ZoneFlow Reactor Technologies, LLC

Innovative ZoneFlow^{TM} Technology Offers Breakthrough Solutions in Refinery Hydrogen Generation

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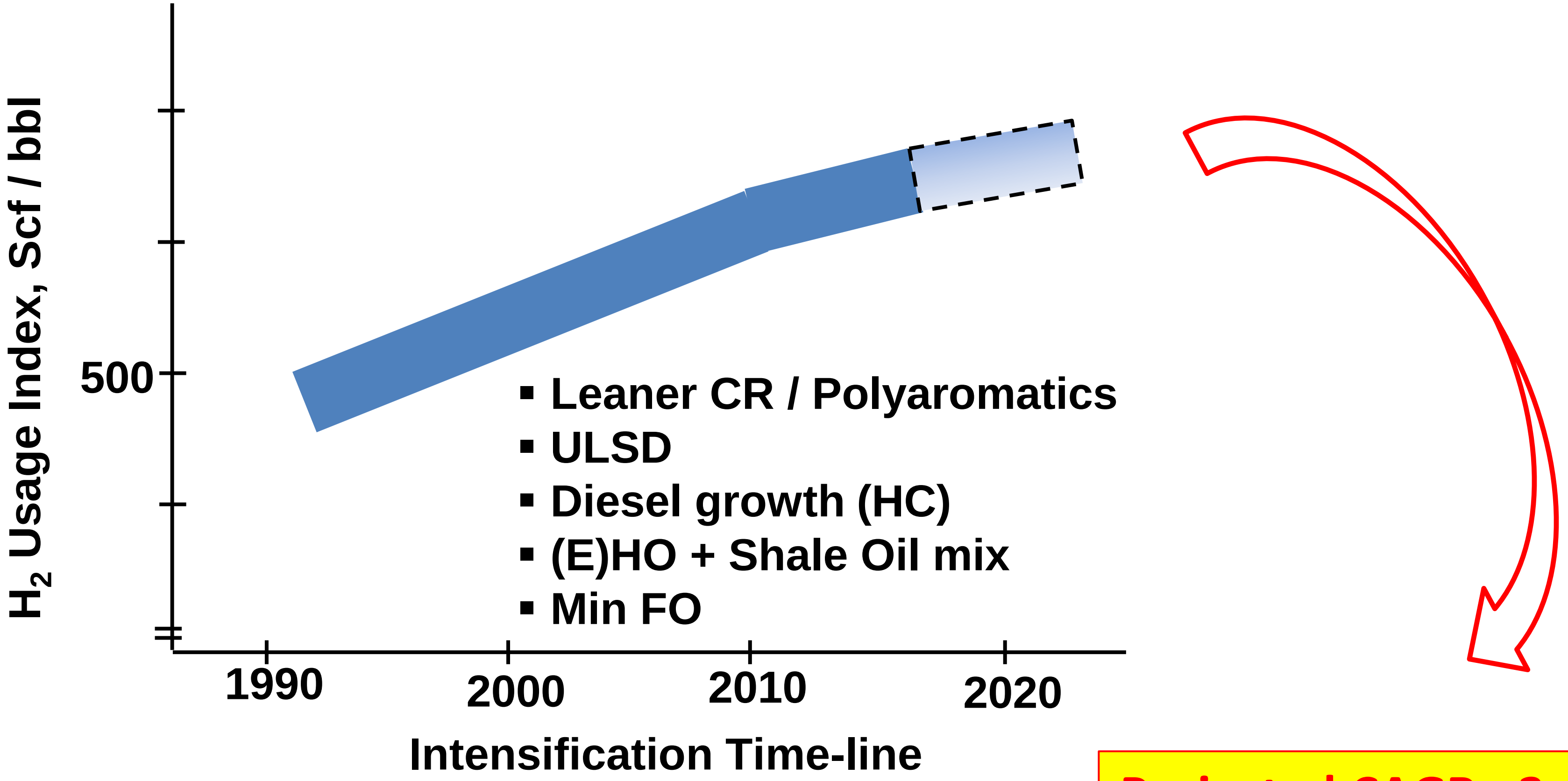
Presentation Outline

- Introduction
- Steam Reforming Pellet catalyst - status quo
- ZoneFlow^{TM} (ZF) Reactor Technology - an innovative breakthrough
- ZF development status and validation programs
- Application of ZF Reactor Technology in hydrogen plants
  - ZF Single-Pass Reactors (ZF-SP)
  - Convective Pre-Reforming Reactors (ZF-CPR)
  - ZF Bayonet for Recuperative reforming (for New SMRs)

Introduction : Refinery Hydrogen Intensification



Projected CAGR : 3-4%
~ 0.8 BCFD

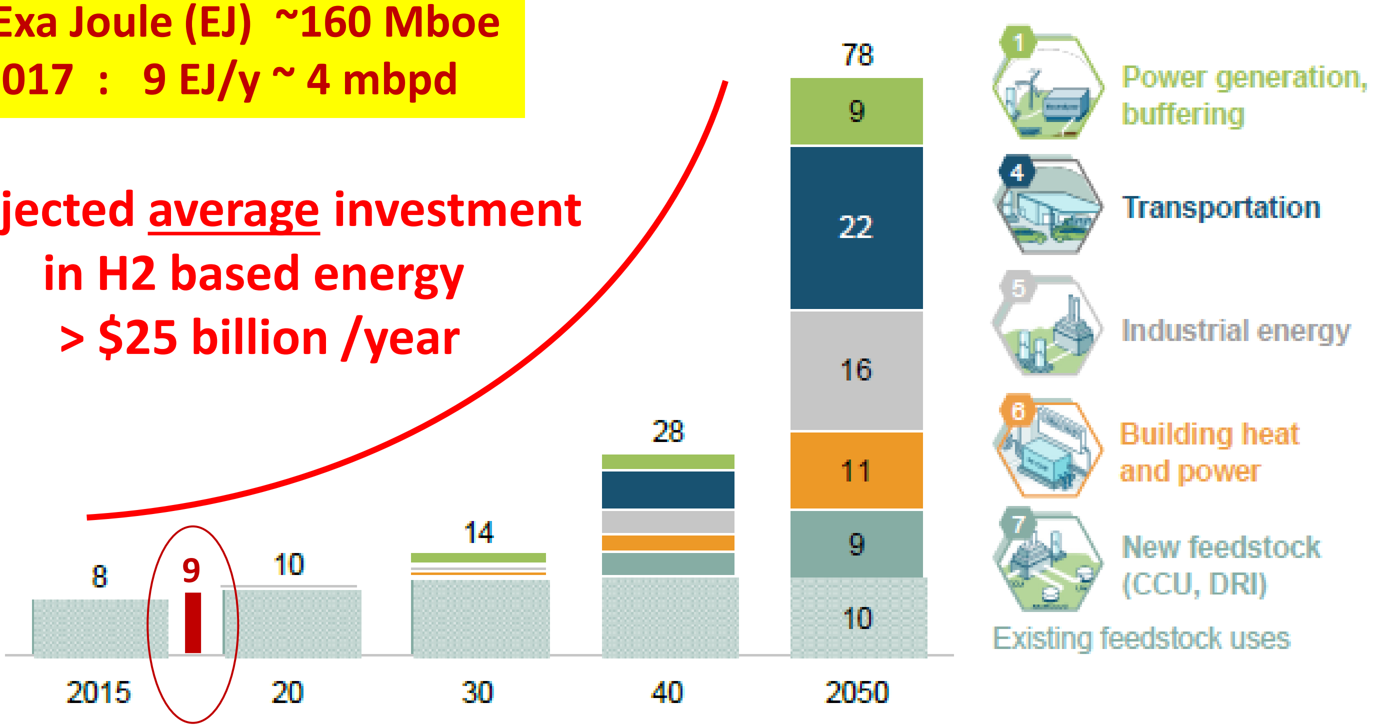
Hydrogen-for-Energy: Demand Projections (EJ)

Hydrogen demand could increase 10-fold by 2050

Global energy demand supplied with hydrogen, EJ

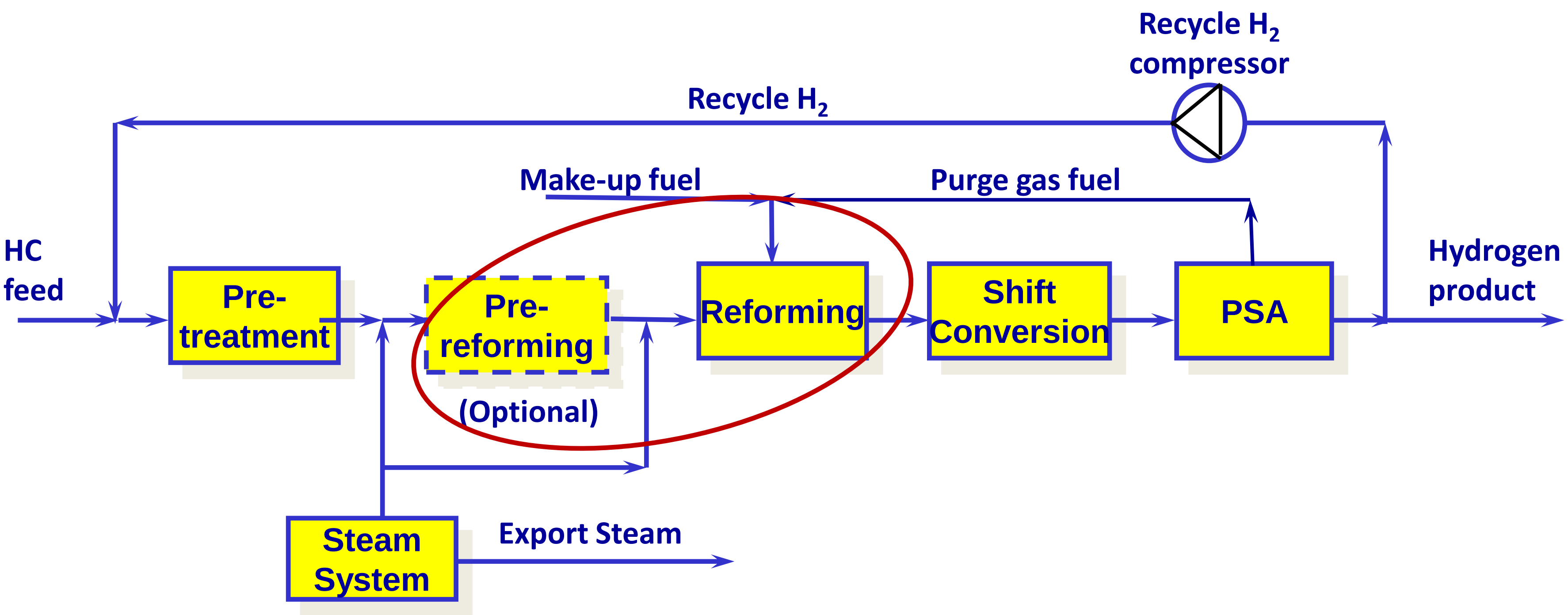
1 Exa Joule (EJ) ~160 Mboe
2017 : 9 EJ/y ~ 4 mbpd

Projected <u>average</u> investment in H2 based energy > $25 billion /year



SOURCE: Hydrogen Council

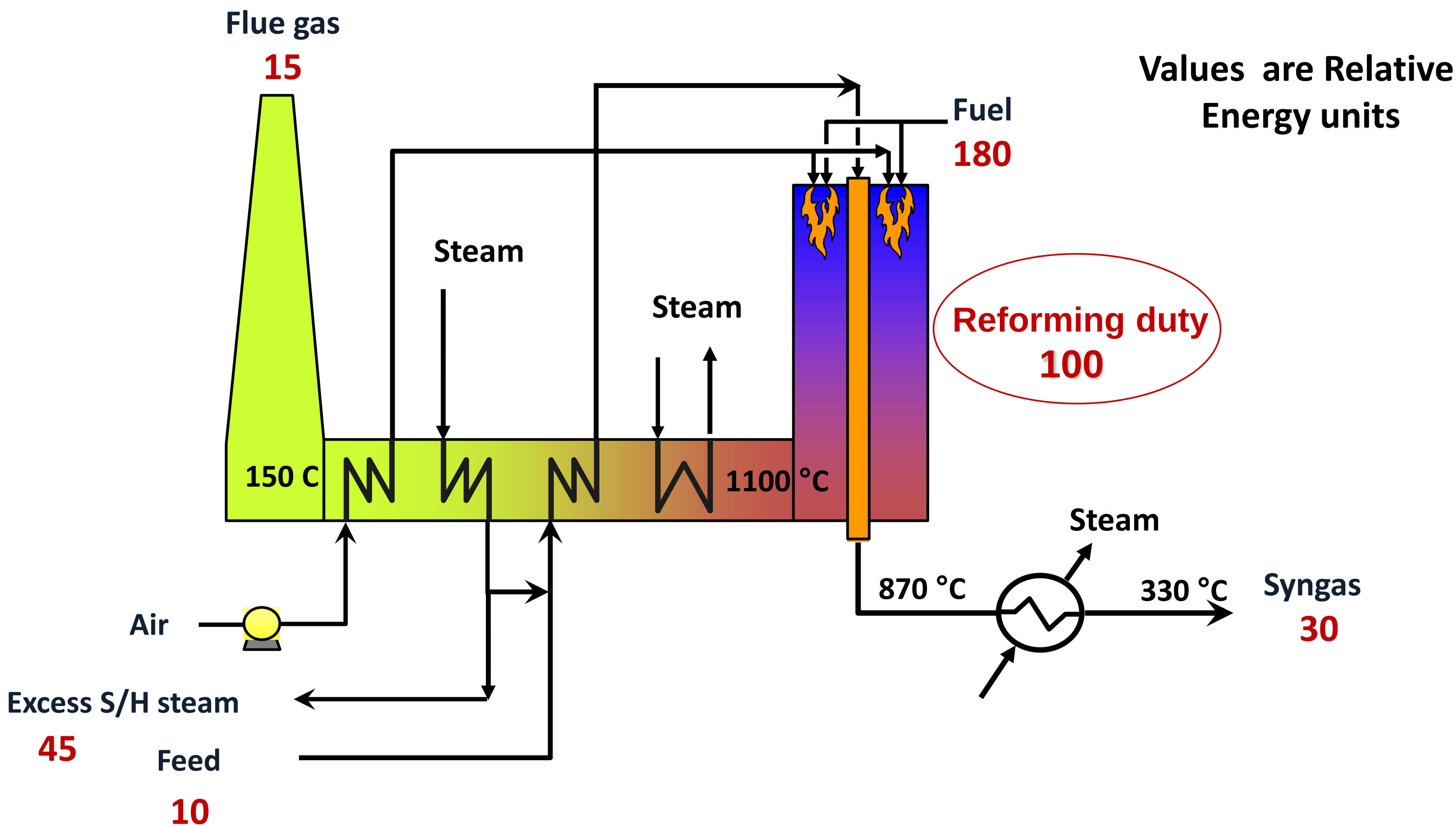
Typical Hydrogen Plant Block Diagram



40 → 400 → 600 → 900 → 350 → 40 Temp, C

Steam Reformer: Heart of Hydrogen Plant

Typical Overview

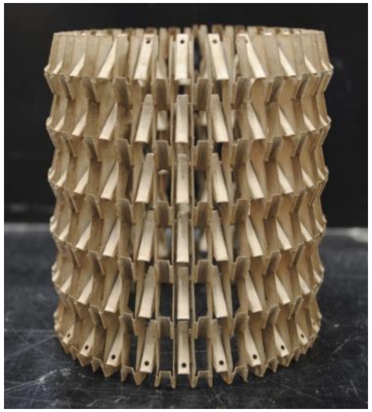


Steam Reforming Catalyst - Status Quo

- State-of-the-art steam reforming catalysts have by and large stayed “pellet-based” and so have the inherent deficiencies (of random packing) in terms of :
  - high pressure drop
  - limited heat transfer (sporadic catalyst-to-wall contact)
  - very low catalyst effectiveness (intrinsically diffusion limited)
  - catalyst attrition / breakage from thermal cycling
  - flow / temperature non-uniformity
- Various attempts for structured catalyst over the years, haven’t been successful due to few core challenges

ZoneFlow Reactor Technology
– an Innovative Breakthrough

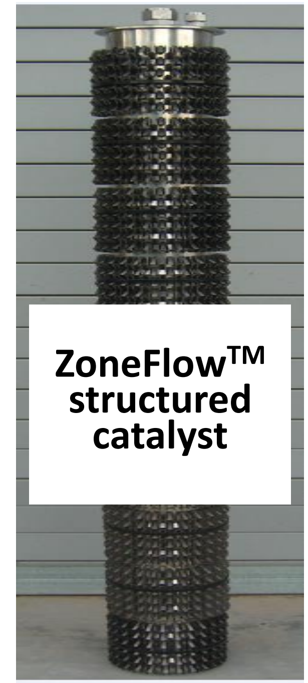
- Advanced high-performance structured catalyst with step improvements on key performance parameters, compared to current pellet catalysts :
  - up to 2 times higher heat transfer (including internal radiative transfer)
  - up to 50% lower pressure drop
  - annular flexible casing design ensures wall proximity in cold and hot conditions and also creates “near-wall” flow
  - up to 10 times higher catalyst effectiveness
  - high strength metal substrate; no attrition from thermal cycling
  - uniformity of flow over (longer) operating life
  - uniquely befitting for Recuperative reforming also



Conventional SMR Catalyst vs. ZoneFlow™ (ZF)

- From random packing to uniform, engineered foil structure
- From irregular and scanty pellet-tubewall contact to uniform structure-to-wall contact in all conditions
- From strength-limited voidage and related flow resistance to robust high-voidage structure with near-wall turbulence

➢ **ZF uniquely offers step-reduction in pressure drop <u>combined with</u> almost doubling of heat transfer coefficient**



Conventional SMR Catalyst vs. ZoneFlow™ (ZF)

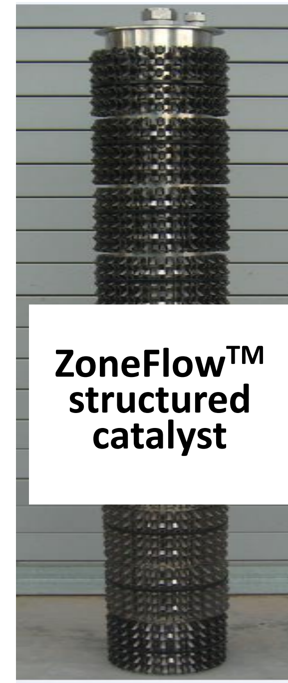
- From diffusion-limited active sites' access to high-GSA thin-fin structure with full surface access

  High activity micro-layer catalyst with non-acidic and steam-stable substrate

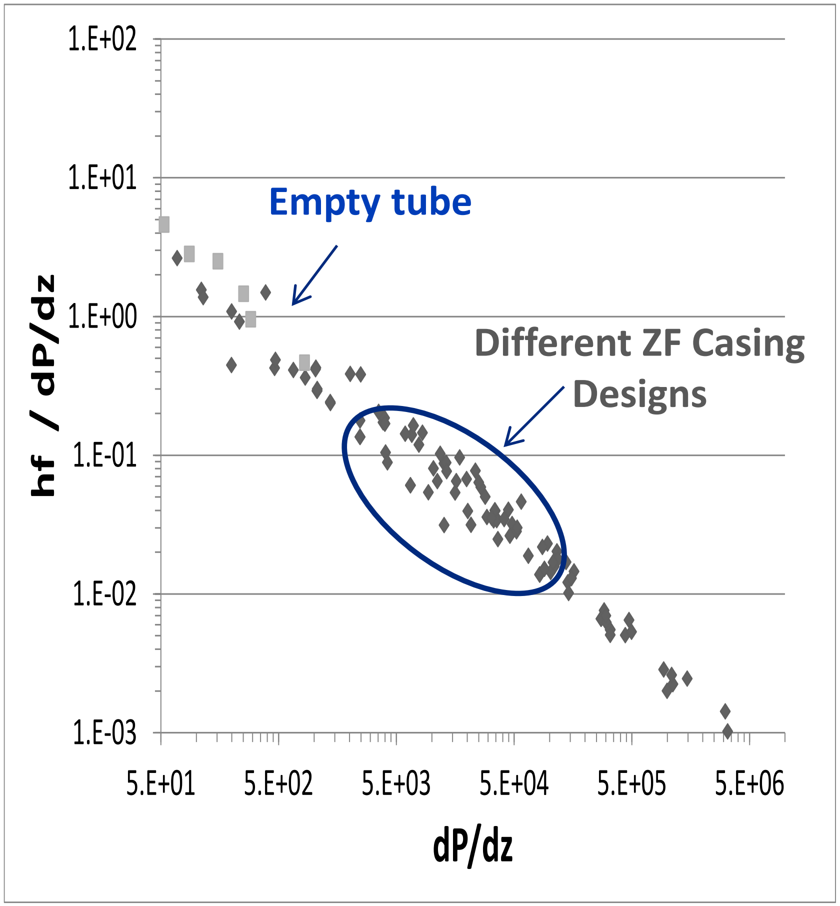
➢ **Multifold increase in catalyst effectiveness; higher resistance to coking and upsets; longer operating life**

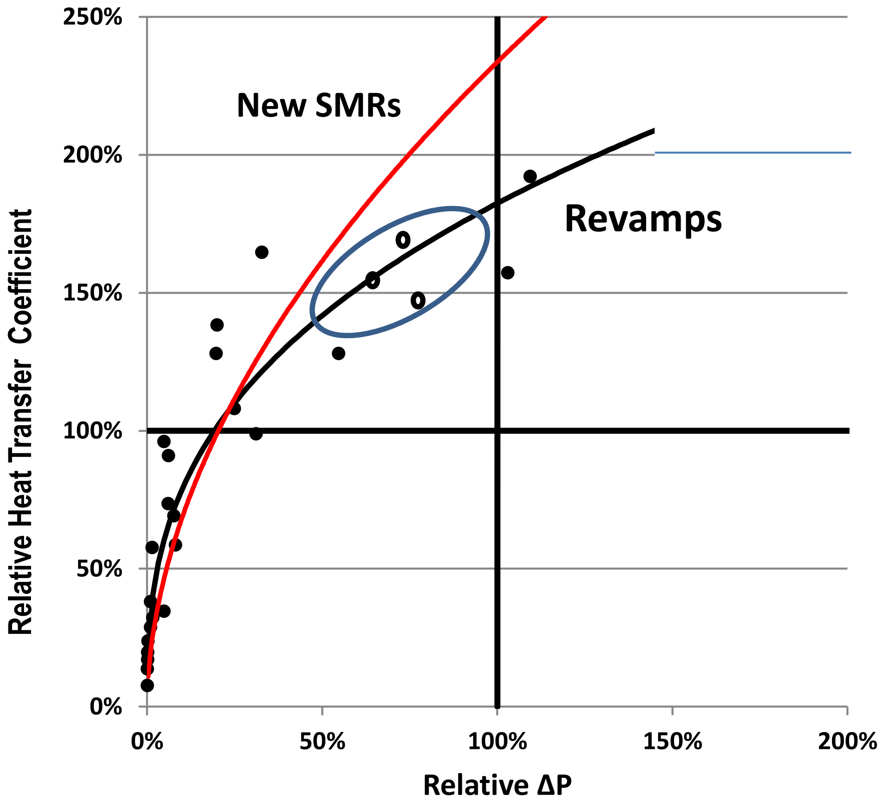
- From limited crush strength to durable & flexible metal structure

➢ **No attrition or any breakage ; stable pressure drop and flow uniformity over full life**

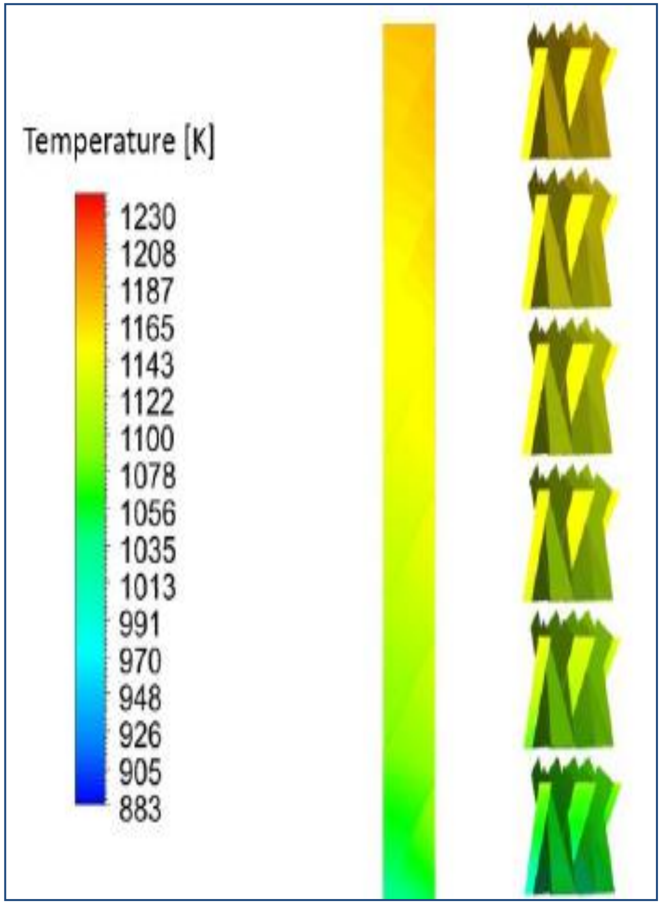


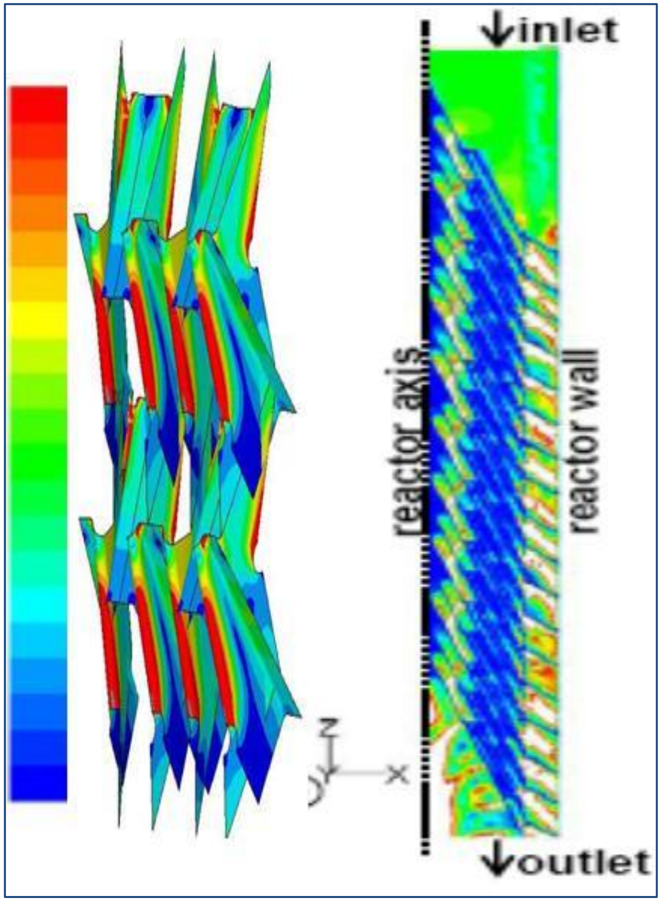
ZF's Development : Detailed CFD Modeling





ZF's CFD Modeling and FE Analysis Results





ZF's Commercial Demonstration

Installation

Operation

Extraction

Demonstrated Results Compared to Pellet Tubes

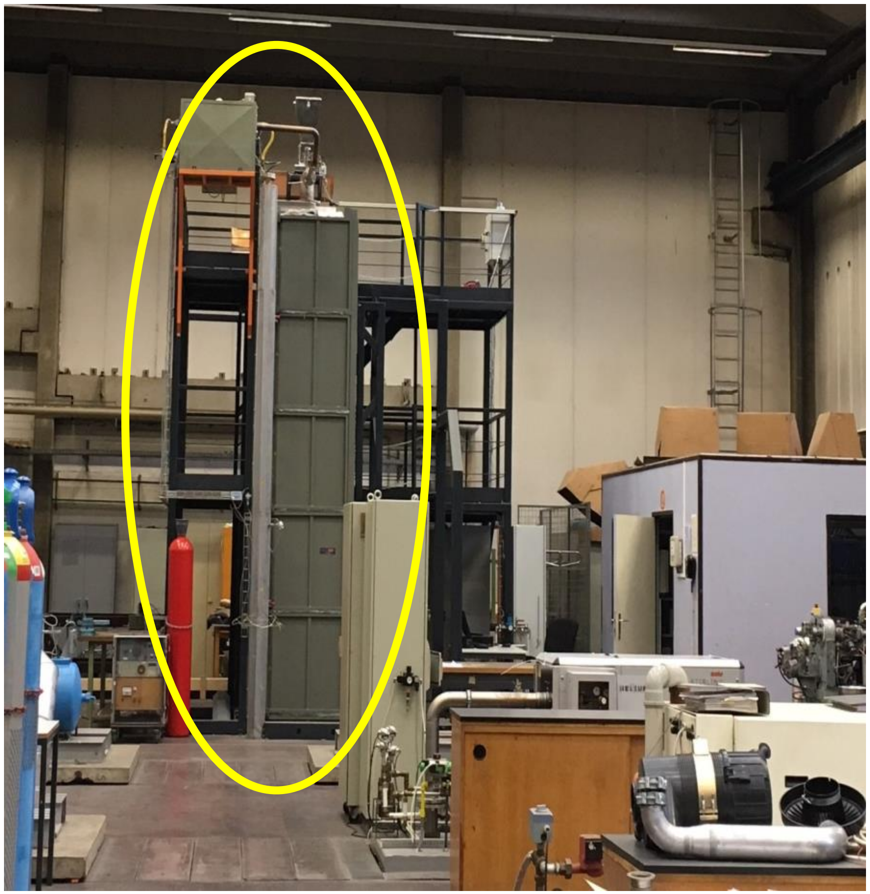
- Up to 80^{o} C lower TMT compared to adjacent tubes
- Up to 24% lower pressure drop
- No hot spots
- ZF structure intact in original form after >15,000 hrs operation and with 5 thermal cycles

- Lower S/C ratio operation was not available

ZFRT Pilot Plant

- At Université Catholique de Louvain (UCL), Belgium
- Fully equipped and instrumented pilot plant for extensive testing of ZF reactors under rigorous commercial conditions and beyond
- In collaboration with Prof. Gilbert Froment and Prof. Juray de Wilde
- Added micro-reactor lab for studying intrinsic reaction kinetics
- Operational 2Q 2018

ZFRT Pilot Plant Installation



ZF applications in (H_2)SMRs: Core-Merit Benefits

- ZF's lower dP, higher HTC and higher catalyst effectiveness allow the following underlying advantages, especially for retrofits :
  - higher throughput without increasing pressure drop
  - higher SMR outlet temp without increasing maximum tube skin temperature (TSM)
  - higher heat flux and/or higher reforming severity without increasing bridge-wall temperature and thus related firing / flue gas
  - lower approach to equilibrium
- Exploitation of ZF's annular structure supports "recuperating reforming"

ZF Solutions for Hydrogen SMRs

- **ZF-Single pass (ZF-SP)**
  - De-stressing and Retrofitting existing SMRs
  - Higher-flux, cost-effective and more reliable new SMRs
- **ZF-Convective pre-reforming (ZF-CPR)**
  - Unmatched in-situ retrofit for additional capacity in existing SMRs without major modifications
  - Efficient and cost-effective applications in new SMRs
- **ZF-Bayonet (ZF-B)**
  - Uniquely applicable for recuperative reforming in new SMRs, overcoming current challenges

ZF-SP for De-Stressing SMRs

- Stressed SMR Indicators / Attributes
  - Pressure drop (or its build up) limiting throughput
  - Loss of catalyst activity → hotter tubes limiting outlet temperature
  - Catalyst attrition / settling from thermal cycling
  - Carbon formation / hot spots
  - Impact on (remaining) tube life
- Constrained reforming capacity
- Replacing (pellet) catalyst in these SMRs with ZF-SP Reactors can overcome these deficiencies

ZF-SP for De-Stressing of SMR

SMR De-Stressing	SMR Design	Stressed Operation	ZF-SP replacing pellets
Relative Capacity, %	**100**	95	100
Capacity limitations	**-**	dP, TSM	removed
S/C Ratio	3.0	3.3	2.8
Outlet temp, C	860	843	868
Approach to Equilibrium EOR C	-10	-12	-7
CH4 slip, dry vol %	5	5	5
Radiant Pressure drop, bar	2.8	2.8	2.3
Relative Radiant duty %	100	97	99
Avg heat flux kW/m2	78	74	78
Bridgwall temp, C	1000	980	998
TSM (avg) C	935	935	926

ZF-SP for De-bottlenecking or New SMR

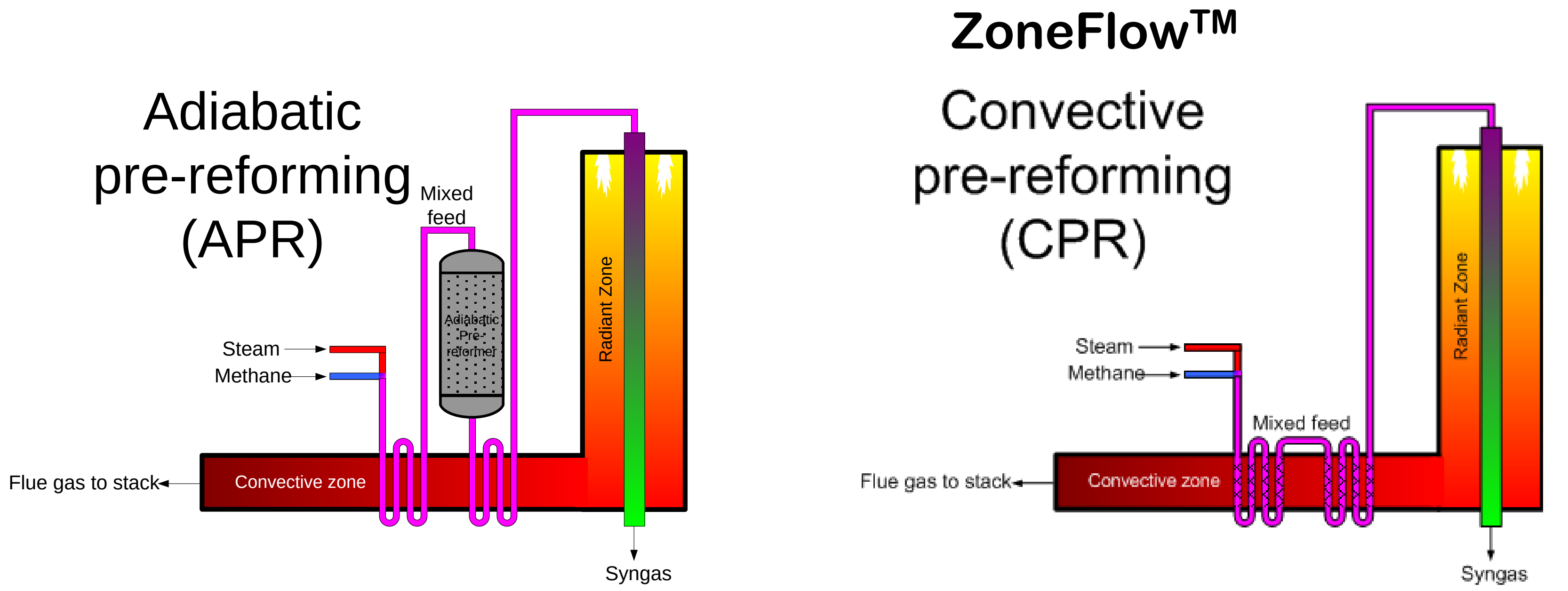
- Achieve >5% more equivalent capacity
- Higher average heat flux (without exceeding tube design temperature)
- Improved temperature uniformity
- Extended tube life and improved reliability
- Extended EOR
- Optimized operation and enhanced reliability

ZF-SP for Debottlenecking

		Reference	ZF-Radiant
Relative Capacity,	**%**	**100**	**105**
Capacity limitations		dP, TSM	removed
S/C Ratio		3.0	2.8
Outlet temp,	C	865	870
Approach to Equilibrium	C	-10	-7
CH_4 slip,	vol %	5.5	5.7
Radiant Pressure drop,	bar	2.8	**2.5**
Relative Radiant duty	%	100	104
Avg heat flux	kW/m2	75	78
Bridgwall temp,	**C**	**1008**	**1004**
TSM	**C**	**940**	**938**

Pre-reforming

In-situ efficient use of higher grade convective heat using existing process coils



ZF Convective Pre-reforming (ZF-CPR)

- Non-adiabatic convective pre-reforming using ZF-CPR inserts
- Tailored structured packing for very low dP, high GSA and (low temp reforming) activity
- **In-situ horizontal loading** in the mixed feed superheat coils
- Avoids major modifications and also the related downtime
- Optimization of pressure drop in combination with ZF-SP in SMR radiant tubes

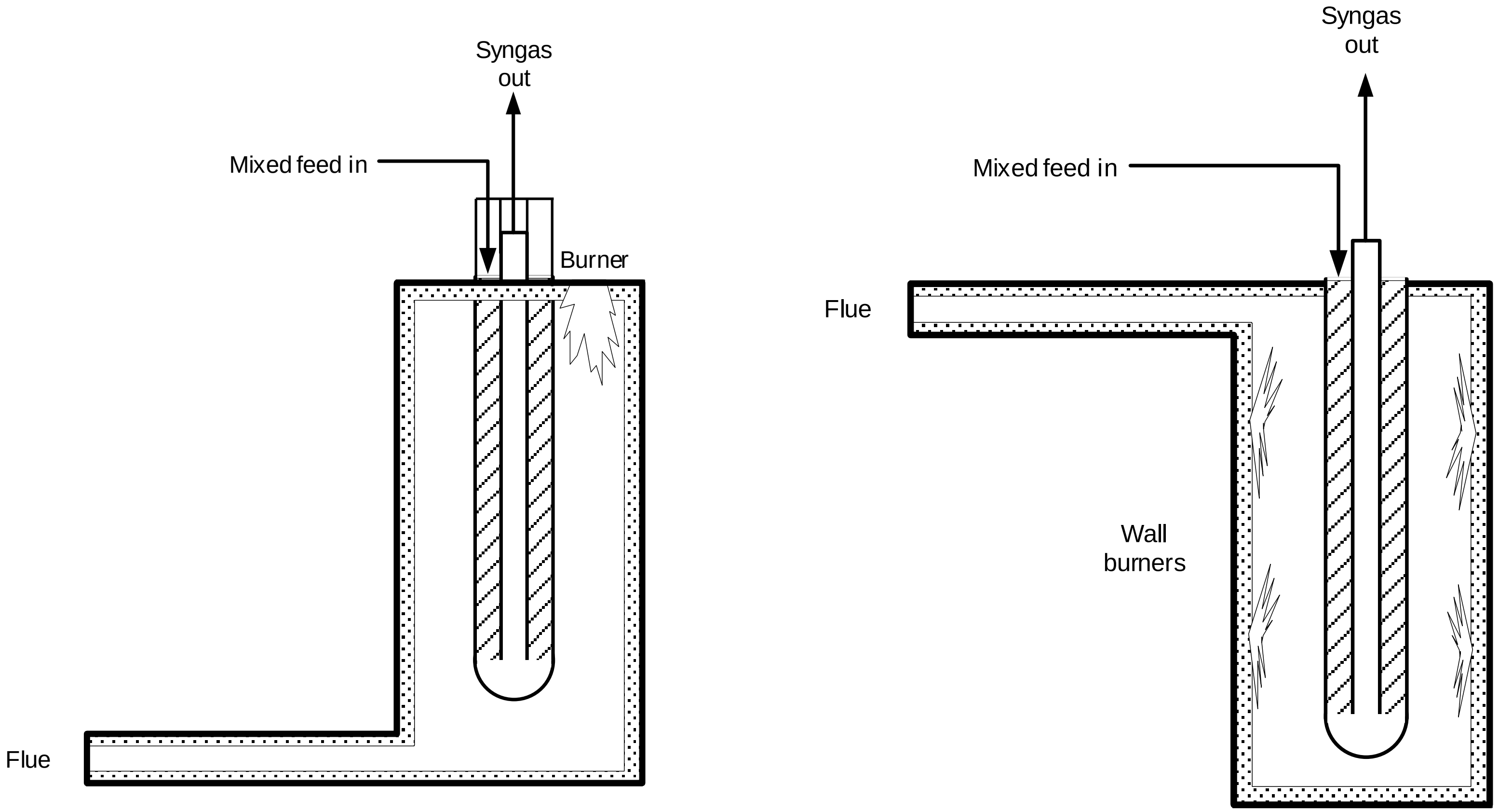
- For revamps, 8-12% additional reforming without increasing SMR firing duty
- For New SMRs, 10-15% smaller SMR and proportionately also the steam system.

ZF-CPR for SMR Capacity Upgrade

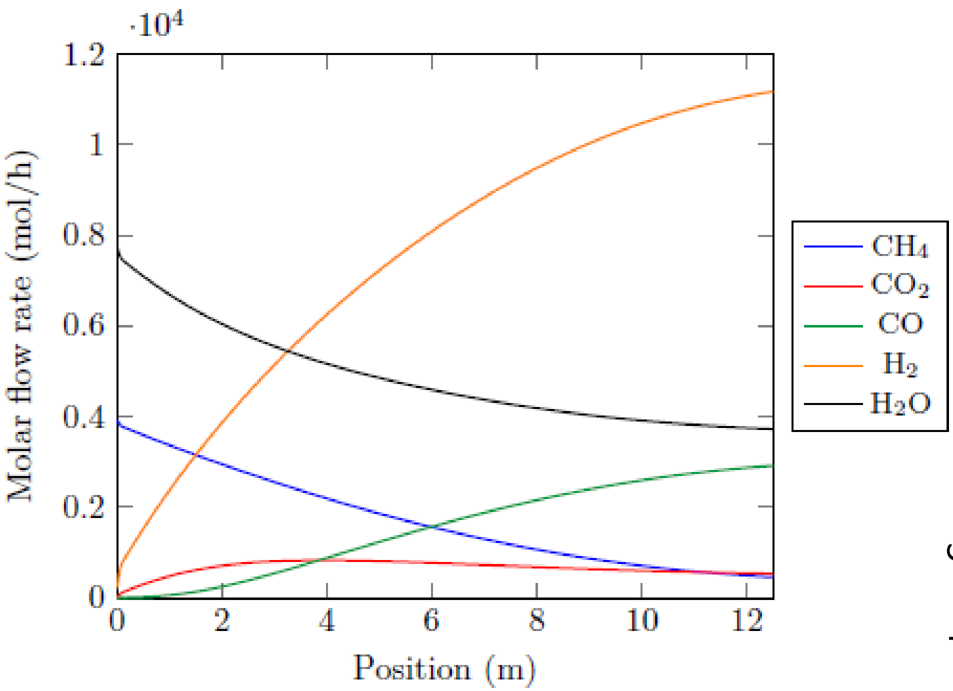
		Existing	ZF + CPR
Relative Capacity,	**%**	**100**	**115**
S/C Ratio		**3.0**	**2.8**
SMR inlet temp,	C	550	550 / 575 *
SMR outlet temp,	C	870	870 **/ 878** *
Approach to Equilibrium EOR	C	-10	-7
CH4 slip,	dry vol %	4.8	5.4 / 5.0
Radiant Pressure drop,	**bar**	**2.5**	**2.3**
Avg heat flux	kW/m2	80	80 - 82
Relative Radiant duty	**%**	**100**	**100 / 103**
Bridgewall temp,	**C**	**1020**	**1009 / 1018**
TSM	**C**	**950**	**938 / 948**

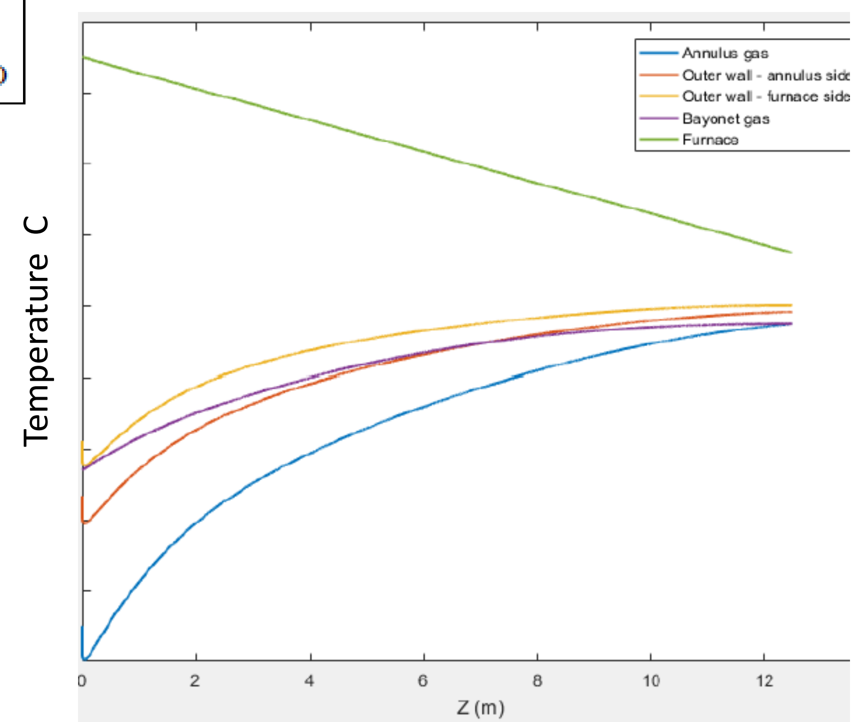
* Exploiting of existing plant design margins

ZF-Bayonet Configurations



ZF-Bayonet Modeling and Simulation Results





Drivers and Benefits of ZF-Bayonet

- Direct exploitation of ZF's inherent annular design
- Overcomes innate limitations of the "pellet" catalyst against crushing from differential expansion / thermal cycling
- SMR size reduction up to 20% based on high grade heat recovery for reforming
- Allows "Zero export steam" hydrogen plants for :
  - remote, stand-alone or "distributed " hydrogen plants not having a steam host
  - cases where export steam has low or no credit compared to fuel
- Allows lowering of carbon-footprint from reduced firing per unit H2
- Compact / modularized SMR units
- Applicable in various SMR configurations and designs

Conclusions

- Hydrogen demand growth projections are strongly encouraging
- Steam reformer is the heart of an H2 plant; its performance and tube life are governed by catalyst
- Current pellet catalysts have inherent deficiencies, thus limiting the extent of possible improvements.
- ZoneFlow Reactor Technologies (ZFRT) has developed an innovative structured catalyst
- Exceptional and advanced solutions for revamping as well as new hydrogen SMRs, offering OPEX and CAPEX benefits.
- Successful demonstrations and pilot plant for testing under commercial / client-specific conditions

ZoneFlow Reactor Technologies, LLC

Thank You !

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