CataLite® Reformers for ammonia cracking

Improving efficiency with CataRex® technology

Catator

Due to its advantages in storage, transport, and energy density, ammonia is rapidly becoming an important hydrogen carrier, allowing for efficient distribution of green hydrogen from producing to user regions. Before being used as fuel for gas turbines or fuel cells, or as feedstock for industrial processes, the hydrogen must be released through cracking of the ammonia. Catator has developed reactors and catalysts for ammonia cracking together with some of the world-leading companies in the field for well over a decade. Our proprietary CataRex® technology enables superior heat transfer capacity and the design of very compact and efficient ammonia cracking reactors. This paper provides an introduction to ammonia's important role to store and carry energy and hydrogen, supporting the transition to a world with abundant but intermittent renewable energy, as well as outlines how the CataRex® and CataLite® technologies offer advantages for technology suppliers that request space and cost-efficient solutions for ammonia cracking.

Ammonia as hydrogen carrier

Hydrogen is believed to become a cornerstone of the future energy and chemical industries, offering a clean and sustainable alternative to fossil fuels. As we aim to reduce carbon emissions and embrace renewable energy sources, hydrogen stands out for its versatility and efficiency. It can be utilized in fuel cells to produce electricity, serve as a fuel for transportation, and act as a crucial feedstock in various industrial processes.

However, using hydrogen comes with its own set of challenges and advantages. Hydrogen is a clean energy source that only emits water when combusted or used in fuel cells, resulting in zero carbon emissions. It is also the most abundant element in the universe and has a high energy content per unit mass, which makes it an efficient energy carrier.

Yet, the drawbacks are significant. Liquifying hydrogen for storage and distribution, requires either high pressure or extremely low temperature, both of which are costly and energy intensive. Furthermore, due to heat leakage during storage and distribution, so called boil-off can result in significant loss of hydrogen to the atmosphere through evaporation. Building the necessary infrastructure for widespread hydrogen use involves substantial investment. Additionally, the highly flammable nature of hydrogen demands strict safety measures for handling and storage.

This is where ammonia (NH_3) comes into play as a superior alternative for storing and transporting hydrogen. Ammonia can be liquified at room temperature and only 10 bar pressure. Its higher energy density per unit volume makes it more efficient for long-distance transport. Furthermore, the infrastructure for ammonia production, storage, and transportation has been built out for more than 100 years and is today well-established globally, especially in the fertilizer industry.

Ammonia is also less flammable than hydrogen, reducing some of the safety risks. Furthermore, it is more economically feasible at present, with lower costs associated with its production and transport. By using ammonia as a hydrogen carrier, we can effectively address the storage, transport, and safety issues linked with hydrogen. This makes ammonia a more practical and cost-effective solution, facilitating a smoother transition to a hydrogen-based energy system and accelerating the global adoption of clean energy technologies. Catator believes that ammonia is the most viable hydrogen carrier for applications where its advantages in storage, transport, and energy density outweigh the challenges associated with its toxicity and energy-intensive production. This includes applications such as long-distance transport, seasonal energy storage and maritime shipping.

While ammonia is a promising hydrogen carrier, it must be cracked into hydrogen and nitrogen before use in applications like fuel cells and gas turbines. Fuel cells, particularly Proton Exchange Membrane (PEM) fuel cells, need pure hydrogen to function efficiently. Ammonia can poison the catalysts in these cells, reducing their efficiency and lifespan. Gas turbines are designed to burn hydrogen or hydrocarbons efficiently, but ammonia has different combustion properties, such as lower flammability, which complicates its direct use. Burning ammonia can also produce harmful pollutants such as nitrogen oxides (NOx). By cracking ammonia into hydrogen before use, and mixing the hydrogen with ammonia, we can generate a fuel blend with combustion properties suitable for combustion engines and ensure cleaner combustion and greater compatibility with existing technologies. This localized and on-demand hydrogen production minimizes transportation and storage losses and allows for seamless integration into the current hydrogen infrastructure, maximizing efficiency and minimizing environmental impact.

Ammonia cracking is the reversed reaction in the Haber-Bosch process where ammonia is produced.

Haber-Bosch process: $1.5\ H_2 + 0.5\ N_2 \rightleftharpoons NH_3$

Ammonia cracking: $NH_3 \rightleftharpoons 1.5\ H_2 + 0.5\ N_2$

The heat of reaction is 46 kJ/mol NH_3 with the synthesis and decomposition reaction being exothermic and endothermic, respectively. This means that the same amount of energy that is released when synthesizing ammonia is required when cracking it back into hydrogen and nitrogen.

CataRex® for ammonia cracking

Considering the endothermic nature of the ammonia cracking reaction, a considerable addition and transfer of heat is required to drive the reaction at reasonable temperatures and reactor volumes. Catator's proprietary CataRex® technology couples the endothermic ammonia cracking with active and/or passive heating via heat exchange technology, which enables the design of very compact and efficient reactors. This makes the CataRex® reactors highly attractive for applications where space is a limiting design factor e.g. gas turbines or fuel cell systems for mobility applications. Over the years, Catator has developed the CataRex® concept to include plate as well as tubular type of catalytic heat exchangers for a range of different reactions such as reforming, water gas shift, methanation and ammonia cracking.

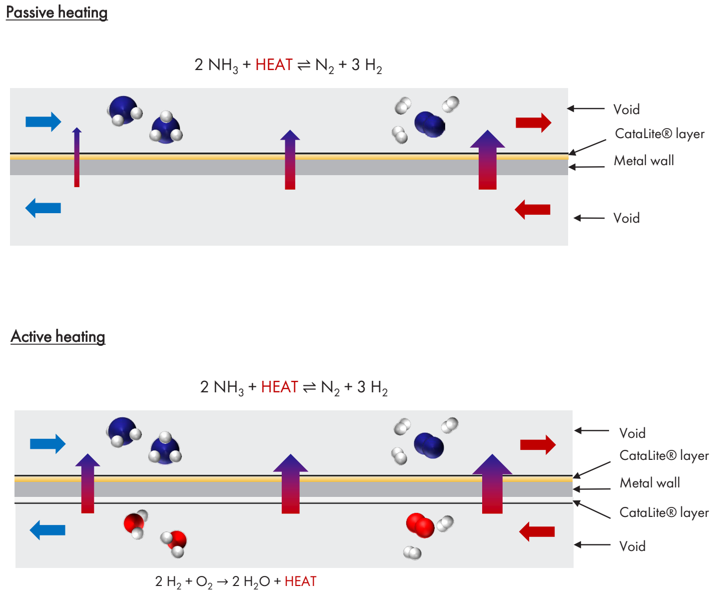


Figure 1. Principle of Catator's CataRex® technology using passive and active heating as demonstrated in upper and lower image, respectively.

As demonstrated in Figure 1, a significant advantage of the CataRex® technology is its ability to couple endothermic and exothermic reactions. For instance, it is possible to burn a fuel on one side of the heat exchange wall and utilize the heat to run an endothermic reaction on the other side. This offers the possibility to design highly compact reactors for ammonia cracking as both the maximum and average reaction temperature can increase by means of a fuel converted on the heating side of the CataRex® reactor. This is illustrated in Figure 2, where the amount of catalyst that is required to reach the equilibrium conversion of ammonia at various temperatures is displayed. Operating the reactor at 500°C instead of 600°C may require some 25 times more catalyst. Hence, irrespective of catalyst selection, if conditions allow the most effective approach for reducing the catalyst mass and the size of the CataRex® unit, is to increase and maintain the reaction temperature through coupled combustion and cracking.

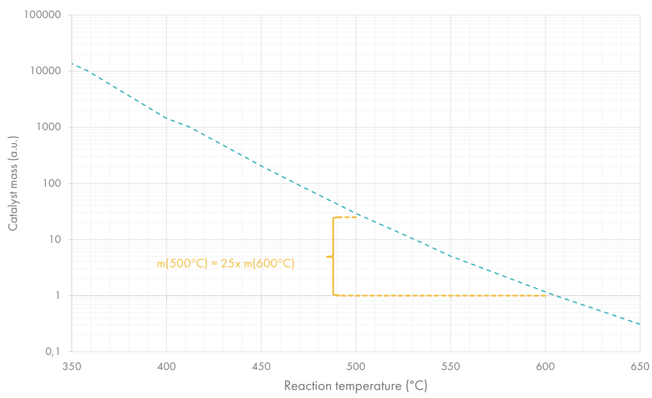


Figure 2. Catalyst requirement as function of reaction temperature. At 500°C operation temperature, some 25 times more catalyst is required than at 600°C to convert an equivalent amount of ammonia per time unit.

Over the years, Catator has developed several reactor configurations for ammonia cracking, including both low and medium-to-high temperature operation. The principal design of two reactor types is displayed in Figure 3. Due to their extremely high heat transfer capacity, in low-pressure applications (< 5 bar) the CataRex® units are generally plate-type heat exchangers, whereas tubular devices are used for high-pressure applications (> 5 bar). Due to the limited heat transfer capacity of the center tube of the tubular design, the reactor volume is typically 5 times larger than the volume of the plate-type design.

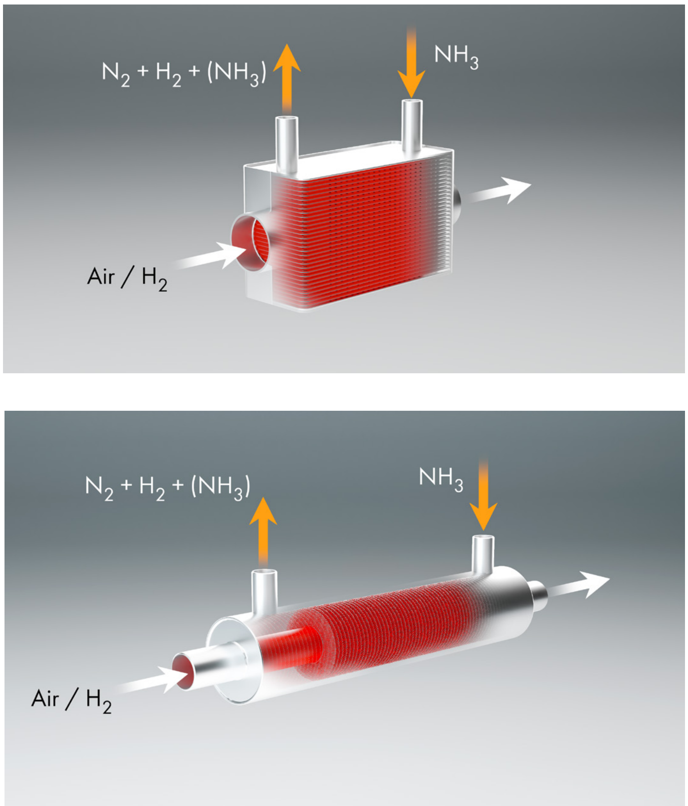
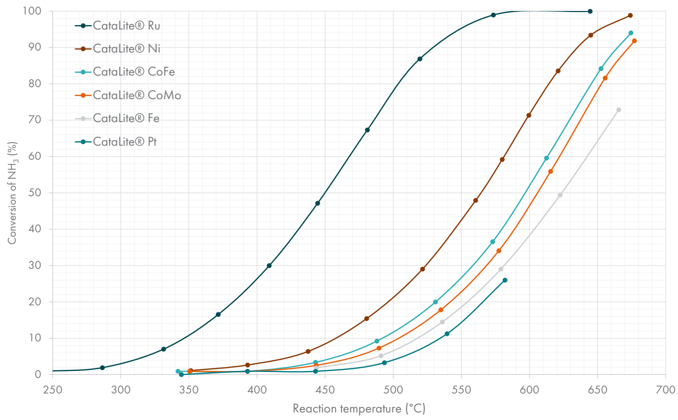


Figure 3. Plate and tubular type of CataRex® reactors.

CataLite® for ammonia cracking

The CataRex® technology allows for the design of very compact and high-performing reactors where the catalyst is efficiently structured directly onto the reactor components through Catator's coating technology, CataLite®. Using our CataLite® technology, a 20-100µm thin coating is strongly fixated onto a metal substrate, making the active catalyst material highly accessible for the chemical reaction. This means that even at high conversion rates of ammonia, the catalyst operates at conditions that are close to its full potential due to the fast transfer rate of heat and reactants (NH_3) enabled through the short diffusion paths and compact reactor geometry. Consequently, the amount of catalyst that is required to complete the reaction can be kept at low quantities, which enables the use of more exclusive catalysts such as Platinum Group Metals (PGMs) as active phases without significantly increasing the cost of the reactor unit.

For ammonia cracking, Catator offers a range of catalysts that are suitable for high to low operating temperatures. For low-temperature operation, our ruthenium based CataLite® Ru type of catalysts offers exceptional performance. However, if the unit is expected to operate at higher temperatures, CataLite® Ni or CataLite® Fe formulations might be a suitable alternative due to cost and safety reasons. Lab scale performance data for a selection of CataLite® catalysts coated onto a mesh-type of substrate is displayed in Figure 4. Apart from our standard CataLite® ammonia cracking formulations, we offer tailor-made formulations taking into account customer specific operating conditions, optimizing the formulation for performance and cost of manufacturing for the specific application. Our experience stretches over different types and material of substrates, coating techniques, coating material as well as active phase, dopants and promoters.



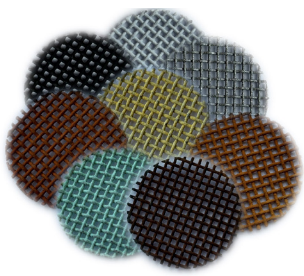


Figure 4. Conversion of ammonia as function of reaction temperature over various types of CataLite® formulations on a mesh type of substrate. Experiments were carried out at steady state conditions with a gas flow and composition entering the reactor of 1.15 Nl/min and $NH_3/H_2/N_2$ = 91/6/3 vol.-%, respectively. GHSV = 10,000 h^{-1}.

Modeling and testing: Closing the feedback loop

To optimize the design and dimensioning of our reactors, Catator uses Computational Fluid Dynamics (CFD) modeling with built-in mass and heat transfer equations as well as reaction kinetic models developed in-house for our own set of ammonia cracking catalysts. CFD modeling offers the possibility to vary many variables without prototyping or experimental testing. Our models support a broad range of modeling variables but typically we help our customers optimize the reactor design by studying the impact of flow direction of the gas and/or liquid phase media that is used in the system as well as the impact of different inlet and outlet temperatures, passive heating or cooling alone, or use of active heating or cooling. We also optimize dimensions and shapes of the plates to maximize reactant conversion and minimize pressure drop.

To verify and, if required, tune the models, Catator offers experimental evaluation of scaled CataRex® reactors for ammonia gas flows up to 1 Nm^3/h. The experimental evaluation do not only give us confidence in the models, thereby improving the confidence in full-scale CataRex® dimensioning, it also provides the opportunity to develop safe and efficient strategies for start-up, shut-down and normal operation.

Catator has over a decade of experience in the ammonia cracking field. We have designed CataRex® reactors with capacities to produce between 1 and 500 Nm^3 H_2 per hour.

Let us know how we can help you! Please reach out for further information to info@catator.com