Selected papers from the 4th European Conference on Supercritical CO_2 for Energy Systems

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DOI
10.1016/j.energy.2022.125780

Publication date
2023

Document Version
Final published version

Published in
Energy

Energy 263 (2023) 125780

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Editorial

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The 4th European Conference on Supercritical CO_2 (sCO_2) for Energy Systems was held online from 22 to March 26, 2021. The event was organised by the European sCO_2 Research & Development Alliance, whose aim is to provide a platform for exchanging knowledge on sCO_2 technologies in the energy sector for academia and industry, as well as to promote this topic to a wider audience. The Conference brought together more than 100 participants from all over the world with expertise from research to policy development. Two keynote and more than 50 podium presentations took place. Based on the recommendations of the Alliance, the Conference Committee proposed a number of high-quality peer reviewed contributions for archival publication in ENERGY. Nine papers passed the additional and independent ENERGY review process, covering a broad spectrum of the sCO_2 energy research area, as follows.

1. Heat Exchanger and Transfer

Wahl et al. [1] experimentally investigated the cooling heat transfer coefficient in a 3 mm diameter tube with vertical flow orientation using the mixed convection criterion to evaluate the heat transfer deterioration. The results showed an influence of mixed convection at a stepwise reduction of the mass flux. More specifically, the transition from forced convection to mixed convection was evidenced by the drop in the heat transfer coefficient. The upwards flow showed a steady decrease in the heat transfer coefficient with the reduction of the mass flux. However, the downwards flow showed significant effects of buoyancy. The separate evaluation of the liquid-like and gas-like region indicated that the deterioration may vary based on the fluid properties. The comparison with the literature data of vertical cooling in 6 mm showed different behaviour which suggests an influence of the tube diameter. Hence, based on the outcomes of this research, the flow direction could be an influencing factor in the design of the chiller for supercritical CO_2 power cycles.

Theologou et al. [2] investigated the heat transfer of sCO_2 in parameter ranges where flow stratification can occur. To this end, more than 50 experiments were carried out with two horizontally oriented heated pipes with inner diameters of 4 mm and 8 mm. The results showed that the influence of the pipe diameter on the temperature stratification is greater than the influence of the Reynolds number. When no stable thermal flow stratification occurs, the inlet temperature influenced the overall temperature profile and, in turn, the heat transfer coefficient. The Petukhov and Richardson buoyancy criteria show that the experimental results are strongly influenced by buoyancy.

2. Turbomachines and Cycles

Gotelip et al. [3] assessed the techno-economic performance of five different sCO_2 cycle architectures as a bottoming cycle of a gas turbine. A multi-objective optimisation based on a thermo-physical model of the sCO_2 bottoming cycle, including knowledge of component design, component behaviour, and costs, allowed the identification of the most promising architecture and the range of optimal operating conditions at different scenarios. Among the layouts investigated, the Sequential Heating architecture resulted in the configuration with the highest potential for bottoming cycle of a gas turbine. This configuration outperformed more complex architectures thanks to a 3% lower levelized costs of electricity and a 19% higher net present value. The results indicated a prominent potential for the proposed cycle configuration and operational conditions for exhaust heat recovery in a combined gas turbine sCO_2 cycle.

Alenezi et al. [4] proposed an exergoeconomic analysis to assess the techno-economic feasibility of a hybrid power cycle based on the Allam-Fetvedt configuration. The hybrid system utilizes Concentrated Solar Power (CSP) as its primary heat source and natural gas Oxy-Combustion (OC) as a complementing heat source that ensures continuity of production when the sun is not available as well as the overall reliability and flexibility of the power generation unit. Both CSP and OC cycle layouts led to similar power output and second law efficiency. However, the unit cost of electricity in (Cent/kWh) for the CSP configuration was approximately 60% higher than for the OC one. The results of the parametric study further showed that increasing the turbine inlet operating conditions led to improved thermodynamic and exergoeconomic performance for both configurations. The exergy analysis eventually outlined cost-optimisation strategies targeting the CSP recuperator design or the replacement of the air separation unit for the OC layout.

3. sCO_2 Applications and Energy Systems

Manzoni et al. [5] proposed innovative large scale energy storage systems based on closed-loop cycles employing different working fluids in subcritical or supercritical conditions, including CO_2, N_2O and SF_6. With reference to a 10 MWe net power output and charging and discharging phases of 4 hours, the thermodynamic performance of the

☆ The 5th European Conference on Supercritical CO_2 (sCO_2) for Energy Systems will be held from 14 to March 16, 2023 in Prague, Czech Republic. More information on the event and the European sCO_2 Research & Development Alliance is available at the conference website: http://www.sco2.eu/.

https://doi.org/10.1016/j.energy.2022.125780

Available online 17 October 2022

novel cycles and fluids have been benchmarked against those of a steam power cycle of the same size. All the investigated layouts reached a Round-Trip Efficiency (RTE) greater than 70%, with supercritical CO_2 leading the comparison with RTE of 76.6%. The diameter of the spherical tanks at atmospheric pressure was found to be a key design parameter for the overall performance of any of the energy conversion systems analysed. Compared to adiabatic compressed air energy storage systems, the proposed approach had the advantages of constant pressure ratio, thanks to the working fluid change of state (or isochoric thermal regulation, in case of supercritical cycle) as well as the site independence, since underground caverns would not be required.

4. sCO_2 Experiments and Loops

Hofer et al. [6] designed and simulated under varying ambient and operating conditions a sCO_2 heat removal system for existing and future nuclear power plants. The system features a self-propelling operational readiness state that enables a fast start-up and consumes only 12% of the design thermal power input. By controlling the compressor inlet temperature via the air mass flow rate, and the turbine inlet temperature via the turbomachinery speed, the heat removal system was successfully operated together with a pressurized water reactor. Moreover, the performance analysis recommended to operate the system at the design compressor inlet temperature of 55 °C at any boundary condition. With decreasing thermal power input, the rotational speed of the turbomachinery must be decreased to keep the system self-propelling. Moreover, the turbomachinery design with a higher surge margin is to be preferred.

5. Fluid and Material aspects

Crespi et al. [7] explored the utilisation of dopants to increase the critical temperature of carbon dioxide as a solution towards maintaining the high thermal efficiencies of sCO_2 cycles even when ambient temperatures compromise their feasibility, such as those related to Concentrated Solar Power (CSP) plants. The numerical study investigated the use of hexafluorobenzene (C_6F_6) and titanium tetrachloride ($TiCl_4$) as possible dopants for the CO_2 at different operating conditions and working fluid compositions, and with reference to two cycle architectures. The study showed that CO_2-blends with 15–25%(v) of the cited dopants led to efficiencies well in excess of 50% for minimum cycle temperatures as high as 50 °C. The outcomes of the research demonstrated that the use of CO_2 blends has the potential to lead to high global efficiencies at attainable turbine inlet temperatures. Furthermore, the study paves the way to new tuneable working fluids and sCO_2 cycle layouts as an approach to maximise the overall efficiency of any sCO_2 power block.

Rath et al. [8] investigated the potential to optimise the performance of sCO_2 power cycles by selectively adding different substances in varying amounts to CO_2. The proposed screening methodology considers the reference equation of state for CO_2 in combination with a novel predictive multi-fluid mixture model that is suitable to a broader range of fluids compared to literature mixture models. After a preliminary screening of 135 fluids carried out with respect to two cycle layouts, five potential mixture candidates were shortlisted given a global efficiency increase of more than 4% compared to pure CO_2. For simple cycle layouts, the use of the noble gases such as xenon and krypton was found to be particularly interesting. In the recuperated case, the largest increases in thermal efficiency was calculated for SF_6 and propane (C_3H_8), when omitting the hydrofluorocarbons having a large GWP and/or ODP.

Harman-Thomas et al. [9] carried out sensitivity and quantitative analysis of four established chemical kinetic mechanisms to determine the most important reactions and the best performing mechanisms over a range of different conditions for direct fired sCO_2 power cycles. CH_3O_2 chemistry was identified as a pivotal mechanism component for modelling methane combustion above 200 atm. The proposed University of Sheffield (UoS) sCO_2 mechanism better modeled the ignition delay time (IDT) of high-pressure combustion in a large dilution of CO_2. Quantitative analysis of the newly developed UoS sCO_2 mechanism adapted from USC II proved its superior ability to model IDT against existing chemical kinetic mechanisms. This allowed the IDT of three different fuels to be more accurately modelled at conditions of the direct fired sCO_2 combustion. This mechanism can henceforth be used to better model the high-pressure combustion of both methane and syngas at the conditions of the Allam-Fetvedt cycle and, in turn, the design of the combustion chamber.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank all the members of the scientific and organising committees: prof. Václav Dostál, Mr. Otakar Frýbort, Mrs. Albannie Cagnac, prof. Uwe Gampe, prof. Markus Haider, prof. Andreas Werner, prof. Martin Rohde, prof. Jörg Starflinger, prof. Teemu Turunen-Saaresti and Mr. Alexander Hacks. A special thanks goes to the Editor-in-Chief prof. Henrik Lund for his agreement to publish the papers in this special issue.

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