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Conceptual Design, Optimisation and Qualification of Highly Efficient Brazed Plates and Fins Heat Exchangers for Heat Removal sCO2 Brayton Cycle to Increase the Safety of Nuclear Power Plants

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The sCO2-4-NPP european project aims to develop an innovative technology based on supercritical CO2 (sCO2) for heat removal to improve the safety of current and future nuclear power plants.
The heat removal from the reactor core will be achieved with multiple highly compact self-propellant, self-launching, and self sustaining cooling system modules, powered by a sCO2 Brayton cycle.
Heat exchangers are one of the key components required for advanced Brayton cycles using supercritical CO2. To this end, two compact and highly efficient brazed plates and fins heat exchangers are designed :
- a main heat recovery heat exchanger (CHX), which allows the heat transfer directly from the steam generator to the sCO2-4-NPP cycle,
- a heat sink exchanger (DUHS), which evacuate the remaining heat to the atmosphere.

An important work has been achieved in the frame of this project to conceive the preliminary design of these components, in close collaboration between Fives Cryo, a French brazed plates and fins heat exchangers manufacturer, the Institut für Kernenergetik und Energiesysteme (IKE) of University of Stuttgart and KSG/GFS Institute, a simulator center, both in Germany.
In fact, several constraints needed to be taken into account, mainly for CHX, the small size of available space in the reactor building to install the heat exchanger and the very high pinch between steam and sCO2 which is responsible for thermal and mechanical stress inside the matrix. For DUHS, the low fans power available for the cycle and the necessary air flow for efficient heat exchange implies considering almost inexisting pressure drops on the air side.
To this end, several fins geometries and new design ideas has been adressed to meet the desired thermal duty.
Also, this project benefits from the recent results achieved among the european project sCO2-flex, related to the mechanical resistance of heat exchanger components, the assembly process and their thermal and hydraulic performances, along with Fives Cryo expertise and background.
Both design configurations for CHX and DUHS are submitted to off-design cases to simulate their operation under different weather configurations and during start-ups, leading to cover a wide performance map.
A second challenge of the sCO2-4-NPP project is to qualify the designed plates and fins heat exchangers mechanical resistance, at cycle operating conditions, in order to meet with pressure vessels codes and regulations according to nuclear requirements.

Modeling and Study of a Printed Circuit Heat Exchanger for Brayton Power Cycles Using Supercritical CO2 Mixtures as Working Fluid

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Brayton power cycle using supercritical carbon dioxide (s-CO2) as a working fluid is a high-efficiency trend technology that has been under study for improvement. As most of the heat transfer in these cycles occurs in the regenerator, printed circuit heat exchangers (PCHE) have proved to be a useful device solution for this application because of their high surface-area-to-volume ratio. Moreover, recent studies have corroborated the improvement in the efficiency of a supercritical Brayton cycle by mixing components that raise the critical point of s-CO2. This study focuses on the CFD modeling and analysis of a PCHE for fully turbulent conditions. The device's performance with straight channels regarding essential parameters such as heat recuperator conductance (UA), temperature, pressure drop, or turbulence is studied, as well as different configurations. A comparison between pure supercritical carbon dioxide and s-CO2 mixtures (s-CO2 /COS, s-CO2 /H2S, s-CO2 /NH3, and s-CO2 /SO2) is carried out.

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Evaluation of deterioration in vertical sCO2 cooling heat transfer in 3 mm tube

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In the frame of EU-project sCO2-flex the design of a 25 MWe supercritical CO2 (sCO2) Brayton cycle will be designed. The system will be optimized to meet flexibility requirements, while reducing environmental impact and focusing on cost efficiency. In the context of a sCO2 Brayton cycle, the gas cooler is a key component to achieve a high overall efficiency. Close to the critical point, due to varying properties, heat transfer and pressure drop of carbon dioxide (CO2) are difficult to predict. In case of vertical flow, acceleration and buoyancy effects induced by strong density gradients can cause a significant deterioration of the heat transfer.

In this publication, the cooling heat transfer coefficient (htc) is investigated in a 3 mm diameter tube with vertical flow orientation. Commonly used calculation methods of the heat transfer coefficient are presented. Although developed for heating of sCO2, the mixed convection criterion of Jackson and Hall [1] is used to evaluate the heat transfer deterioration. The effects of the CO2 mass flux of and bulk fluid temperatures of with a constant pressure of on the heat transfer were examined. The transition between forced and mixed convection can be explained by the -values. The upwards flow shows a steady decrease in the with the reduction of the mass flux. However, the downwards flow shows significant effects of buoyancy. At low mass flux the distinct peak in the at the pseudocritical temperature (Tpc) disappears.

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Characterizing and modelling turbulence in supercritical fluids

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From concentrated solar power plants to rocket engines, energy conversion systems are continually reengineered to perform ever better. Often this involves fluids being pushed into the supercritical region, where highly non-ideal thermodynamic effects are at play. Yet, our fundamental understanding of flow physics at such conditions lags behind to successfully realize these exciting engineering applications. Especially, the sharp variations in all thermophysical properties close to the critical point and the high optical density at supercritical pressures lead to significantly richer flow physics and even more intricate phenomena in turbulence. In this talk we will present our recent fundamental on turbulence in supercritical fluids, which are relevant in all component of a supercritical power cycle. We will elucidate how and when flows with supercritical fluids transition to turbulence and how compressible effects can be characterized and modelled for turbulent heat transfer.

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Numerical dimensioning of a pre-cooler for sCO2 power cycles to utilize industrial waste heat

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The annual waste heat available from industry in the European Union is more than 2,700 PJ. Consequently, the utilization of the unexploited thermal energy will decisively contribute to a reduced overall power consumption and lower greenhouse gas emissions. Supercritical carbon dioxide (sCO2) power cycles offer a variety of advantages for that purpose compared to established power cycles. Such are a high conversion efficiency and a turbomachinery with high power density. The pre-cooler is one of the essential components in a sCO2 power cycle and the prediction of the flow and heat transfer characteristics is a challenging task. In the present investigation, cycle layouts were developed for two waste heat sources: a cement plant and a gas compressor station. The pre-cooler design as well as the boundary conditions of the numerical simulation were assessed by an analytical model. The most promising design was the printed circuit heat exchanger with inlet temperatures of 209 °C and 352 °C for the cement kiln and the gas turbine respectively. Subsequently, these heat exchangers were examined in more detail by the numerical code ANSYS CFX for sCO2 mass fluxes between 100 kg/(m²s) and 900 kg/(m²s). The pressure drop along the sCO2 channel was found insensitive to the channel diameter, but increased with the channel length and mass flux. However, the pressure drop of the coolant stream significantly depends on the channel diameter and thus a larger coolant channel diameter is recommended to maintain a reasonably low pressure drop. The overall heat transfer coefficient is limited by the heat transfer on the coolant side. Ultimately, pre-cooler designs were proposed for both waste heat systems, consisting of compact modular stainless steel plates with an sCO2 channel diameter of 0.5 mm, a coolant channel diameter of 0.8 mm, an sCO2 mass flux of 700 kg/(m²s) and a coolant mass flux of 1029 kg/(m²s). Based on these results more complex channels having internal fins were studied. The connection angle and the fin height was optimized, in order to improve the heat transfer performance.

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Exergoeconomic Analysis of Hybrid sCO2 Brayton Power Cycle

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An exergoeconomic analysis of a hybrid power generation cycle is performed on its standalone constituents. The hybrid is based on Allam cycle configuration. Allam cycle is a supercritical carbon dioxide oxy-combustion (OC) Brayton cycle. The proposed hybrid utilizes solar power as its primary heat source and natural gas OC as a complementing heat source. The purpose of the complimenting heat source is to make up for the lost time when the sun is not available due to bad weather conditions or at nighttime. This is done to ensure the reliability, responsiveness, and availability of the cycle for power generation at all times. The hybrid is an attempt to provide power with minimal adverse effects on the environment. This study is divided into three major steps. The first and second are energy and exergy analysis. The third step is exergoeconomic analysis to obtain the cost contribution of each component relative to the cycle’s final product. Although both configurations brought similar power output and second law efficiency, the energy efficiency was higher for the OC configuration. The total product cost ($/GJ) for the OC configuration was half of that for the concentrated solar power (CSP). The unit cost of electricity in (Cent/kWh) for the CSP standalone configuration is approximately 60% higher than that of the OC configuration. In the CSP configuration, the main heat exchanger and the recuperator are the most critical units to consider for savings. Therefore, reducing the exergy destruction in the CSP main heat exchanger and the recuperator units could be cost-effective for the entire cycle, even if this would increase the component investment costs. Therefore, for exergoeconomic performance enhancement, using a recuperator with higher efficiency is recommended. On the other hand, the combustor and air separation unit (ASU) is the most critical unit to consider for savings for the OC configuration. Therefore, a replacement for the ASU unit with a lower purchasing cost is recommended for overall exergoeconomic performance enhancement. The parametric study results showed that increasing the turbine’s inlet temperature is conducive to improving both configurations' thermodynamic and exergoeconomic performances. Similar trends were also obtained for the turbine inlet pressure for both configurations.

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Simulation and Analysis of a Self-Propelling Heat Removal System using Supercritical CO2 at Different Ambient Temperatures

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Innovative heat removal systems are currently investigated for use in existing and future nuclear power plants. One of them is the supercritical carbon dioxide (sCO2[1]) heat removal system, which is based on a closed Brayton cycle with sCO2 as a working fluid.

This paper provides the design and layout of the sCO2 cycle based on assumptions developed in the project sCO2-4-NPP. The system is analysed over a wide range of ambient and steam-side conditions in ATHLET, using performance maps for the turbomachinery, which were designed recently. Bypasses are considered in the layout of the cycle to cope with special operation conditions, e.g. start-up. Different operational readiness states for the system are shown, which enable a fast start-up of the system. Air mass flow rate control is implemented to keep the compressor inlet temperature constant with controller parameters depending on the ambient temperature.

The performance analysis of the system suggests that it is a good option to operate the system at the design compressor inlet temperature of 55 °C at any ambient or steam-side boundary condition. With decreasing thermal power input, the rotational speed of the turbomachinery must be decreased to keep the system self-propelling. Turbomachinery design with a higher surge margin is preferred and different operation strategies are feasible and need to be tested in interaction with the nuclear power plant.

[1] sCO2 is defined as carbon dioxide at supercritical conditions with $p > 73.8$ bar and $T > 31$ °C

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Mean-Line Analysis for Supercritical CO2 Centrifugal Compressor by using Enthalpy Loss Coefficients

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In order to develop the technology of carbon dioxide at so-called supercritical state (sCO2) further, quick and reliable design tools for the different system components, e.g. centrifugal compressors are required. In this study, a computer program is developed to predict the performance of centrifugal compressors with sCO2 as working fluid. This computer program is based on mean-line analysis, calculates the fluid parameters at selected sections of the meridional plane and plots the performance maps. So-called enthalpy loss coefficients are utilized to describe the difference between the isentropic and the polytropic process. In addition to previous studies, the presented model intends to predict the performance of sCO2 centrifugal compressor with a shrouded impeller and a vaneless diffuser. For this purpose, corresponding loss coefficients are incorporated. Subsequently, the predicted results of this work are compared and validated with computational fluid dynamics (CFD) and experimental results from the EU-project sCO2-HeRo. The prediction of the computer program fits within 5% deviation to the CFD results, and about 4% to the experimental results regarding to pressure ratio.

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An Attempt for Establishing Pressure Ratio Performance Maps for Supercritical Carbon Dioxide Compressors in Power Applications

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Carbon dioxide in the supercritical state (sCO2) has drawn much interest lately. It is considered as a promising fluid for next-gen power plants with many researchers investigating this technology. Cycle simulation and control requires compressor performance maps valid for variable inlet conditions. In this paper, an attempt is made for establishing a pressure ratio based performance map for sCO2 compressors in power applications. For that purpose the so-called Glassman approach is considered. This model has been originally established for fluids obeying the ideal gas law. Therefore, a modification is proposed to take into consideration the real gas equation of state and to allow wide variation of the isentropic volume exponent kv. Computational fluid dynamics (CFD) is used to predict the performance of a single stage radial compressor. Results for different kv values at the compressor inlet confirms the validity of the proposed model with both the polytropic efficiency and the reduced enthalpy deviations limited to 1 percent. On the other hand, predicted pressure ratio shows difference of around 3 percent from kv=7.1 to kv= 4.1. A further decrease of kv to 2.5 extends the difference up to 8 percent

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Binary interaction parameter uncertainty in the optimisation of a transcritical cycle: consequences on turbine design

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Doping CO2 with an additional fluid to produce a CO2-based mixture is predicted to enhance the performance of the super critical CO2 power cycle and lower its cost when adapted to Concentrated Solar Power plants. A consistent fluid mixture modelling process is necessary to reliably design and predict the performance of turbines operating with CO2-based working fluids. This paper aims to quantify the significance of the choice of an Equation of State (EoS) and the uncertainty in the binary interaction parameter (kij) on the cycle and turbine design.
To evaluate the influence of the thermodynamic model, an optimisation study of a 100 MWe simple recuperated transcritical CO2 cycle is conducted for a combination of three mixtures, four equations of state, and three possible values of the binary interaction parameter. Corresponding multi-stage axial turbines are then designed and compared based on the optimal cycle conditions.
Results show that the choice of the dopant fraction which yields maximum cycle thermal efficiency is independent from the fluid model used. However, the predicted thermal efficiency of the mixtures is reliant on the fluid model. Absolute thermal efficiency may vary by a maximum of 1% due to the choice of the EoS, and by up to 2% due to kij uncertainty. The maximum difference in the turbine geometry due to EoS selection corresponded to a 6.3% (6.6 cm) difference in the mean diameter and a 18.8% (1.04 cm) difference in the blade height of the final stage. On the other hand, the maximum difference in turbine geometry because of kij uncertainty amounted to 6.7% (5.6 cm) in mean diameter and 27.3% (2.73 cm) in blade height of the last stage.

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Effect of the ambient temperature on the performance of small size sCO2 based pulverized coal power plants

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The present work focuses on the analysis of a novel coal fired sCO2 power plant concept developed in the frame of sCO2-Flex H2020 EU funded project. Fossil fuel fired power plants are expected to improve their flexibility in the future energy scenario characterized by a large share of non-predictable and non-dispatchable renewable energy sources. This upcoming context requires a new generation of coal fired power plants with a smaller size, a high flexibility and minor requirements for the installation site like no need of water consumption. Carbon dioxide in supercritical cycles is recognized to be a possible solution for this technology shift and could replace in the future common steam Rankine cycles. This paper focuses on the impact of ambient temperature variation on a small size coal fired sCO2 power plants equipped with a dry cooling heat rejection unit, with the aim of understanding the effect on plant operability and system performance. A dedicate tool is implemented for off-design behavior assessment and different control strategies are investigated. Results show that without a proper design of the heat rejection unit a small increase of ambient temperature may drastically limit the maximum attainable power output of the plant. This penalizing effect is more pronounced in hot locations, but this issue can be limited by adopting a sufficient over-sizing of the cycle heat rejection unit (HRU) or wet-and-dry solutions.

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Operational Analysis of a Self-Propelling Heat Removal System using Supercritical CO2 with ATHLET

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This study proposes preliminary guidelines for the design and operation of a supercritical carbon-dioxide (sCO2[1]) heat removal system for nuclear power plants. Based on a thermodynamic optimization the design point is calculated incorporating an existing small-scale compressor map. The behavior of the cycle is tested under varying boundary conditions on the steam side of the compact heat exchanger. The simulations are carried out with the thermal-hydraulic system code ATHLET, which has been extended for the simulation of sCO2 power cycles. The extensions include the thermodynamic properties, heat transfer and pressure drop correlations as well as performance map based turbomachinery models, which take the real gas behavior of sCO2 into account. During the decay heat transient, compressor surge occurs in some of the simulated cases. In order to avoid compressor surge and to follow the decay heat curve, the compressor speed is reduced together with the steam temperature. This enables to operate one single system down to a thermal load of less than 50 % even under the design restriction caused by the application of the existing compressor performance map.

[1] sCO2 is defined as carbon dioxide at supercritical conditions with $p > 73.8$ bar and $T > 31$ °C

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Numerical Investigation Of A Simple Regenerative Heat To Power System With Coupled Or Independent Turbomachinery Drives

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Supercritical CO2 (sCO2) power systems have the potential to revolutionise the power generation sector in so far as recovering high-temperature (>400degC) waste heat and converting it to power is concerned, in energy intensive industries. Among the possible cycle layouts, the simple regenerative cycle is the simplest, yet potentially the most competitive for initial industrial uptake of the sCO2 technology at small-scales (<1MWe). To compensate for the efficiency downside of a simple cycle architecture, this study will investigate how the turbomachinery design and layout could improve the design, part-load and transient performance of sCO2 power systems.

With reference to the 50kWe High Temperature Heat To power Conversion facility (HT2C) available at Brunel University London, the research compares the mechanical coupling of compressor and turbine with an independent drive of the two turbomachines. The research methodology involves a one-dimensional model of the sCO2 heat to power system calibrated on the HT2C hardware in which the turbomachinery sub-models are implemented via zero-deminsional performance maps resulting from a mean-line design approach validated by 3D RANS CFD. More specifically, two compressor and turbine designs are developed in order to optimise the machines' performance with and without the speed matching design constraint.

The analysis of the results focusses on part-load operation due to the topping industrial process, as well as with respect to a transient profile of a real industrial exhaust. In addition, the paper includes a preliminary cost estimation in order to allow a holistic techno-economic comparison to be undertaken.

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Preliminary Aerodynamic Design of a Supercritical Carbon Dioxide Compressor Impeller for Waste Heat Recovery Applications

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Supercritical Carbon Dioxide (S-CO2) Brayton cycles have garnered significant attention in the recent past as an alternative source for renewable energy. It has a potential for delivering high energy efficiencies for low-to-medium heat source temperatures, thus proving to be indispensable technology for waste heat recovery. Operating in proximity to the critical point, the aerodynamic design of an S-CO2 compressor component is complex and requires accurate modelling of the working fluid to analyze the flow physics. The present research provides a simplistic, yet robust methodology to appropriately size and design the impeller of a centrifugal compressor for a 12.5 MWe waste heat recovery S-CO2 power plant.

Three prominent variants of the S-CO2 cycle are studied with the aim of maximizing the power output from a pre-defined waste heat source. A 'Design of Experiments' (DOE) analysis is undertaken to identify the regions and, subsequently, the bounds for maximized performance of the three cycle configurations. The three configurations are comprehensively optimized using a stochastic, non-gradient technique of Genetic Algorithms. It is observed that the simply recuperated cycle (RC) outperforms its peers. For a waste heat source temperature of 450˚C, the reported net-power output is 3.13 MW, with a thermal efficiency of 25% for the optimized cycle.

A one-dimensional mean-line analysis tool is adopted to analyze the aerodynamic performance of an S-CO2 centrifugal compressor impeller. Thermodynamic and aerodynamic properties are calculated at the mean radius of the impeller flow path using conservation equations. To model the internal losses, conventional loss correlations for centrifugal compressors are adopted from the literature. The developed model uses an iterative scheme to obtain convergence of losses and total exit pressure. Using the experimental data from the S-CO2 compressor impeller of Sandia National Labs, the performance model is validated with admissible accuracy. It is observed that the tip clearance loss and blade loading loss contribute majorly to the overall internal loss due to the high-pressure gradient between the suction and pressure side of the impeller blade.

To solve the inverse problem of calculating the geometry from the inlet and exit thermodynamic conditions, the conservation equations of mass, momentum, and energy are solved in a different order. Using Balje's Diagram, the impeller is sized appropriately and the RPM of the impeller is calculated. A brief study on condensation in the impeller throat is performed and the effect of multi-staging on condensation is investigated. Further, the performance model is coupled with the design scheme to dynamically modify the impeller geometry. For the design model, certain design choices are made from prior design experience to define the input parameters. Using the developed model, the geometrical parameters of the S-CO2 impeller are defined. Two Bezier curves are fitted at the hub and tip sections of the impeller to completely define the flow path. In addition to the geometry, total exit thermodynamic properties of the impeller, total-to-total efficiency, slip and distortion factors are reported and are observed to lie within the permissible limits.

Numerical Analysis of a Centrifugal Compressor Operating With Supercritical CO2

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Over the past years, there has been increasing interest in developing sCO2 Brayton cycles, which promise comparatively high conversion efficiencies at a moderate cycle temperature range. This main advantage is based on the fact that in respective power systems CO2 is compressed starting from a thermodynamic state in the vicinity of its vapour-liquid critical point, where fluid density is high. Thus, compression work is reduced significantly. High fluid density also paves the way for compact equipment design and a small physical footprint of the cycle.
Despite remarkable research efforts, there are still several challenges which need to be overcome before sCO2 cycles can be commercialized. Key issues concern reliable process control, the realization of compact and effective heat exchangers as well as the achievement of satisfactory turbomachinery performance characteristics. Improving compressor efficiencies is considered to be one of the main tasks to improve the cycle performance. Centrifugal compressors are predominantly applied in sCO2 Brayton cycles and especially the main compressor is expected to be a radial configuration for a broad range of system scales due to its lower volume flow and wider range to facilitate variations in gas properties. Centrifugal compressor design and analysis methods are very sophisticated for working fluids which behave like an ideal gas. However, their applicability for real fluids with non-linearities outside of the ideal gas domain, particularly near the critical point, remains uncertain. In this respect, high-fidelity CFD simulations accounting for accurate thermodynamic modelling of state variables allow for an insight into the dynamic development of flow field and, thus, can be utilized to improve aerothermodynamic design and performance predictions for sCO2 turbomachinery.
This work presents an investigation of the performance characteristics and flow field of a sCO2 centrifugal compressor by means of three-dimensional CFD. The candidate geometry is based on the main dimensions of the main compressor operated in a compression test-loop by Sandia National Laboratories [1]. Simulations are performed with a recently developed in-house hybrid CPU/GPU solver [2]. To account for the thermodynamic properties of sCO2, these are derived from the Span-Wagner EOS [3] and assessed through an efficient and accurate tabulation technique, the Spline Based Table Look-Up Method (SBTL) [4], which is particularly optimized for the density-based solution procedure. Computational results are compared to experimental data provided in [1,5].

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Design and off-design analysis of a highly loaded centrifugal compressor for sCO2 applications operating in near-critical conditions

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The closed gas cycle based on supercritical carbon dioxide (sCO2) is a promising solution to realize highly efficient power systems arranged in compact devices. However, the technical feasibility of these so-called sCO2 power systems relies on the development of non-conventional components, whose features are dictated by the peculiar character of the working fluid.
The compressor is a key component of the system and its design demands the set-up of novel guidelines, due to the near-critical thermodynamic condition of the fluid, which (i) makes the machine operate with a very low flow function, (ii) experiences steep changes in properties across the machine, and (iii) is prone to phase-change in the intake part of the machine.
In this study we revise the entire design workflow of a prototype sCO2 centrifugal compressor, from the preliminary definition of the machine, to the mean-line design, and finally to the detailed definition of the meridional channel and of the blade shape, highlighting the aspects making the machine alternative to conventional ones. The compressor aerodynamics is then analyzed by resorting to a high-fidelity Computational Fluid Dynamics (CFD) model in both design and off-design conditions, considering three speed-lines and low/high flow rate margins. Results show the capabilities and limitations of conventional low-fidelity design procedures for designing sCO2 compressors, especially at off-design conditions, and shed light on the technical implications of the thermodynamic character of the fluid, especially in connection to the onset of phase change in the intake region of the impeller and in the tip clearance.

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Design considerations of sCO2 turbines developed within the CARBOSOLA project

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Power cycles based on supercritical carbon dioxide (sCO2) are promising higher thermal efficiencies, lower plant complexity and a more compact design the components compared to state-of-the-art steam processes. They also offer the possibility to cover a much wider temperature range with the same working fluid and thereby to efficiently use such heat sources, which today are above the application areas of steam cycles and below gas turbine processes.

The German research project CARBOSOLA shall drive the sCO2 technology development in Europe by providing a test loop for research programs and basic component tests followed by an initial system and component design for a future demo plant. In a first project phase, the economic potential of the sCO2 technology was evaluated and optimized for different use cases based on initial component designs and corresponding cost assumptions.

This paper provides firstly an overview of the CARBOSOLA project, followed by the presentation of initial component designs for the different applications. Focusing the CO2 turbine further details considering design topology, technology and optimization approaches are discussed.

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Optimal design of supercritical CO2 (S-CO2) cycle systems for internal combustion engine (ICE) waste-heat recovery considering heat source fluctuations

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Supercritical CO2 (S-CO2) cycle systems have emerged as an attractive alternative for internal combustion engine (ICE) waste-heat recovery thanks to the advantages, such as robust performance and system compactness, offered by CO2 as a working fluid. Engine exhaust gases and jacket water are two available heat sources with promising potential to be utilised, of which the conditions, i.e., temperature and mass flow rate, will vary based on the ICE operating strategy. These heat source variations have a critical influence on the S-CO2 cycle system and the performance improvement on the ICE, which needs to be carefully considered in the design stage of the heat recovery system. This paper seeks to explore the optimal design of an S-CO2 cycle system for ICE waste-heat recovery considering the heat source fluctuations as well as the probability of occurrence arisen from actual ICE operations. A variety of heat source conditions are selected for separate design of the S-CO2 cycle system and performance evaluation under all possible scenarios via detailed design and off-design models of all the components, so as to select the optimal design scheme that is able to match the heat source fluctuations and exhibit the best performance from both thermodynamic and economic perspectives. The advantage of the presented approach against the conventional one that only sticks to one specific design condition is to avoid either over-sizing or under-sizing of the S-CO2 cycle system, which also achieves comprehensive insight of the interplay between the bottoming heat recovery system and the ICE, and provides valuable guidance for further system optimisation and operation.

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Utilizing Industrial Waste Heat for Power Generation Using sCO2 Cycles

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The industrial sector accounts for approximately 30% of the global total energy consumption and 50% of that is lost as waste heat. Recovering waste heat from industries and utilizing it as an energy source is a sustainable way of generating electricity. Supercritical CO2 (sCO2) cycles can be used with various heat sources including waste heat. Current literature primarily focuses on the cycle's thermodynamic performance without investigating the economics of the system. This is mainly due to the lack of reliable cost estimates for the cycle components. Recently developed cost scaling makes it possible to perform more accurate techno-economic studies on these systems. This work aims to model waste-heat-to-power systems and by performing sensitivity analysis on various system components, attempts to determine which factors require the most attention to bring this technology into commercialization. The industries with the largest unutilized waste heat are cement, iron and steel, aluminum and gas compressor stations. In this work, models of different sCO2 cycle configurations were developed and simulated for these industries. The techno-economic model optimizes for the highest Net Present Value (NPV) using an Artificial Bee Colony algorithm. The optimization variables are the pressure levels, split ratios, recuperator effectiveness, condenser temperature and the turbine inlet temperature limited by the heat source. The results show industries can cut down costs by €8-34M using this system. Furthermore, the system can achieve an LCOE between 2.5-4.5 c€/kWh which is competitive with ORC (3.2-18 c€/kWh) and steam cycles (3-9 c€/kWh). Out of the modeled industries, waste heat recovery in the steel industry yields the highest NPV of €34.6M.

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sCO2 Power Cycle Development and STEP Demo Pilot Project

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Supercritical CO2 (“sCO2”) power cycles offer the potential for higher system efficiencies than other energy conversion technologies such as steam Rankine or organic Rankine cycles, especially when operating at elevated temperatures. These sCO2 power cycles are being considered for a wide range of applications including fossil fuel-fired systems, waste heat recovery, concentrated solar power, and nuclear, and the potential for efficient thermal energy storage.
GTI is leading several sCO2 power cycle technology development projects ranging from component level technology development to large scale integrated pilot testing. The efforts highlighted in this paper include: (1) The 10 MWe Supercritical Transformational Electric Power Pilot plant (“STEPDemo”, www.stepdemo.us) and (2) its relevance for sCO2 development in general and of note, also in the context of waste heat recovery and thermal energy storage (TES) applications. In the STEPDemo project, a team led by GTI, Southwest Research Institute (SwRI), and General Electric Global Research (GE-GR), along with the University of Houston and the University of Wisconsin), Natural Resources Canada (NRCan), and the Electric Power Research Institute (EPRI)), is executing a project to design, construct, commission, and operate an integrated and reconfigurable 10 MWe sCO2 Pilot Plant Test Facility located at SwRI’s San Antonio, Texas campus. The majority of the project funding is provided by the U.S. Department of Energy, and the remaining funding is by the project team members and a global consortium of industry partners: Engie, American Electric Power, Korea Electric Power Corporation (KEPCO), Natural Resources Canada, and Southern Company. This project is a significant step toward commercialization of sCO2 cycle based power generation and will inform the performance, operability, and scale-up for commercial implementation of sCO2 technology across the potential application spectrum. The pilot plant is currently in the final construction phase, with installation of major equipment underway, and commissioning planned for early 2022. By the end of this six-year project, the operability of the sCO2 power cycle will be demonstrated and documented starting with a simple recuperated cycle configuration initially operating at a 500°C turbine inlet temperature and progressing to a recompression closed Brayton cycle technology (RCBC) configuration operating at 715°C. The paper will also present a vision for the use of the STEPDemo facility as a testbed for other sCO2 component testing, such as thermal energy storage. In TES applications, a thermal storage system could be installed adjacent to the STEPDemo power block to demonstrate the integrated operation of TES with a commercially relevant sCO2 cycle. This is relevant to both concentrated solar power (CSP) applications as well as power-to-power storage systems that utilize sCO2 cycles.

sCO2 power cycle design without heat source limitations: Solar thermal particle technology in the CARBOSOLA project

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Supercritical CO2 (sCO2) power cycles have the potential to reach considerably higher thermal efficiencies than state of the art steam cycles while minimizing the size and number of components. However, to reach high thermal efficiencies, the average temperature at which heat is supplied to the cycle has to be very high. Concentrating solar power (CSP) technology allows for this as the heat transfer medium downstream the sCO2-primary heat exchanger is reintroduced into the solar receiver, making CSP-sCO2 processes appear like a perfect match.
Contrary to common heat transfer media used in CSP plants (molten salt or oil) solid particles have no temperature limitations within the relevant technological range (0 °C… 1000 °C). Therefore, large approach temperatures in the primary heat exchangers and a large temperature spread in the thermal energy storage system are possible, lowering the cost of the respective subsystems.
As part of the CARBOSOLA Project, different CSP-sCO2 technologies are investigated in techno-economic terms and compared amongst each other and to reference systems featuring steam power cycles. Based on preliminary models, a small number of sCO2 processes were pre-selected to be designed in more detail. Interestingly, the sCO2 processes predicted to generate electricity at the lowest cost are not the ones with the highest turbine inlet temperatures and highest thermodynamic performance. Instead these do not feature reheat or recompression and have a reasonable turbine inlet temperature. It could also be shown that solid particle-based CSP technology integrates better with these sCO2 processes than state of the art or even advanced molten salt technology. A first comparison with a typical Rankine steam cycle showed comparable techno-economic performance of the two for the investigated CSP applications.
Currently, the main components of the chosen processes are designed by Siemens Energy using design point data from the pre-selection study. The updated component models will then be used to generate optimized solar subsystems and all of the models will be merged into an overall plant model used to simulate the annual energy yield. Together with developed cost models, this is used to calculate the levelized cost of electricity generated in a commercial size power plant.

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Transient Analysis of the Super-critical Carbon Dioxide Cycle Coupled to Pressurized Water Reactor for Nuclear Powered Ships

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Recently, nuclear-powered ships have attracted attention due to international regulations on greenhouse gas emissions and the trend of rapid and large-scale ships. In order for a nuclear system to be used in marine propulsion, it is important to achieve small in size and should be able to respond to rapid load demand changes. In this study, a super-critical carbon dioxide (S-CO2) cycle is proposed as a power conversion system for pressurized water reactors (PWR) for marine propulsion. The S-CO2 cycle has been attracting attention as the next-generation power conversion system that can be alternative for the steam Rankine cycle due to its small system size and higher efficiency. The conceptual design of the S-CO2 power conversion system is first performed under the reference reactor conditions, including cycle design and component design. To conduct system analysis, MARS-KS code, one of the nuclear thermal-hydraulic safety analysis codes developed by Korea Atomic Energy Research Institute (KAERI) and actively used for the safety review calculation of a nuclear power plant by Korea Institute of Nuclear Safety, is improved to accurately simulate the S-CO2 power conversion system combined with PWR. The PID controller based automatic control strategy of the entire system is designed to respond to rapid load changes. Transient analyses are performed with the newly developed system analysis code under various scenarios.

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The Development of a New Chemical Kinetic Mechanism for Combustion in Supercritical Carbon Dioxide

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The Allam cycle is a thermodynamic cycle for the combustion of gaseous fuels under oxyfuel conditions with inherent carbon capture. As the CO2 is captured intrinsically, the efficiency penalty of capture on the overall plant is small, meaning that Allam cycle power plants achieve a similar efficiency to traditional fossil fuel power plants without carbon capture and storage. At high-pressures and a high-CO2 dilution, combustion mechanisms are poorly understood. Sensitivity and quantitative analysis of four established chemical kinetic mechanisms were used to determine important reactions and the best performing mechanisms at different conditions. CH3O2 chemistry was identified as a pivotal mechanism component for modelling methane combustion above 200 atm. The University of Sheffield (UoS) supercritical CO2 (sCO2) mechanism created in the present work better models the ignition delay time (IDT) of high-pressure combustion in a large dilution of CO2. Quantitative analysis showed that the UoS sCO2 mechanism was the best fit to the greatest number of IDT datasets and had the lowest average absolute error value, indicating the superior performance compared to four existing chemical kinetic mechanisms, well-validated for lower pressure conditions.

Techno-economic optimization method and its application to a sCO2 gas turbine bottoming cycle

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Cycle architecture, fluid parameter selection and component design of an exhaust/waste heat recovery cycle require an integral approach. The exhaust/waste heat shall be utilised to a maximum, but at minimum costs. In addition, the bottoming cycle needs to be aligned with the topping cycle regarding operational behaviour, especially for part load. To analyse potentials of exhaust heat recovery in a combined gas turbine-sCO2 cycle, optimum cycle architecture and fluid parameters of the bottoming cycle have to be determined. A thermo-physical model of the sCO2 bottoming cycle including knowledge of component design, component behaviour and costs is the basis of the optimization procedure. As part of the CARBOSOLA project, techno-economic optimizations for an use case of exhaust heat recovery have been carried out. The paper is aimed at presenting the optimization methodology followed by boundary conditions of the specific use case, investigated sCO2 cycle architectures and results of optimum cycle architecture and fluid parameters for maximum heat recovery and minimum costs. Attention will also be paid to accurate modelling of heat exchangers operating near the critical point.

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Experiences of supercritical CO2 applications in refrigeration and air conditioning systems

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Carbon dioxide (CO2) is a working fluid, which is suitable for various applications. Excellent heat transfer properties, especially in the supercritical area, make it attractive for thermal systems. As it is an nvironmentally friendly and non-flammable fluid, it is used in larger stationary systems e.g. in supermarket refrigeration systems as well as in small cycles, e.g. for mobile air conditioning (A/C) systems. There is no risk of pollution or major environmental damage due to leakage or accidental release of fluid. In addition to power cycles, CO2 is suitable for cooling circuits for both subcritical (liquid-gas phase change) and transcritical applications. The latter includes supercritical heat rejection and subcritical heat absorption. Therefore, CO2 refrigeration systems and their components, e.g. compressors, have special design requirements. They need to be specially adapted to the fluid properties such as pressures above 10 MPa and pressure differences up to 8 MPa. The efficiencies of refrigeration systems must be competitive to those of conventional refrigerants. This requires advanced system designs, which will be presented. Finally, possible synergies between CO2 power systems and CO2 refrigeration and heat pump systems will be discussed.

Environmental assessment of a 25 MWe fossil fired supercritical CO2 cycle

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In a global effort to decrease human-sourced GHG emissions, the operation of GHG-emitting plants is only justified if they offer a sufficient ability to smoothen the variability of the net electric demand. The EU-funded project sCO2-Flex aims at designing a highly flexible 25-MWe supercritical CO2 cycle suitable for such a cohabitation with renewable energies, and testing its main components. However the performance of such a cycle should not be reached at the expanse of its environmental impact. Therefore the present paper focuses on the analysis of the environmental impact of such a plant, following most of the guidelines of the LCA method, as described in the ISO 14040-14044 standards.
Its purpose is to quantify these impacts on a wide range of environmental and human health issues, covering the whole life cycle of a product in a "cradle to grave" approach. In many cases, this assessment comes after the commercialization once the production process is known, the emissions and resource consumption clearly identified. In the present study, an anticipation effort was necessary to evaluate the impacts of the project once it comes to commercial maturity.
The LCA described in this paper was conducted on the open source software OpenLCA using the database Ecoinvent, both acknowledged by the life cycle assessment community. It encompasses four major steps: goal and scope definition of the project, inventory analysis of the data, impact analysis and interpretation. Data was picked directly from the ecoinvent database, gathered from the project's contributors, or extrapolated from hypotheses if data was to be missing in the inventory analysis. To compensate the uncertainties due to lack of data on equipment scaling and operation practices, an extensive sensibility analysis has been carried out to bring additional robustness to the study.
Overall, this paper shows that the majority of impacts appear to be driven by coal consumption. Hence, thanks to its higher efficiency, the sCO2-flex power plant outperforms the reference water/steam plant in all the most robust environmental impact categories: global warming potential at 100 years scope, human and resource use. Among the considered impacts categories, the most significant uncertainties arise from the use of nickel-based-alloys in the boiler.

Estimated Cost and Performance of a Novel sCO2 Natural Convection Cycle for Low-grade Waste Heat Recovery

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Energy recovery from low-grade heat sources is a challenging topic with potentially broad application to various industries. Low-grade heat sources at <100-300°C exist almost ubiquitously in a wide variety of industrial, commercial, and residential processes. The primary challenge with low-grade heat recovery systems is that the thermal conversion efficiency is inherently very low, resulting in a prohibitively high cost of electricity. This work focuses on development of a natural-convection-driven system for low-cost power generation from low-grade heat sources using supercritical carbon dioxide (sCO2) as the working fluid. Employing a simplified system, by limiting the required hardware (turbomachines) and incorporating a sealed power conversion concept (eliminating shaft seals and minimizing auxiliary systems), may allow waste heat recovery to be applied to applications where organic Rankine or Kalina cycles are not considered practical. Utilizing a vertical process loop with heat addition near the bottom and heat rejection near the top will generate buoyant forces within the working fluid, motivating mass flow with temperature difference as the only driver. Energy would then be extracted for small-scale electric power generation.
Cycle modelling sensitivity studies were conducted to predict available power generation and estimated installation cost for six applications of various thermal and physical scales; applications considered ranged from a 300 kW-th compact application to an 80 MW-th geothermal application. Sensitivity studies included variations in the source and sink temperatures, the sCO2 temperatures and pressures, the flow loop pipe sizing, and the flow loop elevation change to quantify the impact of each design variable on the recoverable power, the thermal efficiency, and the estimated installation cost per power. Results of this study show that increasing the elevation change across the cycle and decreasing low-side CO2 temperature (to near or slightly below the critical temperature of 31.1°C) generated the most significant improvements in cycle performance and specific cost. It was also found that the cost per power is lowest for the largest thermal scales, namely geothermal type applications. However, even though the small- and medium-scale applications have higher specific costs, the actual installation cost is still considered relatively low. Therefore, it is expected that these waste heat recovery cycles could still pose competitive solutions for small electrical power requirements where very low-grade waste heat is available.

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Energy Storage Through CO2 Closed Cycles

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As the energy market is moving worldwide towards low-emission solutions, there is a growing interest in plants capable of storing non-dispatchable renewable power, contributing to maintain the high quality level of current electrical infrastructure and ensuring spinning-reserve capability, complementing the lack of frequency control by most of solar and wind technologies. CO2 cycles, including supercritical ones, could be a solution to achieve this goal. Most of current efforts on CO2 cycles are devoted to study the most promising configurations for power production, including supercritical CO2 plants for solar energy conversion. Basing on such extensive state of the art and growing knowledge, this paper aims to analyse innovative energy storage solutions involving closed cycles, and employing different working fluids in sub-critical or supercritical conditions, including CO2. Different plant configurations and operating conditions at 10MWe design point are compared in terms of Round Trip Efficiency (RTE) and costs, being benchmarked against traditional large scale storage solution such as CAES. Subcritical CO2 cycles is shown to be a very promising solution with RTE>70% and attractive cost features, thus being a potential candidate for utility scale energy storage.

Analysis of sCO2 Cycles for District Heating Applications

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Supercritical CO2 (sCO2) power cycles provide the possibility to significantly improve power generation from fossil fuels and renewable sources considering thermodynamic efficiency, economic feasibility, and operational flexibility. In addition to standalone power generation, the application of sCO2 cycles to cogeneration for combined heat and power processes can be a highly attractive option with respect to further development, and commercialization. In particular, the incorporation of a heat extraction option for district heating can be favorable regarding the overall cycle efficiency for temperate and cold climate regions because of the thermodynamic properties of sCO2. The current study thus focuses on the modeling, simulation, and thermodynamic analysis of different, simple sCO2 cycle designs for waste heat applications incorporating heat extraction for district heating. Different technological options, like backpressure turbines, split-flow recooling, as well as turbine extraction designs, and their effects on cycle design, operation, and efficiency are analyzed. The results show that sCO2 based cycles enable engineers to achieve high-efficiency power generation also in combination with heat extraction for district heating, comparable to conventional water-steam-based cycles. Furthermore, the split-flow recooling design provides the possibility to extract a significant amount of heat without affecting the power generation.

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Greening a Cement Plant using sCO2 Power Cycle

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This paper presents a case study for the greening of a cement plant located in India. Operating characteristics of the plant are described as well as sustainability actions previously undertaken to meet power requirements supplied by one of two subcritical coal boilers with renewables (photovoltaic and wind) and use of Municipal Solid Waste (MSW) to augment the cement kiln's heat requirements. The feasibility of deploying a sCO2 power cycle was determined to recover waste heat from different extraction points. Current assessment indicates opportunities for a Demo plant to extract 700 kWe (Turbine power output) while minimally disturbing plant operations. The Demo is expected to provide data for a larger, 8MWe (net) sCO2-derived power at higher turbine inlet temperatures and with potentially increased MSW use. Deployment of the larger sCO2 system could lead to partially or fully replacing the second coal boiler, leading to further "greening" of the plant with a potentially attractive pay-back period. Related modeling and design considerations are described.

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Thermal design of latent heat thermal energy storage facility with supercritical CO2

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Conversion of electric power to heat and from the stored heat back to power is the energy storage concept that allows high temperature and high-capacity accumulation (hundreds of MWh stored in the heat). Combination of the high temperature heat storage with use of the sCO2 energy conversion cycle may provide highly efficient and very flexible energy storage system. An aluminum alloy was identified as a suitable accumulation material for the latent heat storage due to its high latent heat, appropriate melting point (577°C) and acceptable price. The energy storage system with Al-Si12 alloy as the heat storage material and the sCO2 conversion cycle is being developed at CVR.
In this paper, design of a mock-up of the storage tank with the aluminum alloy, an electrical heating system and a sCO2 heat exchanger will be presented. The storage tank with capacity of 300 kWht will be fabricated, connected to the sCO2 experimental loop of CVR and operated at the relevant conditions to demonstrate capabilities of the energy storage concept. A thermal computational model that was developed to support design and optimization of the sCO2/metal heat exchanger will be also presented. Based on the computational model results, feasibility of this concept for the high capacity energy storage will be discussed.

Microstructural Evaluation of Preselected Steels for Turbine after Supercritical CO2 Exposure

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The energy conversion cycles with supercritical carbon dioxide (sCO2) are being considered as an innovative technology with potential for replacement of conventional steam cycles within various applications such as nuclear, fossil or renewable energy resources. Due to extreme operational conditions including temperatures above 550°C and pressures up to 25 MPa, proper selection of materials is essential for a suitable design of the thermal circuit. Several materials that were identified as potentially suitable for the main components of the sCO2 circuits were exposed in the sCO2 relevant conditions in the sCO2 experimental loop at Research Centre Rez (CVR). The experimental conditions were represented by the sCO2 temperature of 550°C, pressure of 25 MPa, flow conditions and 1000 hours of exposure. Moreover, an additional test section where the sCO2 flow velocity up to 100 m/s was achieved was designed and utilized to simulate turbine relevant conditions. Suitability of the materials preselected for the sCO2 turbomachinery will be evaluated and discussed in this paper. For the experiments, four types of materials (FB2, 17-4-PH, 625M, IN718) were selected. After the exposure, the corrosion behavior and oxidation of the materials was investigated including surface analyses and cross sections examination. The paper presents the experimental parameters including the high velocity test section design. The materials degradation will be evaluated as well as the effect of the high velocity flow.

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Investigation of material degradation and coolant chemistry for sCO2 power cycles

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sCO2 power cycles are characterized by the enhanced efficiency of thermal to electric power conversion and more compact turbine size compared with the steam power cycle. The organizations from Czech Republic take part the extensive research activities in this field. The research infrastructure including sCO2 experimental loop was constructed. The sCO2 coolant chemistry and material degradation are among the solved topics. The objectives are to identify impurities in sCO2 medium and propose the purification and purity control system. Another objective is to gain data of structural material degradation in sCO2 medium. First results concerning impurities and materials were obtained during laboratory tests and the 1000 h operation of the sCO2 loop. The most important of them are presented in the paper and also conference presentation.

Thermal efficiency gains enabled by using supercritical CO2 mixtures in Concentrated Solar Power applications

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Supercritical Carbon Dioxide (sCO2) power cycles have been proposed for Concentrated Solar Power (CSP) applications as a means to increase the performance and reduce the cost of state-of-the-art CSP systems. Nevertheless, the sensitivity of sCO2 systems to the usually hot ambient temperatures found in solar sites compromises the actual thermodynamic and economic gains that were originally anticipated by researchers of this innovative power cycle.
In order to exploit the actual potential of sCO2 cycles, the utilization of dopants to shift the (pseudo)critical temperature of the working fluid to higher values is proposed here as a solution towards enabling exactly the same features of supercritical CO2 cycles even when ambient temperatures compromise the feasibility of the latter technology. To this end, this work explores the impact of adopting a CO2-based working mixture on the performance of a CSP power block, considering hexafluorobenzene (C6F6) and titanium tetrachloride (TiCl4) as possible dopants. Different cycle options and operating conditions are studied (250-300 bar and 550-700ºC) as well as molar fractions ranging between 10 and 25%.
The results in this work confirm that CO2 blends with 15-25%(v) of the cited dopants enable efficiencies that are well in excess of 50% for minimum cycle temperatures as high as 50 or even 55ºC. It is also confirmed that, for these cycles, turbine inlet temperature and pressure hardly have any effect on the characteristics of the cycle that yields the best performance possible. In this regard, the last part of this work also shows that cycle layout should be an additional degree of freedom in the optimisation process inasmuch as the best performing layout changes depending on boundary conditions.

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Advanced Thermodynamic Power Cycles Utilizing Carbon Dioxide Based Mixtures as Working Fluids for High Temperature Waste Heat Recovery

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One of the possible ways of energy recovery from industrial waste heat is to use highly efficient thermal power thermodynamic engines. Organic Rankine Cycles (ORCs) and Steam Cycles are two prominent power cycles commercialized in last years for waste heat recovery. In recent years, supercritical carbon dioxide (sCO2) cycles are also investigated for vast range of waste heat sources from medium to high temperatures. sCO2 cycles offer lower compression work due to higher density near critical point, compact turbomachinery and zero emissions. However, sCO2 cycles requires high operating pressures and shows lower heat recovery efficiencies which can only be improved by resorting to complex cycle layouts with mass split, cascade heating and/or dual expansion processes. To mitigate this drawback, this paper proposed CO2 mixtures as working fluids in power cycles using flue gases at relatively high temperature (400-450 °C) as waste heat source. Typical industrial waste heat temperatures which can comply with this study are for example, waste heat from cement plants (300-500°C), steel and glass manufacturing plants. Firstly, a selection criterion is defined for choice of working fluids to be used as additives in CO2 mixtures. It includes the evaluation of thermal stability, physical properties, safety and environmental characteristics of some candidate working fluids. The selection procedure dictates R134a, R1234yf, R1234ze(E), NOVEC 5110 and NOVEC 649 as promising additive compounds owing to favorable physical properties and good environmental and safety characteristics. Standard enthalpy of formation per bonds is used as an indicator to quantify the thermal stability of selected compounds relative to highly chemically inert CO2. Moreover, the thermodynamic properties of the mixtures are calculated at different molar compositions using an appropriate equation of state. The binary interaction parameters involved in the equation of state are obtained with the help of available experimental VLE data or by estimation method in case of non-availability of the VLE data. With an aim to achieve higher heat recovery effectiveness, numerous advanced sCO2 cycle layouts are analyzed in literature. This study also investigates the thermodynamic performance of advanced layouts as a benchmark to compare with the performance of cycles operating with CO2 mixtures. In addition, preliminary sizing of axial turbine is developed assuming isentropic turbine stages and involving free vortex theory. Preliminary analysis reveals that the power cycles operating with CO2-R134a mixtures show an appreciable increase in cycle efficiencies as compared to simple recuperative sCO2 cycles at all cycle maximum pressures. In case of CO2-R134a mixture (0.3 mole fraction of R134a), total heat recovery efficiency of about 0.15 is obtained at cycle maximum pressure of 200 bars compared to simple recuperative sCO2 cycle with total efficiency of 0.12. Comparative analysis shows that cycles operating with CO2 mixtures show comparable total heat recovery efficiency as obtained with complex cycle layouts with sCO2. Results suggests that, employing CO2 mixtures as working fluid is a much more convincing option for high temperature heat recovery owing to higher heat recovery efficiencies achievable with rather simple cycle layout and lower cycle maximum operating pressures compared to sCO2 cycles.

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Study of the Influence of Additives to CO2 on Performance Parameters of a sCO2-Cycle

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Compared to existing technologies, thermodynamic cycles based on supercritical carbon dioxide (sCO2) are leading to higher efficiencies and a more compact design of the components. However, it is possible to improve the performance of sCO2-based power cycles by using mixtures of CO2 with suitable additives, as also discussed in the literature for some applications such as concentrated solar power plants or the usage of geothermal heat.

The large variety of possible fluid combinations makes an experimental investigation of all conceivable additives considerably difficult. Therefore, a more viable alternative is to set up a model for the power cycle and conduct a screening in order to identify promising candidates for working fluid mixtures. In a next step these could subsequently be experimentally verified. In order to carry out a screening, a preferably accurate and likewise predictive mixture model is needed.

This work investigates the potential to optimize the characteristics of sCO2 power cycles by selectively adding different substances in varying amounts to CO2. For the theoretical screening, the reference equation of state for CO2 was applied in combination with a multi-fluid mixture model. In the literature studies were mainly limited to mixtures for which adjusted mixture models are available. In contrast, in this work the use of a predictive mixture model allows a screening of additional fluids for which multi-parameter equations of state are available (e.g. alkanes, alkenes, alcohols, and hydrofluorocarbons). The predictive model, which was recently developed at our institute, allows the use of the excess Gibbs energy model COSMO-SAC in combination with the multi-fluid mixture model. Applied to an exemplary thermodynamic cycle, changes in efficiency compared to the use of pure CO2 have been evaluated. Several promising mixture candidates have been identified. Additionally, shifts of the critical point have been investigated and are discussed.

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Experimental investigations on the heat transfer characteristics of supercritical CO2 in heated horizontal pipes

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In the frame of the sCO2-QA (qualification of analysis tools for the evaluation of a residual heat-driven, self-sufficient system for decay heat removal) project, a residual heat-driven self-sufficient sCO2-operated decay heat removal system based on a Brayton cycle is simulated with the German thermal-hydraulics system code ATHLET (analysis of thermal-hydraulics of leaks and transients). The heat removal system consists of a compact heat exchanger in the containment, a turbo-compressor system located in the reactor building and a gas cooler in the outdoor area. The validation of ATHLET and other numerical codes as well as understanding the heat transfer characteristics of sCO2 near the critical point requires experimental data. At IKE (Institute of Nuclear Technology and Energy Systems), the SCARLETT (supercritical carbon dioxide loop at IKE Stuttgart) test facility is available for various experiments with sCO2.

This publication includes an experimental investigation of the thermal stratification in heated horizontal sCO2 pipe flows. For this investigation, eight test series with overall 48 experiments were carried out in two pipes with inner diameters of 4 mm and 8 mm. The experiments were carried out at a pressure of approximately 7.75 MPa. The target values of mass flux were set at 400 kg/m2s and 800 kg/m2s and those of heat flux at 50, 90 and 130 kW/m2, resulting in a heat to mass flux ratio of 62.5-225 J/kg. The inlet Reynolds numbers are between 16000 and 120000. The measured parameters are the flow rate, the pressure, the inlet and outlet fluid temperature as well as the outer surface temperature along the test pipe in three different radial angles. The results show the influence of the pipe diameter, Reynolds number, mass and heat flux on the temperature stratification. Also, inflow lengths were determined for a fully developed temperature stratification. This data set can be used for the validation of computer codes.

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Sofia – sCO2 facility for Supercritical Brayton Cycle Research

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In the frame of national project sCO2 Efekt supported by Czech technological agency TAČR, Research Centre Rez (CVR) is developing an inovative, effective and flexible energy storage system. This system is based on the P2H2P (Power to Heat to Power) technology also called Carnot battery, with utilization of a sCO2 Brayton cycle for heat to power conversion. In frame of the project, key components of the storage system will be developed and experimentaly verified. The key components are mainly the compresors and turbines and the storage tank. To be able to test the compresor and turbine, experimental test facility called Sofia is also being developed. The main parameters of the Sofia facility are temperature up to 550°C, maximal test pressure 25MPa and the flow rate about 25kg/s. The highest possible power of the turbine to be tested is up to 1,5MW electrical. In this paper, conceptual design of the large scale experimental faclity is descibed including its main components.

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Closed-Loop Supercritical Carbon Dioxide Wind Tunnel: Design and Components

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Closed-loop supercritical CO2 cycles (sCO2) offer an innovative and efficient solution to achieve a reduction in primary energy consumption. CO2 has a low Global Warming Potential (GWP) compared to conventional fluorocarbon-based refrigerants, which makes it suitable for refrigeration cycles. Successful deployment of this technology is dependent on further experimental research. A significant effort is required to study the behavior of CO2 in the thermodynamic region close to the critical point, where sharp variations in thermophysical properties and real gas behavior are observed.
This paper presents the preliminary design of the LUTsCO2 facility. The experimental setup is designed to allow detailed studies on expansion and heat transfer of CO2 near the critical point. The transcritical refrigeration cycle is preferred as the experimental layout because of its operational flexibility and the commercial availability of components. Furthermore, a closed-loop cycle has the major advantage of running the loop continuously, which would not be possible with a blowdown test rig. The preliminary design of the main components is discussed with an emphasis on the heat exchangers. The latter are designed to operate by crossing the pseudo-boiling line, and they thus experience a considerable variation in CO2 properties. This phenomenon has a direct consequence on the design of the heat exchangers and requires the application of advanced heat transfer correlations that consider whether the CO2 is in a liquid-like or gas-like state. In addition, the supersonic test section is briefly described. This component comprises a converging-diverging nozzle, which performs a supersonic expansion from the supercritical region up to the two-phase region, followed by a normal shock wave, which allows the large kinetic head available to be recovered in the diverging section.

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Design and Specification of a 10MW-Class sCO2 Compressor Test Facility

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The use of supercritical CO2 as the working fluid in closed-loop Brayton Cycles and advanced electrothermal energy storage systems has shown great promise in delivering electricity with high efficiency, flexibility of heat source, and reduced power-plant size and cost. A number of new technology advancements must be realized in order to make sCO2 cycle a commercially viable solution. One of the major components is the compressor, which provides the pressure increase needed in the cycle. Some characteristics of sCO2 in regard to its application in a compressor differ from those seen with air or gas which is widely used for turbo compressors. Higher density inside the compressor, overall higher operating pressure ranges, and drastic change of fluid property near critical point are some of them.

Recent experimental studies of sCO2 compressor in compressor test loops or in power cycle loops have successfully demonstrated the operation of sCO2 compressors in closed loops test environment. However, due to the small demonstration scale or due to limited available driving power, most of them were designed with a centrifugal type compressor with small scale where efficiency must be sacrificed resulting in low overall cycle efficiency. Also detail flow measurement studies were not suitable due to the very small flow passages through the compressor.

With this background, Notre Dame Turbomachinery Laboratory and Echogen Power Systems has designed a 10MW-class sCO2 compressor test facility to be built at the University of Notre Dame. The Test compressor is driven by a 10MW variable speed motor with speed increasing gear box. A water/Glycol cooled heat exchanger absorbs added energy from the test compressor. The closed loop is designed to have energy balance between the addition of energy through the drive motor and the absorption of energy through cooling flow rate control. A CO2 inventory management system with CO2 tank and supply system is designed to supply CO2 from initial operation to test operation.

10MW-class sCO2 compressor test facility has various merits in terms of scale. It enables the facility to test the multi-stage axial compressor as well as centrifugal compressors with flow passages wide enough to allow a detailed flow field investigation through various flow measurement technologies. The experiments will include detailed measurements that will significantly advance our understanding of the design, performance, efficiency, and operability of sCO2 compressors for advanced power systems. Construction of the drive train with a variable speed motor, a gear box, and a torquemeter is complete and the data acquisition/control system is finished. Design of the closed CO2 test loop is funded by the U.S. Department of Energy and will be complete in mid-2021. Initial sCO2 axial compressor tests will begin in 2021.