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A supercritical CO2 low temperature Brayton-cycle for residual heat removal

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Abstract

In this paper an innovative reactor safety system based on a sCO2 brayton cycle is presented. It will be developed within the next 2-3 years and this paper is a consciousness-raising publication showing the required steps of development. The research project is presented together with the objectives and the necessary developments and improvements of methods and technical components are discussed. Based on the thermodynamic cycle parameters are reflected and the initial design of the main components is introduced.

Introduction

Several researchers and institutes (Conboy et al. 2012, Dyreby et al. 2013, Fuller et al. 2013) are working on supercritical sCO2 loops with the objective to use them for conversion of thermal energy to electrical energy. Instead of having the focus on converting energy, the "supercritical CO2 heat removal system", sCO2-HeRo, safely, reliably and efficiently removes residual heat from nuclear fuel without the requirement of external power sources. This system therefore can be considered as an excellent backup cooling system for the reactor core in the case of a station blackout and loss of ultimate heat sink in nuclear power plants. sCO2-HeRo is a very innovative reactor safety concept as it improves the safety of currently operating boiling water reactors (BWRs) and pressurized water reactors (PWRs) through a self-propellant, self-sustaining and self-launching, highly compact cooling system powered by an integrated Brayton-cycle using supercritical carbon dioxide. This system provides breakthrough options with scientific and practical maturity, which will be finally demonstrated and experimentally proven by reactor simulation studies in the unique glass model of the Gesellschaft für Simulatorschulung GfS, accompanied by simulation studies with the German thermalhydraulic system code ATHLET.

The objective of the project is to show the proof of the concept of the sCO2-HeRo system. The proof of the concept is defined as the capability of handling different accident scenarios.

Fig. 1 – The self-propelling, self-sustaining and self-launching sCO2-HeRo System

In the case of a station blackout and/or loss of the primary ultimate heat sink sCO2-HeRo transports the decay heat to an alternative ultimate heat sink, as shown in Figure 1, and thus increases the safety of nuclear power plants. The system operates with supercritical CO_2, whose particular properties enable the circuit to be extremely compact. The compact design allows a retrofit into currently operating BWRs and PWRs and is therefore a breakthrough in nuclear safety. The functionality of the advanced self-sustaining safety system will be demonstrated by:

- Designing a compact heat exchanger to transport the decay heat to the supercritical CO_2 cycle which energy is also used for driving the self-propellant cycle,
- Designing a turbomachine set which is self-propellant and self-launching,
- Evaluation of a sink heat exchanger to transport the decay heat from the supercritical CO_2 cycle to the alternative ultimate heat sink (ambient air),
- Proofing the concept of sCO2-HeRo regarding safety, reliability and the possibilities for retrofitting by implementing the system into a unique glass model run by the Gesellschaft für Simulatorschulung GfS.

The feasibility of this very innovative reactor safety concept was already shown in reactor simulation studies and, for this reason, has the potential to become a breakthrough option by demonstrating its scientific and practical maturity. Different accident cases will be simulated to demonstrate the functionality of the self-propellant system and to validate that it is able to start without manual activation. This will be validated in the glass model and shows the robustness of the cooling system. sCO2-HeRo will proof that autarkic systems will increase the safety of nuclear power plants and lead to new orientation in nuclear safety.

System description

The system, simplified in Figure 2, consists of a compact heat exchanger, a turbomachine set (turbine, generator and compressor), a sink heat exchanger and interface components for the specific integration at the different laboratories. To design the individual components advanced numerical simulation (CFD) as well as experimental verification will be used. For the integration and validation of the system the German reference code ATHLET and the glass model will be used. The aim of the project is to show the proof of the concept of the sCO2-HeRo system to open-up new avenues towards reactor safety design. Considering the Technical Readiness Level process the sCO2-HeRo system will be brought from the "concept TRL-2" to "experimental proof of concept TRL-3".

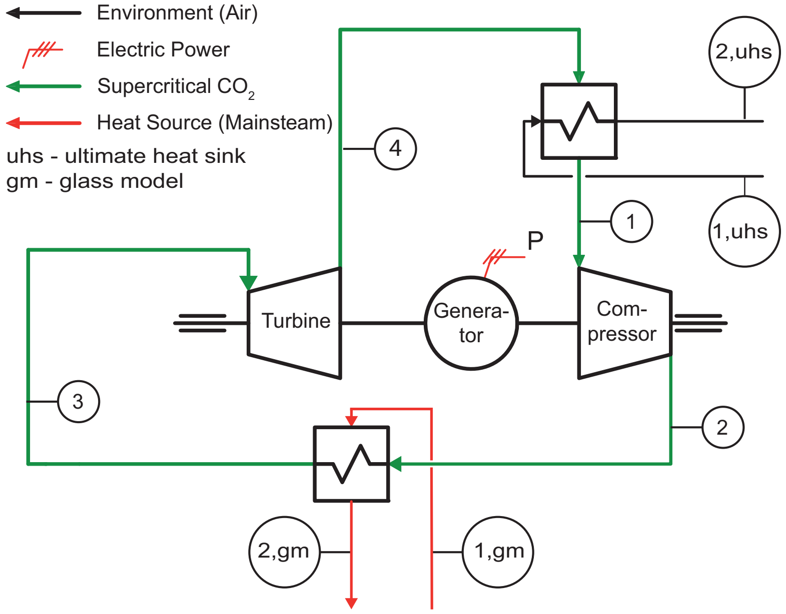

Fig. 2 –Brayton cycle of sCO2-HeRo system

Methodology

Numerical simulations using the German reactor accident analysis code ATHLET were already used to show the general feasibility of the concept (Venker, 2013). Venker et al. (Venker, 2014) performed simulations of station blackout and loss of ultimate heat sink events for a generic boiling water reactor equipped with the sCO2-HeRo cooling system. The results show a strong potential to increase the grace period significantly, if the selfpropelling residual heat removal system is installed. However, it should be mentioned that there are many assumptions in the code, which are based upon simplified models without the appropriate validation.

To retrofit the sCO2-HeRo system into operating EU LWR fleet it needs to be a very compact system on those parts (mainly the compact heat exchanger) installed as close as possible to the reactor core. For this reason, supercritical CO2 has been selected which has the benefit of being non-hazardous and enables a compact design. CFD Large Eddy Simulation (LES) will be conducted to design and optimize the compact heat exchanger on a fundamental research level. The sink heat exchanger, transferring the heat to the alternative ultimate heat sink preferably air; will be supported by the research results from the compact heat exchanger. The focus for the sink heat exchanger is on the energy consumption and not on compact design. The sink heat exchanger will be electrically driven from the turbomachine set assuming electrical energy to be submitted from the generator. The turbomachine set consisting of the compressor, turbine and generator mounted on one shaft will be designed to have a positive energy balance. This requires an optimized design also for off-design conditions regarding performance. A CFD closed loop approach is intended to be used to connect the turbine, compressor and generator characteristic in one loop which provides the flexibility to optimize the performance in one step. The CFD closed loop approach is an advanced simulation method within the research of turbomachines from Benra und Dohmen (Benra, 2010). The system integration strategy of the sCO2-HeRo approach is shown in Figure 3. The integration of each component is ensured by using the German reference code ATHLET which represents the thermodynamic characteristic of the whole sCO2-HeRo system by modelling the individual components based on performance maps. These individual performance maps will be developed in a first step with advanced numerical simulation and will be verified in a second step by experimental results. A final validation of the code ATHLET will be achieved with the experimental results of the glass model especially considering different accident scenarios.

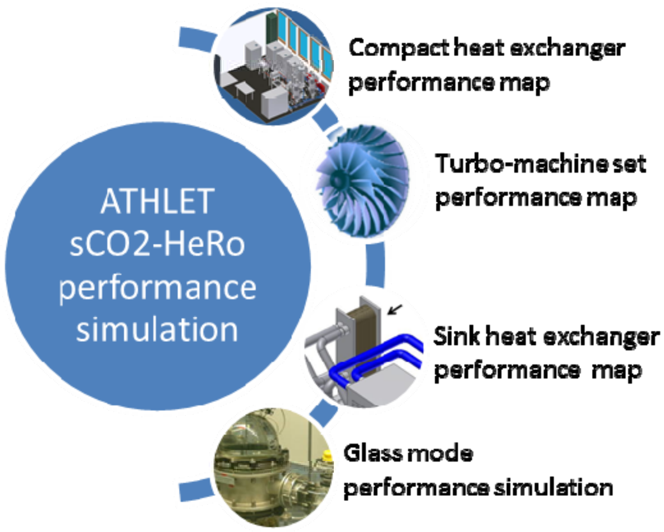

Fig. 3 – System integration strategy

Ambition

Ground breaking aspects of the project are:

- Development of a self-propellant safety system for heat removal in nuclear power plants

- Fundamental knowledge about heat transfer in turbulent, supercritical flows, and its translation to practical heat transfer correlations
- The application of diffusion welded compact heat exchanger to nuclear reactors
- Design criterions for the turbomachines working in the supercritical regime close to the critical point
- Advanced blade contouring for operation in the supercritical regime close to the critical point
- Autarkic start-up system (self-launching)

The overall ambition is the development of a **self-propellant safety system** for heat removal in nuclear power plants. For the development of this system several aspects must be understood and fundamental knowledge on specific aspects must be gained:

- A **profound understanding of the turbulent flow of supercritical fluids** is especially important when considering wall to fluid heat transfer. Reynolds averaged models for such flows do not have predictive capabilities that are useful for design purposes. Large Eddy Simulations (LES) of the supercritical flow in parts of the compact heat exchanger, including conjugate heat transfer in the wall regions, will be performed in the geometry of the heat exchanger to provide in depth understanding of the underlying physics. Moreover, the project will deliver fundamental knowledge about heat transfer in heat exchangers in the supercritical regime.
- To fulfill the objective of the project, **diffusion welded compact heat exchanger,** a technology that has never been applied before to such an application, will be developed. Diffusion welded heat exchangers offer excellent opportunities to reduce the dimensions of a heat removal system significantly. Thus the sCO2-HeRo system will become very attractive to existing nuclear power plants. Although a compact heat exchanger is used in a supercritical CO2-loop at Sandia National Laboratories, U.S.A. as a recuperator, the application range in a nuclear reactor is very ambitious. The operation performance of such a compact heat exchanger is unknown taking for instance the declining decay power into account which moves the system's (and the heat exchanger's) state from design point to off-design point conditions. The way to get this information is to perform experiments in a two-stage approach: At first experimental data will be gained testing only a few heat exchanger plates in the SCARLETT test facility from University of Stuttgart (Flaig et al. 2015). The data shall be used to validate the numerical predictions. The second step is to investigate the full heat exchanger and get data up to the limits of it. Even partial blockages will be investigated. With these experiments the robustness of the heat exchanger will be demonstrated. Finally, one full heat exchanger will be built and implemented into the glass model.

- Cycle analyses have shown the potential of the system, but have also pointed out the need of high efficient turbo-machines, working over a wide range of inflow conditions. The thermodynamic state point at the compressor inlet is close to the critical point. Moderate changes in inlet temperature, which result from temperature changes at the heat sink, can result in a change of density by a factor of two and more. This ultimately results in a change of volume flow also by factor of two. Thereby the operation point of the compressor is shifted from shock limit to surge limit or vice versa. The ambition is to provide the **design criteria for turbine-machines in supercritical CO2** applications near the critical point. An **advanced blade contouring** for compressors shall be developed which will be very robust to flow angle variations and allows reliable operation for changing inlet conditions. The advanced blade contouring shall be scalable and therefore shall allow the use in different nuclear power plants.

Thermodynamic process

The Fig. 4 below is showing the initial thermodynamic process in the *h*-*s* diagram. Hence, the figure is used for qualitative explanations in the following. Compressor inlet conditions are close to the critical point and a pressure ratio of 1.5 is used.

Only one compressor stage is needed for this pressure ratio making the design simple and thereby more robust then a multi stage design. The sCO_2 is heated up to 200 °C by the decay heat from the steam generator. It is also possible to increase the turbine inlet temperature because the steam generator has a maximum temperature value of 280 °C. Higher temperature leads to higher surplus work and is hence a benefit. This benefit is not used for the first prototype to have a safety margin. At this early stage of development efficiency of the compressor and the turbine can only be assumed. Flow coefficient is considered and a safety margin is applied. Finally this gives a compressor efficiency of about 65 %.

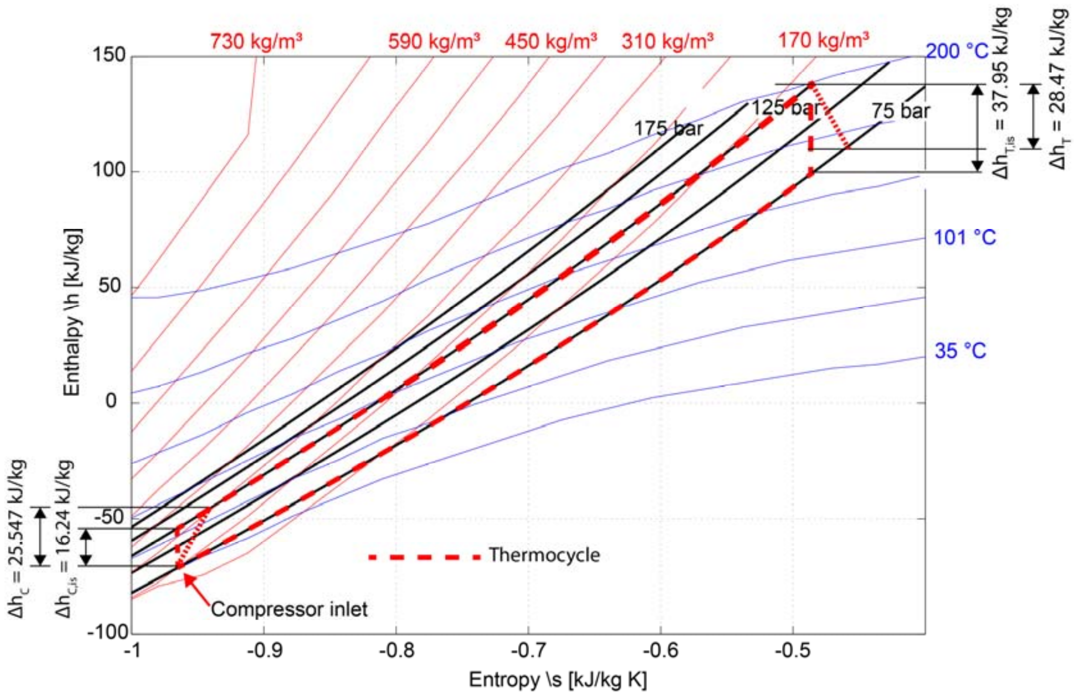

Fig. 4 – Thermodynamic cycle in the h-s diagram

Basic design of the turbomachine including the generator

A first design of the components is already conducted. Figure 5 is showing the compressor, generator, and the turbine. On the left shaft end the compressor wheel (green) is mounted. Rolling bearings are used to cover the radial and axial loads. The rolling bearings are permanent lubricated hence no oil supply is necessary making this system independent from external aggregates. The generator is shown in yellow color. At the right shaft end the turbine wheel (red) is mounted. The through-flow via both wheels is radially oriented. The passages that are changing the flow direction from axial to radial and radial to axial are blade less. On the one hand this design is very simple and on the other hand it is an appropriate design for small mass flow.

A part of the CO_2 outlet mass flow of the compressor is taken for cooling purpose. This mass flow is directed through holes to the generator and flows to the turbine where it is mixed with the flow coming from the turbine stator. The cooling mass flow can roughly be adjusted by the number of labyrinth seals used.

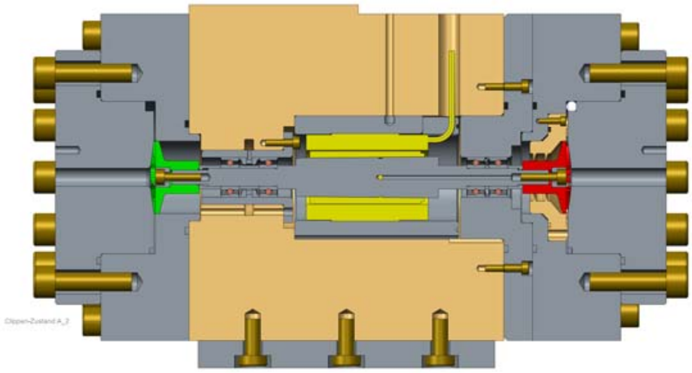

Fig. 5 – Design concept of the turbomachine including the generator

Design of the turbomachines

In order to achieve the foregoing described objectives first the available tools for the design process of compressors and turbines must be adapted to the supercritical CO_2 fluid. The enhanced design tools deliver data for generating a flow path geometry by using a standard CAD volume model. This geometry shall allow the operation of the turbo-machines in the supercritical regime of the flow and especially for the compressor close above the critical point. Utilizing the flow path geometry of each turbo-machine component numerical models will be derived in order to generate performance maps of the compressor and the turbine by a numerical simulation tool (CFD) which requires the adaption to the supercritical CO_2 fluid as well. Outgoing from this aerodynamic behavior an optimization of the turbo-machines will be performed in order to pay detailed attention to the interaction of the components.

After assembling the turbomachine set will be tested in the SUSEN CO_2 loop at CV Rez (Hajek and Frybort, 2014). After a successful test, the turbo-machine is implemented in the glass model at GfS.

Design of the flow path

The turbo-machine design process starts with a one dimensional calculation (1D) along a streamline to fix the velocity triangles at each position of the turbo-machine components. At this point, a main challenge of the design is the aerodynamic state at the inlet of the compressor which is close above the critical point. In this flow regime changes of the inlet temperature will have a strong impact on the density of the fluid. The design of the compressor has to cover the induced variation of inlet volume flow which requires a special blade shape design in order to preserve a wide range of operation and to sustain the efficiency on a high level.

The size of the turbomachine set is very challenging. Because of the limited capacity of the heat source from the glass model the mass flow of the supercritical CO2 fluid in the loop will be very small. This inevitably leads to very small dimensions of the turbo-machines which are hard to design in terms of high efficiency regarding the leakage flow. A proper concept to sustain the leakage flow rates at very small values is essential for high efficient small machines. This can be achieved by using shrouded impellers which allow for controlling the internal leakage flow by labyrinth seals. The outcome of the 1D method is a set of basic geometry parameters, e.g. outer wheel diameter, shaft diameter, blade height, meridional shape of the flow channel, blade count and casing geometry together with the velocity triangles which define the rotational speed of the impeller by the maximum circumferential velocity. A commercial three dimensional CAD volume model is fed by these preliminary geometry data for both turbo-machine components in order to develop a volume model for the compressor and for the turbine including also the casing.

From the CAD volume model an appropriate numerical model will be derived for both turbo-machines. The calculation of the performance maps is conducted with the commercial numerical solver of the Reynolds Averaged Navier-Stokes equations (RANS) CFX 15.0. The solver will be adapted to the supercritical CO2 fluid before performing the calculations (Schuster, 2012).

The attained performance maps for compressor and turbine are on a preliminary basis, because a collaboration of both maps is requested in order to run both machines at the same speed of rotation with the same mass flow and the appropriate pressure ratios. This demands an optimization process which covers both turbo-machines. Because independent optimization of each machine may lead to an optimum for the regarded machine but must not lead to the optimum for the combination of both machines, a progressive optimization procedure is planned. A numerical model of the complete Brayton cycle will be built up which allows to take into account all components of the loop for the numerical simulation. The flow field in the compressor and in the turbine for the same speed of rotation will be calculated by CFD. The outlet conditions of the heat exchangers, temperature and pressure and mass flow of the supercritical CO2 fluid will be determined from their characteristic performance maps. It is necessary to treat the turbine to have at least the same or even more power output than the compressor requires for its compression work. This procedure is based on the advanced approach presented by Benra and Dohmen (Benra, 2010). After a certain number of iteration procedures the performance maps of both turbo-machine components should show coaction which qualifies the maps to be used in the nuclear safety code ATHLET to determine the decay heat removal by the sCO2-HeRo system. For this, the performance maps need to be generalized and converted into non-dimensional form in order to show validity for all sizes of turbo-machine sets. Besides the proof of the concept within the glass model the software ATHLET is then able to perform simulations showing the applicability of the sCO2-HeRo system for nuclear reactors of BWR and PWR types.

The turbomachine set will be validated in a component test in in the lab of CV Rez. Pressure as well as temperature upstream the compressor respectively upstream the turbine will be adjusted to consider different load points. Thereby, changes in ambient temperature and decay heat can be covered. During the measurements pressure and temperature at the inlet and outlet of the turbo-machines as well as the electrical power output of the generator are recorded. Based on these data the experimental performance map of the sCO2-HeRo system is derived and compared to the predicted one. To verify the mechanical calculations measurements of vibration and stresses will be performed as well.

Heat Transfer Design

Important parts of the sCO2-HeRo system are the heat exchangers that transfer the heat from the nuclear core to the ultimate heat sink. The compact heat exchanger has to be extremely small, due to stringent space limitations. Although similar heat exchangers are available on the market, no data are available regarding their performance under the applied conditions and for the corresponding working fluids. For these reasons, it is of major importance to design, investigate and test the compact heat exchanger and the sink heat exchanger first before connecting them to the glass model.

Research will be performed by using numerical and experimental tools. Both serve ATHLET and the performance maps in a complimentary way. Ultimately, the compact heat exchanger for the PWR glass model will be manufactured and delivered to GfS. The work flowchart can be found in the figure below.

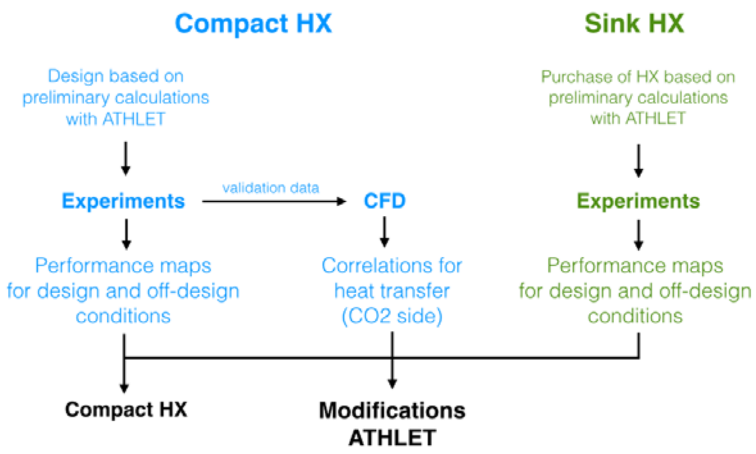

Fig. 5 – Scheme showing the heat transfer investigations and heat exchanger development

Experiments shall be carried out in the test loop SCARLETT at University of Stuttgart (Flaig et al. 2015). The first tests will be carried out with max. two plates that are joined by diffusion welding. It is intended to evaluate four different test configurations, with different channel geometries for both the CO_2 and the condensing steam side. After the selection of the channel geometry, a prototype compact heat exchanger will be diffusion-welded and tested in the SCARLETT facility as shown in Fig. 5.

It is important to obtain data under design and off-design conditions for the performance map. The parameter range selected will cover both the low temperature application (80°C, condensing) and the high temperature application for BWR or PWR steam generators (70 bar, 270°C). In this way, the conditions of both the glass model and a possible reactor application are investigated. In addition, the limits of the heat exchanger, e.g. under part load, will be evaluated. In a subsequent testing phase, the effect of local blockages on the overall heat transmission will be investigated. These blockages shall be applied to both sides of the compact heat exchanger. The gained data will be translated to performance maps and will be for validation purposes of the numerical methods.

CFD will primarily be used to develop practical and accurate heat transfer correlations for this specific application for ATHLET. Moreover, once validated, CFD will deliver complementary information to the performance maps for conditions and geometries that cannot be covered by the experiments and will help to optimize the design of the compact HX. Amongst other studies, a recent international benchmark study (Rohde et al., 2015) revealed that current generic Reynolds averaged models and heat transfer correlations for supercritical flows have very limited predictive capabilities for design purposes. For this reason, Large Eddy Simulations (LES) of the supercritical flow in parts of the heat exchanger (HX) will be performed including conjugate heat transfer in the wall region Such LES are an enormous challenge due to the great variability of the properties in supercritical fluids, the small scales due to the high Prandtl number near the critical point and the non-straightforward geometry in the HX. Nevertheless, LES seems to be a necessity to be able to capture the relevant characteristics of heat transfer in these flows and to develop meaningful correlations for ATHLET. To perform the LES on the CO2 side of the HX a recently developed Navier-Stokes solver based on the discontinuous Galerkin Finite Element Methods (DGFEM) to LES with variable properties will be extended. DGFEM methods are well known from the radiation transport field, are very robust for large variation of properties and have recently attracted interest in CFD due to their robustness and high accuracy. Especially the robustness is an attractive feature when considering supercritical fluids with the mentioned large variability in properties. This DGFEM automatically is applicable to generic geometries.

On the steam-side of the HX a loop-based flow model augmented with state-of-the art correlations from literature for the local heat transfer with the wall will be used. In this way a complete coupling between CO_2 and the steam side is established. Most of the difficulties are to be expected on the CO_2 side as here the most complex physics takes place.

Summary and Conclusion

The aim of the “supercritical CO2 heat removal system”, sCO2-HeRo, is to safely, reliably and efficiently remove the residual heat from the nuclear reactor vessel without the requirement of external power sources. The sCO2-HeRo system is a backup cooling system for nuclear reactors or the spent fuel storages in the case of a station blackout and the loss of ultimate heat sink. The sCO2-HeRo aims to improve the safety of both currently operating and future BWRs and PWRs through a self-propellant, self-sustaining and self-launching, highly compact cooling system powered by an integrated Brayton-cycle using supercritical carbon dioxide. The system is powered by the decay heat alone and, thus, can deal with accidents that are beyond design.

Main components of the sCO2-HeRo brayton cycle are a compact heat exchanger, a turbomachine set and a heat exchanger connecting the cycle to the diverse ultimate heat sink. A demonstration unit of the sCO2-HeRo system will be installed in the glass model located at KSG|GfS in Essen, Germany in order to demonstrate the feasibility of the system. Finally, the potential of this system to deal with a range of different accident scenarios and beyond-design accidents will be shown with the help of the German nuclear code ATHLET.

Acknowledgment

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