ETN sCO_2 WG meeting
7th sCO_2 Symposium takeaways

17 March 2022

Agenda

- **Opening & meetings objectives** (WG's chair Marco Ruggiero, Baker Hughes)
- **Introduction** (Rafael Guedez, KTH – Royal Institute of Technology)

1. **Turbomachinery** (Giacomo Persico, Politecnico di Milano)
2. **Heat Exchangers** (Renaud Le Pierres, Heatric)
3. **System Integration & Cycle Modelling** (Francesco Crespi, University of Seville)

Meeting's objectives

- Identify **trends in public research** and current state-of-the-art of sCO_2 technology
- Use ongoing research as a benchmark to **prepare a concise document about the sCO_2 technology need**s that will be used to continue a discussion with the EC (roadmap, project calls, …)
- Brainstorm about **path to TRL 8-9**, building on current project results

sCO_2 Symposium

Introduction

- **Topics of the sessions**:
  - Power Plants & Applications, Turbomachinery
  - Components, Fundamentals, Materials
  - Modelling & Control, Testing
  - Oxy-Combustion
- **10 keynote speakers**: GE, GTI, 8 Rivers, Echogen, Siemens Energy, Heliogen, Bechtel, Hanwha Power Systems, Office of Nuclear Energy
- **5 panel sessions**:
  - Status of Technology Maturation
  - Steps to Commercialization
  - High-level DOE
  - University R&D
  - National Laboratories R&D
- **243 participants (approx. half in person, most USA)**

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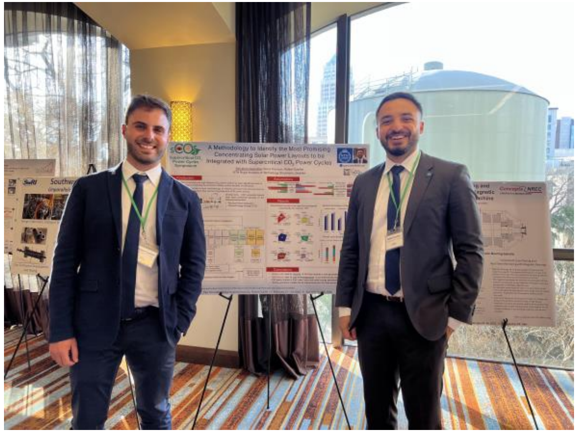


ETN Global

sCO_2 Symposium

Introduction

SwRI Facility Tour

- STEP 10 MWe Pilot Plant Facility
- SunShot 1 MWe Test Loop and Expander
- APOLLO Barrel Compressor and Integrally-Geared Compander
- Large Turbine Seal Test Rig
- sCO2 Component Test Loops

1. Turbomachinery

Turbomachinery (1/4)

Paper # 126 – Modeling the Variations in an sCO_2 Compressor's Map Characteristics Operating Near the Critical Point

Robert Pelton, *Hanwha Power Systems Americas*

Paper # 177 – Experimental and Numerical Performance Survey of a MW-Scale Supercritical CO_2 Compressor Operating in Near-Critical Conditions

Lorenzo Toni, *Baker Hughes*

Paper # 161 – Radial Compressor Design and Off-Design for Transcritical CO_2 Operating Conditions

Selcuk Can Uysal, *US Department of Energy, NETL*

Paper # 164 – Mechanical and Rotordynamic Test Results of a Supercritical CO_2 Compressor Operating Near the Critical Point

Jeff Moore, *Southwest Research Institute*

Paper # 15 – Lessons from Testing the sCO_2-Hero Turbo-Compressor-System

Sebastian Schuster, *University of Duisburg-Essen*

Turbomachinery (2/4)

- **Paper # 100 – Aeromechanical Design of a 10 MWe sCO_2 Turbine**

  Stefan Cich, *Southwest Research Institute*

- **Paper # 138 – CFD Evaluation of Shroud Gap Performance Effects on a Supercritical CO_2 Radial Inflow Turbine**

  David Stevens, *Peregrine Turbine Technologies, LLC*

- **Paper # 59 – An Improved Off-Design Prediction Model Based on Similarity Analysis for Turbomachinery under sCO_2 Condition**

  Yongju Jeong, *KAIST*

Paper # 122 – Next Generation Additive Manufacturing of Shrouded Turbine Wheel

Andrew Carter, *Stratasys Direct Manufacturing*

Paper # 32 – Experimental Testing of a 1 MW sCO_2 Turbocompressor

Logan Rapp, *Sandia National Laboratories*

Turbomachinery (3/4) - Topics

Ten papers focused on turbomachinery, ranging:

- from compressor to turbines
- from modelling to **testing**
- from design to **operation**
- from aerodynamics to **manufacturing**

Topics not systematically considered, but focused:

- compressors: focus on operation and testing
- turbines: focus on clearance flow, structural issues, manufacturing

Turbomachinery (4/4) – Main findings

Testing:

- BH & PoliMi presented tests on sCO2-Flex MW-scale compressor: first-ever demonstration of anticipated choking due to two-phase flows and assessment of the related CFD modelling

- UDE presented the testing of sCO2-Hero compressor operating in multiple near-critical conditions

- SWRI presented rotor-dynamic tests of Apollo MW-scale compressor, with detailed analysis of test issues and their solution, and considerations on (successful) start-up

Operation:

- KAIST and HANWHA presented methods for the corrections of turbomachinery maps for different operating conditions, considering both empirical and theoretical approaches. Crucial for compressors

Turbine design & manufacturing:

- SWRI presented the mechanical design of the STEP turbine, emphasis on blade modes & vibration

- Peregrine studied numerically the effects of tip clearance in a small-scale radial-inflow sCO2 turbine

- Stratasys presented an experimental study on the additive manufacturing of a radial-inflow sCO2 turbine, discussing surface finishing, defects, material composition, additional tests with samples

2. Heat Exchangers

Heat Exchangers* (1/6)

Heat Exchanger Session** (23rd Feb – 10:45 AM)

1) Paper # 3 – Measurement of Convective Heat Transfer Coefficients with Supercritical CO_2 in Novel Additively Manufactured Helically Patterned Pin Fin Tubes Using the Wilson Plot Technique

Matthew Searle, US Department of Energy, NETL

2) Paper # 175 – Design, Fabrication and Testing of Novel Compact Recuperators for the Supercritical Carbon Dioxide Brayton Power Cycle

Marc Portnoff, Thar Energy, LLC

3) Paper # 181 – Innovative Flue Gas-to-sCO_2 Primary Heat Exchanger Design for Cement Plant Waste Heat Recovery

Ladislav Vesely, University of Central Florida, CATER

*7th sCO_2 Symposium was dominated by US companies, R&D Labs, Universities, with some European content and very little Asian content

**Originally planned 7th sCO_2 symposium in 2020 had 2 Heat Exchangers Sessions

Heat Exchangers (2/6)

Various reference to Heat Exchangers (non-exhaustive) 1/2

- sCO2 Heat Exchangers Tutorial (SWRI, Thar Energy, Heatric)
- Presentations on silicon carbide, and silicone carbide fibre composite tubes for elevated temperature applications (WHR) from Ceramic Tubular Products LLC
- One Scarabeus project slide showing Kelvion’s K-Bond recuperator considering S-Fin profiles
- Siemens Energies stating TransCanada project cancelled due to overall project cost increase >30% from FEED to FID with WHRU as one of the main issue to address cost and technology wise
- Some slides from GE GRC about their work on ALM for elevated temperatures and pressures

Heat Exchangers (3/6)

Various reference to Heat Exchangers (non-exhaustive) 2/2

- Some slides from Oakridge showing their work on ALM tubes with external heat transfer enhancement features

- One reference from ARPA-E about the HITEMMP high temperature and pressure exchangers conceptual works by the likes of Oregon State Uni, Altex Tech Corp, Brayton Energy, Thar energy

- Some references of work for Fossil Energy DoE (now called Fossil Energy and Carbon Management) with little details – only name of project and associated company

- An interesting table created by GE about GAP for sCO2 components.

Heat Exchangers (4/6)

GE GRC sCO2 Applications GAP Analysis

Technology	TRL	GAPS (3-5 yrs)
Oxy-Fuel	Expander Heat Source Compressor Heat Exchangers	- Scale up - Expander inlet temperature - Limited retrofit opportunity
Waste Heat Recovery	Expander Heat Source Compressor Heat Exchangers	- Efficiency Challenge vs Recip Engines - Variety of Markets limits standardization
Concentrated Solar Power	Expander Heat Source Compressor Heat Exchangers	- Turbine content low fraction of CAPEX - Overall CSP system needs to meet LCoE targets
Nuclear	Expander Heat Source Compressor Heat Exchangers	- Paced by advanced reactor timeline

Heat Exchangers (5/6)

Of interests with regards to GAP Analysis (Heat Exchangers) 1/2

- Current technologies in development for sCO2s Heat Exchangers reported during sCO2 Symposium :
  - Additive Layered Manufacturing (Compact type mostly)
  - Tubes (Ceramic, Carbon Fibres, ALM)
  - Printed Circuit Heat Exchangers type
  - Hybrids (Fins + microchannels)

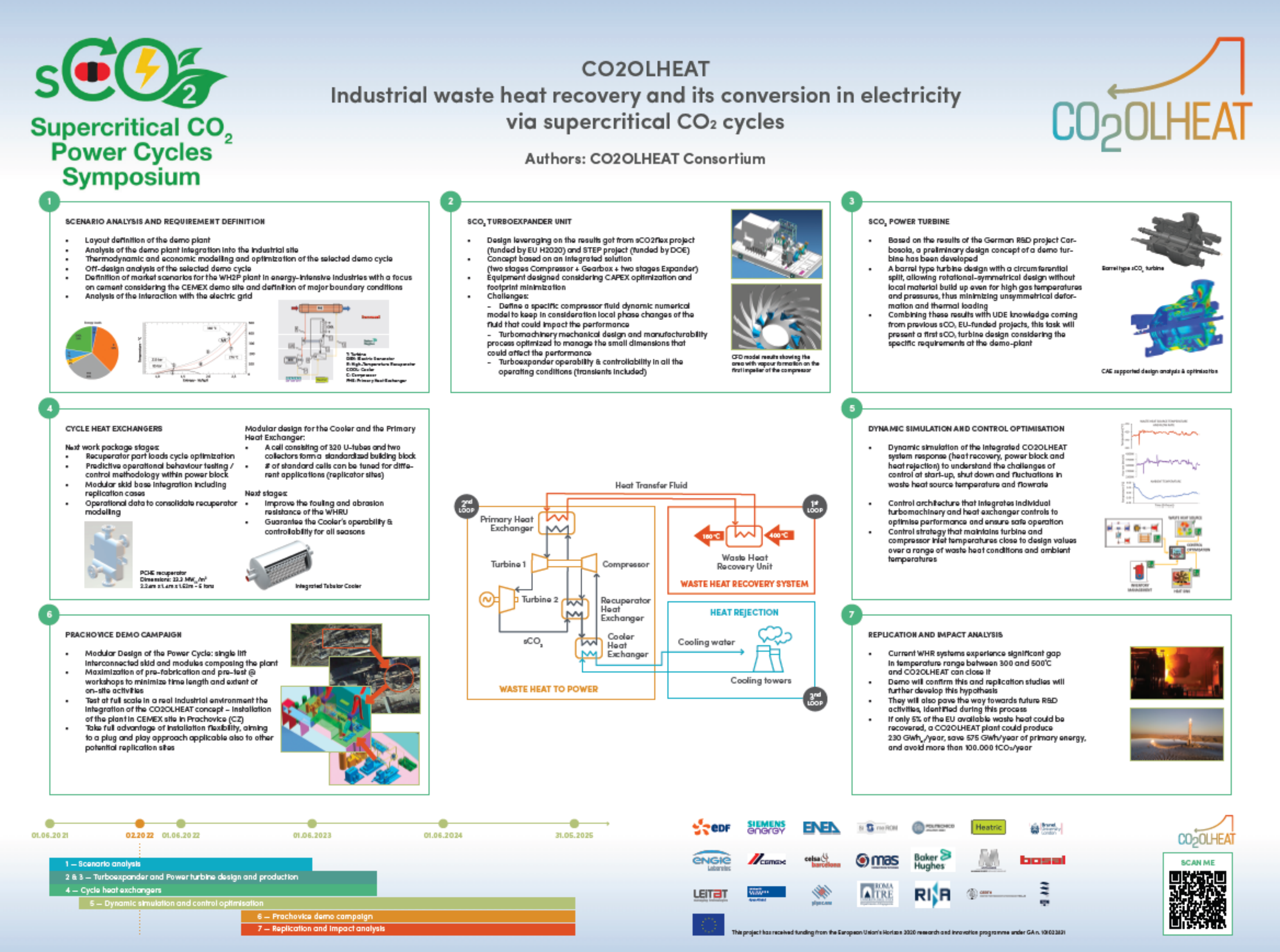
- Reduction in R&D development of Heat Exchangers in the US (HITEMMP nearing completion) as new funding focusing on other developments with no presentations (poster excepted if any) from previous companies such as:
  - Altex Technologies
  - Comprex LLC
  - HEXCES
  - Brayton Energy

Heat Exchangers (6/6)

Of interests with regards to GAP Analysis (Heat Exchangers) 2/2

- Many new technologies are still at early stages of development needing:
  - Further material characterisation (ALM, Ceramic tubes, carbon)
  - Manufacturing Up-scaling (ALM)
  - Joining technologies (Ceramic tubes, carbon fibres)
  - Industrialisation and standardisation
  - **And most important code qualified (ALM, Ceramic, Carbon Fibres)**

- Recognition of the supply chain issue having massive impact on prices referred in several papers / presentations due to the bespoke nature still of most projects (i.e. Siemens TransCanada, GTI STEP)

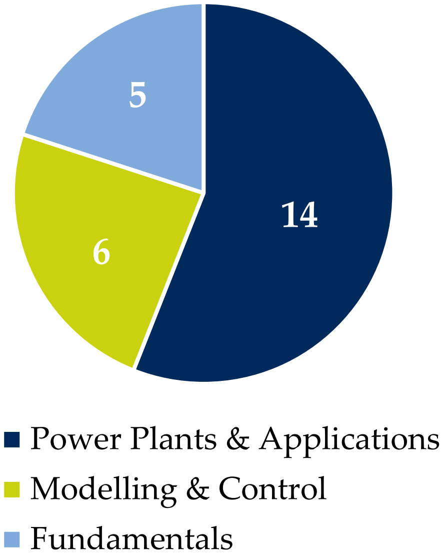

sCO2 Supercritical CO2 Power Cycles Symposium
CO2OLHEAT
Industrial waste heat recovery and its conversion in electricity via supercritical CO₂ cycles
Authors: CO2OLHEAT Consortium
CO2OLHEAT
1
SCENARIO ANALYSIS AND REQUIREMENT DEFINITION
• Layout definition of the demo plant
• Analysis of the demo plant integration into the industrial site
• Thermodynamic and economic modelling and optimization of the selected demo cycle
• Off-design analysis of the selected demo cycle
• Definition of market scenarios for the WH2P plant in energy-intensive industries with a focus on cement considering the CEMEX demo site and definition of major boundary conditions
• Analysis of the interaction with the electric grid
2
SCO2 TURBOEXPANDER UNIT
• Design leveraging on the results got from sCO2flex project (funded by EU H2020) and STEP project (funded by DOE)
• Concept based on an integrated solution (two stages Compressor + Gearbox + two stages Expander)
• Equipment designed considering CAPEX optimization and footprint minimization
• Challenges:
– Define a specific compressor fluid dynamic numerical model to keep in consideration local phase changes of the fluid that could impact the performance
– Turbomachinery mechanical design and manufacturability process optimized to manage the small dimensions that could affect the performance
– Turboexpander operability & controllability in all the operating conditions (transients included)
CFD model results showing the area with vapour formation on the first impeller of the compressor
3
SCO2 POWER TURBINE
• Based on the results of the German R&D project Carbosola, a preliminary design concept of a demo turbine has been developed
• A barrel type turbine design with a circumferential split, allowing rotational-symmetrical design without local material build up even for high gas temperatures and pressures, thus minimizing unsymmetrical deformation and thermal loading
• Combining these results with UDE knowledge coming from previous sCO2 EU-funded projects, this task will present a first sCO2 turbine design considering the specific requirements at the demo-plant
Barrel type sCO2 turbine
CAE supported design analysis & optimisation
4
CYCLE HEAT EXCHANGERS
Next work package stages:
• Recuperator part loads cycle optimization
• Predictive operational behaviour testing / control methodology within power block
• Modular skid base integration including replication cases
• Operational data to consolidate recuperator modelling
PCHE recuperator
Modular design for the Cooler and the Primary Heat Exchanger:
• A cell consisting of 320 U-tubes and two collectors form a standardized building block
• # of standard cells can be tuned for different applications (replicator sites)
Next stages:
• Improve the fouling and abrasion resistance of the WHRU
• Guarantee the Cooler's operability & controllability for all seasons
Integrated Tubular Cooler
Heat Transfer Fluid
2nd LOOP
1st LOOP
3rd LOOP
Primary Heat Exchanger
Turbine 1
Compressor
Turbine 2
Recuperator Heat Exchanger
sCO2
Cooler Heat Exchanger
WASTE HEAT TO POWER
180 °C
400 °C
Waste Heat Recovery Unit
WASTE HEAT RECOVERY SYSTEM
HEAT REJECTION
Cooling water
Cooling towers
5
DYNAMIC SIMULATION AND CONTROL OPTIMISATION
• Dynamic simulation of the integrated CO2OLHEAT system response (heat recovery, power block and heat rejection) to understand the challenges of control at start-up, shut down and fluctuations in waste heat source temperature and flowrate
• Control architecture that integrates individual turbomachinery and heat exchanger controls to optimise performance and ensure safe operation
• Control strategy that maintains turbine and compressor inlet temperatures close to design values over a range of waste heat conditions and ambient temperatures
6
PRACHOVICE DEMO CAMPAIGN
• Modular Design of the Power Cycle: single lift interconnected skid and modules composing the plant
• Maximization of pre-fabrication and pre-test @ workshops to minimize time length and extent of on-site activities
• Test at full scale in a real industrial environment the integration of the CO2OLHEAT concept – installation of the plant in CEMEX site in Prachovice (CZ)
• Take full advantage of installation flexibility, aiming to a plug and play approach applicable also to other potential replication sites
7
REPLICATION AND IMPACT ANALYSIS
• Current WHR systems experience significant gap in temperature range between 300 and 500°C and CO2OLHEAT can close it
• Demo will confirm this and replication studies will further develop this hypothesis
• They will also pave the way towards future R&D activities, identified during this process
• If only 5% of the EU available waste heat could be recovered, a CO2OLHEAT plant could produce 230 GWh/year, save 575 GWh/year of primary energy, and avoid more than 100.000 tCO₂/year
01.06.2021
02.2022
01.06.2022
01.06.2023
01.06.2024
31.05.2025
1 – Scenario analysis
2 & 3 – Turboexpander and Power turbine design and production
4 – Cycle heat exchangers
5 – Dynamic simulation and control optimisation
6 – Prachovice demo campaign
7 – Replication and impact analysis
edf
SIEMENS energy
ENEA
Heatric
engie
cemex
mas
Baker Hughes
bosal
LEITAT
RINA
This project has received funding from the European Union's Horizon 2020 research and innovation programme under GA n. 101022831
CO2OLHEAT
SCAN ME

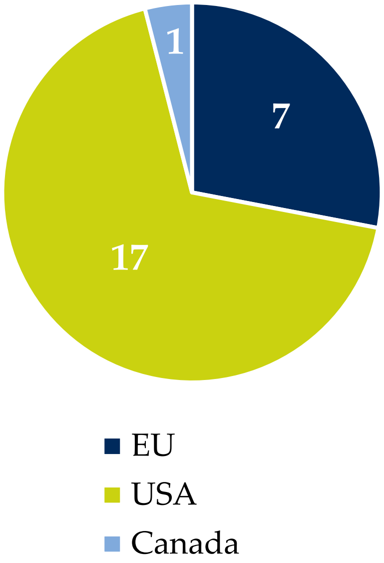
ETN Global

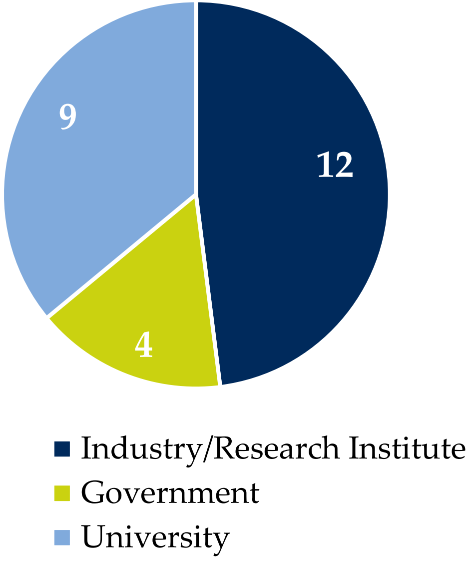
3. System Integration & Cycle Modelling

System Integration & Cycle modelling (1/7)

General Overview: 25 papers







System Integration & Cycle modelling (2/7)

Power Plants & Applications (4 sessions)

Session 1

#191: Potential and Challenges of the Utilization of CO_2-Mixtures in Supercritical Power Cycles of Concentrated Solar Power Plants

#205: First Year of the EU SolarSCO2OL Demonstration Project – Enabling Hybrid Supercritical CO_2 CSP Plants Integrated with PV

System Integration & Cycle modelling (3/7)

Power Plants & Applications (4 sessions)

Session 2

#88: Low-Cost, Low-Grade Waste Heat Recovery Using sCO_2 Natural Convection

- → Very simple layout, Extremely low efficiency (30ºC ΔT hot and cold sources)
- → Possible use: Geothermal applications, very site specific

#90: A Conceptual Evaluation of a kW-Scale sCO_2 Power Cycle for Waste Heat Recovery on a Heavy-Duty Diesel Engine Truck

- → Alternative to ORC units
- → Very preliminary investigation

System Integration & Cycle modelling (4/7)

Power Plants & Applications (4 sessions)

Session 3

#112: A Performance and Economic Comparison of Partial Cooling and Recompression Cycles for Coal-Fueled Power Generation

NATIONAL ENERGY TECHNOLOGY LABORATORY

→ Best layout: Partial Cooling
→ High PR, low $\dot{m}$ → significantly lower LCoE

#113: Cooling System Cost and Performance Models to Minimize Cost of Electricity of a Direct sCO_2 Power Plants

NATIONAL ENERGY TECHNOLOGY LABORATORY

→ Reduction in cooler outlet T (down to 20ºC, transcritical embodiment)
→ Significant rise in thermal efficiency, further investigations needed on TM

System Integration & Cycle modelling (5/7)

Power Plants & Applications (4 sessions)

Session 4

#9: Carbon Dioxide Capture and Sequestration by Integrating Pressure Swing Adsorption with an Open Cycle Supercritical CO_2 Brayton Power Generation System

→ Similar niche-market to Allam
→ Novel cycle configuration
→ Very preliminary investigation

#120: sCO_2 Primary Power Large-Scale Pilot Plant FEED Summary

→ Host Plant: University of Missouri Cogeneration Plant (MU CCHP)
→ Fired heat exchanger efficiency: 84.3% (economizer added)
→ Expected plant efficiency: 30.2% (> Steam Rankine)

System Integration & Cycle modelling (6/7)

Modelling & Control (2 sessions)

#98: Dynamic Modeling for the 10 MWe sCO_2 Test Facility Program

→ Developed with Flownex, will be validated with STEP Demo facility data

#104: Inventory Management Operational Strategies for a 10 MW sCO_2 Power Block

→ Developed for STEP Demo programme

SOUTHWEST RESEARCH INSTITUTE

#121: Integrated Transient Modeling of Gas Turbine and sCO_2 Power Cycle for Exhaust Heat Recovery Application

→ Developed with GT-Suite (simple load step signal)

System Integration & Cycle modelling (7/7)

Fundamentals (2 sessions)

#14: New Reference Equation of State for Carbon Dioxide

- → Replacing Span-Wagner with novel EoS (better extrapolation at high T)
- → Significant reduction in computational time
- → Future works in 2022 will include transport properties

#167: Impact of Selective Admixture of Additives to Carbon Dioxide on the Size of sCO_2 Power Cycle Key Components

→ Increasing interest in CO_2-based mixtures

TECHNISCHE UNIVERSITÄT DRESDEN

Next WG meeting:
30 March 2022 @ 17h00,
Hotel Le Plaza, Brussels

Thank you for your attention