catacel™

Driving Reaction Technology

Catalytic Heat-Exchanging Materials Technology

White Paper No. 101

Custom Solutions for Fuel Cell Applications That Are Smaller, Lighter, Less Costly and/or More Efficient

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Keywords:

Fuel cells

Catalytic heat-exchanging materials

Energy efficiency

Smaller & lighter solutions

Lower cost

Introduction

Driving reaction technology! That is the overall goal today – creating high-performance, low-cost reaction solutions that combine catalytic and heat transfer functions that lead to breakthroughs in production and energy efficiency. Specifically, these solutions are geared toward the advanced energy and chemical industries with emphasis on the fuel cell, hydrogen, gas-to-liquid process, petrochemical and aerospace sectors.

Custom designed to fit the requirements of each application, users benefit from solutions that are smaller, lighter, less costly and/or more energy efficient than possible with previous alternatives.

This white paper takes an in-depth look at Catacel's current industry-leading reaction technology expertise and special competency strengths. In addition, substantial detail is provided on the following:

- Catalytic heat-exchanging materials
- Lightweight, cost-effective heat exchanger platforms
- Special problem-solving geometric combinations
- Fuel cell application solutions including Catacel's HEP® Fuel Cell Heat Exchange Platform

Catalytic Heat-Exchanging Materials Technology

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Current Industry-Leading Reaction Technology for Fuel Cells

Chemistry textbooks list, define and provide all of the necessary details on a variety of catalytic materials. But, in fuel cell development, the answer is rarely about the catalyst materials that are available. Instead, it is *all* about what you do with the catalytic materials and how you deploy them.

Ordinary catalytic materials are now being employed in new and interesting ways that provide superior results. This is especially true when the catalyst is deployed on high surface area metal foils in the right structural shape and form that combine both catalytic and heat exchange functions to deliver breakthrough performance in size, weight, throughput and energy efficiency.

Heat Management

Most catalytic reactions include heat flux. Exothermic reactions release heat, while endothermic reactions require a heat input.

One classical design approach is to perform the catalytic reaction and then deal with the heat issues elsewhere, such as with a heat exchanger or with dilution. Another classic approach uses ceramic packed bed catalysts, which support the reaction and enable a modest heat flux.

The Catacel approach is to combine reaction with high performance heat transfer. Combining high performance reaction with high performance heat transfer allows operation in less space, with less weight, and for less money over time. In many reactions that are heat transfer limited, it is often possible to achieve higher throughput rates.

Catacel's approach in combining these two functions is to put the catalyst on formed foil surfaces, which also serves as the heat exchanger. To move heat in different directions and quantities, the foil surfaces can be arranged in a wide variety of ways and a wide variety of structures *(Figure 1).*

Figure 1 – Catacel specializes in the design and engineering of a wide variety of metal foil honeycombs and structures that operate in hostile conditions while providing high-performance heat transfer and heat management

The trade-offs and constraints between surface area, pressure drop and heat transfer normally drive the design of a reactor. Each of these three important properties is directly related to the materials used for the reactor. Ceramic pellet catalyst supports designed for good surface area and reasonable pressure drop will offer modest heat transfer. Ceramic pellet supports with higher heat transfer usually pay a strong pressure drop penalty. Hence, the operating window of the reactor is limited by the fundamental properties of the support. Catacel's metal foil catalyst supports can be configured for high-performance heat transfer, with high surface area, at modest pressure drop.

Table 1 – *Heat Transfer Comparison, shows the effect of attempting to modify a ceramic support to operate in a higher heat transfer window. More surface area is available, but pressure drop becomes intolerably high. Metal foil changes the operating window, delivering the required heat transfer and much higher surface area at only a modest increase in pressure drop.*

Table 1 – Heat Transfer Comparison

	Ceramic	Modified Ceramic	Metal Foil
Heat Transfer	1.0	1.3	1.3
Surface Area	1.0	~ 1.5	~ 2.5
Pressure Drop	1.0	~ 5.0	~ 1.5

The fundamental properties of the foil support allow the process to be operated in a previously unavailable operating window. This new operating window is normally very favorable in terms of size, weight and throughput.

High Temperature Foil Substrates

Most catalytic combustion and many reforming reactions operate in the 800°C to 900°C range. Thus, the foil substrate for the applied catalyst needs to be strong and stable at those temperatures. This normally limits the choice to one of the very expensive super alloys in the $100.00/lb. cost range.

To reduce costs, Catacel uses a special alloy for its foil structures – Fecralloy – which can be purchased for significantly less. Fecralloy is a blend of iron, chrome, aluminum and rare earth. Fecralloy, when heated, makes aluminum oxide, which is ideal for the application of catalyst to the foil surface. This oxide also provides protection that makes the alloy chemically stable in most high-temperature environments. Fecralloy is considered by many to be a difficult material to work with because its ductility is very low. It tends to break easily when formed, and its strength at high temperatures is modest at best.

Catacel has been working with Fecralloy for many years and has developed a strong expertise in using this inexpensive alloy in place of the super alloys. Catacel can form this material into a myriad of useful support shapes in spite of its brittle properties. More importantly, Catacel can deliver this alloy in configurations that are mechanically stable at high temperatures, even though the inherent strength of the material is low. This expertise with Fecralloy allows Catacel to deliver low-cost foil-supported solutions for high temperature catalytic reactions.

Metal Foil Structures

Foil Forming

Catacel can custom engineer and manufacture catalytic heat-exchanging materials in a wide range of geometries, forms and shapes *(Figure 2)*. Coated foils can be supplied in virtually any shape including:

- Cylinders and annular constructs
- Rectangles and cubic or planar forms
- Rhombic, trapezoidal or tapered forms
- Pie and disc shapes
- Combinations of the above

Figure 2 – Catacel's catalytic heat-exchanging materials are available in a wide range of geometries, forms and capabilities – each custom developed for specific customer needs

Corrugations and fins are possible from simple flat foils to complex forms including:

- Straight, herringbone and skew corrugations from 20 to 2000 cpsi
- Triangular or rectangular formed fins, with straight or complex profiles in the flow direction

In determining the proper foil shape or heat exchanging structure for the application, the temperature and heat transfer properties must be correctly evaluated. The key issue with using Fecralloy foil is to make sure that the structure will function as intended and remain mechanically stable when supporting high temperature reactions. Example: In some hydrogen production systems that operate under pressure, the tubes creep and get larger in diameter over time. In such an application, it is critical to make sure that the foil structure follows the growth of the tube. Combustion environments are always hot with high flow, so structure design must be such that it will stay in place. Catacel has 30+ years of structure design engineering and manufacturing experience with Fecralloy metal foil.

Foil Surface Coating and Durable Bonding of Catalytic Material

Much has been written on the application of catalytic coatings to Fecralloy foil. In Catacel's 30+ years of experience with the material, we've learned that there are a number of critical issues that must be overcome if the catalyst material is to correctly bond and stay in place in a high temperature or other challenging environment. Questions that need to be answered include:

- What the history of the foil is as received?
- What mechanical and/or heat treating preparations must be done to provide a foil surface that is ideal for the end use and coating process?
- How should the catalyst coating be prepared for the foil surface? Coatings designed for different reactions can have different coating and adherence properties.
- What is the best way to bring the catalyst coating and prepared foil surface together?

At Catacel, we firmly believe that our experience in foil surface coating and durable bonding of catalytic material is second to none in the world.

Catalysts

Catalysts for Steam Reforming of Natural Gas

Beyond the "textbook" catalysts that are used for reforming reactions, Catacel has developed a number of formulations that work extremely well in specific application situations. An example is a catalyst used for steam reforming of natural gas. This catalyst maintains stability in Catacel reactors that are operated in a temperature range between 850ºC to 900ºC.

Catacel nickel catalysts are used for steam reforming in large, well-controlled hydrogen plants. Because the temperature and feed chemistries at these plants are well controlled, it is possible to employ a less expensive catalyst. On the other hand, a catalyst used for steam reforming in a fuel cell application needs to be more robust, as the temperatures and chemistries are often not as well controlled as that in a hydrogen plant. Excursions, start-ups, transients and other factors are present that can put the catalyst at risk. It is therefore necessary to utilize a more expensive catalyst with a different metal package, particularly for fuel cell systems under development. When the system transients are well understood, expense can be removed from the catalyst by changing the catalytic metals being used.

Catalysts for Steam Reforming Heavier Fuels

For steam reforming of diesel, jet aircraft and military logistics fuels, the choice of available catalytic materials is more difficult, as these materials tend to generate coke, plus most contain some level of sulfur – a poison to catalytic materials. Catacel has developed a line of catalysts that are appropriate for reforming these fuels. Some are very sulfur tolerant. Others have lower tolerance to sulfur, and rely on upstream sulfur control. Reforming these fuels is extremely difficult, and depending on the application, catalyst performance life can be limited.

CPOx (Catalytic Partial Oxidation) Catalyst

Catacel has also developed a CPOx catalyst that works very well. Typical catalysts found in the industry deliver a favorable mix of CO, CO2 and H2 only at 900°C+. Catacel's catalyst, when displayed on metal foil, delivers a favorable mix at 800°C and below. The benefit here is that less energy is used in heating the gas stream.

Combustion Catalysts

It is sometimes desirable to operate combustion at temperatures of 900°C and above. Temperatures significantly above that will cause stability issues with a number of catalysts and the Fecralloy foil that is used as the substrate. Catacel has developed a palladium-based catalyst for combustion applications that is robust at high temperatures, is stable, and if necessary can be operated for short periods of time into the 925°C to 950°C range. In one application, fuel cell anode tailgas – a high-energy combustible mixture of hydrogen and carbon monoxide (CO) accompanied sometimes by a bit of methane – is combusted to make heat as it exhausts from the fuel cell. Additionally, this is the catalyst of choice for high-temperature combustion of natural gas.

Methanol Reforming Catalysts

Some fuel cells are expected to use reformed methanol as fuel. The low temperature methanol reforming process has traditionally posed stability challenges for catalysts. Catacel methanol reforming catalysts displayed on foil have demonstrated good conversion and stability.

Fischer-Tropsch Catalysts

Fischer-Tropsch is a catalytic process used to synthesize liquid hydrocarbons by the controlled reaction of hydrogen and CO. This reaction is highly exothermic and the reactor must be designed for adequate heat removal to control the sensitive reaction temperature. Catacel has a good understanding of catalysts used for this reaction, which are based on iron and cobalt, although nickel and ruthenium have also been used.

Catacel Capabilities

Design

Here, it is important to think in terms of systems. How do you create the balance between reaction needs, surface area, pressure drop, heat transfer, size, weight, manufacturability and cost? What are the tradeoffs that need to be made to arrive at the ideal design? At Catacel, we have a substantial "toolbox" we can draw on to design fuel cell solutions that are smaller, lighter, less costly and/or more efficient *(Figure 3)*. In addition, we have the capability to test various combinations of heat transfer, pressure drop and reaction, so we can understand the matrix and how they will come together in the application.

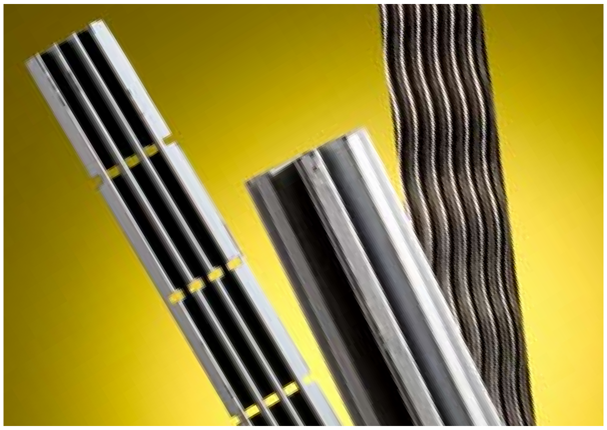

Figure 3 – Catacel fuel cell solutions are smaller, lighter, less costly and/or more efficient

Also, durability tests are often run on the foil structure. As an example, one Catacel test unit cycles heat exchanger designs with 900°C hot gas feeding one side, and cold gas on the other. This hot-cold-hot-cold test is cycled for a predetermined number of hours.

Synthesis and Evaluation

Synthesis is all about high-performance reactions. Depending on the type of reaction desired, such as reforming or combustion, and the reactants and desired products, it is critical that the catalyst material selected will perform as intended. Often, this requires adjustments in the formulation and advanced testing to make sure the catalyst performs at a high level, with minimum deterioration over time. At Catacel, we routinely run small scale accelerated time reactions in our laboratory to evaluate how catalyst materials will perform over hundreds and thousands of hours.

Bonding

Bonding relies on three critical elements: foil preparation, slurry preparation and how the two are successfully brought together. As products are being developed, at the end of the day you need to know if you have created successful bonds. The key questions are the strength of the bond, and how to make sure that the catalytic coating will stick over time. Bonding evaluation at Catacel involves a whole family of testing and evaluation tools to determine longevity and system strength – both of the foil material and the catalyst bonded to the foil. This evaluation process is done in a variety of environments including the anticipated hot temperature conditions.

Key Application Design Questions

Prior to actual system design, it is important to provide input regarding the following questions:

- What is the application?
- What type/kind of reaction will be run?
- What are the "ins and outs" of the reaction?
- What is the heat involvement?
- Where does the catalytic material have to fit?
- What are the pressure drop requirements?
- What are your cost targets?
- At what temperature will you operate?
- What special requirements are involved in the design?
- How will you start the reaction and shut it down?
- Will there be cyclic operation, or steady state, or both?
- What are the durability requirements?
- Are there other specification levels, such as a UL listing?

- What are the quality and performance requirements?
- What tolerances need to be met?
- What are the anticipated production levels?
- When will you need evaluation prototypes?

Fuel Cell Application Designs

HEP® Heat Exchange Platform

A lightweight, cost-effective solution, Catacel's HEP® platform is a compact, high-temperature, low cost heat exchanger that can be easily configured to work as a reactor. Specifically designed for fuel cells, its key benefits include:

- Heat transfer up to 2.4kW per module
- Easily bundled for greater heat exchange
- Readily customized by using a wide range of foil inserts
- Easily constructed as a reactor by depositing catalysts

A variety of corrugation geometries *(Figure 4)* can be inserted into the HEP modules to tailor heat transfer and pressure drop characteristics to specific needs without having to do costly custom engineering. Catalytic coatings can be applied to the inserts to enable the HEP to work as a reactor as well as a heat exchanger.

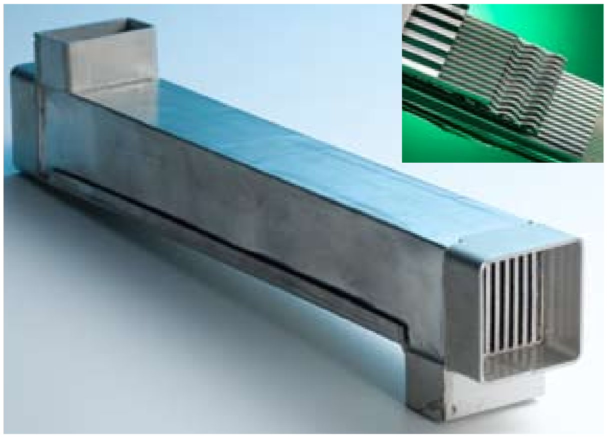

Figure 4 – The HEP offers unprecedented size, weight and cost advantages among today's heat exchanger and reactor designs

The HEP is an excellent way to breadboard all common fuel processing reactions. Different catalysts and reactions can be tested to see how they are going to behave, and what might happen over time. It will also help determine the amount of space that will be needed for a production unit. Simply, HEP is a low cost heat exchange and reactor platform for fuel cell breadboard development.

Tightly Integrated Reformer and Combustor Reformer Packages

Reforming and combustion functions are often combined. A reforming action requires heat. A combustion reaction gives up heat. By combining the two functions, you can take the heat from one and give it to the other. This can be done in a heat-exchanging reactor where reforming catalyst coated on foil inserts are on one side, and combustion catalysts coated on foil inserts are on the other side. In such a reactor the trick is to balance the heat and manage the transients.

Other system designs place formed foil inserts coated with reforming catalyst near a hot fuel cell (normally solid-oxide) stack, taking radiant heat off the stack to drive the reforming reaction. This is a good example of a steam reforming reaction designed and built directly into the packaging of a fuel cell, using coated foil inserts as the catalyst carrier and heat transfer media.

Low Pressure vs. High Pressure Systems (It Really Doesn't Matter)

Some fuel cell systems are designed to operate at low pressure near one atmosphere. Other designs will operate at high pressure. High-pressure systems often use micro-channel devices as fuel processing reactors, which can easily tolerate the pressure. Low-pressure systems can use Catacel reactors constructed from foil (the HEP, or custom design), which offer considerable savings in weight and cost. In either case, the reaction surface of choice is a Catacel coated foil insert. Such inserts have catalyst on their surface, and slip into the channels of a micro-channel or foil structure device.

Anode Tail Gas Combustion

There are a myriad of ways to set up fuel cell systems to manage heat, and to get one heat source balanced against a heat sink. The goal is to achieve maximum efficiency so that all heat sources are fully utilized and none are given away.

Some fuel cell systems have anode tail gases that must be handled. Sometimes this gas is recycled back to the fuel cell anode. Other times the tailgas is burned to avoid exhausting it into the atmosphere. Catalytically burning this tailgas provides heat that can be used to heat cathode air, provide a fuel stream, make steam, or drive a reforming process.

Of interest is the fact that such tail gas streams, more often than not, contain hydrogen in them. Consequently, the stream will be a combination of hydrogen, left over methane and CO – all combustibles. In many cases, the tailgas stream will already be hot.

However, a major concern is that if you put hydrogen on a hot catalytic surface, it will create a hot spot and instantly burn. If not handled correctly, such an event can damage or destroy the combustor or the fuel cell. As such, the objective in burning this type of stream is to spread out the catalytic reaction to remove the heat as it is generated – a basic heat transfer problem. How do you slow down the burn sufficiently to avoid the possibility of a hot spot and an instant burn?

At Catacel, our experience in overcoming this heat transfer problem goes back to early work on catalytic combustion for gas turbines. The problem is similar in that the firing temperature on a gas turbine is in the 1500°C range – a temperature that will completely melt the catalyst. The solution is to burn just a part of the fuel. Based on this, Catacel has developed many strategies over the years to delay burning to a certain area. These same strategies are now being used to manage the heat problem in fuel cell combustion where the tail gas stream is burned.

System Design With A CPOx Start-up Catalyst

One fuel cell system design utilizes a small CPOx start-up catalytic reactor to provide heat. The reactor uses a special CPOx catalytic material supported on a formed foil core. The output from this reactor is a hot mix of hydrogen, CO and CO_2. Conducting this reaction on foil results in a very favorable CO/CO_2 ratio at temperatures of 800°C and below.

The CPOx reaction is triggered with a small electrical heater or glow plug. The hot gas produced is circulated through the fuel cell system until it reaches operating temperature, when the steady-state power-producing processes can begin. The CPOx reaction is sometimes discontinued after power production is established.

PEM (Proton Exchange Membrane) Cells

PEM cells operate solely on hydrogen. If you are using one of the common fuels, a reforming process is needed to make hydrogen. This is conveniently done using a Catacel heat-exchanging reactor. Reforming delivers a mixture of hydrogen, water, CO_2, CO and sometimes left over hydrocarbons. CO must be removed completely, as it is toxic to PEM cells. Sometimes a membrane is used that only lets the hydrogen go through to the PEM cell.

Other fuel cell designers will utilize a water-gas shift reaction to remove CO, where it reacts with water vapor to make hydrogen and CO_2. The curious thing about shift reactions is that the catalytic materials have a specific temperature window that they must operate within. Too hot or too cold, and the catalyst won't work. A heat-exchanging shift reactor using foil-supported catalysts is a convenient way to ensure that there is a constant temperature all the way through the reaction. A cooling fluid is typically used on the backside to carry away the heat.

About Catacel Corporation

Catacel makes engineered materials that combine catalytic and heat exchange functions to deliver breakthrough performance in size, weight, through-put and energy efficiency to a wide range of energy and industrial reaction processes *(Figure 5)*. These materials are made by coating catalysts or sorbents on thin-formed metal foils. The company is a manufacturer that provides solutions for challenging applications using its diverse background in durable metal reactors, heat management, reaction design, catalytic chemistry and large-scale integrated production techniques. Currently, the company is developing and commercializing products for the fuel cell, hydrogen, gas-to-liquid process and aerospace industries. The technical and scientific foundation for these products lies in the strong crossover application of the technology its principals have pioneered in the catalytic conversion industry.

Figure 5 – Catacel has research and manufacturing facilities centrally located in Northeast Ohio to serve your needs.

Catacel's technology strengths are designing, creating and effectively coating shaped metal foils and heat exchange solutions relating to fuel reforming, catalytic chemistry and combustion. The company's core competencies include:

- Catalytic materials synthesis and evaluation
- Application of materials to metal foil (especially catalysts)
- Heat and mass transfer to honeycomb surfaces
- Metal foil design for long-term durability
- High temperature alloys, uses and properties
- High temperature and high pressure evaluation of catalysts and monoliths
- Continuous coating and continuous foil processing
- Catalytic combustion and catalytic system design
- Design and implementation of manufacturing processes for catalytic and heat exchange products
- Metal forming, welding and joining.

Catacel uses patented technologies and proprietary-coating processes to apply catalysts to formed metal substrates. To date, the company has been awarded 21 utility and design patents, with nine patents pending.

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