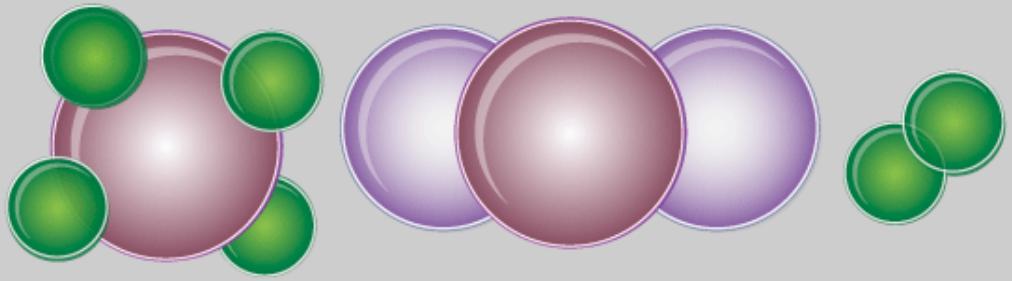

1st Trondheim
Gas Technology Conference
21-22nd October 2009

Microstructured reactors in compact conversion of natural gas and biomass to liquid fuels and hydrogen

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The Research Council of Norway

StatoilHydro

KIT Karlsruhe Institute of Technology

UOP A Honeywell Company

DNV MANAGING RISK

AkerSolutions

Bayerngas Norge

OUTLINE

- Motivation and background
- Results from
  - *Synthesis gas* (hydrogen) production in metallic microchannel monoliths
  - *Methanol* synthesis in a Integrated Micro Packed Bed Reactor-Heat Exchanger
  - Compact synthesis of *dimethyl ether (DME)*
  - *Fischer-Tropsch* synthesis in a microstructured reactor
- Summary and outlook

Motivation and background

BP Statistical Review of World Energy 2009

Proved reserves at end 2008

Trillion cubic metres

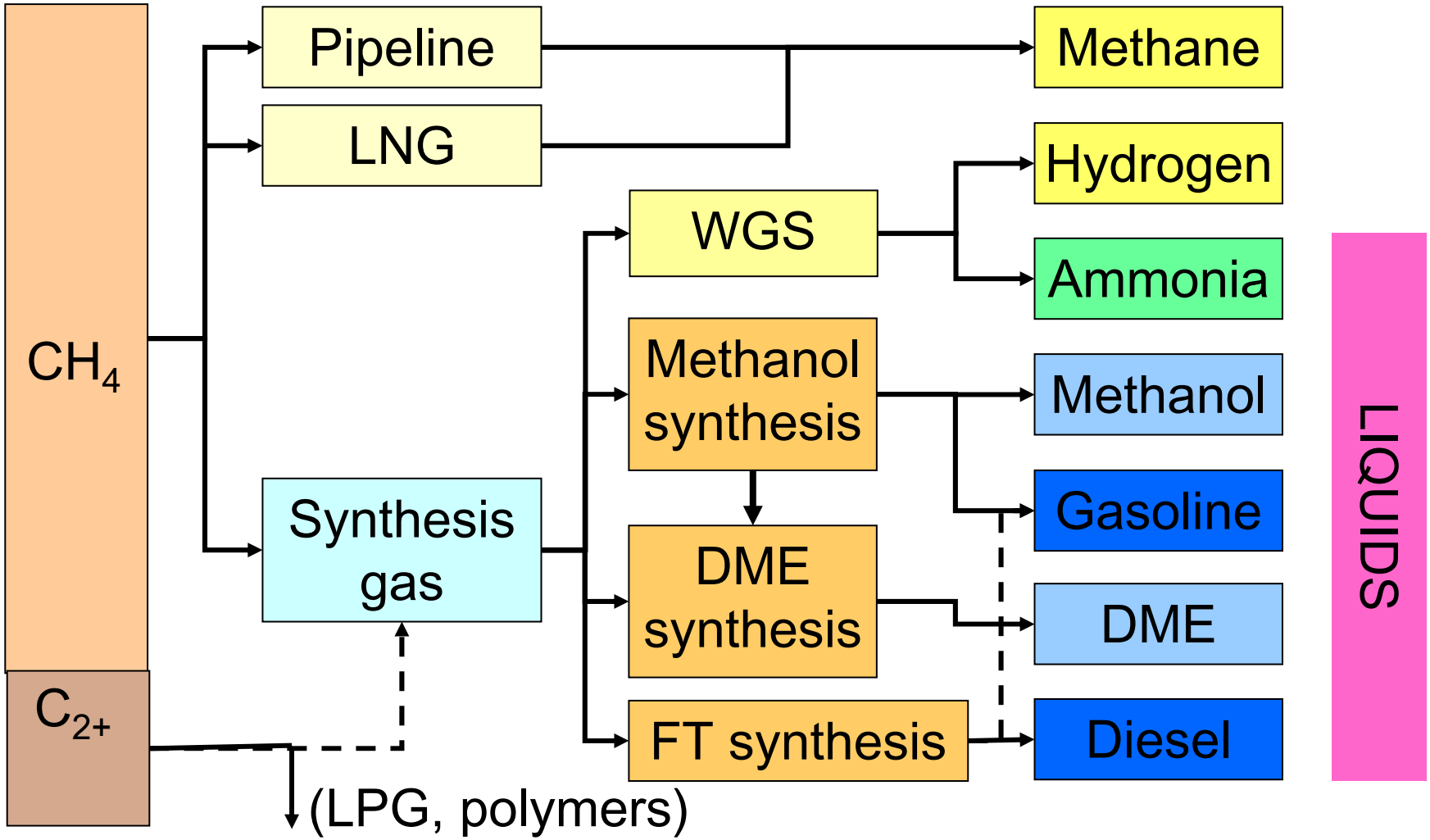
"Global proved reserves of natural gas in 2008 is 185.02 TCM "

25% (?) is stranded natural gas

- Long distance to market
- Volume too low for pipeline
- Complicated/costly production

- Examples
  - Associated gas
  - Arctic gas
  - Off-shore

Natural gas to market



Natural gas processing/conversion

StatoilHydro Tjeldbergodden methanol plant

900.000 tons/year of methanol

25 % of production capacity, 13 % of consumption in Europe

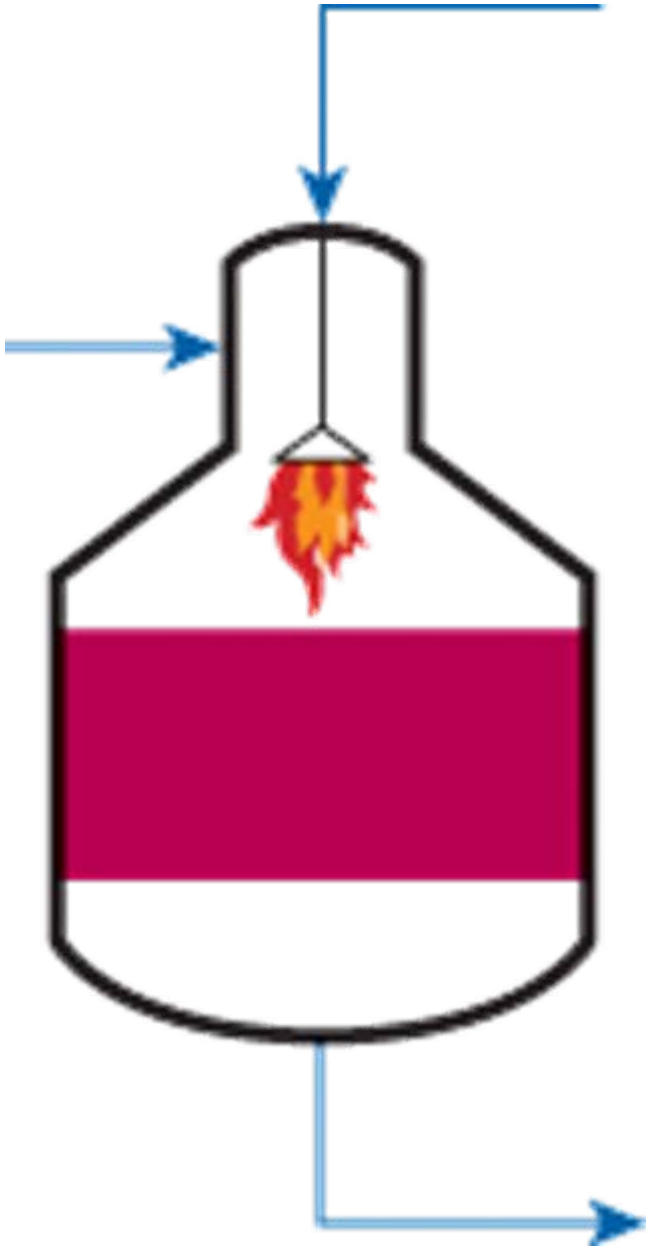
Natural gas processing/conversion

Shell Pearl GTL, Quatar.

140,000 barrels/day of GTL products

120,000 barrels/day of associated condensate and LPG

...economy of scale.



Autothermal reformer for synthesis gas production with partial combustion zone

...requirements to operation:

Safety

Stability

...

COMPACT GAS TO PRODUCTS TECHNOLOGY

Offshore conversion of remote gas to liquids

Challenges:

- **Footprint**
- **Weight**
- **Robustness**
- **Safety**
- **Tilting**

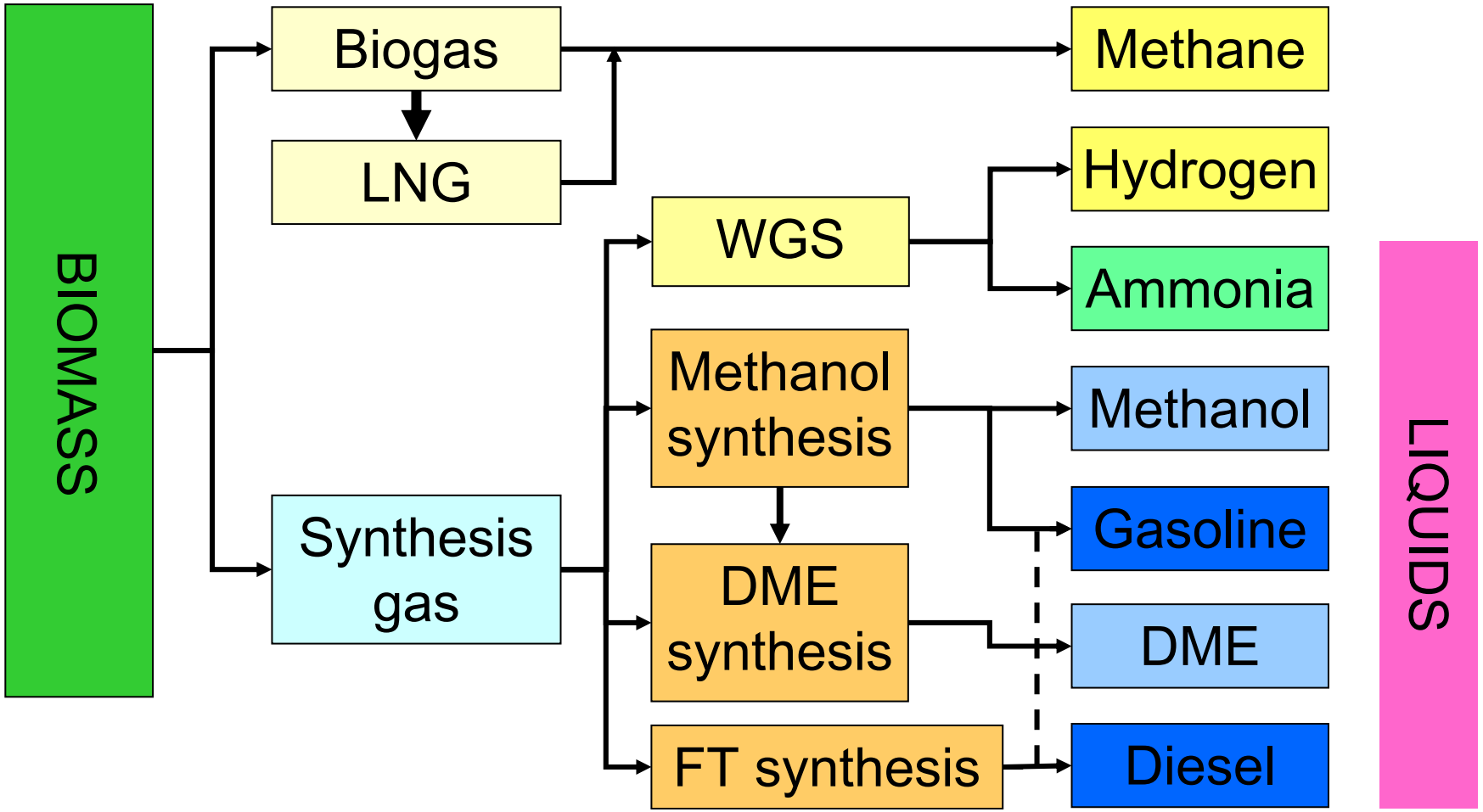
Future Solution for Stranded Gas Fields?

... and then there is BTL

Wisconsin farmland

Distributed, compact and efficient conversion of biomass to fuels.

Natural gas to market



Results from different projects on microstructured reactors

Microstructured reactors

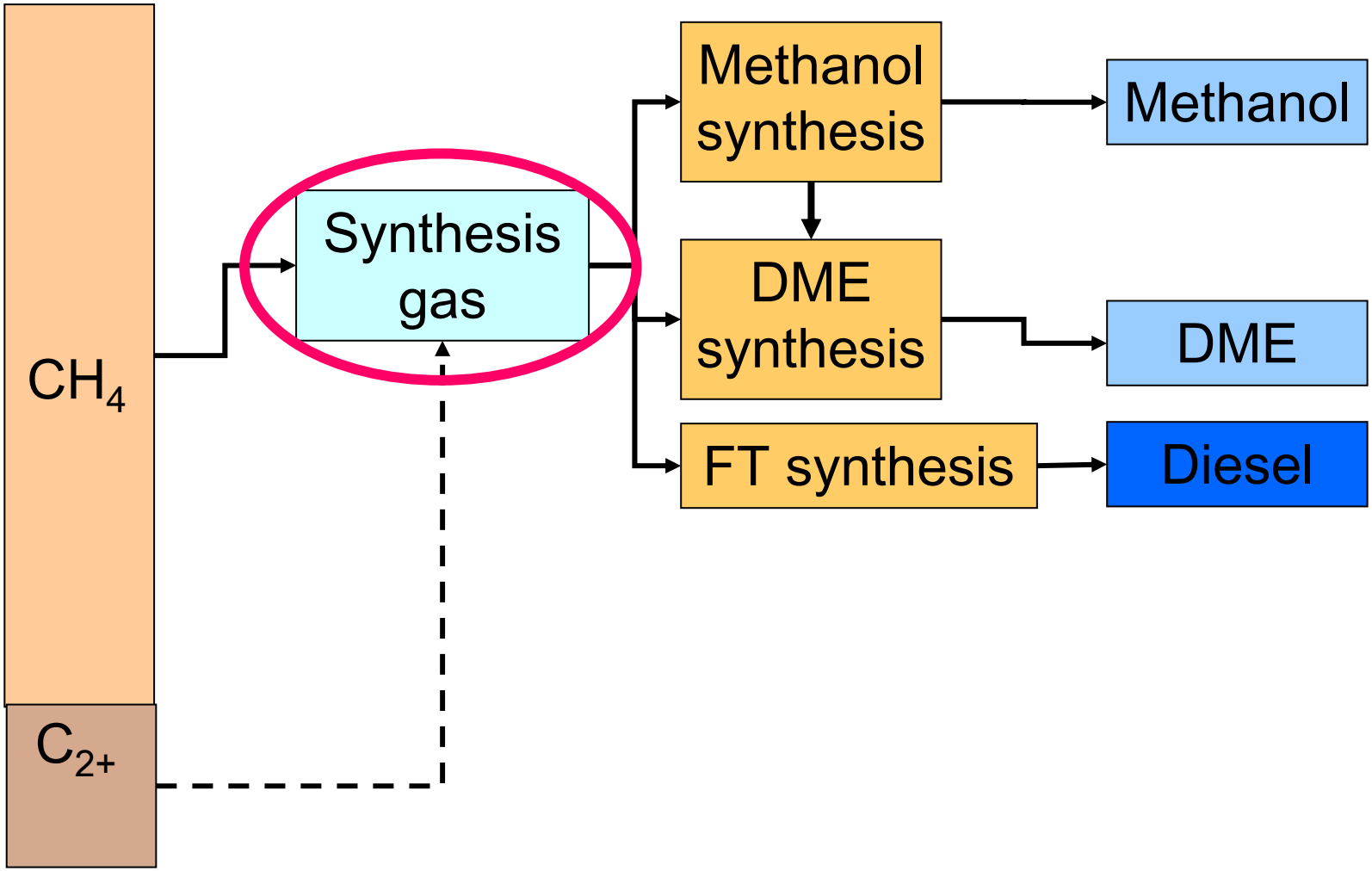
- Good heat and mass transfer
- Up-scaling by parallellization

Overcome “economy of scale”?

- Inherent safety

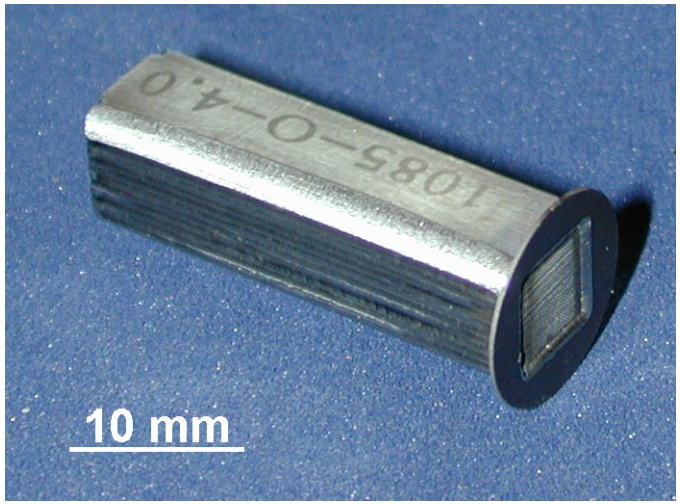
On ships, platforms and farms?

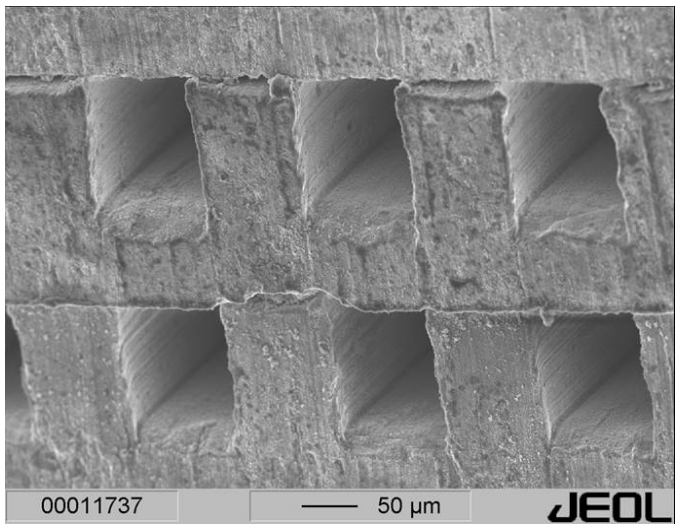
Natural gas to market



Syngas (hydrogen) production from alkanes in metallic microchannel monoliths

Metallic microchannel reactors (Rh/Al_2O_3/Fecralloy) with 100 µm wide channels



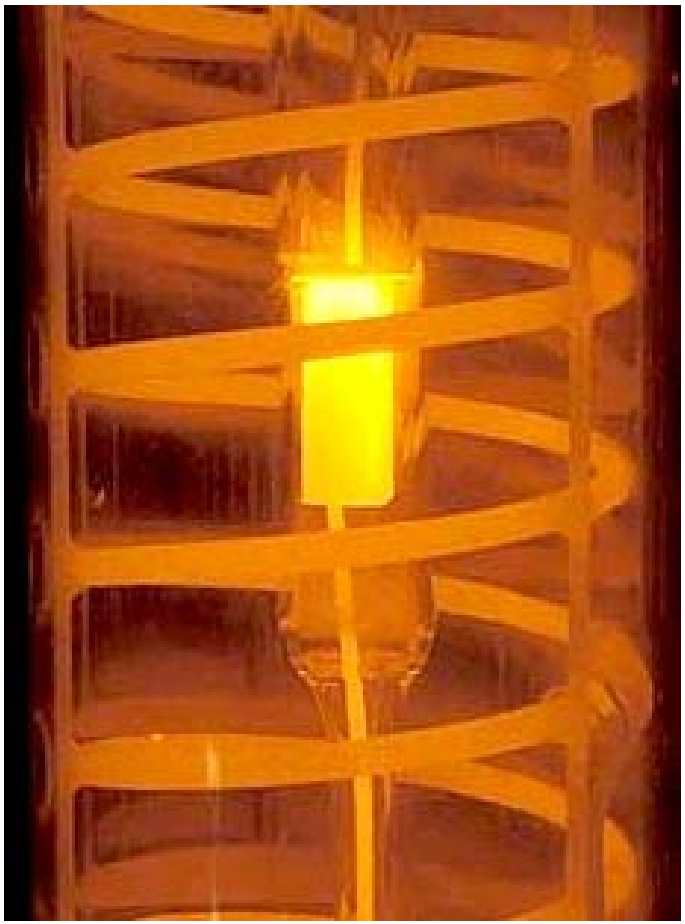


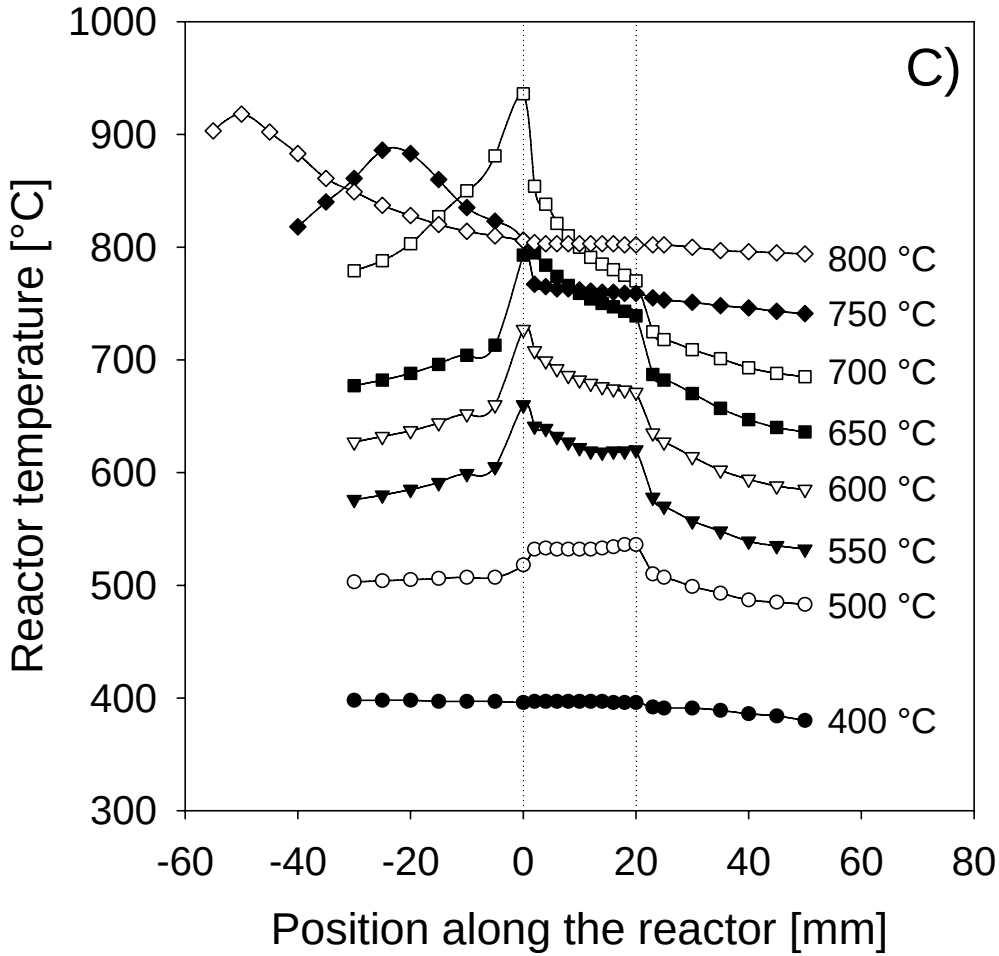
Reactor no.	1	2	3	4
Material	Fecralloy	Rh	Fecralloy	Fecralloy
H×W [mm²]	5.5×5.6	5.5×5.6	5.5×5.6	5.5×5.6
Length [mm]	20	20	20	20
No. of channels	676	676	676	572
Channel dimension [µm²]	120×130	120×130	100×120	100×120
Thermocouple channel dimension [µm²]	-	-	-	600×600
Geom. surface of channels [cm²]	67.5	67.5	59.5	50.8
Porosity	0.34	0.34	0.26	0.22
Flow at 12.7 ms residence time [Nml/min]	1000	1000	769	614
Impregnated with	Rh	-	-	- / Rh

Reactors are produced at Institute for Micro Process Engineering (IMVT), Forschungszentrum Karlsruhe*.

* Now Karlsruhe Institute of Technology

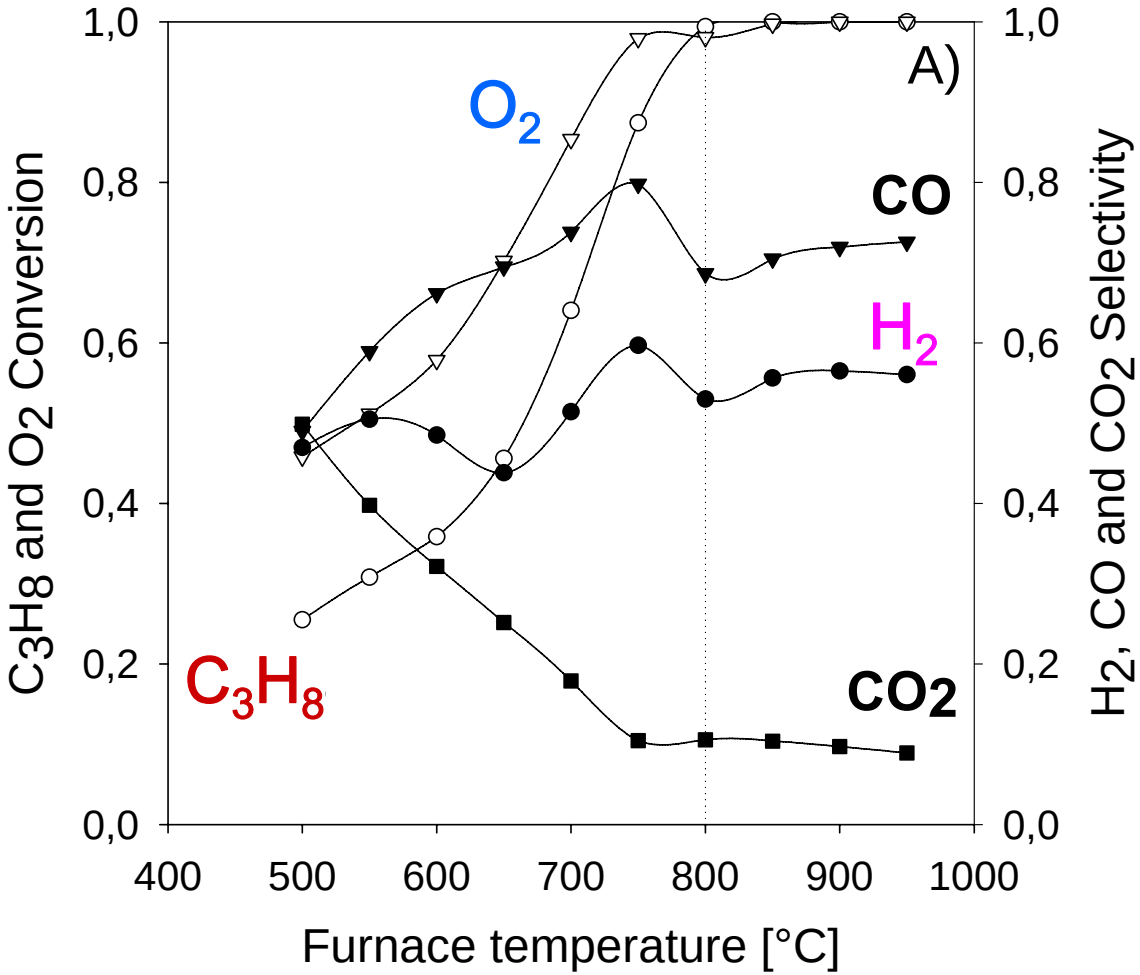
Temperature profile, propane partial oxidation in Rh/Al_2O_3/Fecralloy (100µm)





I. Aartun, H. J. Venvik, A. Holmen, P. Pfeifer, O. Görke, K. Schubert, Catalysis Today 110 (2005) p.98.

Conversion and products,
propane partial oxidation in Rh/Al_2O_3/Fecralloy (100µm)



Synthesis gas at

- high conversion and
- $H_2/CO/CO_2$ useful for downstream process (methanol, DME, FT syn. diesel)

Ambient pressure
$C_3H_8/O_2/N_2$ feed
→C/O=0.8
Feed gas flow: 1000 Nml/min
→12.7 ms residence time.

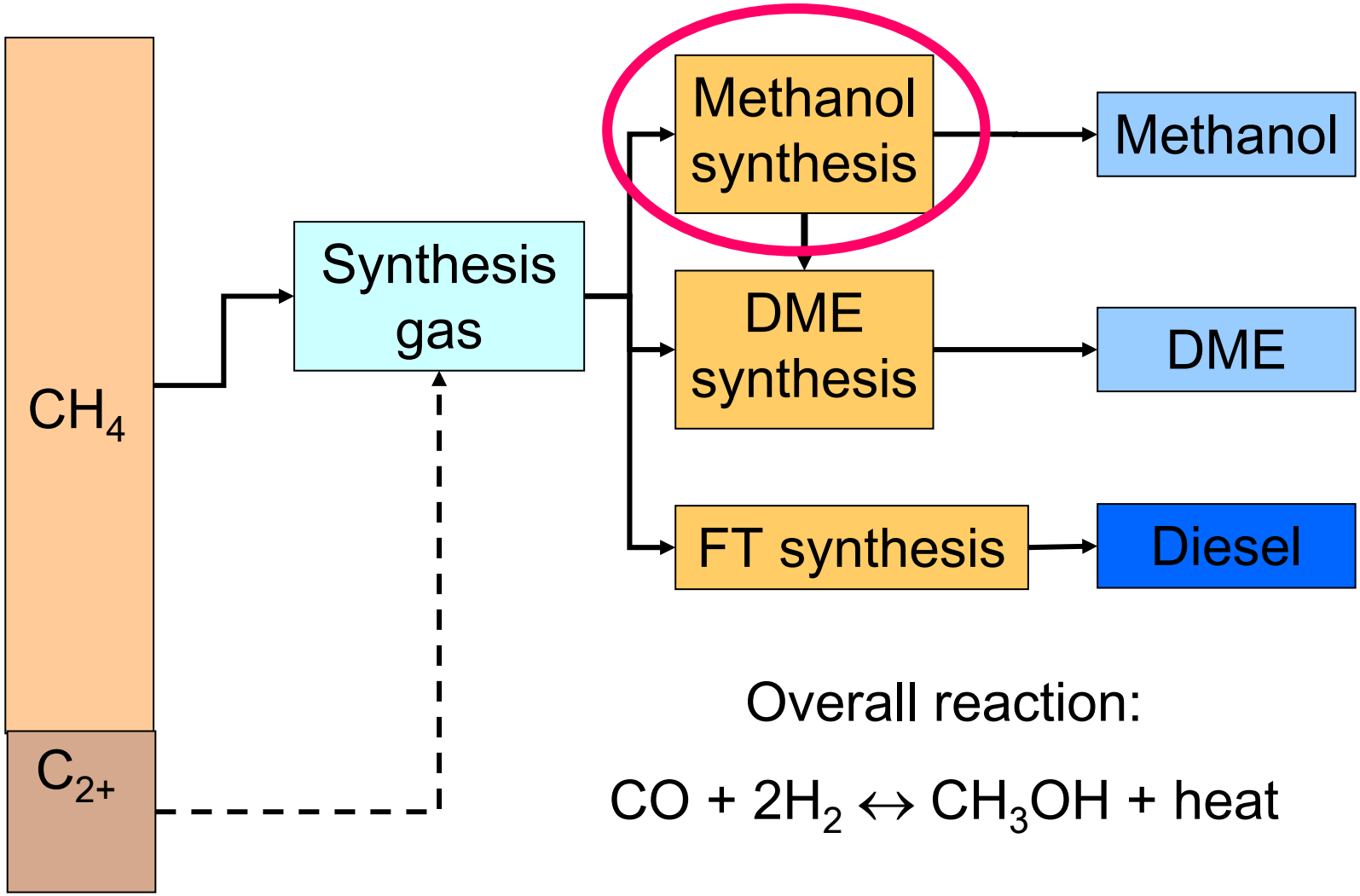
I. Aartun, H. J. Venvik, A. Holmen, P. Pfeifer, O. Görke, K. Schubert, Catalysis Today 110 (2005) p.98.

Partial oxidation and oxidative steam reforming in metallic microchannel reactors, additional results:

- ✓ Good results also with CH_4 in Rh/Al_2O_3/Fecralloy *
- ✓ Rh/Al_2O_3/Nicrofer not so good *
- ✓ Addition of steam to reactant mixture increases hydrogen production
- ✓ Microchannels suppress gas phase reactions leading to C_{2+} by-products

* B. C. Enger, J. Walmsley, E. Bjørgum, R. Lødeng, P. Pfeifer, K. Schubert, A. Holmen, H. J. Venvik Chemical Engineering Journal,144(2008) p. 489

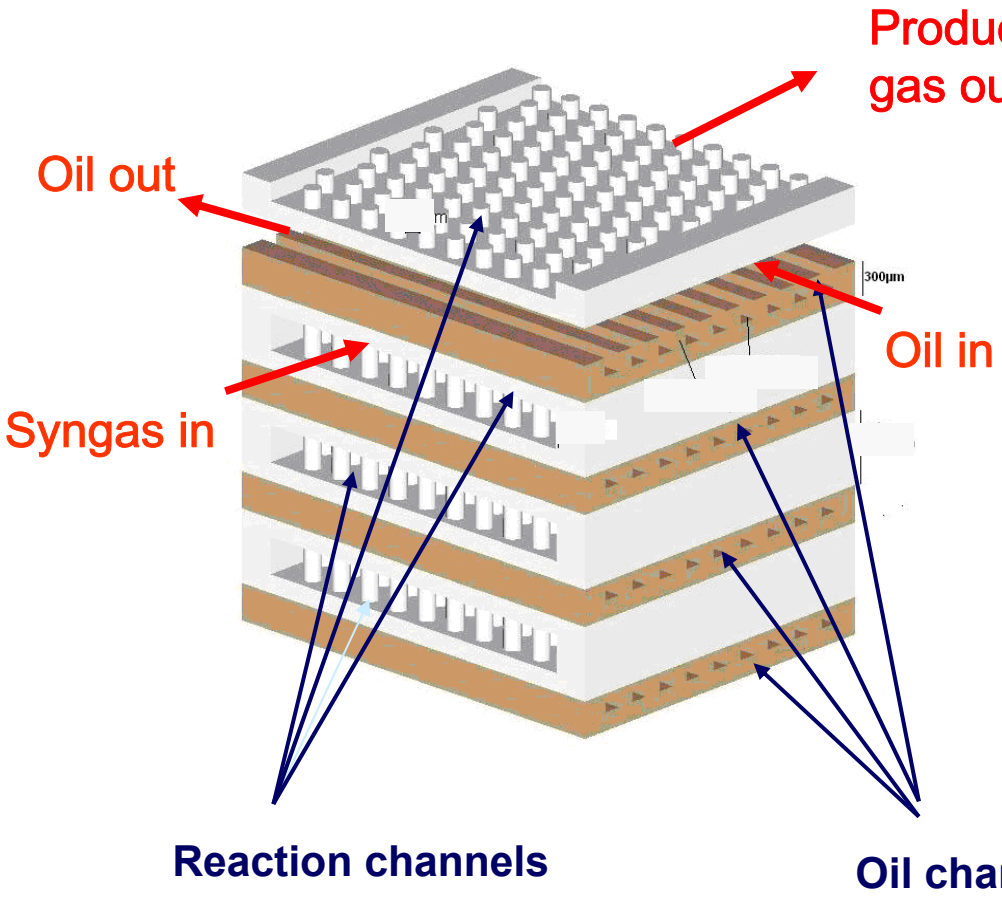
Natural gas to market



Overall reaction:

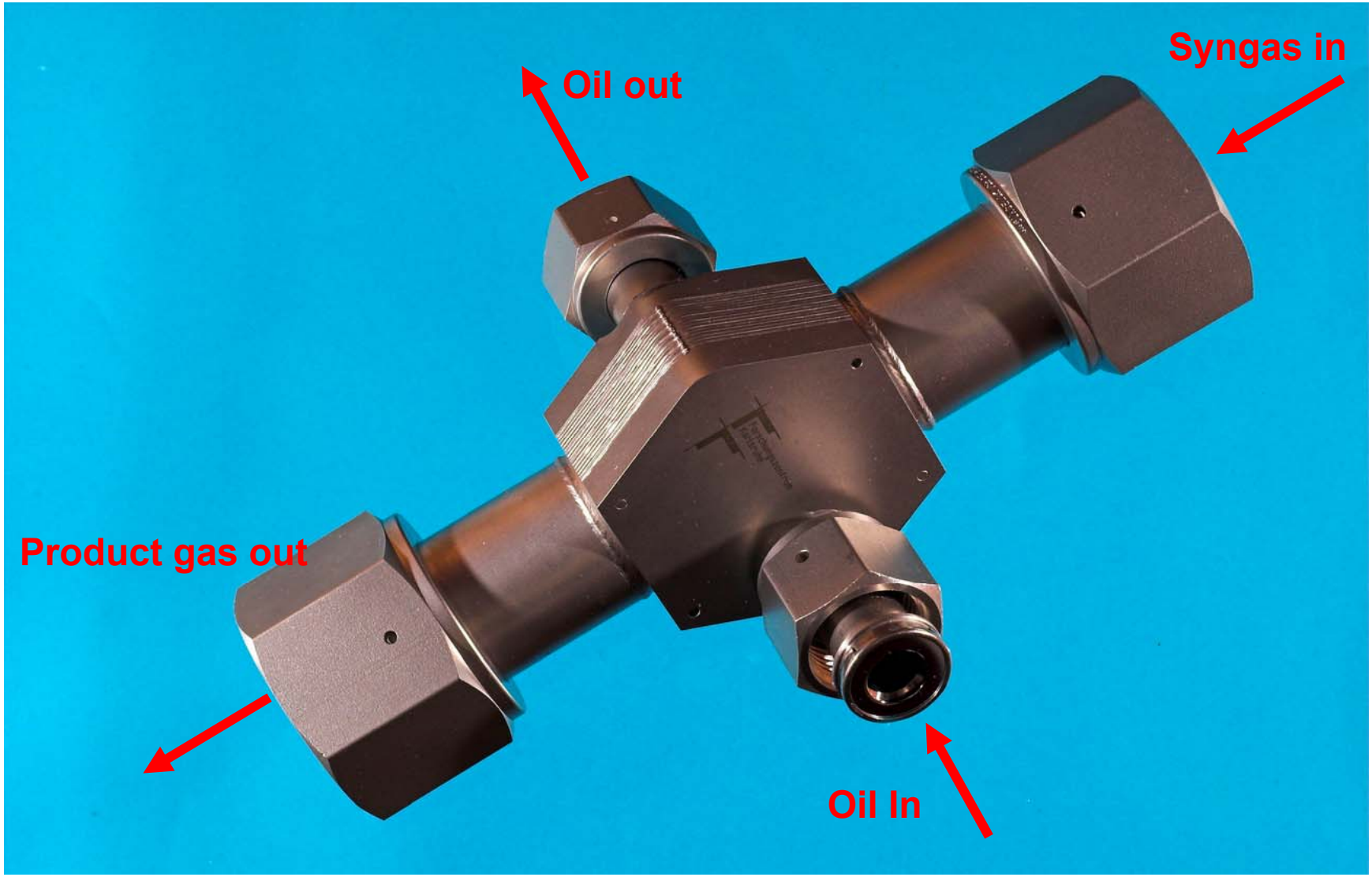
$$CO + 2H_2 \leftrightarrow CH_3OH + heat$$

Methanol synthesis in a Integrated Micro Packed Bed Reactor-Heat Exchanger (IMPBRHE)

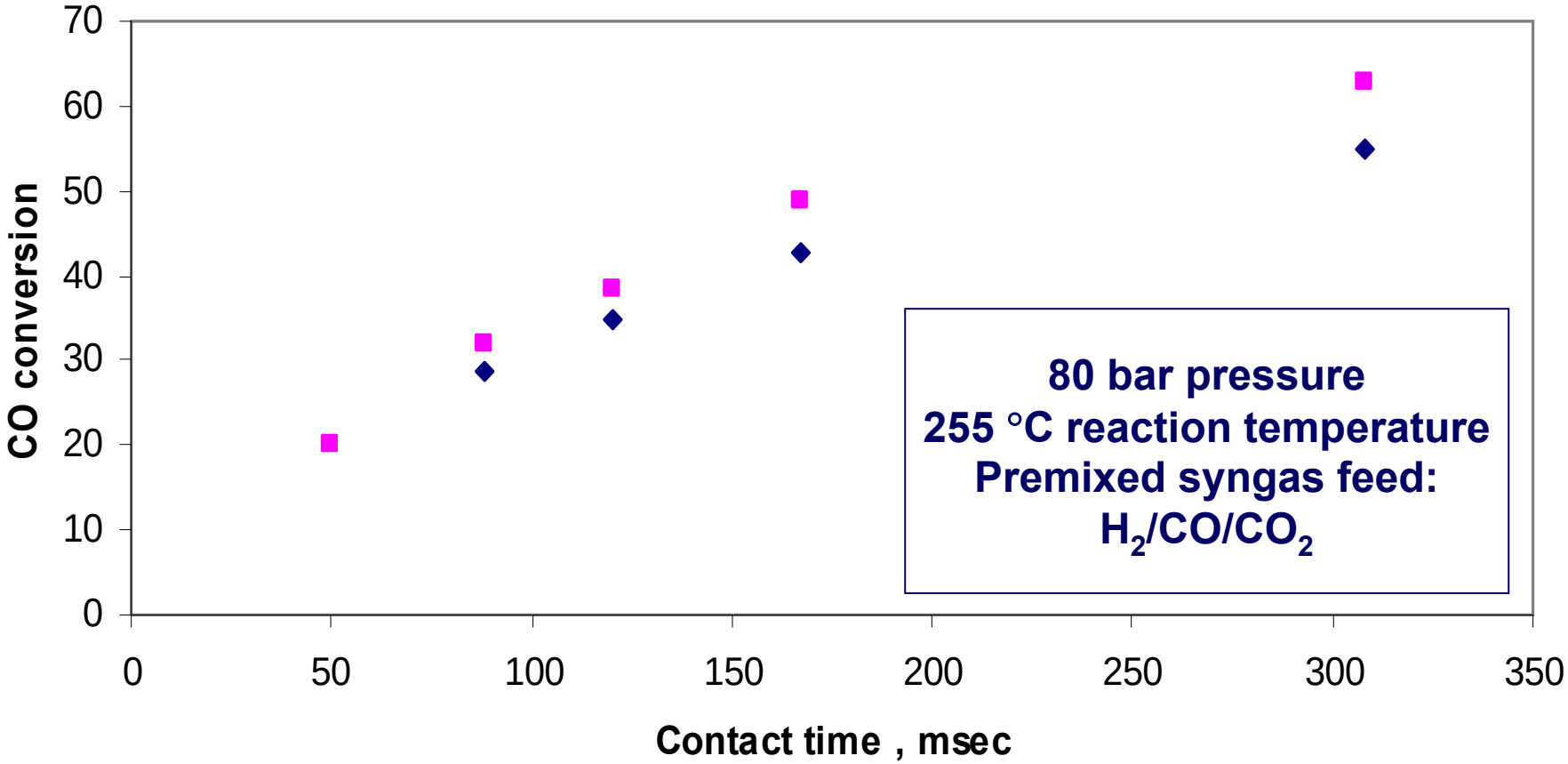


800 µm channels with pillars, packed with particles of Cu-based catalyst

Microchannel reactor made by Karlsruhe Institute of Technology, Germany



Conversion comparison between IMPBRHE (---MSR) and laboratory fixed bed reactor (--- FBR) - Equal conditions, commercial Cu based catalyst

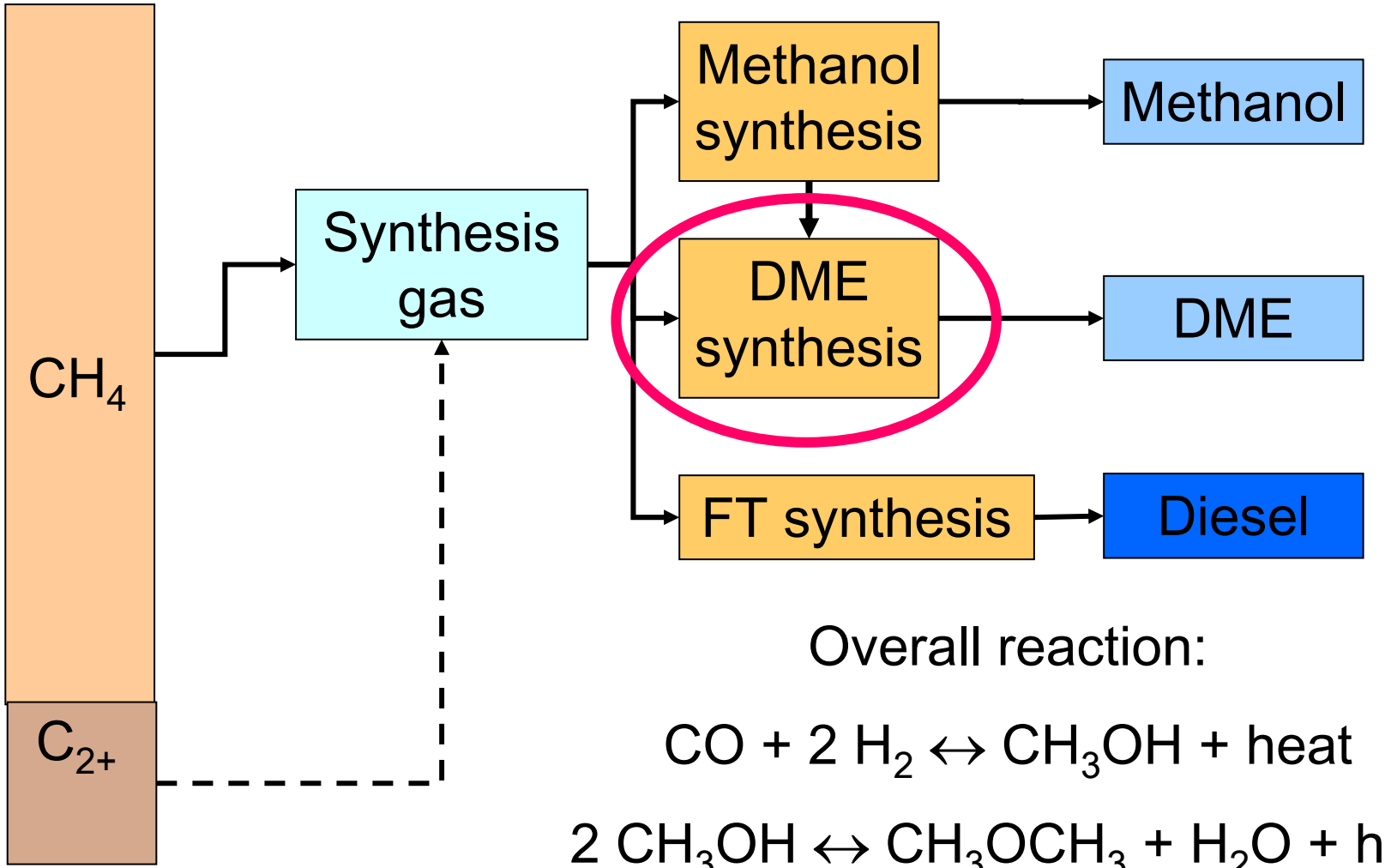


H. Bakhtiary D., F. Hayer, X. K. Phan, R. Myrstad, H. J. Venvik, P. Pfeifer, A. Holmen, in preparation

Compact synthesis of DME

Also with IMPBRHE

Natural gas to market

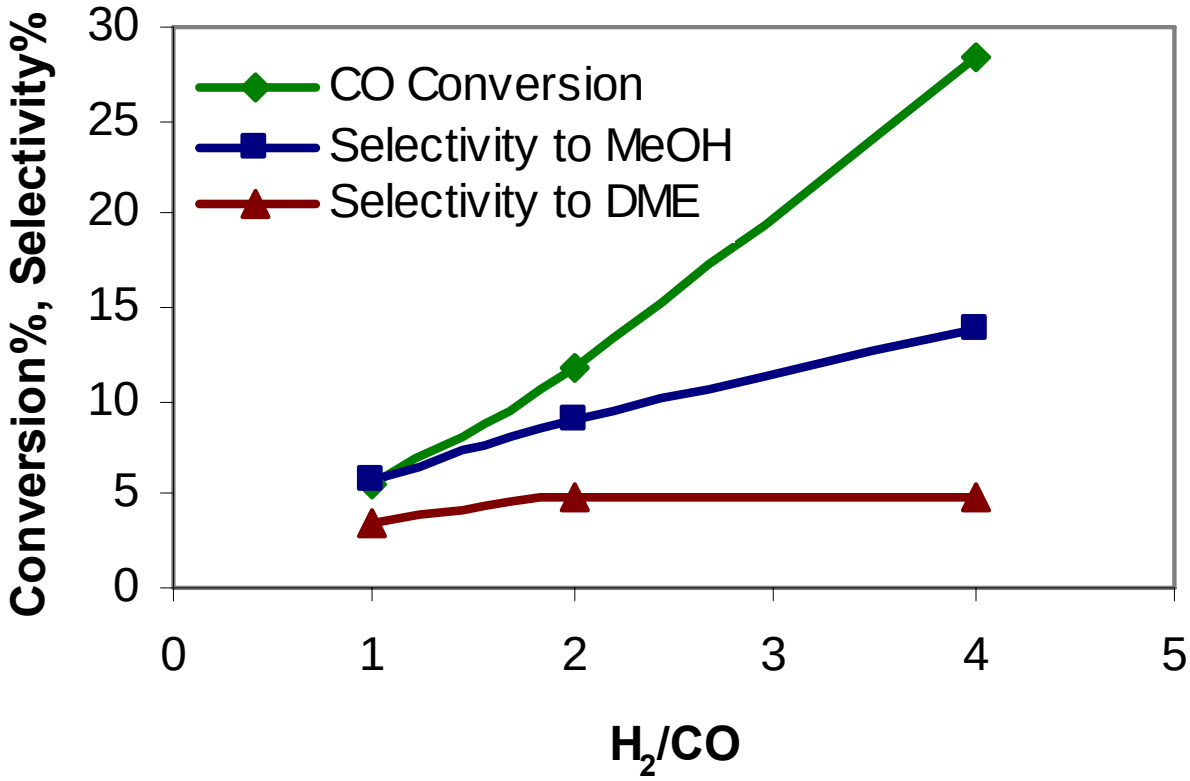


Overall reaction:

$$CO + 2\ H_2 \leftrightarrow CH_3OH + heat$$

$$2\ CH_3OH \leftrightarrow CH_3OCH_3 + H_2O + heat$$

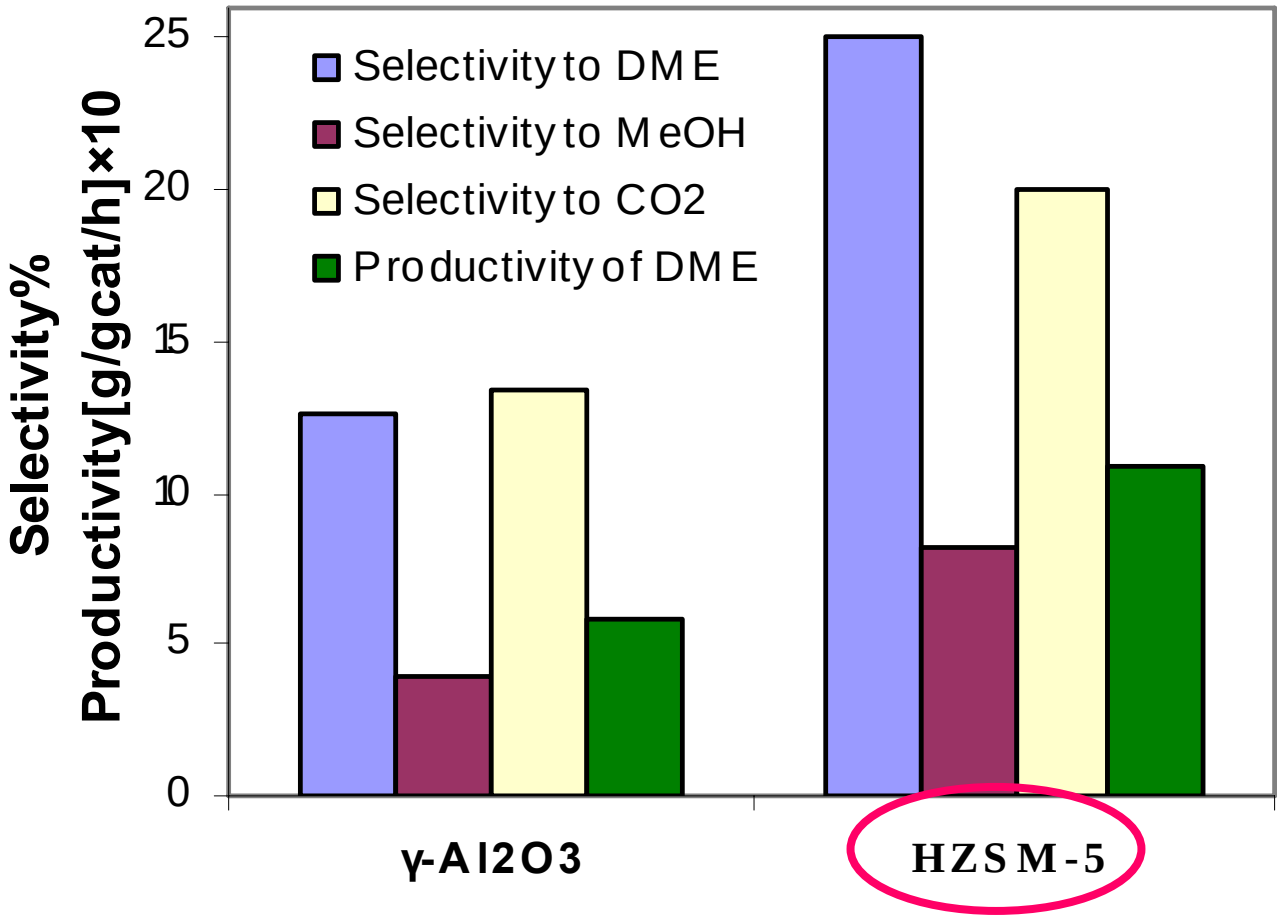
Direct synthesis of DME in IMPBHE



Reaction conditions:
Temp.: 250 °C
Pressure: 50 bar
GHSV:
9000 ml $gcat^{-1}$ h^{-1}
Premixed synthesis gas mixture
($H_2/CO/CO_2/CH_4/N_2$)

F. Hayer, H. Bakhtiary D. , R. Myrstad, P. Pfeifer, A. Holmen, H. J. Venvik, in preparation

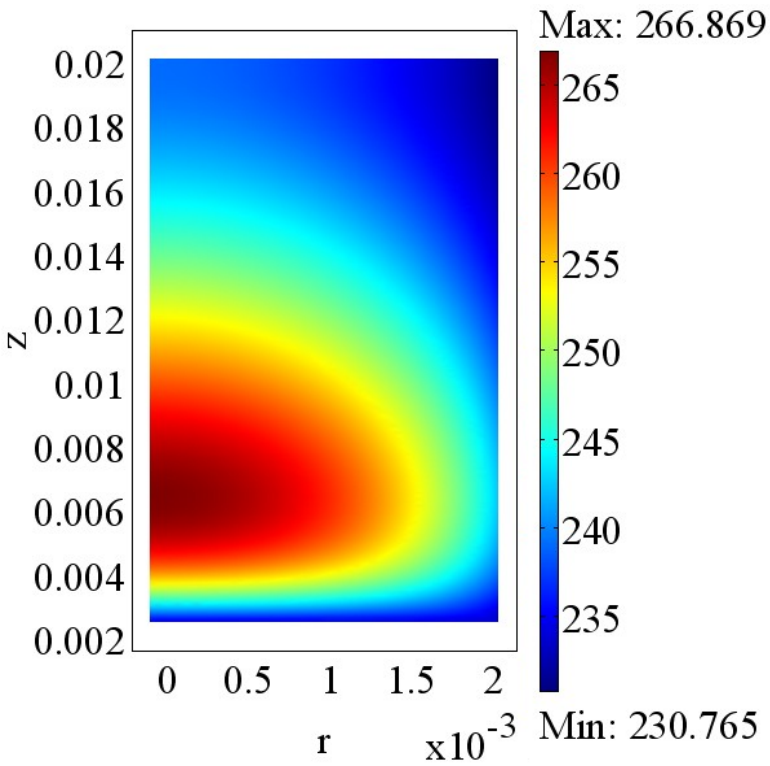
Effect of dehydration catalyst



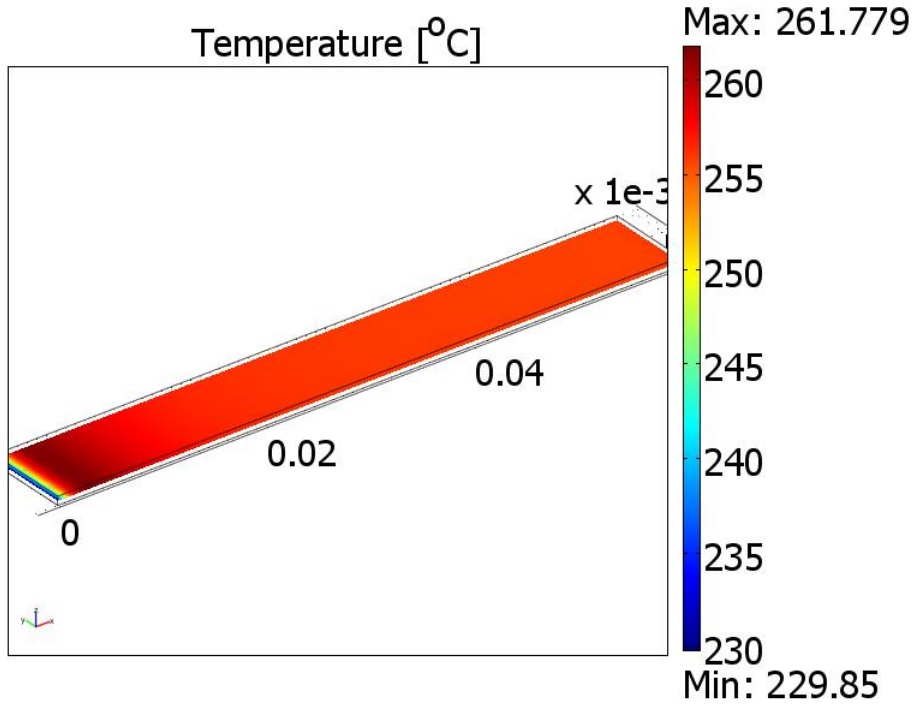
Reaction conditions:
Temp.: 250 °C
Pressure: 50 bar
GHSV:
9000 ml $gcat^{-1}$ h^{-1}
Premixed synthesis gas mixture
(H_2/CO/CO_2/CH_4/N_2)

F. Hayer, H. Bakhtiary D. , R. Myrstad, P. Pfeifer, A. Holmen, H. J. Venvik, in preparation II

Temperature profiles methanol and DME synthesis



Simulation of fixed bed temperature peak



Simulation of single channel of IMPBRHE - practically isothermal

Simulations supported by temperature measurements

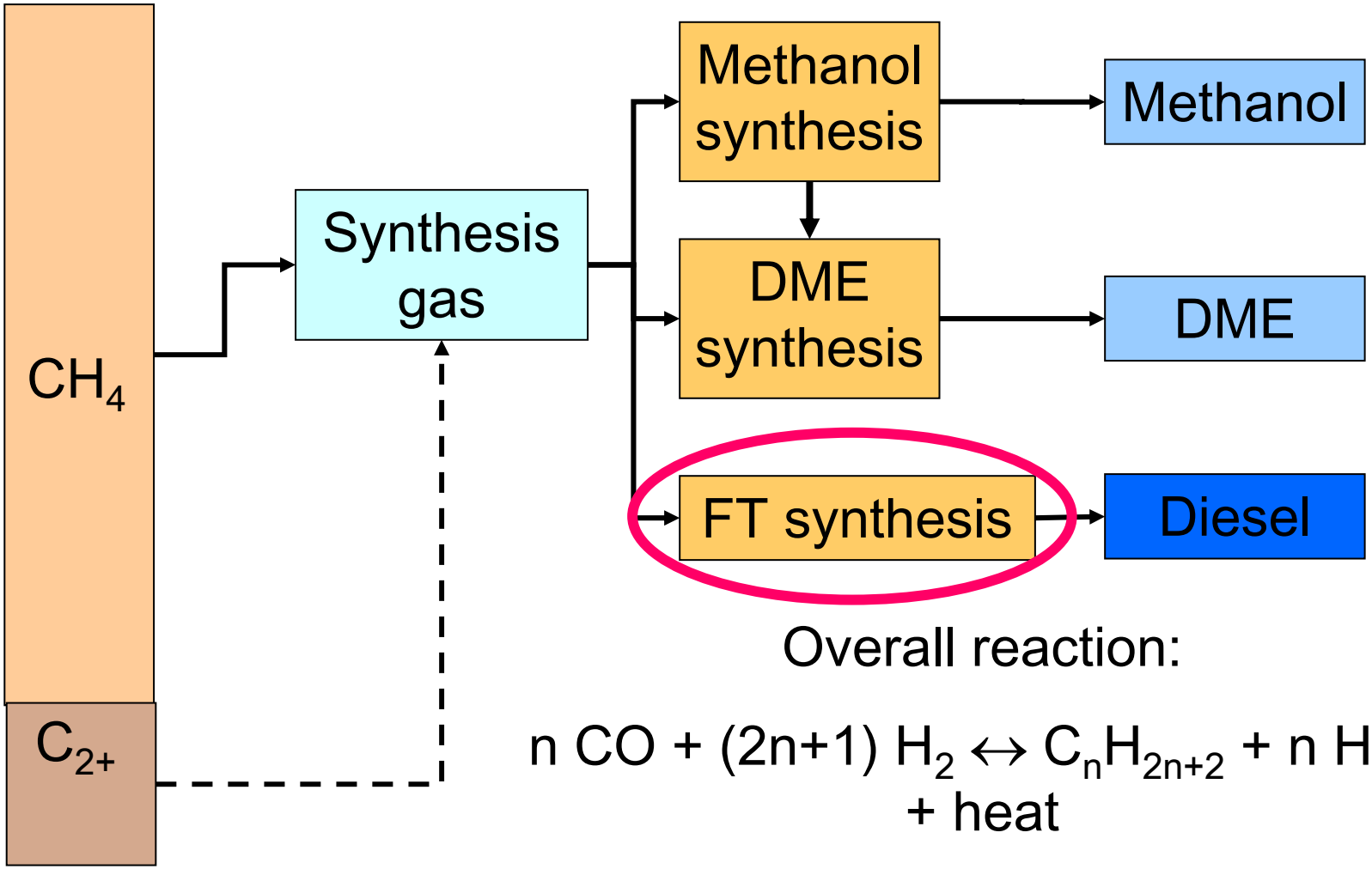
H. Bakhtiary D., F. Hayer, X. K. Phan, R. Myrstad, H. J. Venvik, P. Pfeifer, A. Holmen, in preparation

Summary: Methanol and DME synthesis in the IMPBRHE

- Promising in terms of
  - ✓Methanol/DME production
  - ✓Catalyst integration
  - ✓Operation at high pressure
  - ✓Compactness
  - ✓Thermal behaviour (isothermal)
  - ✓Negligible pressure drop and diffusion limitations

Fischer-Tropsch synthesis in a microstructured reactor

Natural gas to market



Overall reaction:

$$n\,CO + (2n+1)\,H_2 \leftrightarrow C_nH_{2n+2} + n\,H_2O + \text{heat}$$

...works as well!

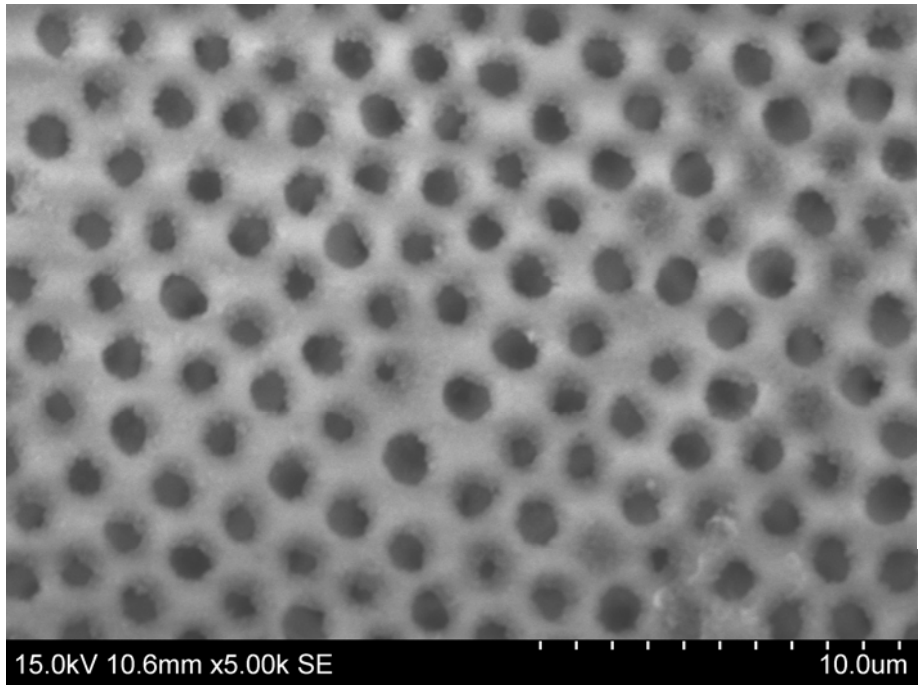
See presentation by
Rune Myrstad, SINTEF
at 10:00 Thursday (tomorrow)

and

R. Myrstad, S. Eri, P. Pfeifer, E. Rytter, A. Holmen
Catalysis Today 147 (2009) p. S301

Microstructured reactors need new/different catalyst innovations

- Structure
- Ratio of components
- Reaction conditions

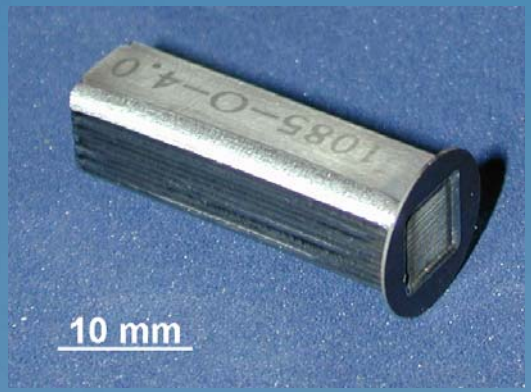


Synthesis of macroporous structured Al_2O_3 support from a polystyrene-Al_2O_3 core-shell composite

Xuyen K. Phan, J. Yang, H. Bakhtiary D., R.. Myrstad, H. Venvik, A. Holmen, in preparation

Conclusion

- Microstructured reactors show promising performance for GTL.
  - ✓Syngas production step included
  - ✓Methanol production for fuel or petrochemical application
  - ✓Dimethyl ether (DME) by direct synthesis, as a fuel or LPG alternative
  - ✓Synthetic diesel via the Fischer-Tropsch synthesis



YES WE CAN OFFSHORE GTL!

Thank you for your attention!

Questions?