HONEYWELL UOP AND ZONEFLOW™ REACTOR TECHNOLOGIES

STRUCTURED CATALYST FOR STEAM METHANE REFORMING

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Honeywell UOP | ZF

PRESENTATION OUTLINE

I. Introduction

II. ZoneFlow™ structured catalyst system (ZF) for Steam Reforming

III. ZF benefits / differences over state-of-the-art Pellets

IV. ZF development update and validation programs

V. Pilot Plant Test Program and results

VI. ZF Value creation

VII. Conclusions

GLOBAL HYDROGEN OUTLOOK THROUGH 2050

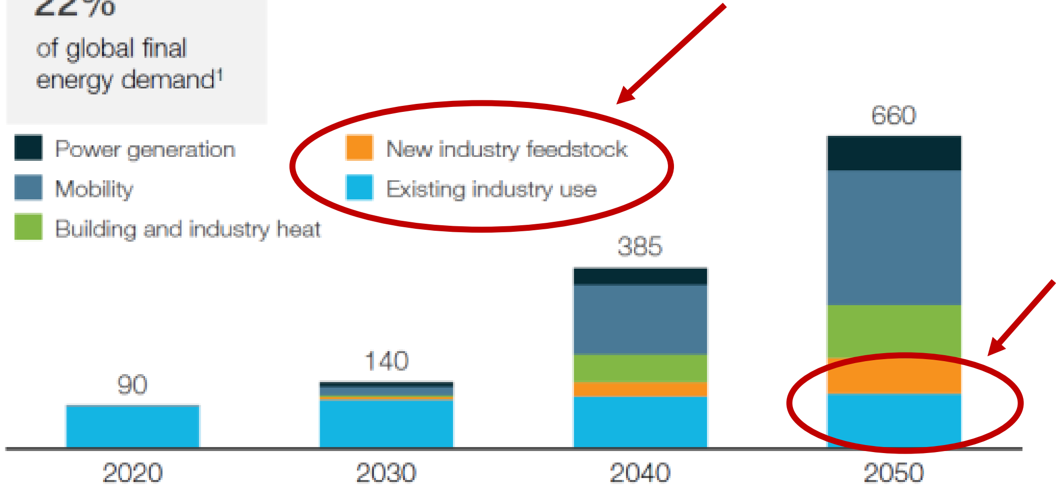
Demand

Global hydrogen demand by segment until 2050

660 MT
hydrogen required p.a. in 2050 for net-zero

22%
of global final energy demand[1]

Hydrogen end-use demand by segment, MT hydrogen p.a.



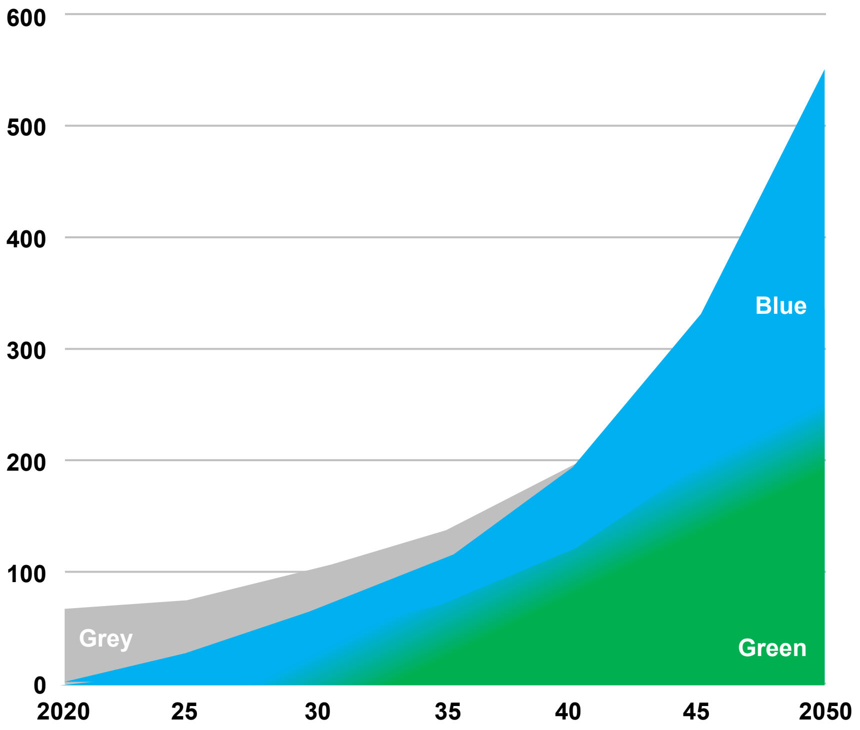
1. IEA net-zero scenario with 340 EJ final energy demand in 2050. HHV assumed. Excluding power.

7 Clean hydrogen is in this publication defined as either renewable or low-carbon hydrogen; Renewable hydrogen refers to hydrogen produced from water electrolysis with renewable electricity, while low-carbon hydrogen refers to hydrogen produced from fossil fuel reforming with carbon sequestration.
8 Assumes 35 GT anthropogenic emissions in 2050 in current trajectory.
9 Considers the share 80 GT CO_2 abated from hydrogen in terms of cumulative emissions from 2021 to 2050, subtracting the remaining carbon budget of 420 GT.

Source: Hydrogen Council: Scaling Up, McKinsey

Supply

H_2 Production Growth (Mt/yr)



SOURCE: Hydrogen Council, Decarbonization Pathways, 2021

22% of final energy demand

6Gt annual CO_2 abatement

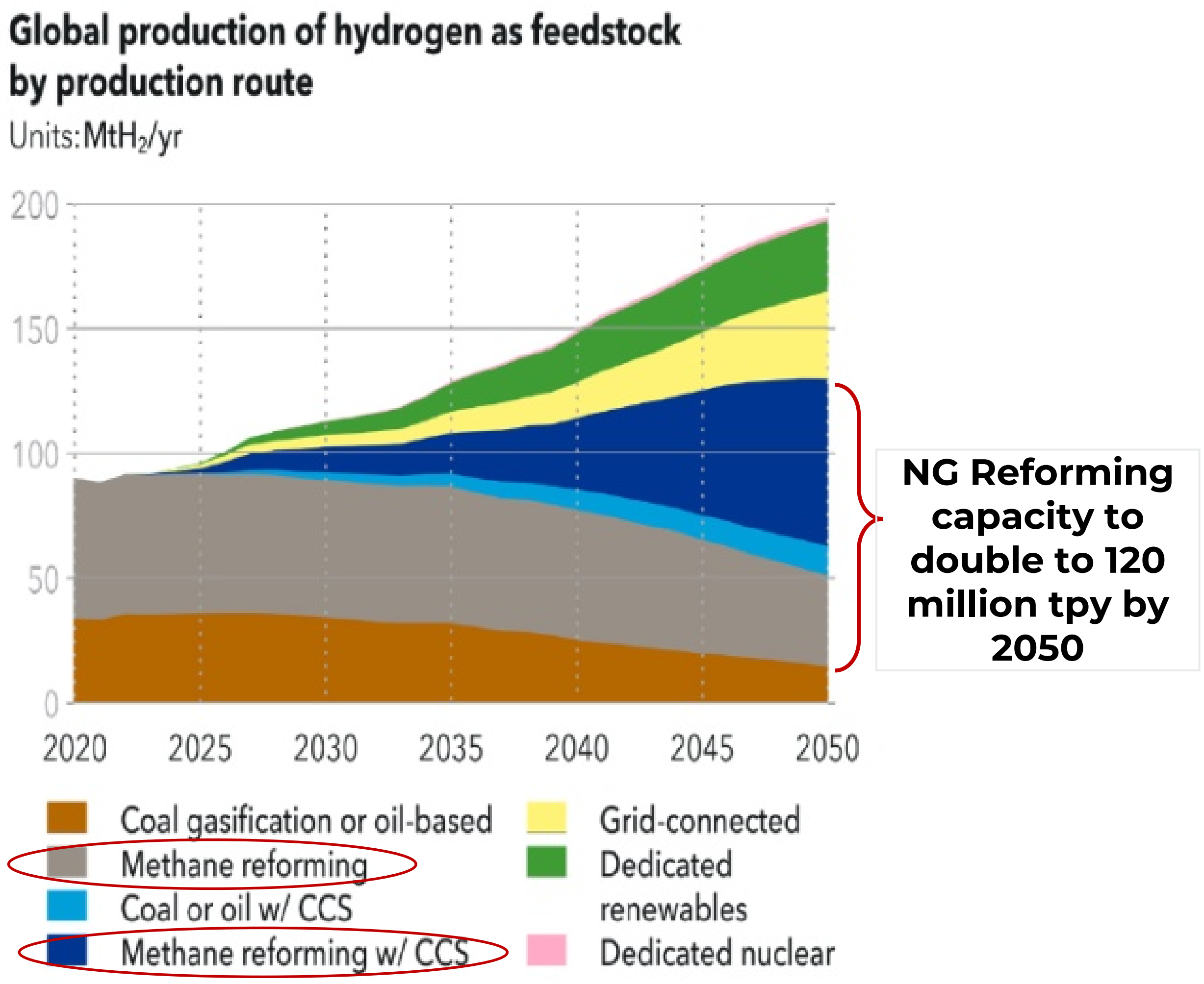
$2.5tn annual sales (hydrogen and equipment)

30m jobs created

In a decarbonized world, H_2 demand could grow up to ~7-fold

SMR - BASED HYDROGEN FORECAST TILL 2050

- Latest DNV report 2022 on Hydrogen Forecast till 2050, projects the current global Methane reforming based (grey) hydrogen generation capacity of ~ 60 million TPY to nearly double to 120 million TPY by 2050, mainly to cater for the industrial decarbonization, esp, hard-to-abate sectors.
- Within such growth, Methane reforming with CCS (blue) hydrogen will take off around 2025 with an exponential growth rate and is projected to get to twice the capacity of grey H2 by 2050.
- Steam methane reforming (SMR) has been the predominant process route for hydrogen - syngas production (> 90% till date) and is projected to stay dominant growing at CAGR of ~ 4% in the coming decades



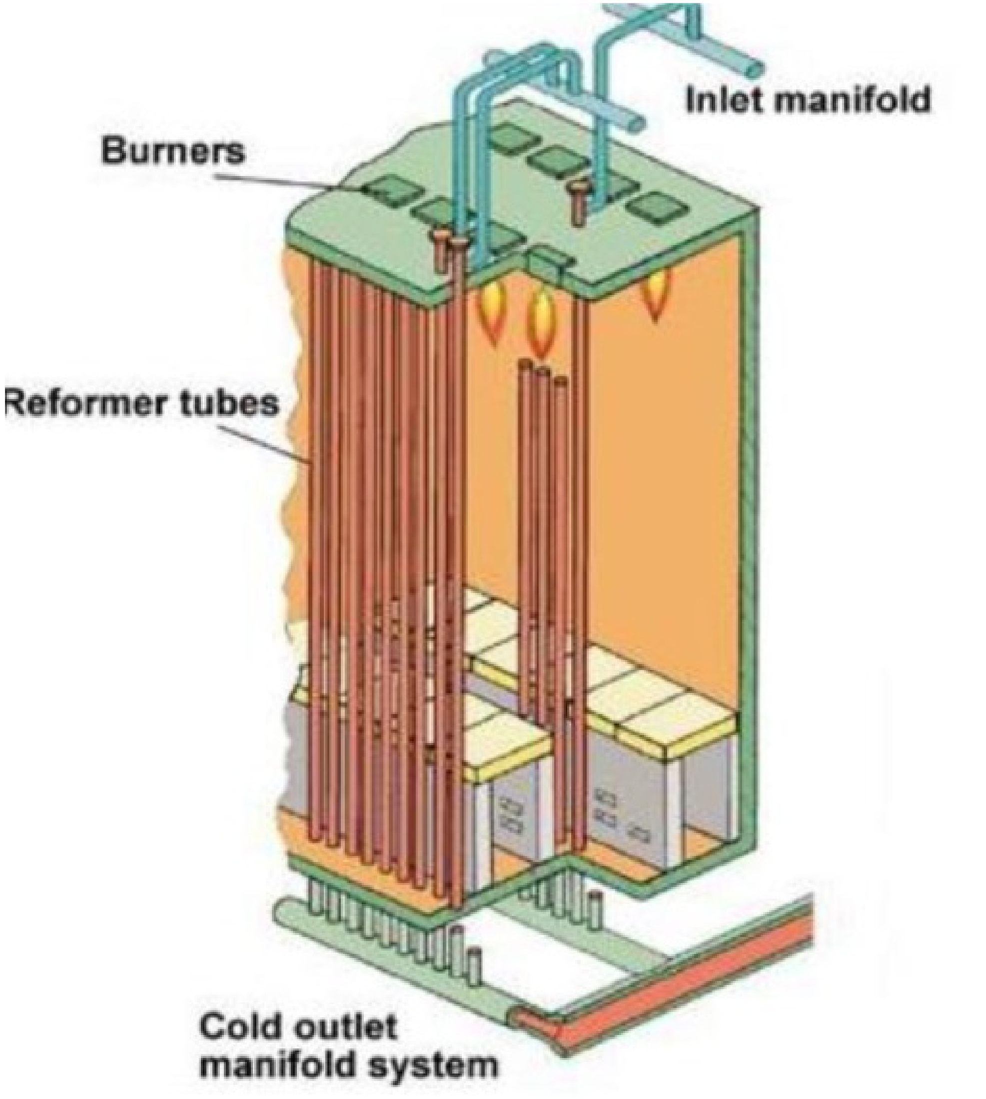
Source : Hydrogen Forecast to 2050, DNV ETO 2022 Report

STEAM METHANE REFORMING BASICS

- Mainly involves reaction of a hydrocarbon with steam over a catalyst

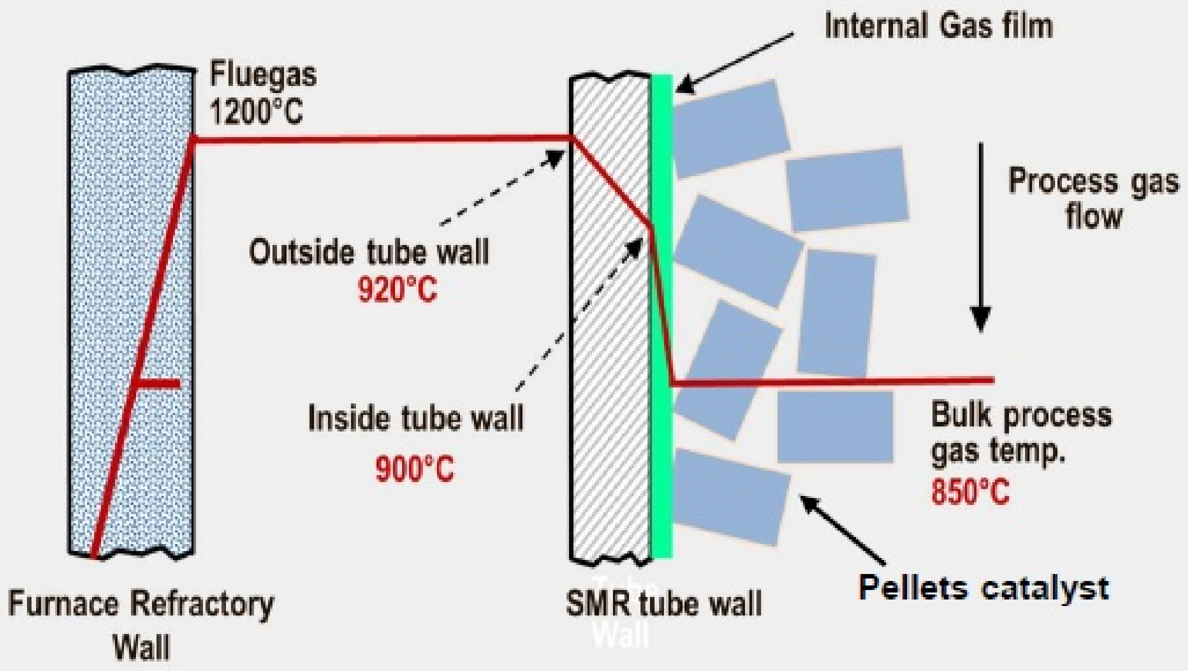
$$CH_4 + 2H_2O \leftrightarrow 4\,H_2 + CO_2 \qquad \Delta H = -165\ \text{kJ/kmol}$$

- Highly endothermic thus requiring substantial heat input at elevated temperatures
- The reaction is favored by more steam, higher temperatures and lower pressures
- To realize the required heat input efficiently, the catalyst is put in multiple tubes and suspended in a furnace called the steam methane reformer or SMR
- One such (top-fired) configuration is shown in the schematic at the right.



STEAM METHANE REFORMING
IS PRIMARILY HEAT TRANSFER CONSTRAINED

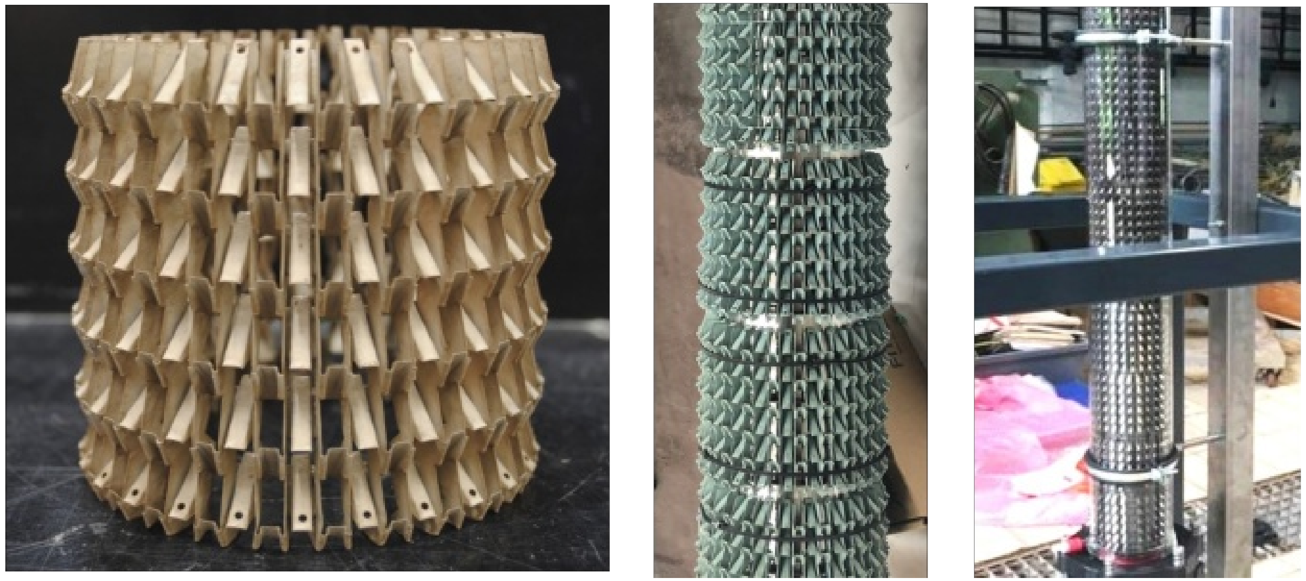
- Furnace side : Radiative and convective transfer to tube
- Through the tube : wall thickness and conductivity
- Reactive zone: convective transfer through the gas film



Typical SMR temperatures around catalyst tube exit

ZONEFLOW™ STRUCTURED CATALYST (ZF)
GEARING FOR THE FUTURE IN STEAM REFORMING

Conventional Pellet
SMR catalyst



ZoneFlow™ Reactor
structured catalyst system

Stacked modules – in close contact with the tube wall

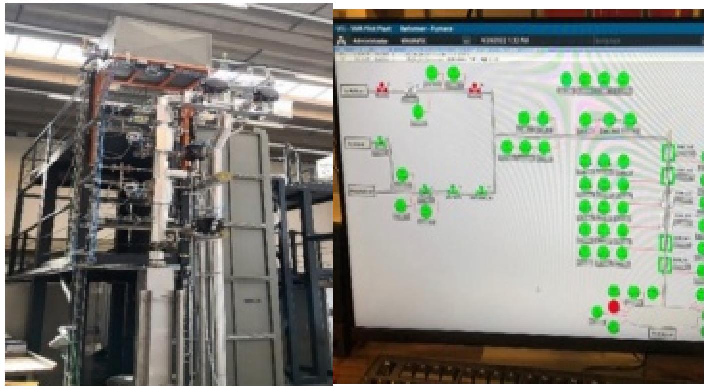
ZF BENEFITS / DIFFERENCES
AGAINST STATE-OF-THE-ART PELLETS FOR SMR

CHARACTERISTIC	PELLETS – STATUS QUO	ZONEFLOW™ – A BREAKTHROUGH
Substrate	Alumina - ceramics	Thin metallic foil
Geometry / shape	Pellets in various shapes	Structured annular casing
Loaded pattern	Random packing, non-uniform	Aligned modular stack, fully uniform
Strength and voidage	Mutually exclusive and limiting	Robust, high voidage, flexible
Flow / temp mal-distribution[1]	Inherent – increasing over time	None or minimized – same entire life
Thermal cycling effects	Attrition & settling; dP >>	No attrition & settling, stable dP
Geometric surface area and active sites access	Limited, intrinsic diffusion limitations	Higher, 'open-access' surface, minimized diffusion limitations
Catalyst effectiveness	Inherently very low	>>Higher (by a multi-fold factor)
Pressure drop	Base, increasing over life	Lower; same over entire life
Heat transfer	Base, stagnant inner film	~ Double; near-wall turbulence
Catalyst to tube wall proximity; radial temperature gradient[2]	Sporadic wall contact, irregular gaps; steep gradient	Full peripheral contact in cold AND hot condition, flattened gradient

1) Based on the industry best practices and modern methods deployed for loading pellets in the SMR tubes (in random packing), the target is to achieve as low as +/- 3 to 4 % variation in pressure drop around its average value over the multiple tubes (measured using a pre-set air flow in each tube during their loading.). Such variation is the best achievable in random packing, whereas ZF being a uniformly stacked identical metallic structure assembly in all the tubes, the non-uniformity of pressure drop and related flow rate per tube is negligible (as also confirmed by 1-D CFD modeling). The uniformity of feed flow per tube also minimizes the variations in heat pick-up across the multiple tubes (based on homogeneous stirred fire box) and thus also minimizes the temperature spread and mal-distribution in terms of tube-skin temperatures as well as the outlet gas temperature from each tube, thereby also requiring lower design margins for the outlet system.

2) ZF reactor's unique design offers the demonstrated "game changing" differentiation of maintaining the catalyst coated casing proximity to the tube wall in cold as well as hot condition owing to its exceptional flexibility and its movement over its support assembly. This was also demonstrated and verified in all the test campaigns with ZF reactors based on the measured methane slip being very close to that simulated from the operating conditions (and expected approach-to-methane equilibrium). In case there was any feed bypassing along the tube wall due to gaps between the ZF assembly and tube wall under hot / operating condition the methane slip in the reformed gas (and the approach to methane equilibrium) would have been far higher than observed.,

ZF DEVELOPMENT AND VALIDATION PROGRESS



Catalyst Assessment

- CFD modeling and FEA
- Kinetic testing & modeling
- Catalyst selection

Heat Transfer-PD Test Rig

- Elaborate Heat transfer & Pressure drop testing at near- commercial flowrates
- Derivation & correlations

Pilot Plant Validation

- Comparative Performance ZF vs Best Available Technology (BAT) Pellets
- Reactor modeling

Multi-scale modeling led to important conclusions and correlations

KINETIC TESTING & MODELING

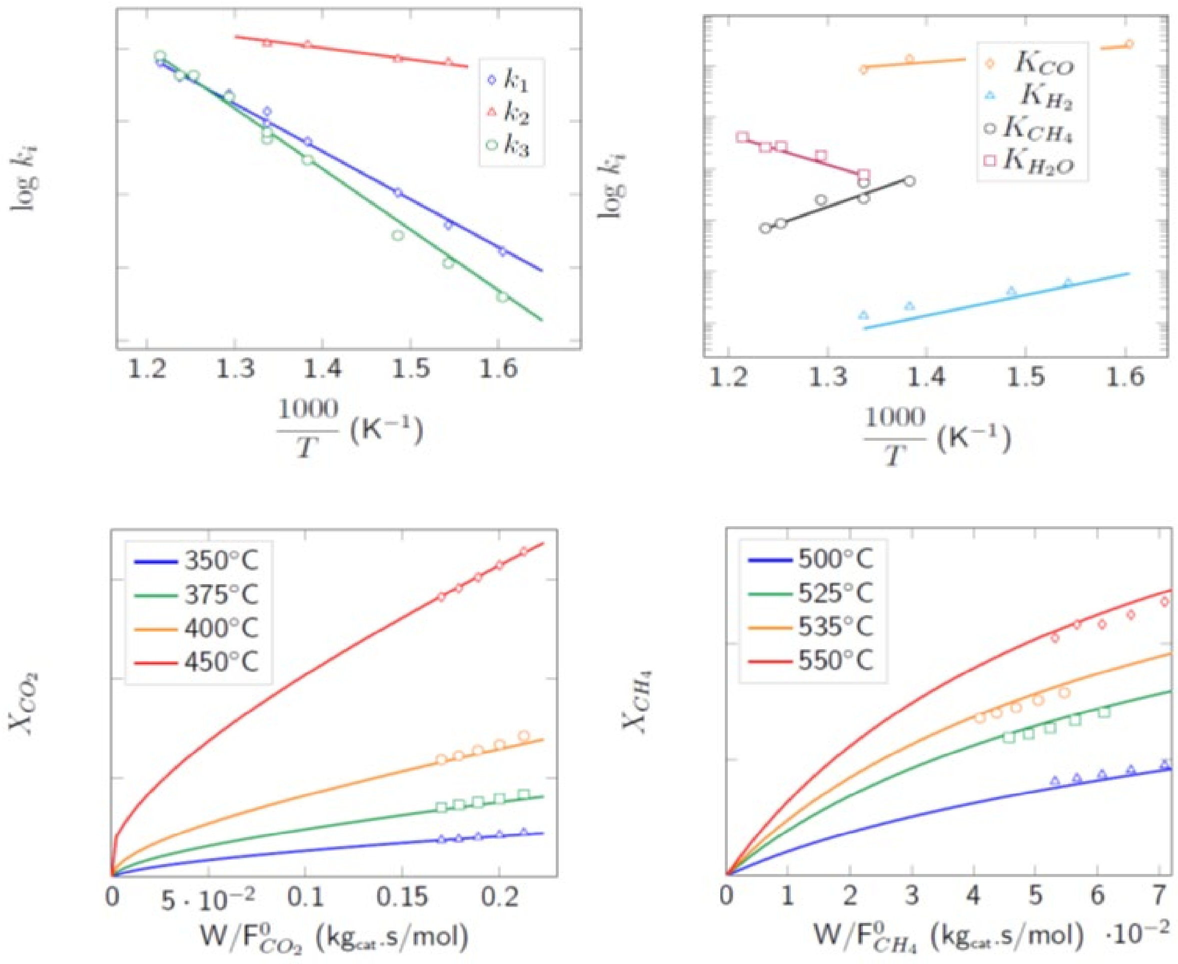
NON-ISOTHERMAL DATA TREATMENT

Methanation and reverse of water-gas shift	
Temperature (°C)	350, 375, 400, 450, 475
Pressure (bar)	10, 15, 20
H_2 / CO_2 molar	2, 4
Ar / H_2 molar	6
Flow rate CO_2	100 – 250 Ncm³/min

Steam methane reforming	
Temperature (°C)	475, 500, 525, 535, 550
Pressure (bar)	10, 15
S/C molar	3, 3.5, 4
H_2 / CO_2 molar	1.2
Ar / H_2 molar	6-10
Flow rate CO_2	200-400 Ncm³/min

- Measured versus predicted conversion of CH_4 (SMR tests) or CO_2 (methanation tests) versus space time at different reaction temperatures.
- SMR tests shown at p_{tot} = 10 bar, S/C = 3.04, H_2/CH_4 = 1.2 Methanation tests shown at p_{tot} = 15 bar and H_2/CO_2 = 4
- Model predictions using parameter values from the non-isothermal data treatment.

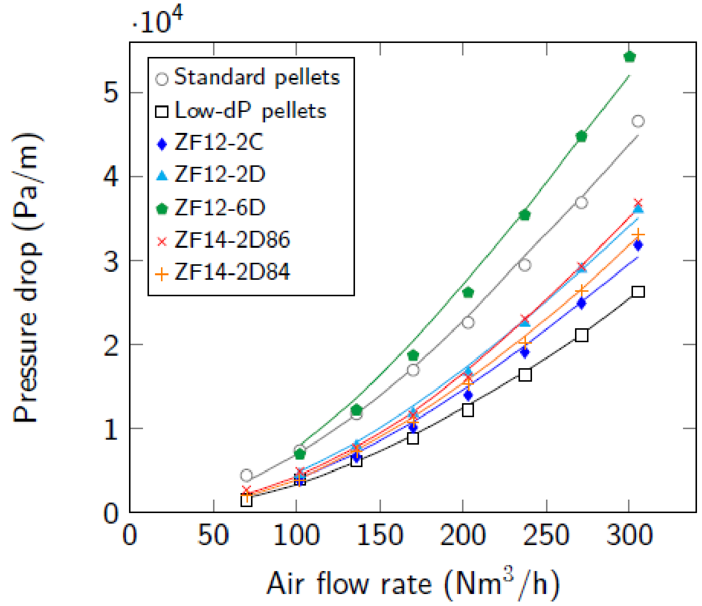
ISOTHERMAL DATA TREATMENT

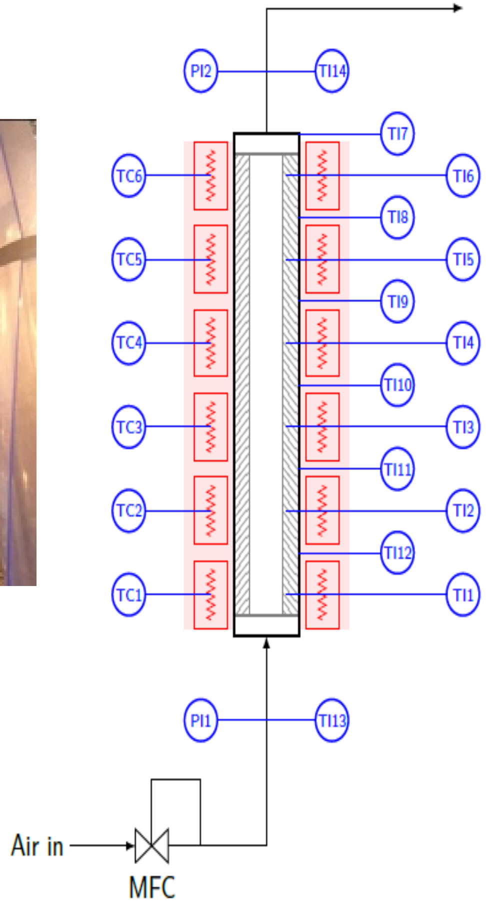


1. Florent Minette, Juray De Wilde, “Multi-scale modeling and simulation of low-pressure methane bi-reforming using structured catalytic reactors”, Chem. Eng. Journal. 407, 127218, 2021. Florent Minette, Luis Calamote de Almeida, Sanjiv Ratan, Juray De Wilde, “Multi-Scale Modeling of ZoneFlow™ Structured Catalytic Reactor for Steam Methane Reforming” presented at the AIChE Annual Meeting, September 2019 Orlando, FL

HEAT TRANSFER - PRESSURE DROP TEST RIG
RESULTS WITH COMMERCIAL FLOWS[1]

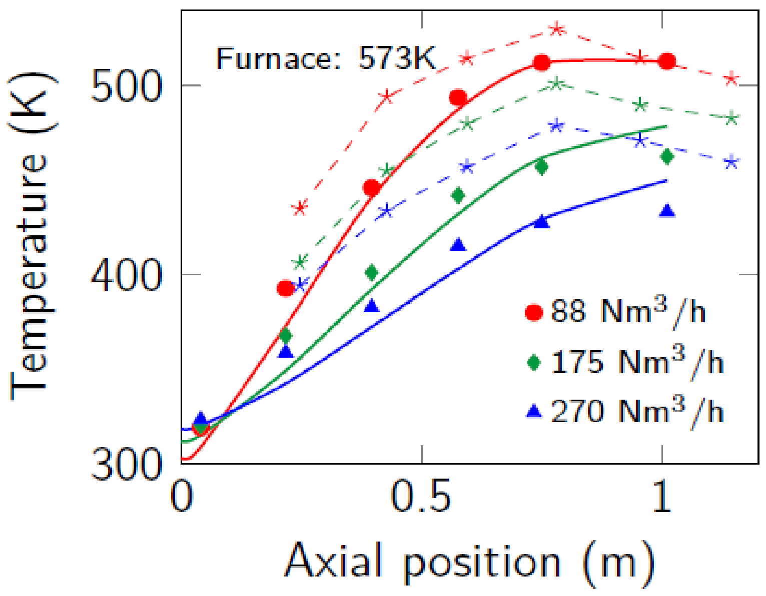
- Experimental measurements of **pressure drop** and **heat transfer coefficient** in a specifically designed experimental setup
- Air flow rates from 70-330 Nm^3/h
- Furnace temperature from 100-500°C

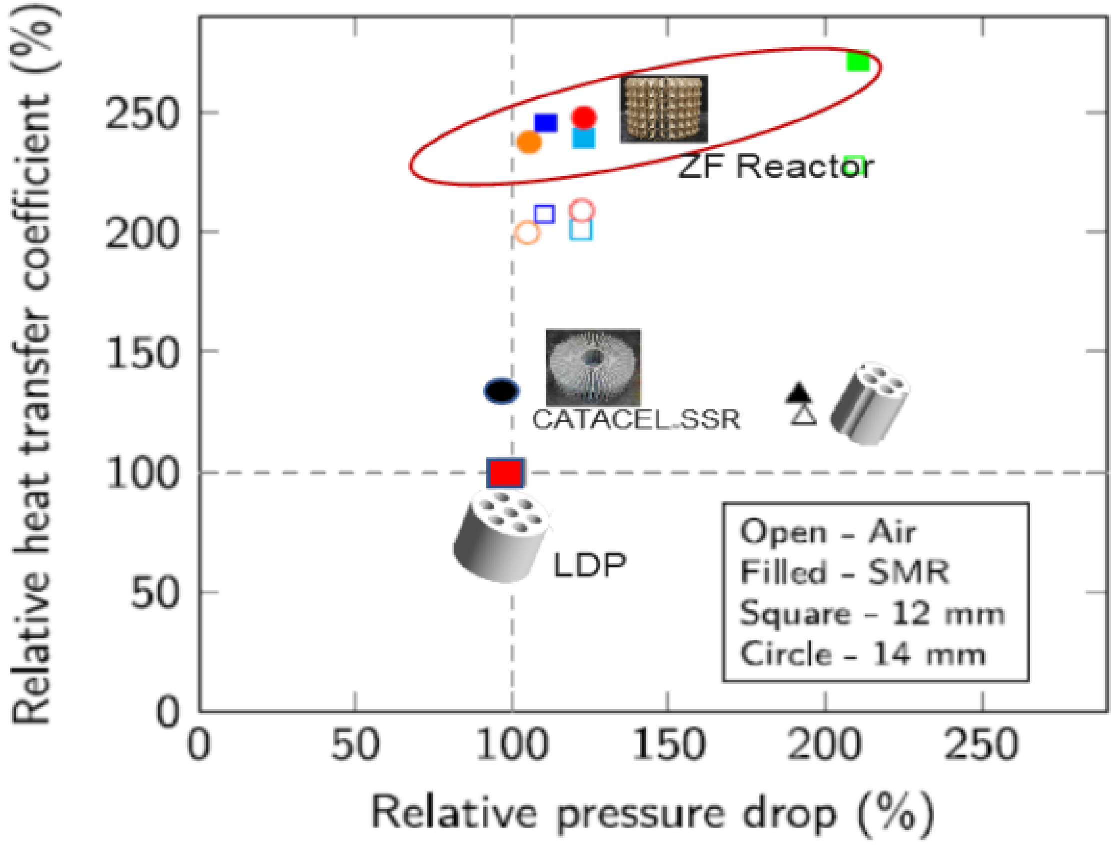




1. Florent Minette, Luis Calamote de Almeida, Sanjiv Ratan, Juray De Wilde, "Pressure drop and heat transfer of ZoneFlowTM structured catalytic reactors and reference pellets for Steam Methane Reforming", Chem. Eng. Journal. 417, 128080, 2021

HEAT TRANSFER-PRESSURE DROP TEST RIG
OBSERVED RESULTS AND DERIVED CORRELATIONS[1]





1. Florent Minette, Luis Calamote de Almeida, Sanjiv Ratan, Juray De Wilde, "Pressure drop and heat transfer of ZoneFlowTM structured catalytic reactors and reference pellets for Steam Methane Reforming", Chem. Eng. Journal. 417, 128080, 2021

Unique heat transfer and pressure drop advantages compared to pellets

PILOT PLANT OVERVIEW & TEST PROGRAM

PILOT PLANT
SALIENT FEATURES

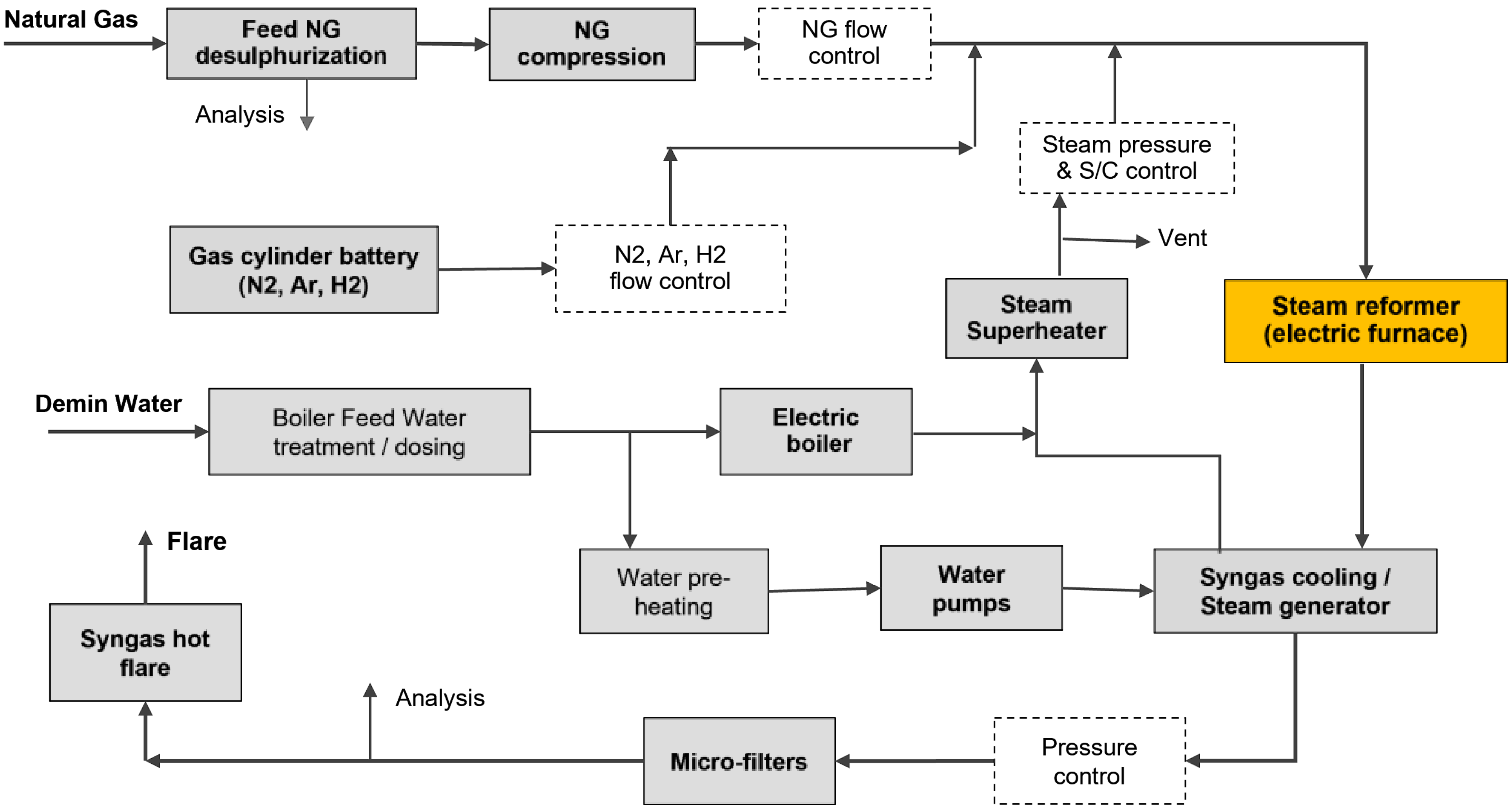
WORLD CLASS PILOT PLANT FOR CONDUCTING TEST CAMPAIGNS AT NEAR-COMMERCIAL STEAM REFORMING CONDITIONS

- Up to 30 Nm^3/h NG feed flow
- Reformer tube outlet temp up to 870 C with up to 28 barg
- S/C ratios 2.5 to 3.0
- Average heat flux up to 75 kW/m^2

EXTENSIVE INSTRUMENTATION FOR PROCESS CONTROL, ANALYTICS, DATA COLLECTION, DIAGNOSTICS AND SAFETY

- > 300 Instruments, I/Os and >120 valves & SPMs
- Temperature profiles along the tube length (18 TCs each for tube skin and process gas temp measurements; 2 out of 3 voting)
- Online syngas analytics based on online Mass Spectrometer and Gas Chromatograph for reformed gas
- NG feed analysis by separate GC
- On-line advanced organic Sulphur detection (>100 ppb)

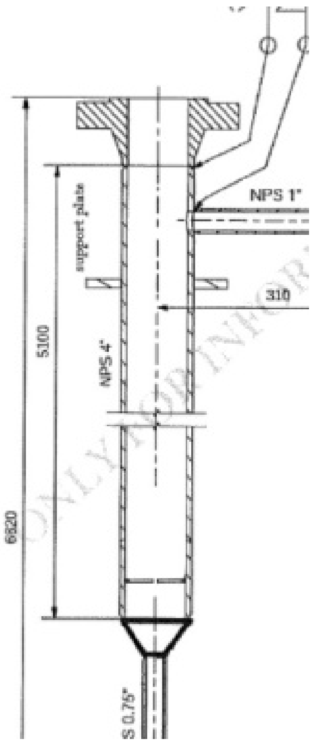
PILOT PLANT PROCESS SET-UP
BLOCK FLOW DIAGRAM



PILOT PLANT CORE UNITS

SMR tube geometry

- 94 mm ID, 117 mm OD
- Design T, P = 880°C, 31 barg
- 5 m within furnace
- 1 m preheat section, without catalyst
- 4 m reactive zone

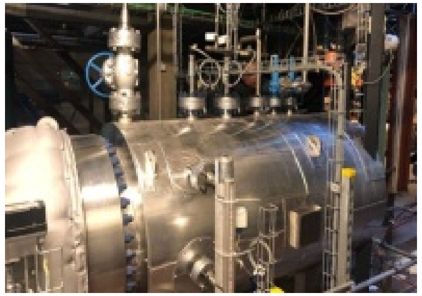


SMR electric furnace

- 6 independent heating zones along the length
- 22.5 kW preheat (zone 1)
- 90 kW reactive (zone 2-5)
- Allowing up to 70 kW/m2 avg heat flux

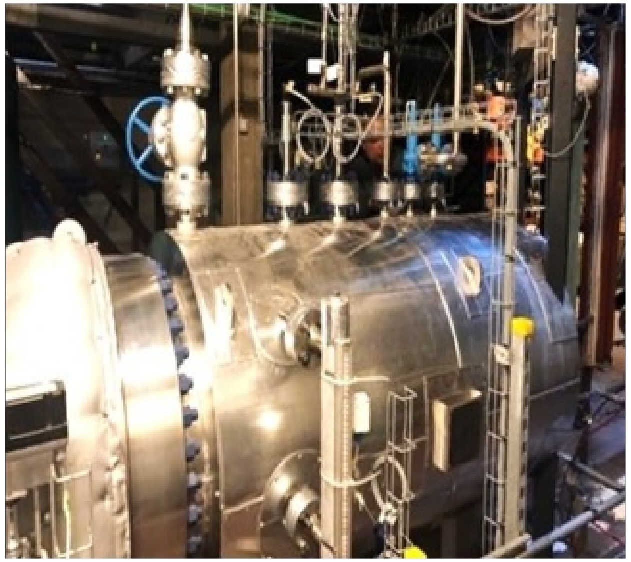
Syngas boiler

- Coil designed for 850 C
- Rated for 35 barg steam make

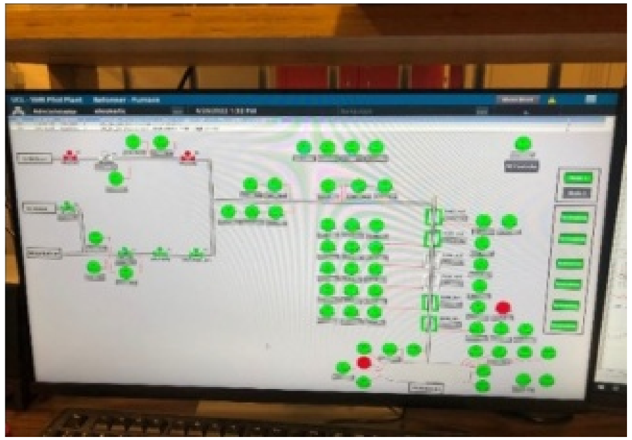


Design capabilities for the full range of comparative performance validation and model development

PILOT PLANT INSTALLATION
GLIMPSES



JUDICIOUS TEST PLAN[1]
FOR COMPARATIVE ASSESSMENT OF ZF AGAINST REFERENCE PELLETS

FOUR CAMPAIGNS (2-3 WEEKS EACH)

- Commercial reference Pellet catalyst
- ZoneFlow-Catalyst 1
- ZoneFlow-Catalyst 2
- ZoneFlow-Catalyst 3

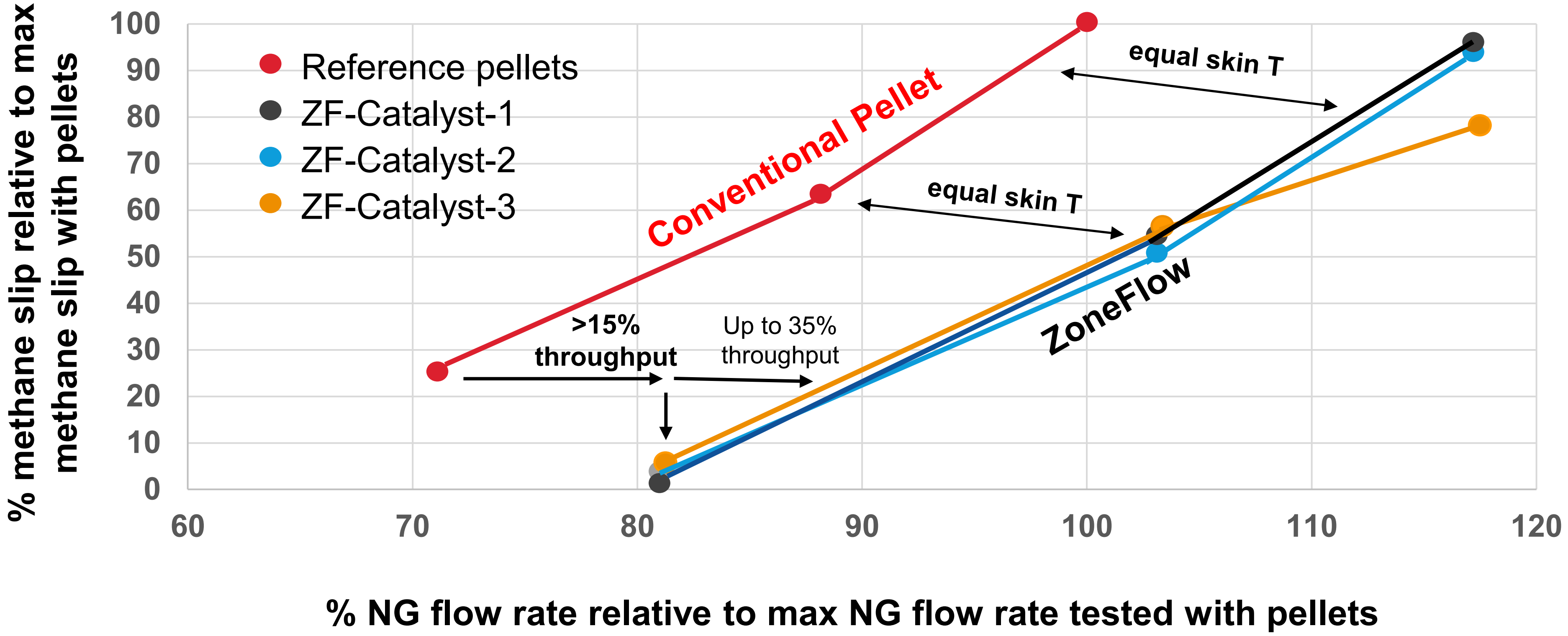
DIRECT DEMONSTRATION FOR INCREASED CAPACITY WITH NO HIGHER METHANE SLIP AND MAX TUBE SKIN TEMPERATURE WITH LOWER PRESSURE DROP

OPERATING CONDITIONS

- 8 barg; S/C = 3 (also 2.5 for ZF campaigns)
- Varying NG flow rate (up to 29 Nm^3/h)
- Varying furnace power (up to 22.5 kW per zone)

1. Pilot Plant Test Program- Final Report, Feb 2023 delivering the results and conclusions based on detailed simulation and reconciliation of the collected data from all the test campaigns, as described in this presentation.

COMPARATIVE PERFORMANCE[1]
ZF AGAINST BAT REFERENCE PELLETS



Confirmed >15% increase in capacity with reduced methane slip & same or lower max tube skin temp. & pressure drop

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VALUE CREATION MODES
ZF DEPLOYMENT IN SMR

SMR CATALYST REPLACEMENT IN EXISTING SMRS

- Overcoming capacity limitations from "stressed" reformers
- Energy (heat & power) savings
- Prolonged tube life and enhanced reliability

CAPACITY UPGRADING OF EXISTING SMRS

- 15% reforming capacity increase without increasing pressure drop, maximum tube-skin temperatures and methane-slip
- Related product capacity increase with only minor (case-specific) modifications
- Improved energy efficiency by improved heat transfer efficiency and the potential to operate at lower S/C-ratio
- Enhanced SMR reliability by the possibility to operate at lower tube skin temperatures for given capacity as compared to pellets, by avoiding catalyst crushing and by the flexibility of the ZF reactor structure ensuring close contact with the wall during its lifetime

NEW PLANT SMRS

- Capex and Opex gains, enhanced reliability and potential for design optimization in terms of S/C vs. conventional pellets

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ADDITIONAL ZF CATALYST SYSTEM DIFFERENTIATORS
VERIFIED FOR COMMERCIAL DEPLOYMENT

Apart from reforming capacity increase of >15%, following attributes were confirmed advantageous of ZF's performance[1]

- Heat transfer rate increased to such an extent that heat-transfer-limited steam reforming transitions to catalyst-activity constrained
- No by-passing of gas along the reactor tube wall in hot condition
- More than sufficient intrinsic catalyst activity compared to state-of-the-art catalyst pellets
- Contribution of internal radiative heat transfer from inner tube wall to catalyst surfaces
- Significant flattening of the temperature gradient curve from the tube wall to the process gas.

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ZF - RETROFIT
SMR CAPACITY INCREASE

Parameter	SMR De-stressing	SMR Upgrading
Maximum current capacity (nameplate 100) (%)	95	100
Post-ZF retrofit capacity (%)	100	115
S/C Ratio (molal)	3.1	2.8
Outlet temperature (ºC)	860	878 *
Approach to equilibrium (end-of-run) (ºC)	-10	-10
CH4 slip (vol. %, dry)	5.5	5.4
Catalyst pressure drop (design 2.8 bar) (bar)	2.8	2.8
Average heat flux (kW/m^2)	75	84
Bridgewall temperature (ºC)	1003	1014
Max. tube skin temperature (design 940 ºC) (ºC)	912	912 **

* Within existing Outlet system design temp based on minimized temp non-uniformity and related margin
** Based on enhanced heat transfer and flattened radial temp gradient

ZF - RETROFIT VALUE CREATION
CASE ANALYSIS (OPEX + CAPEX)

	15% upgrade for retrofit (vs BAT)
15-yr NPV[1]	$25 Million

Basis

- **80 MMSCFD (~89,300 Nm^3/hr)H2 plant SMR capacity increase to 92 MMSCFD (~102,700 Nm^3/hr) H_2 equivalent**
- **$6.6/MMBTU ($6.9/GJ) Fuel Price (HHV)**
- **15 years term**

1. Internally developed Techno Economical Analysis using Honeywell UOP developed simulation models, Unisim simulation model, standard PDD tool and optimization. Key variables include, stream composition, utility price set, price of H2 of $1685/MT, natural gas feed of $327/MT, fuel price (HHV) of $6.6/MMBTU, and steam HP steam export of $25.28/MT, cost of capital of 12%, 350 days per year on-stream, and 2022 US gulf coast basis. ZoneFlow Reactor Technologies has established the heat transfer and pressure drop properties of ZF Reactors, relative to conventional catalyst pellets, through rigorous experimental testing that has been reported most recently in Chemical Engineering Journal. https://en.x-mol.com/paper/article/1338397261714743296 and through pilot plant testing. Simulations of steam methane reformers with ZF Reactors and pellets, using Aspen© process software, reactor and reaction models developed by Prof. Juray De Wilde (Materials and Process Engineering Dept., Université Catholique de Louvain, co-author with Prof. Gilbert Froment of Chemical Reactor Analysis and Design, 3rd Edition (Wiley)), and SMR cost data, were then used to compare the efficiency (including level of carbon emissions) and cost of ZF Reactors and conventional catalyst pellets.

ZF - RETROFIT CAPACITY UPGRADING
ADDITIONAL BENEFITS AGAINST BAT

ZF’s unique merits for capacity increase provides following benefits against the alternative BAT route of recuperative Post-reforming

- Involves just replacing the pellets catalyst by ZF catalyst, and some case-specific minor modifications executable during plant turnaround, compared to the capital intensity and major revamp with post reforming and related extended project schedule and downtime
- No energy efficiency penalty as in case of post-reforming due to lower feed conversion based on temperature approach
- No concerns over minimum % make-up fuel or curtailed steam balance
- High reliability without cost and risks associated with metal-dusting

CONCLUSIONS

- Steam Methane Reforming (SMR) is projected to stay as the predominant technology for hydrogen – syngas generation.
- SMR design, performance, efficiency, tube life and operational reliability are governed to a large extent by its catalyst.
- Current pellet catalysts suffer from inherent deficiencies, thus limiting the extent of possible improvements leading to their status-quo.
- ZoneFlow Reactor Technologies LLC has developed its innovative ZoneFlow^{TM} structured catalyst (ZF) for steam reforming.
- The results from our recently conducted Test Program in our world class pilot plant in collaboration with Honeywell-UOP, have more than validated the target of 15% higher SMR capacity with ZF compared to state-of-the-art pellets without any increase in the max. tube skin temperature, pressure drop and methane-slip, thus establishing a “game-changing” development for steam methane reforming.[1]
- ZF offers an exceptional value through combination of cost-effective higher capacity and improved reliability of SMRs, especially in addressing the imminent and future needs for blue hydrogen-syngas based energy transition.

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