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DESIGN AND SETUP OF THE SUCOO-LAB SCO_2 TEST FACILITY AT TU DRESDEN

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ABSTRACT

Compared to the current state of the art, power cycles based on supercritical CO_2 (sCO_2) offer the potential for significant increases in power density and efficiency and are thus seen as a promising element for a more sustainable and flexible heat utilization in the future. There is a particular need for experimental work in order to bring this technology to market maturity. For instance, it is necessary to validate theoretical approaches and to test and develop components.

As part of the supercritical carbon dioxide laboratory (suCOO-Lab), a test facility was set up at TU Dresden. The aim is to provide a flexibly usable and expandable test infrastructure for basic research, validation work, as well as small-scale component tests and development.

Key components of the system are an electric heater, two compressors and a powerful cooling system. Temperatures up to 300 °C and pressures up to 20 MPa allow covering of a wide range of parameters in the trans- and supercritical fluid region of CO_2. The integration of a capable measurement and data acquisition system ensures the continuous availability of measurement data at all relevant points in the rig. Experimental setups can be flexibly integrated into the process at various locations, which additionally allows the simultaneous use of different parameter ranges in one or more experimental setups. Furthermore, special care was taken within the selection of the components itself. All parts, including the compressors, are designed for a lubricant free operation ensuring high fluid purities. This is beneficial for experiments with pure CO_2 and also enables investigations of CO_2-mixtures.

This paper describes the design and the current status of the suCOO-Lab test facility at TU Dresden. Special emphasis is placed on the targeted parameter range, characteristic design aspects of the rig, and on the capabilities of measurement and data acquisition.

INTRODUCTION

The increasing global demand for energy calls for further development of existing technologies for a more economical, sustainable, and, above all, a more complete usage of available energy sources. Power cycles based on supercritical carbon dioxide (sCO_2) are a current topic in science and industry for a variety of applications, such as concentrated solar power (CSP), nuclear plants, waste heat recovery, or the utilization of geothermal heat [1–5]. Compared to other working fluids such as, e.g., steam, sCO_2 offers distinct advantages. Its special (non-ideal) properties in the supercritical state, as for example a liquid-like density, a low viscosity, or the absence of a phase change, enable the potential for a significant reduction in complexity and size of the cycle and its components as well as high thermal efficiencies with even simple cycle configurations and moderate temperature levels. Furthermore, the relatively low critical temperature of CO_2 ($\vartheta_{\mathrm{crit}} \approx 31$ °C), makes it applicable for a wide range of thermal heat sources of both, conventional and renewable origin.

However, there is still a considerable need for research to bring the technology to market maturity. Herein, a major aspect are the strong fluctuations in fluid properties in the near- and the supercritical region, which means that even small changes in temperature may lead to large variations for example in density or heat capacity. This affects all levels of development from fundamental research, process stability and control, up to design, manufacturing, and testing of components.

Referring to the compressor inlet temperature, for instance due to variations in the ambient temperature, this for example can result in significant operating point deviations with corresponding changes in efficiency [6,7]. In terms of the heat exchangers, especially the changes in the heat capacities can massively impede the heat transfer with corresponding effects on the proper performance of the device [8]. As a combination of individual effects, this consequently results in a noticeable

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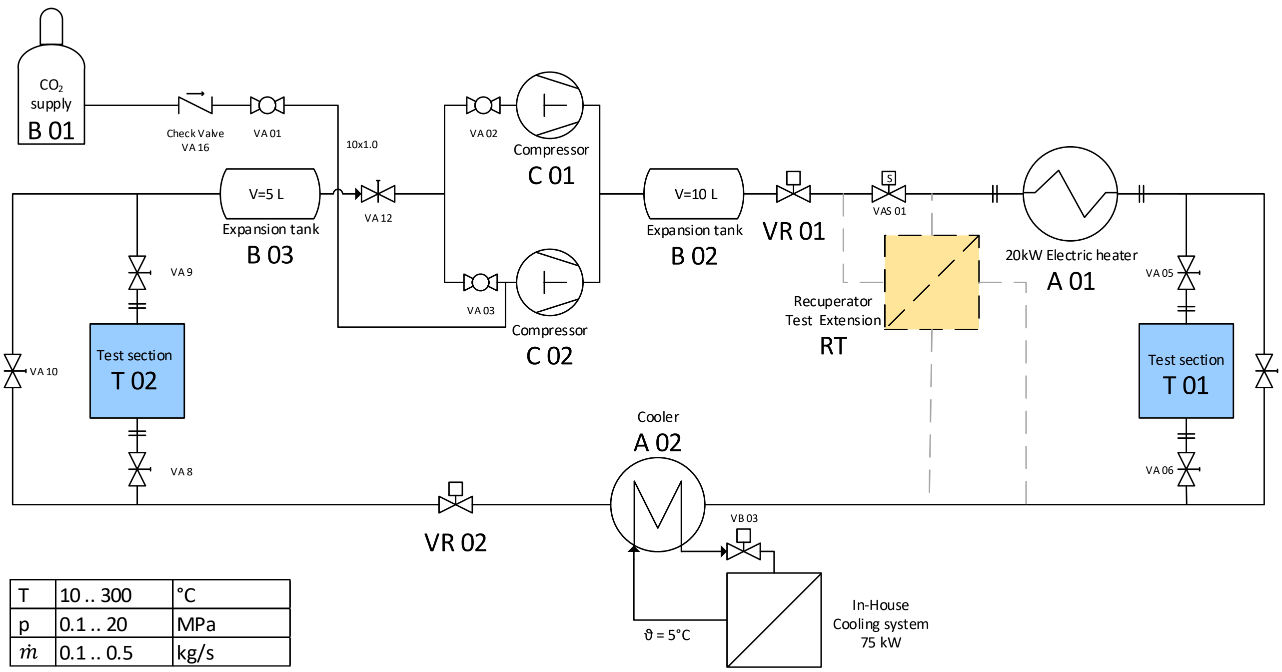

Figure 1: Basic layout of the test rig including targeted design parameters

temperature dependence of the whole cycle's efficiency which needs to be taken into account [9]. Furthermore, it has been (mostly theoretically) shown that CO_2 purity can also have a significant impact on process performance. On the one hand, even minor impurities can unintentionally lead to significant changes in efficiency [10]. On the other hand, efficiency increases are also conceivable through the selective admixture of additives [2,11,12].
For all these reasons, there is a particular need for experimental work to support and validate theoretical approaches, requiring a further expansion of experimental capacities. This includes in particular the previously mentioned aspect of fluid composition, which has so far only been experimentally addressed to a limited extent.

suCOO-Lab TEST-FACILITY –BASIC SETUP

To establish sCO_2 as an alternative working fluid in power systems in research and teaching at TU Dresden, the supercritical carbon dioxide laboratory (suCOO-Lab) was founded as a central platform for interdisciplinary sCO_2-projects with partners from research and development. As a part of this lab, a test facility was set up, providing a flexibly usable and expandable test infrastructure for basic research and validation work, as well as small-scale component tests and development.
Consequently, boundary conditions for the base setup were chosen to cover a sufficiently wide range in the near- and supercritical fluid region as well as to maintain the possibility for future extensions of the facility. As shown along with the block diagram in Figure 1, all components are designed to handle maximum CO_2-temperatures of 300 °C at pressures of up to 20 MPa. Mass flows of the supercritical fluid were targeted from 0.1 kg/s, for higher compression ratios and/or lower densities, up to 0.5 kg/s for near-critical compressor inlet states or in the case that the fluid circulates at higher pressures by only compensating pressure losses. Within this context, pipe sizes were set to18x2.00 mm and 2x 10x1.00 mm for sections of parallel flow.
As can be seen in the block diagram in Figure 1, the basic layout of the test rig consists of a closed-loop cycle in which the fluid circulates. Referring to the labels C 01 and C 02, the pressure build-up is realized via two piston compressors connected in parallel. For this purpose, air-driven gas boosters supplied by Maximator are used, which operate according to the principle of a double-acting piston. A principle sketch is given in Figure 2. By charging the large pistons with compressed air as driving medium, the smaller pistons are used to raise the pressure of the CO_2 up to targeted values. Herein, the dry-running principle enables a continuous lubricant-free operation. Furthermore, they are able to cover a wide operating range, from pure gas phase at ambient pressure up to trans- and supercritical regions. A separate connection of the second compressor (C 02) to the CO_2 supply (B 01) (cf. Figure 1) allows initial filling and pressurization of the system as well as simultaneous refilling

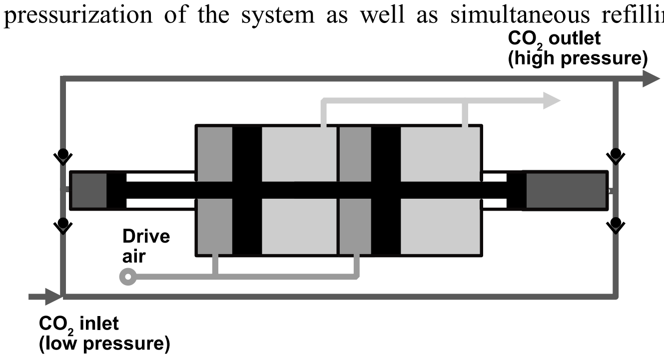

Figure 2: Principle sketch of the compressors

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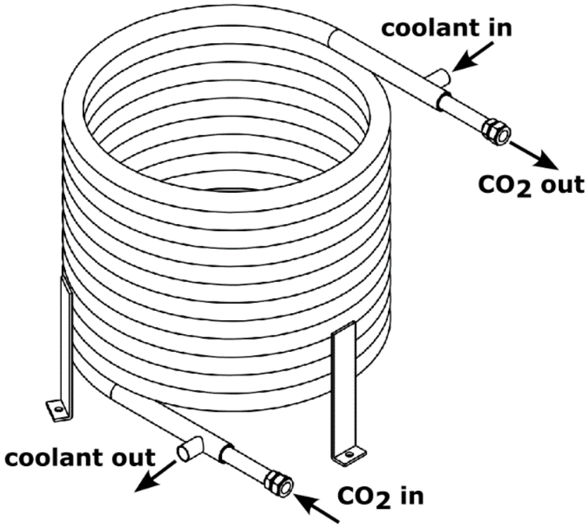

Figure 3: Coaxial heat exchanger used as cooler

during test runs. Two expansion tanks, located upstream (B 03) and downstream (B 02) of the compressors, provide hydraulic compensation for pulsations. Driving air is supplied via an in-house compressed air system, allowing volume flows of up to 6500 l(S)/min at pressures up to 10 bar, which fits the estimated requirements of the compressors for the aforementioned mass-flow conditions. However, as mostly lower driving pressures are needed for the gas boosters, upstream regulating valves allow precise control of the driving pressure separately for each device. In this initial stage of the rig, thermal input is provided by a 20 kW electrical heater (A 01), which, based on the previously mentioned mass-flow of 0.1 kg/s, provides sufficient capacities for temperatures up to 250 °C. However, as already mentioned, note that all components are designed for temperatures of up to 300 °C at pressures up to 20 MPa. Therefore, temperatures higher than 250 °C also at higher mass-flows than 0.1 kg/s will be achievable after the planned extensions of the rig.

Heat rejection is achieved by a coaxial heat exchanger (A 02), depicted in Figure 3. The strict implementation of a counterflow design with the CO_2 in the inner tube and the coolant in the outer tube enables precise temperature control as well as investigations of the heat transfer close to the critical point. The integration into the in-house cooling water system gives access to cooling capacities of up to 75 kW at constant coolant inlet temperatures of 5 °C and maximum pressures of up to 5 bar (limited by the coaxial heat exchanger). Temperature control is done by means of the mass flow, allowing the use of increased return temperatures of the coolant of up to 80 °C.

For experimental setups, two test sections are available, consisting of two face seal flanges, which allow a flexible integration of various test assemblies. The arrangement of one section directly after the heater (T 01) and one section downstream of the cooler (T 02) allows simultaneous investigations of different temperature levels. The pressure level in each test section can additionally be set by the two regulation

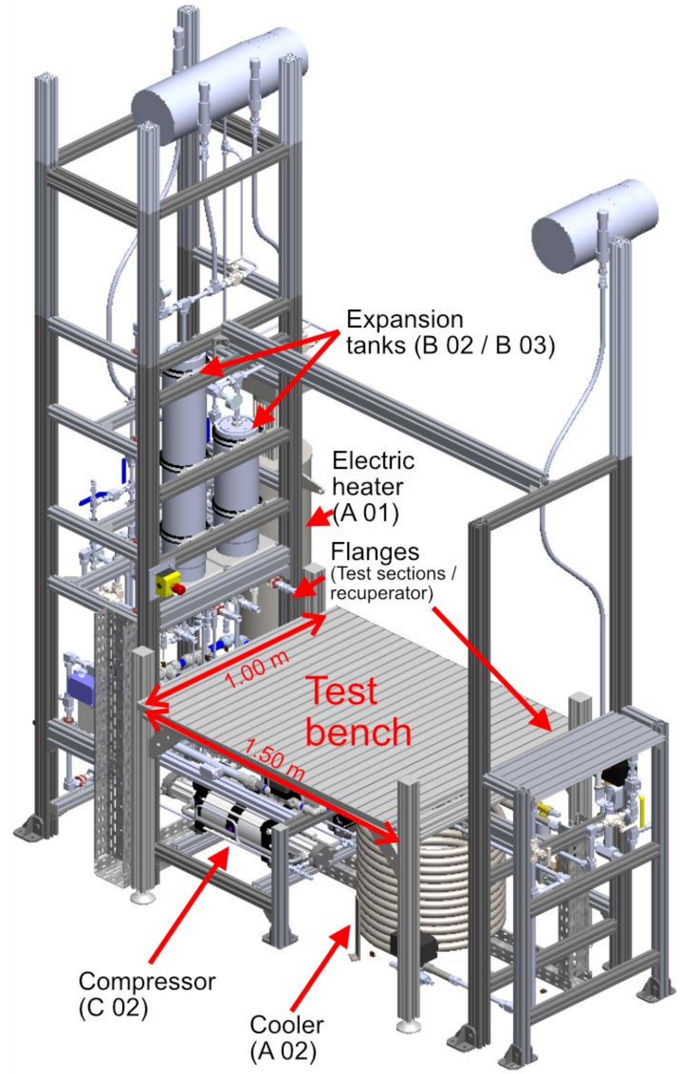

Figure 4: Assembly of the test-rig (CAD model)

valves VR 01 and VR 02. In addition to the test sections, further flanges are available which allow the direct integration of recuperator modules (RT).

To meet the space requirements on site and as can be seen in Figure 4, the components are arranged in a rack-like support system around a central test bench. In addition to a space-saving and clear structure, this also allows good accessibility to all components. The compressors (only C 02 visible in Figure 4) are mounted close to the ground and can be removed laterally with comparatively little effort if necessary. The large rack on the left side of the picture contains both expansion tanks as well as all pipe assemblies directly connected to the heater. The back-open construction, as well as a vertical arrangement of the pipes in different tiers, allows easy access to all valves and measurement equipment. The right side of the test-rig, on the other hand, contains the cold end of the system with the cooler situated next to the compressors. Again, the pipe assemblies directly connected to it are mounted in a small rack, which provides

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Table 1: Measuring device types installed on the test-rig

Fluid	Property	Measurement Device	Range	Uncertainty of the sensor	Location / Purpose
CO_2	Temperature	Thermocouple Type T, Class 1	−185 °C .. 300 °C	±0.5 K (≤ 125 °C) / $\pm 0.004 \cdot \lvert T \rvert$	Process monitoring / Test sections T 01/T 02
CO_2	Temperature	RTD PT1000, 1/3 DIN B	−100 °C .. 450 °C	$\pm(0.1 + 0.0017 \cdot \lvert T \rvert)$ °C	Test sections T 01/T 02
CO_2	Pressure	Piezoresistive pressure transmitter Keller PA23SY	0 .. 300 bar	±0.25 % FS	Process monitoring
CO_2	Pressure	Piezoresistive pressure transmitter Keller PA35XHTC	0 .. 300 bar ($T_{max} = 300\ °C$)	±0.05 % FS	Process monitoring HT / Test section T 01
CO_2	Pressure	Piezoresistive pressure transmitter Keller PA33X	0 .. 300 bar	±0.05 % FS	Test section T 02
CO_2	Mass-flow	Coriolis flow meter Rheonic RHM08L	0.008 .. 0.8 kg/s	±0.2 %	Process monitoring
Air	Temperature / Flow rate	Calorimetric flow meter IFM SD8500	−10 .. 60 °C; 14 -3750 l/min	±0.5 K ± (2 % MV + 0.5 % MEV)	Process monitoring
Air	Pressure	Piezoresistive pressure transmitter Keller PAA21Y	0 .. 10 bar	±0.5 % FS	Process monitoring
Water	Temperature	Thermocouple Type T, Class 1	−185 °C .. 300 °C	±0.5 K (≤ 125 °C) / $\pm 0.004 \cdot \lvert T \rvert$	Process monitoring
Water	Flow rate	Magnetic-inductive flow meter IFM SM6000	0.1 .. 25 l/min	± (0.8 % MV + 0.5 % MEV)	Process monitoring

access to all controls and instrumentation at its rear facing away from the test bench.

The central test bench consists of a height-adjustable table situated in-between the two mounting racks that can be used for variable test setups of both test sections. The flanges of the two test sections are placed to face each other along the length of the table, giving a total space for individual setups of approximately 1.50 m x 1.00 m.

DATA MEASUREMENT AND ACQUISITION

For process monitoring and control, the facility is equipped with a variety of measuring devices, to monitor selected fluid properties at all relevant process points in the loop. With reference to this, Table 1 shows a list of the sensor types used within the rig.

For temperature measurement at a total of 14 locations in the CO_2 part of the rig, type T thermocouples were chosen as they can measure punctually in the core flow, exhibit a high response capability to sudden changes and have a sufficient accuracy for the scoped range of temperatures. For an even better accuracy at the inlet and the outlet of both test sections, PT1000 resistance thermometers are optionally available.

Pressure measurement is performed throughout with piezo-resistive pressure transmitters. For general process monitoring, all relevant system points can be captured with an accuracy of ± 0.25% FS (Full Scale). At the inlet and outlet of the test sections, as well as in the high temperature sections of the rig, transmitters with an extended accuracy of ± 0.05% FS are installed. Furthermore, for safety reasons, all separable system parts are equipped with manual pressure gauges giving a direct information of the system pressure even when the data acquisition system is not running. The mass flow is determined after the compressors, between the expansion tank and the heater inlet. The Coriolis flowmeter used for this purpose covers mass flows of up to 0.8 kg/s, giving calibrated accuracies of ± 0.2%. Within the scope of the secondary media, the inlet and outlet temperature as well as the flow rate for the cooling water are measured. Again, temperature measurement is done by means of type T thermocouples.

For the flow-rate, a magnetic-inductive flow meter is used providing a range of 0.1 .. 25 l/min with accuracies of ± (0.8 % MV + 0,5 % MEV). With regard to the compressed air used to drive the compressors (C 01, C 02), pressure, temperature, and flow rate are monitored separately for each device. This allows a separate control as well as an exact balancing of both compressors, which particularly enables a more detailed analysis of their individual performance. The pressure is measured by piezoresistive pressure transmitters providing an accuracy of ± 0.5% FS for pressures up to10 bar. Temperature and flow are measured by calorimetric flow meters, which have a measuring range of −10 ... 60°C / 14 - 3750 l/min with accuracies of ± 0.5 K / ± (2 % MV + 0,5 % MEV).

Data acquisition is done via a WAGO 750 industrial IO System in connection with LabVIEW. The measurement data is redundantly available on several local hard disks as well as on a network storage, which also can be accessed remotely.

SAFETY ASPECTS

For safe operation, a number of precautions have been adopted concerning both the equipment and the installation site. The test rig is equipped with two solenoid valves, which are closed when no voltage is applied. The first one disconnects both compressors from the compressed air supply. The second valve, which is also depicted in Figure 1 (VAS 01), is located directly in the CO_2 line upstream of the heater preventing any circulation of the CO_2 in the closed state. This means that no operation can take place without an explicit and continuous signal by the control system. Similarly, a loss of power supply, e.g. also triggered by a manual emergency stop, causes the implicit closing of the valves.

To protect against impermissibly high operating temperatures, the fluid and the core temperature of the heater as well as the recooling temperature are monitored. If the measured values exceed the allowed temperatures, the heater is disconnected from the power supply and the fluid circulation is stopped by closing the solenoid valves leading to a safe power-off state. For protection against impermissibly high pressures, all separable sections are equipped with safety valves. Their direct connection to a ventilation line provides a safe removal of the blown-off media from the building in case of response.

Regarding the integration on-site and as shown in Figure 5, the space for the test-rig is spatially separated by metal-stud walls to

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Figure 5: Test facility in housing on-site

adjacent areas. System operation takes place from a separate control room so that no personnel is required within the immediate vicinity of the test rig during runs. Manual emergency stops in every reach in the test- and control room enable a direct and immediate shutdown of the system in any situation, leading to the aforementioned safe power-off scenario by switching off the power-supply for the heater and the solenoid valves. A gas warning system continuously records the CO_2 concentration within the ambient air of the test rig area. At elevated concentrations, a warning is set in the control interface and a ventilation system is switched on, which exchanges the room air via ventilation ducts integrated into the floor. If, nevertheless, higher CO_2 concentrations are reached, a gas alert is triggered giving optical and acoustic warnings to the user and the surroundings. Additionally, if the gas alarm persists over a certain time span, the system is automatically shut down.
The system has been designed throughout in accordance with the European Pressure Equipment Directive 2014/29/EU [13]. Additionally, compliance with the regulations is confirmed by a certified authority.

CURRENT STATE AND FUTURE EXTENSIONS

At time of submission of this paper, the mechanical work has been successfully completed. Current work is concerned with the wiring of the sensors, as well as the integration into the user interface of the control software. In parallel, preparations are being made for approval within the European Pressure Equipment Directive by a certified authority.
Beyond the commissioning and the initial tests, a first use of the test facility is planned within the SHARP-sCO_2 project, which has been started in November 2022 and which is funded by the European Union's HORIZON EUROPE Research and Innovation Programme. Herein, the suCOO-Lab test facility will be used to design and investigate sCO_2-air heat exchangers for use with concentrated solar power (CSP). As shown in Figure 6, in this context the test rig will be extended by a hot air loop providing a continuous hot air stream within the test sections. Recirculation of the air is intended to enable cost-efficient supply of the requested air temperatures. By doing so, blower inlet temperatures up to 300 °C and a targeted heater capacity of 60 kW will allow hot air temperatures up to 700 °C at mass flows of 0.15 kg/s and near ambient pressures.

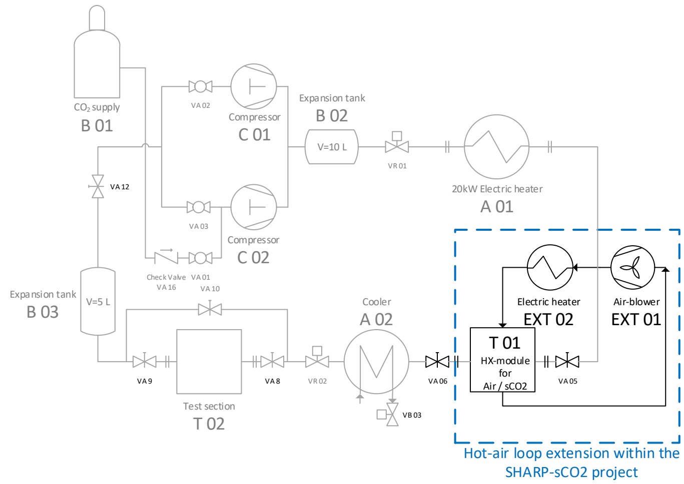

Figure 6: Planned hot-air-loop extension of the test-rig within the SHARP-sCO_2 project

CONCLUSION

As part of the suCOO-Lab at TU Dresden, a test facility was set up, providing a flexibly usable and expandable test infrastructure for basic research and validation work, as well as small-scale component tests and development. In addition to a wide operating range, the system offers flexible integration of experimental setups into two separate, simultaneously usable test sections. As a unique feature, the rig is designed to operate completely free of lubricants. On the one hand, this enables investigations with CO_2 at defined purity without the risk of dissolved lubricant residues influencing the results. On the other hand, this also makes the system suitable for use with CO_2 mixtures, which for instance enables the targeted investigation of the influence of impurities or the use of predefined sCO_2-blends.

NOMENCLATURE

Symbols

$\dot{m}$	[kg/s]	Mass flow
p	[Pa]	Pressure
ϑ	[°C]	Temperature

Subscripts

crit	Critical property

Abbreviations

CSP	Concentrated solar power
FS	Full scale
MEV	Measuring range end value
MV	Measured Value
S	Standard state ($T = 213.15$ K, $p = 101325$ Pa)

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