pressure	Low	High
Efficient agitation/ gassing system	Low	High
High temperature	High	High
Catalyst type	High	High

Table 1 shows that high pressures and efficient gassing systems at a first glance lead to reduced selectivity at increased productivity. If more hydrogen is available on the catalyst surface, it attacks all double bonds in a more unselective manner. High temperature increases the conversion rate, thereby reducing the concentration of locally available hydrogen, so selectivity goes up. The competitive situation

between productivity and selectivity can be overcome by modern catalysts: they are available today for competitive prices and result in high selectivities plus high productivities when combined with a high-performing gassing system.

Cis-Trans Isomerization

The arrangement of hydrogen atoms around a carbon double bond can exist in two configurations. In all natural fats and oils only the *cis*-configuration occurs (Fig. 1). After a sufficiently long processing time, a certain fraction of the remaining double bonds is transferred to the *trans*-configuration. The *trans*-isomer is undesired, as it is speculated to have negative health effects.

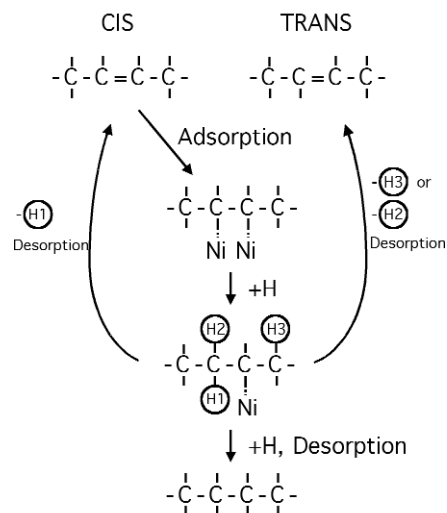


Figure 1. Mechanisms of *cis-trans* isomerization.

Short hydrogenation times with excess H_2 available on the catalyst surface promote saturation of the double bonds rather than isomerization to the *trans*-configurations. Lab tests have shown that better gas-liquid mass transfer tends to reduce the *trans*-formation. Nevertheless, these *trans* fatty acids cannot be completely suppressed during the hydrogenation process. A new route to gain *trans*-free fats and oils involves splitting the feedstock, fully saturating one part, followed by an interesterification with the unhydrogenated part.

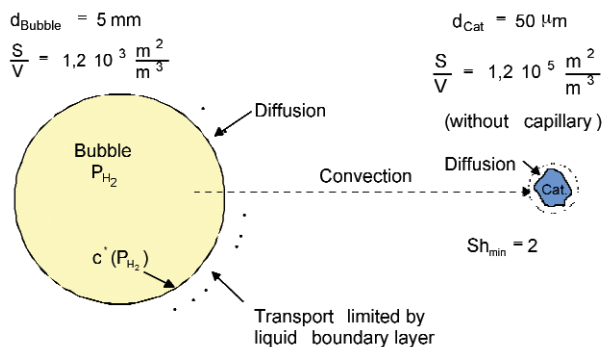


Figure 2. Hydrogenation, transport mechanisms.

Mechanisms of Hydrogenation

To promote the reaction, hydrogen must be dispersed into the oil and transported out of the gas phase and onto the surface of the catalyst. At the onset of the batch, when the reaction is fast, this mass transfer determines the conversion rate.

Three resistances must be overcome for the transport of hydrogen from the gas phase to the catalyst surface (Fig. 2):

- the liquid side boundary layer around the bubble
- the convective transport to the catalyst
- the liquid side boundary layer around the catalyst.

Convective transport is relatively fast as mixing times are short, assuming the agitator is properly designed. The diffusion through the boundary layer around the catalyst is

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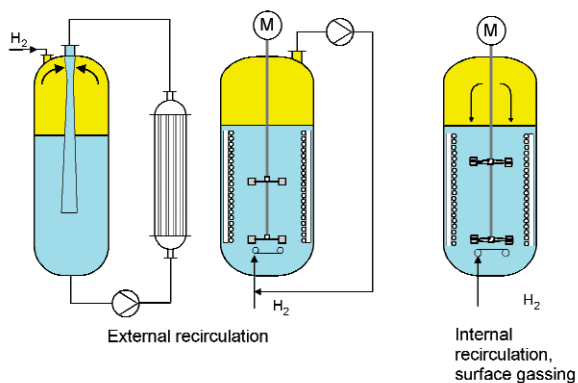


Figure 3. Gassing systems.

also not limiting: due to the small diameter of the particles, their specific surface is extremely high compared with the gas bubbles. Even with a minimum Sherwood – number $Sh_{min} = 2$, sufficient mass transfer will occur at the catalyst surface.

Of these three resistances, the diffusive transport through the boundary layer around the gas bubble is the rate-limiting step.

The hydrogen mass flow rate out of the gas bubble is quantified by

$$m = k_L a \cdot (c^* - c)$$

- c^* = saturation or solubility of hydrogen in oil, according to Henry’s law proportional to the pressure p . Higher pressure increases the transfer rate at the cost of compressor power and selectivity.

- c = actual concentration of dissolved hydrogen. $c \approx 0$ as long as the mass transfer is limiting.
- k_L = mass transfer coefficient, given by physical properties and material constants of the gas–liquid system. k_L is practically not influenced by agitation in the usual P/V -range.
- a = g–l-interfacial area, strongly influenced by gassing system.

The $k_L a$ is the key control parameter for the engineer designing the process. $k_L a$ depends on the type of agitation or gassing system and obeys the correlation,

$$k_L a = C \cdot \left(\frac{P}{V}\right)^x \cdot v_{sg}^y,$$

where P/V is the mechanical power per liquid volume (e.g., agitation power) of the gassing system, v_{sg} is the superficial gas velocity in the tank, and C represents the type of the gassing system. When operating under mass transfer limitation, any increase of $k_L a$ inversely reduces the hydrogenation time. Moreover, an improved gassing system with higher dissolved hydrogen concentration c extends the “service life” of the catalyst.

“Classical” Gassing Systems

Most oil converters are batch-operated. The incoming hydrogen is dispersed, but only a fraction of it is immediately dissolved. The rest rises to the headspace of the reactor. This unreacted hydrogen must be recycled and redispersed to prevent a buildup of pressure in the headspace that leads to decreased hydrogen feed, ultimately stalling the reaction. Figure 3 and Table 2 display the most common types of systems used in the industry.

Table 2
“Classical” Converter Types

Type	Description	Advantages	Disadvantages
Liquid loop reactor	Liquid is pumped through an external cooling loop and back to reactor through a suction nozzle. Gas feed to headspace, gas recirculation by suction nozzle.	High heat exchanging area available. Due to good gas recirculation suitable for dead-end operation.	Expensive, external equipment requires additional floor space. Hydrogen is fully consumed on the way through the loop: faster aging or poisoning of catalyst, by-product formation, etc.
Agitated reactor with external loop	Gas feed at the bottom via sparge ring, unreacted gas recirculated by external loop.	Due to good gas recirculation suitable for dead-end operation.	External loop is space-consuming and causes high investment cost. Compressor for H ₂ difficult in terms of safety and maintenance.
Agitated reactor with reinforced and surface gassing	Gas feed at the bottom via sparge ring, unreacted gas recirculated by surface gassing.	Compact design, no external equipment.	Surface gassing is not of utmost efficiency, therefore limitations in productivity. Function of surface gassing extremely dependent on exact liquid level.

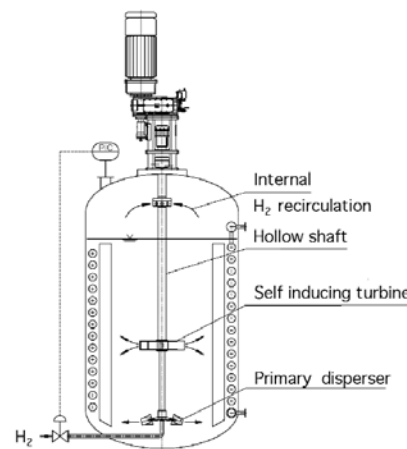


Figure 4. Hardening reactor, EKATO combined gassing.

Combined Gassing: Increased Efficiency and Less Catalyst Consumption

Figure 4 shows a new design for hardening reactors, which has demonstrated improved productivity in many full-scale applications. It avoids the disadvantages and combines the advantages of the “classical” systems.

The gas is fed into the bottom of the vessel where it is pre-dispersed by a concave-type turbine (EKATO Phasejet). The head pressure controls the primary feed rate, i.e., the conversion of hydrogen determines the feed rate. The unreacted gas is recirculated out of the headspace by a self-inducing turbine (EKATO Gasjet). This gives a maximum gas holdup in the beginning when the reaction is fast. Toward the end of the batch, it ensures no “starvation” of the catalyst from hydrogen due to the permanent recirculation. Enhanced catalyst activity and a fast achievement of IVs <1 are the results.

The design as described is very compact, with no additional equipment outside the reactor. This results in minimum investment and maintenance cost as well as required floor space.

Features of Combined Gassing

The primary impeller for dispersing the feed gas (Phasejet) is a concave-type turbine with the open end of the blades pointed in the direction of rotation. Contrary to the Flat Blade Disc Turbine (often known as Rushton turbine), the Phasejet power draw under gassing is very stable. On a Rushton turbine, stable gas cavities adhere to the trailing side of the blade, reducing the power number. Power goes down to at least 50% of the ungassed situation. This leads to significant losses in mass transfer capability as $K_L a \propto (P/V)^x$. In this situation, the speed of the turbine must be increased to regain performance. This requires a variable-speed drive at added cost. In compar-

ison, the concave shape of the blades on the Phasejet prohibits the adherence of these gas cavities. The full-power and mass transfer performance are retained with constant speed (i.e., no speed variation is required).

Another feature of the Phasejet is the rotating sparger at the rim of the conical disk. No sparge ring is needed; a simple feed pipe coming close underneath the impeller is sufficient (Fig. 5).

Compared with a full sparge ring with the Rushton turbine, this feed system is very easy to clean before product change.

The EKATO Gasjet recirculates hydrogen from the vessel headspace via a hollow shaft and special hub with suction holes in the flange coupling (Figs. 4 and 5). The vanes of the Gasjet widen to the tip, with the orifice for hydrogen release on the low-pressure side of the vane. When the speed of the Gasjet (and hence the pressure drop) is sufficiently high, then the hydrostatic head above the turbine is overcome and suction starts. The gas rate in different production scales and converter sizes can be precisely calculated based on a set of dimensionless numbers.

But fat-hardeners are not primarily interested in recirculation rates; they are interested in the productivity of the converter. This can indirectly be expressed by the achievable $k_L a$ -values.

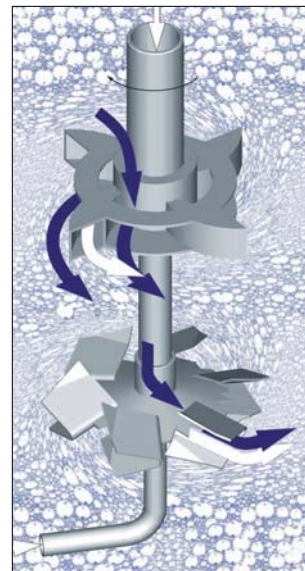


Figure 5. EKATO combined gassing.

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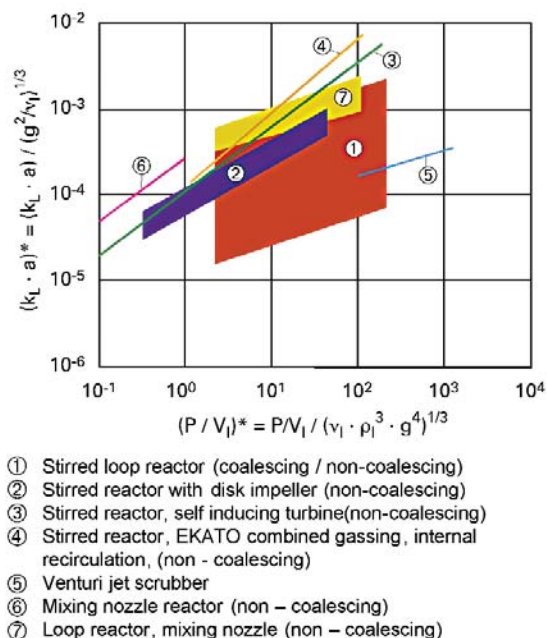


Figure 6. Gas-liquid reactor performance overview (Keitel-Onken-Diagram).

Figure 6 shows a general comparison of different gassing systems. $k_L a$ values are plotted vs. power input/volume in a dimensionless way where the viscosity of the system is considered.

The typical range for fat hardening is $(P/V)/(v\rho^3g^4)^{1/3} \cong 10$ corresponding to $P/V = 1$ to 2 kW/m^3 . Of special interest for the application discussed are numbers 2, 3, 4, and 7. The comparison shows the advantages of the Combined Gassing among the agitated systems and that it is in the upper range of technical available systems for gassing in general.

Potential Improvements

The Combined Gassing System (Fig. 7) has shown enhanced performance in many hydrogenation reactors. Figure 8 illustrates the potential improvements: assuming a 22.5-ton converter, operated at 3 bar and 2 kW/m^3 agitator power, which represents the design of modern converters with high productivity. The H_2 feed rate corresponds to the conversion rate or to the “ $\Delta\text{IV}/\text{min}$.” The difference to the upper line (combined gassing) is the additional gas rate due to the recirculation. Another effect of the additional gas holdup is shown in the lower graph of Figure 8, where $k_L a$ factor of the combined gassing system is compared with forced gassing alone. The benefit of better mass transfer is twofold:

In the beginning, when the reaction is fast and the conversion mass transfer limited, any increase in $k_L a$ leads to a proportional increase in the reaction rate. The overall reaction time gets correspondingly shorter. In the case of full saturation, the conversion rate and hence the H_2 feed rate go to zero at the end of the reaction per the first-order kinetics. The permanent recirculation maintains a high dissolved H_2 concentration, which finally raises to saturation. The high presence of H_2 on the catalyst surface protects it



Figure 7. Impellers for Combined Gassing system.

from adsorption of poisoning impurities. A reduced catalyst consumption is the consequence as operating experience shows.

Catalyst Suspension and Heat Removal

The article primarily focuses on increased productivity by efficient gassing. Two other important tasks

of the agitator are now discussed briefly:

First: The catalyst must be homogeneously suspended in the oil. A thorough investigation of the suspending behavior of the radial acting turbines proved that nickel or noble metal catalysts with their typical particle-size distribution are evenly distributed in the tank. Very tall reactors may require an intermediate axial pumping impeller stage.

Second: To bring the batch to reaction temperature requires first heating and in addition the adiabatic use of the increasing reaction heat. During the reaction itself, the temperature is kept on a certain level or range by cooling. In the end, the oil may be cooled to the temperature of the following process step. The heat transfer internals like coils or tube bundles must be properly adjusted to the flow pattern of the agitator. This ensures that heat transfer does not become a limiting factor as mass transfer rates are enhanced.

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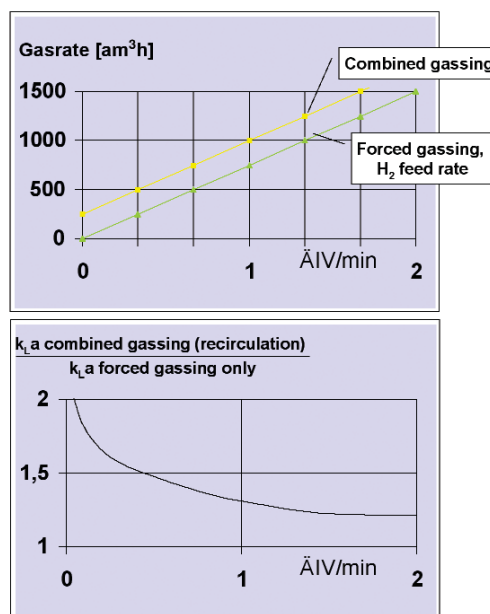


Figure 8. Comparison of mass-transfer performance.