sCO2-4-NPP: Innovative sCO2-Based Heat Removal Technology for an Increased Level of Safety of Nuclear Power Plants

Deliverable 5.4

Thermodynamic performance of the heat recovery system integrated into the plant

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R	Document, report excluding the periodic and final reports	X
DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	
Dissemination level		
PU	PUBLIC, fully open, e.g. web	X
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Table of contents

List of Tables

List of Figures

1 List of Acronyms

Abbreviation / Acronym	**Description / meaning**
ATHLET	Analysis of THermalhydraulics of LEaks and Transients (system code of GRS)
CHX	Compact Heat Exchanger
ClaRaPlus	Component library in Modelica
CVR	Centrum výzkumu Řež
Dymola	Dynamic modelling laboratory, modelling and simulation environment
EDF	Électricité de France SA, French utility
KSG-GfS	Kraftwerks-Simulator-Gesellschaft Gesellschaft für Simulatorschulung (company)
MODELICA	Standardized object-oriented modelling language
NPP	Nuclear Power Plant
PV	Pressure Vessel
P&I	Piping and Instrumentation (diagram)
SBO	Station Black Out
sCO_2	Supercritical carbon dioxide
TAC	Turbo Alternator Compressor
TISC	Co-simulation environment developed by TLK-Thermo GmbH
TS Media	Library in Modelica for thermodynamic properties
UHS	Ultimate Heat Sink
UJV	ÚJV Řež a.s.
USTUTT	Universität Stuttgart
XRG	XRG Simulation GmbH

2 Executive Summary

The content of the current deliverable D5.4 follows on from the deliverable D2.2 (Hofer, et al., 2021) where the dynamic response of the sCO_2 system integrated into the specific NPP to the station blackout was presented considering that the ambient air temperature is +45 °C.

Working on this deliverable D5.4 the aim was to (1) simulate the integrated sCO_2 system response for changing ambient air conditions and to (2) present one of the possible start-up procedures, namely the push-up starting procedure. In the present deliverable, the starting procedure shall be presented for +45 °C ambient air temperature. Concerning task (1) CVR make use of changing the sCO_2 loop filling and ultimate heat sink (UHS) bypassing to achieve constant CO_2 pressure and temperature at the compressor suction. As a variant approach USTUTT make use of changing the number of UHS sections that are in operation during the changing ambient air temperature. Concerning task (2) CVR and UJV propose that the sCO_2 loop is being filled and started with the help of an expansion tank (bladder or diaphragm). From this tank, liquid CO_2 is transported to the CO_2 evaporator and then through the appropriate valves to the sCO_2 loop interior. The next variant of the start-up procedure, namely the operational readiness state procedure, was already analysed in D2.2 with ATHLET (chapter 5.3.3) and additional analysis with the Dymola will be conducted in the future to further support the comparison of the pros and cons of the two methods so that the more convenient of them might be utilised. However, before we can make this comparison, we will need to perform the push-up start simulation for as low an ambient air temperature as -45 °C which turns out to be a rather complicated task with two phase CO_2 in the loop. Results of such a simulation shall be part of one of the next deliverables.

As for the deliverable D2.2, the sCO_2 system model was prepared by CVR in the Dymola environment and coupled with the VVER-1000 nuclear power plant block model prepared by UJV in ATHLET. To couple these two models the TISC software was utilised. The USTUTT coupled model (Konvoi PWR+sCO_2 system) was prepared within the ATHLET environment completely.

The results of this deliverable may serve as an input for the subsequent decisions about the sCO_2 system control strategies and start-up procedure. Since the sCO_2 loop model used in this simulation does not consider the current state of the heat exchangers design, it is not possible to conclude about their temperature load limits.

3 Introduction

The present deliverable consists of two main parts. In chapter 4, the coupled simulation of the sCO_2 system with VVER-1000 (UJV and CVR application case in ATHLET and Dymola) and Konvoi (model prepared by USTUTT; KSG-GfS NPP simulator application case) nuclear power plant block after the SBO occurs is described for low ambient air temperatures. In chapter 5 we concentrate on the sCO_2 loop push-up starting procedure when the ambient air temperature is +45 °C. In some of the next deliverables the push-up starting procedure will need to be simulated also for -45 °C ambient air temperature which turns out to be rather difficult case with two phase CO_2 in the loop.

In the deliverable D2.2 (Hofer, et al., 2021), the dynamic behaviour of the sCO_2 system integrated into the specific nuclear power plant (NPP) was mainly studied for the ambient air temperature of +45 °C. In that case, turbo alternator compressor (TAC) speed control, UHS fan speed control and water condensate outlet temperature control (ATHLET side) were adopted. For low ambient air temperatures such as -45 °C, CVR adopted additional measures to compensate for very low CO_2 temperature within the UHS that causes not only low CO_2 temperature at compressor inlet but also a decrease of the CO_2 pressure within the loop if this loop is treated in the same way as for +45 °C (closed loop with all UHS sections in operation). In this respect, CVR suggests incorporating UHS bypassing and sCO_2 loop change of the filling. A change of the sCO_2 loop filling would be made possible by the presence of the expansion tank that is suggested here to serve also for the sCO_2 loop start-up (Figure 28).

Concerning the push-up starting procedure, the sCO_2 loop before the SBO occurs is kept at some overpressure above the ambient air pressure to ensure that no air may penetrate the loop. After the station blackout (SBO) occurs, liquid sCO_2 from the expansion tank flows through the CO_2 evaporator and appropriate valves into the loop and starts to rotate the TAC. The variant method of the sCO_2 loop start-up, namely the operational readiness state, was already analysed in D2.2 with ATHLET (chapter 5.3.3) and additional analysis with the Dymola will be conducted in the future to further support the comparison of the pros and cons of the two methods so that more convenient of them might be utilised.

4 Analysis of VVER-1000 with ATHLET/Dymola

In this chapter, we will concentrate on the description of the sCO_2 loop model in Dymola and the main results of the coupled simulation of the sCO_2 system and VVER-1000 block after the SBO occurs. During the 72 hours of the heat removal campaign, the ambient air temperature changes continuously from +15 °C to -45 °C that corresponds to the conservative and extreme weather conditions. USTUTT summarized its results in chapter 4.5.

4.1 Heat removal system

Figure 1 shows the CO_2 side of the sCO_2 heat removal loop in the Dymola modelling environment. The meaning and basic function of the individual components are described in Table 1. More detailed information about the design of the components is given in the deliverable D2.2 (Hofer, et al., 2021). The whole heat recovery system consists of four sCO_2 loops (one loop per one steam generator). One loop of the heat removal system is being switched off when the heat absorbed in the CHXs by the CO_2 drops below 5.4 MW per one loop.

Table 1: sCO_2 loop components

Symbol	Component	Note
1	Turbocompressor	Placed in a shelter (20 °C)
2	Interconnecting piping	The compressor outlet (ground level) is connected to the CHX (33 m above the ground). Mostly in the building (20 °C)
3	CHX (CO_2 side)	CHX is an interface for coupling of ATHLET (water side) with Dymola (CO_2 side). The water side of the CHX is then connected with the steam generator of the VVER 1000 secondary loop. In the building (20 °C)
4	Interconnecting piping	Connects CHX with the turbine. Mostly in the building (20 °C)
5	Turbine	Placed in a shelter (20 °C)
6,7	Interconnecting piping	Modelled as if in the shelter (20 °C)
8	UHS	Ultimate heat sink (CO_2/air heat exchanger). Outdoor
9,10	Interconnecting piping	Modelled as if in the shelter (20 °C)
a	Filling	Serves for changing the sCO_2 loop filling during the heat removal campaign. Control variable is mass flow rate (PI controller). Controlled variable is the pressure at compressor suction (126 bara)
b	Divider	This component function is to switch off one sCO_2 loop when the heat to CO_2 medium falls below 5.4 MW within one CHX.
c	TAC speed control	Serves for changing the sCO_2 loop CO_2 mass flow rate. Control variable is speed of TAC (PI controller). Controlled variable is the temperature at the turbine inlet (250 °C). Component serves in place of the frequency converter and motor/generator (electrical part of the loop has not been modelled yet. In the future, simple electrical/mechanical coupling of chosen components shall be incorporated to the model.

Table continuation

Number Letter	Component	Note
d	UHS bypass valve	For low ambient air temperatures, this valve opens and bypasses the UHS so that the cold stream of CO_2 coming from UHS is mixed with the hot stream coming from the turbine outlet. Mass flow rate is a control variable (PI controller). The controlled variable is compressor inlet temperature (+55 °C)
e	Fan speed control	Fan speed is a control variable (PI controller). The controlled variable is a compressor inlet temperature (+55 °C)

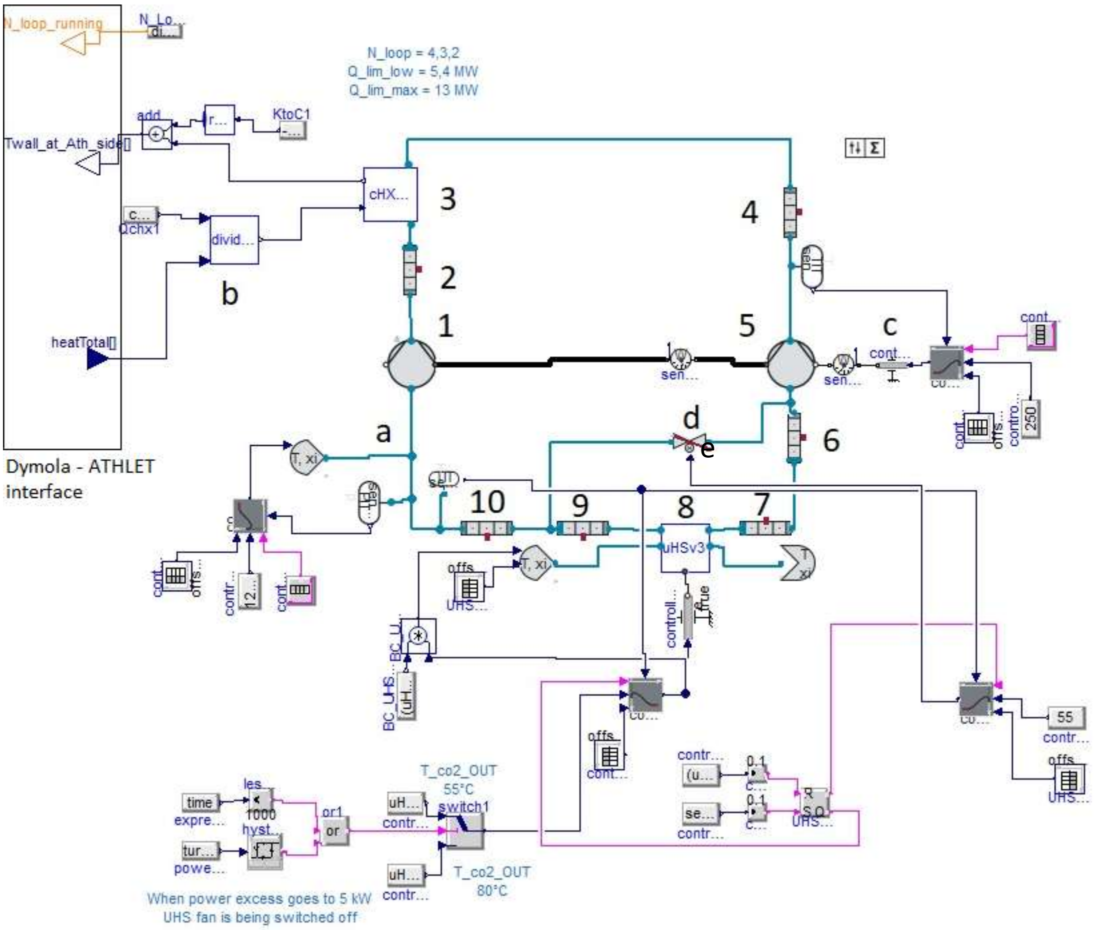


Figure 1: Scheme of the CO_2 side of the heat removal system in Dymola modelling environment

Comparing the current Dymola model of the sCO_2 loop with that presented in the deliverable D2.2, here the UHS bypass valve (component d) and the loop filling line (component a) were added in addition. If the push-up starting method would be adopted (Figure 28), adding a new filling line (Figure 28, line a) to the sCO_2 loop would not probably be a serious problem as in this case the expansion tank usage is assumed already for the starting period. Modelling instruments are summarized in Table 2.

Table 2: Modelling instruments

Software	Version	Note
Dymola	2021x	Commercial modelling and simulation environment
Modelica Standard Library	4.0.0	Free Modelica library
ClaRaPlus	1.4.0	Commercial Modelica library
ClaRaPlus_CVR	1.3.5	Adopted ClaRaPlus library
TS Media	1.6.1	Commercial fluid properties Modelica library
TISC	2.7.3	Commercial coupling environment
ATHLET	2.2a	Thermal-hydraulic code for nuclear power plants simulation

4.2 Integration into the NPP

The ATHLET model of Temelin NPP (VVER-1000/V320) is used in the simulation with the operating sCO_2 system. The water side piping and CHX of the sCO_2 loop were added to each of the four steam generators in the ATHLET model. The CO_2 side of the sCO_2 loop including the CHX walls is modelled in Dymola. The coupling interface between ATHLET and Dymola is at the steam-water side of the CHX walls. A coupled system of the ATHLET and Dymola uses the coupling method previously developed at UJV Rez for coupling ATHLET and FLUENT codes. Supervisor code written in C programming language manages the run of the coupled system. Communication of supervisor with Dymola is done with the help of the TISC Suite developed by TLK-Thermo company. Adaptation of the supervisor for communication with TISC was created by XRG.

The coupling method is explicit in time. Coupling parameters are exchanged between the codes in constant 0.5 s coupling time steps. The coupling time steps are different from the variable internal time steps used in ATHLET and Dymola. During every coupling time step, Dymola sends to ATHLET temperatures along the water-steam side of CHX walls and the number of working CHX. ATHLET sends back to Dymola heat powers removed by the individual control volumes of working CHX and also the temperature of condensate at CHX exits. Dymola models only one sCO_2 loop. It is assumed that all operating sCO_2 loops have the same parameters. Every CHX consists of 15 control volumes. Condensate temperature is regulated by condensate throttling.

4.3 Coupled simulation (ATHLET/Dymola)

In this simulation, four sCO_2 loops are started 1800 s after the SBO. Compared to the previous simulation as described in the deliverable D2.2 (Hofer, et al., 2021), the current simulation ambient air temperature changes during the time from +15 °C (see the explanation below) to -45 °C as visualized in Figure 2 (UHS air inlet temperature corresponds to the ambient air temperature). Where applicable, the thick curve represents the current simulation results, and the thin curve represents the results for +45 °C ambient air temperature simulation (deliverable D2.2). The simulation starts at +15 °C ambient air temperature to capture the moments of: average ambient air temperature in the Czech Republic (approximately +8 °C) and moments when the UHS fan is switched off (Figure 3, time 42 hours, T amb = -22 °C) and when the UHS bypass valve starts to open (Figure 4, time 42 hours, T amb = -22 °C).

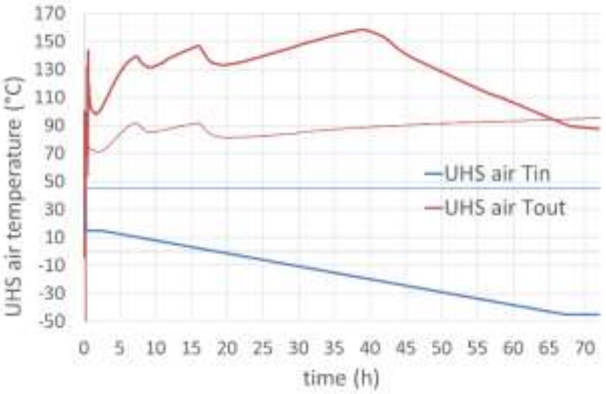


Figure 2: UHS air inlet and outlet temperatures

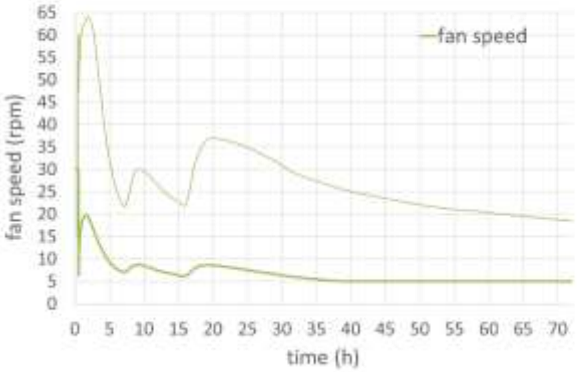


Figure 3: UHS fan speed (nominal speed 60 rpm)

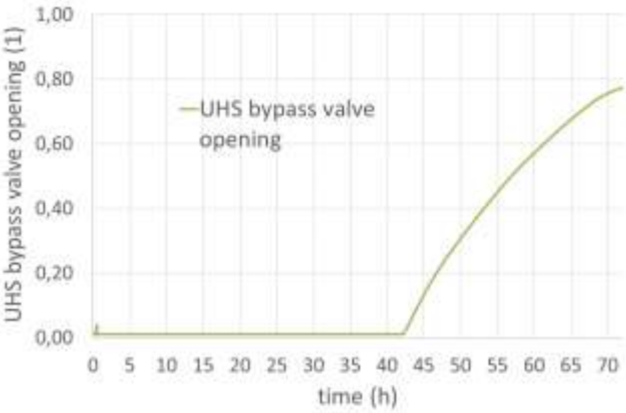


Figure 4: UHS bypass valve opening

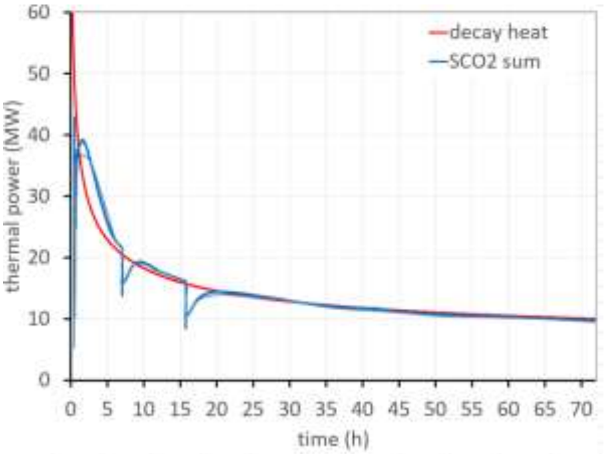


Figure 5: Decay heat and sCO_2 system total heat (ATHLET data)

As the detailed design of the UHS fan is not known yet the fan speed should be understood relatively (nominal speed is 60 rpm). The fact that the speed is not zero when the fan is switched off has two reasons. First there will be still some airflow through the UHS even if the fan will be switched off and then the non-zero air mass flow helps to the numerical solver. Figure 5 depicts the reactor decay heat course and heat removed via the CHXs (ATHLET data). The course is very similar to that obtained from the simulation for +45 °C ambient air temperature except for the first peak of the sCO_2 sum curve. Compressor inlet and outlet pressures and pressure ratio are visualized in Figure 6. Inlet pressure is kept constant at 126 bar absolute with the help of changing the loop filling (Figure 8) that was held constant during the simulation performed for an ambient air temperature +45 °C. Now, CO_2 content changes between approximately 1 170 kg at the SBO beginning and approximately 1 500 kg after 72 hours. Qualitatively the filling evolution might be explained as follows: CO_2 is concentrated mainly in three loop elements: UHS CO_2 piping, piping from compressor to CHX and piping from CHX to turbine. Regarding the CO_2 mass content in the UHS, this is determined by the CO_2 inlet and outlet conditions that are almost constant until the fortieth hour since the UHS CO_2 outlet temperature starts to decrease (low ambient air temperature) what cause the steep increase in CO_2 mass content in the UHS. The smaller waves before the fortieth hour follow the compressor outlet pressure.

Compressor CO_2 inlet temperature controllers (UHS fan speed; UHS bypass valve) function is to keep this temperature close to +55 °C (in the deliverable D2.2 this temperature was set to +57 °C). To handle low ambient air temperatures the controllers are set so that the UHS fan is switched off and the UHS bypass valve is put into operation after the compressor CO_2 inlet temperature falls below +50 °C (Figure 7 and Figure 4). If the compressor CO_2 inlet temperature oversteps +60 °C UHS fan speed controller is switched on and the UHS bypass valve is closed.

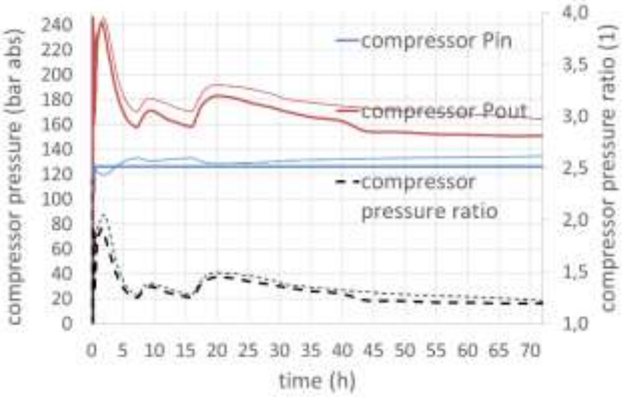


Figure 6: Compressor inlet and outlet pressure

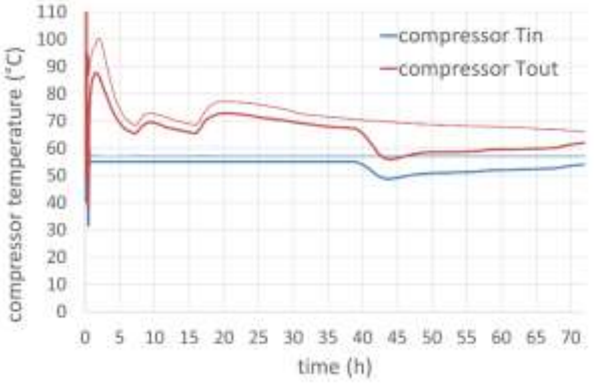


Figure 7:Compressor inlet and outlet temperature

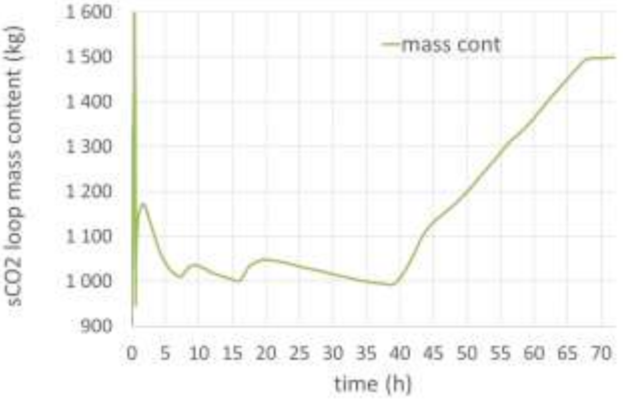


Figure 8: sCO_2 loop filling (mass content)

Figure 9: UHS inlet and outlet temperatures

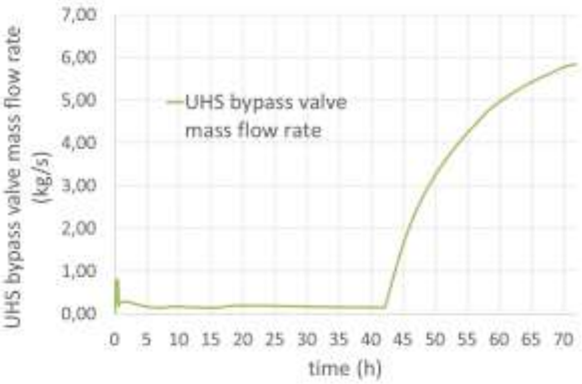
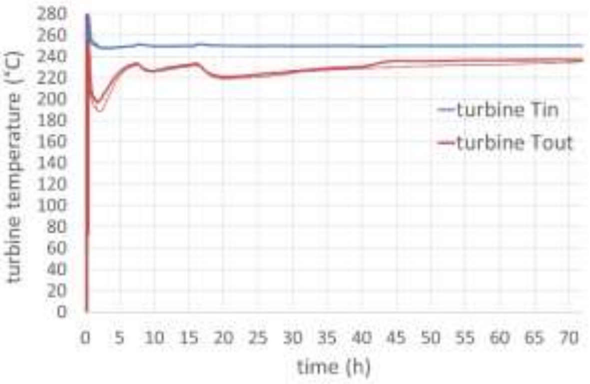


Figure 10: UHS CO_2 mass flow rate

Figure 11: UHS bypass valve CO_2 mass flow rate

UHS inlet and outlet CO_2 temperatures are depicted in Figure 9. After 40 hours the UHS cannot more keep the outlet temperature at 55 °C and this temperature is then continuously decreasing even if the UHS fan is switched off. UHS and UHS bypass valve CO_2 mass flow rates are visualized in Figure 10 and Figure 11. After 42 hours, the CO_2 temperature at compressor inlet starts to rise again with the help of mixing the cold stream from UHS and hot stream from UHS bypass valve. The ambient air temperature continues to decrease.

Turbine inlet temperature (Figure 12) is controlled by changing the TAC speed of revolution (Figure 13) and is kept constant at 250 °C. The corresponding CO_2 mass flow rate is depicted in Figure 14.



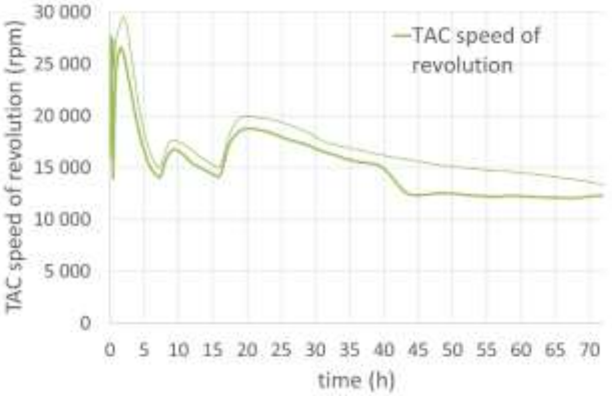


Figure 12: Turbine inlet and outlet temperature

Figure 13: TAC speed of revolution

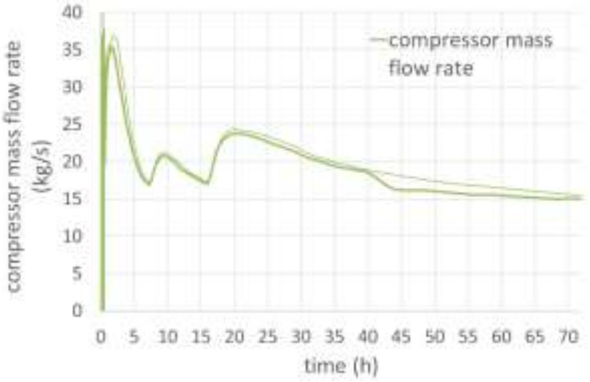


Figure 14: Compressor mass flow rate

The ultimate function of the sCO_2 system is to transfer the reactor decay heat through the CHX and UHS to the atmosphere. These heats are visualized in Figure 15 (Dymola data). They are very similar to the D2.2 simulation except at the SBO beginning. sCO2 system self-propelling capability is demonstrated by the power excess that is obtained as a difference between the turbine power output and the sum of the compressor and the UHS fan power consumption (Figure 16). This power excess should be high enough to ensure electricity supply to the sCO_2 system auxiliaries (control system, valve actuators, etc.) and to compensate for the motor/generator windage losses.

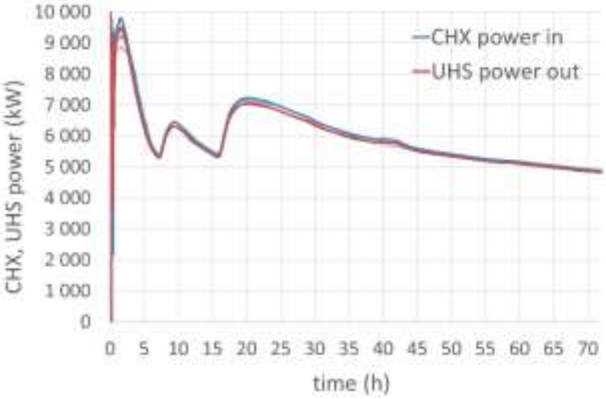


Figure 15: UHS inlet and outlet temperature

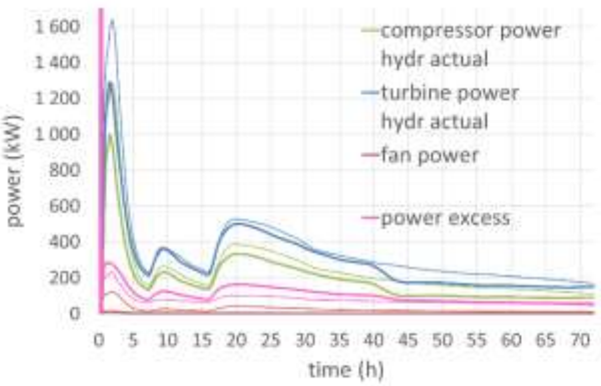


Figure 16: Powers

The compressor (Figure 17, Figure 18, Figure 19) and turbine (Figure 20, Figure 21, Figure 22) working conditions in a form of similarity numbers do not exceed the limits defined by the previous simulation for +45 °C ambient air conditions.

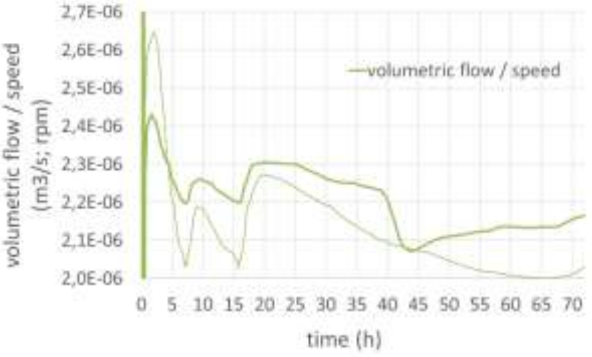


Figure 17: Compressor flow (similarity number form)

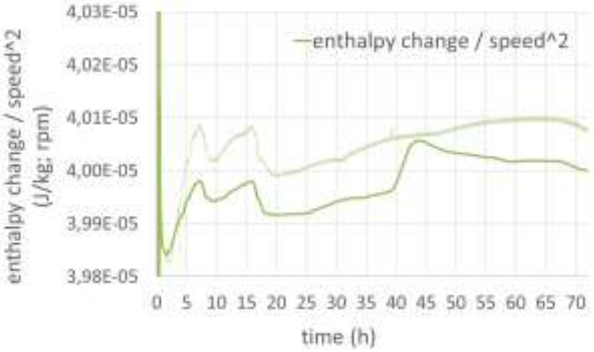


Figure 18: Compressor work (similarity number form)

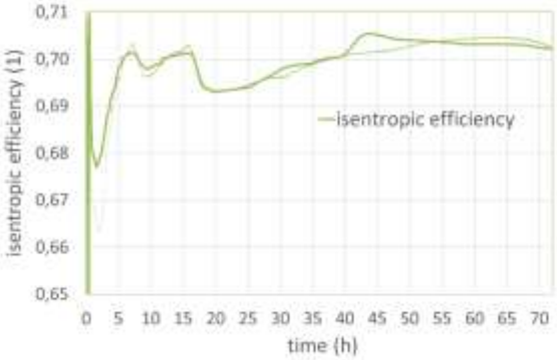


Figure 19: Compressor isentropic efficiency

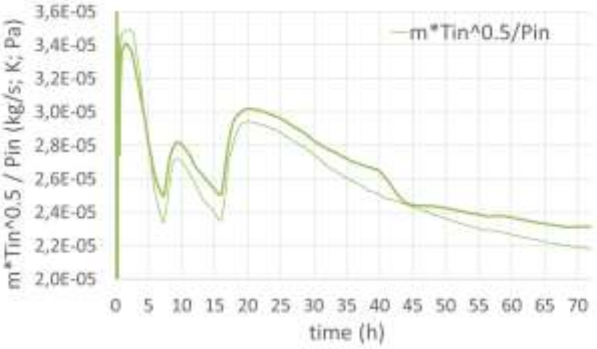


Figure 20: Turbine flow (similarity number form)

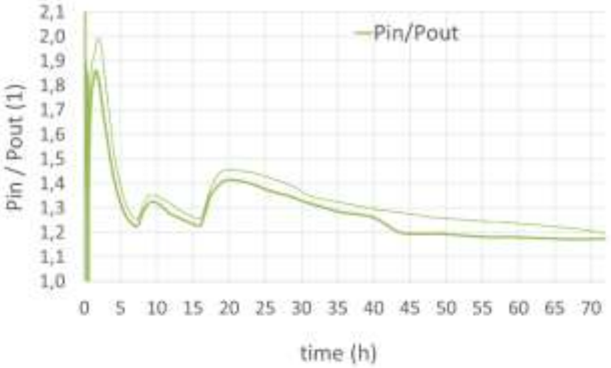


Figure 21: Turbine expansion ratio

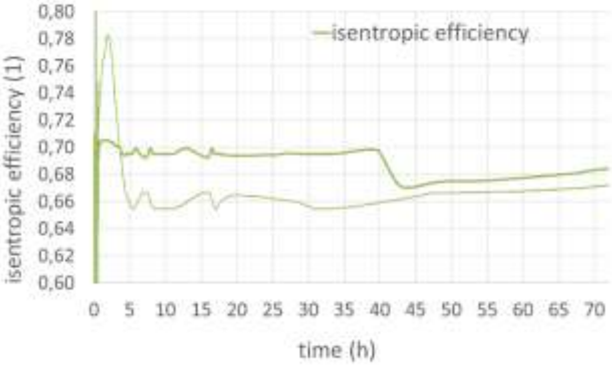


Figure 22: Turbine efficiency

The ATHLET side results of the current scenario follow. The main result is that the maximum core cladding temperature stays within the safety limits as seen from Figure 23.

Figure 24 presents the evolution of pressures in the main steam lines (MSLs). Steam dumps to the atmosphere (SDAs) are activated after the SBO, and they keep the pressure in the secondary circuit for an initial 1.5 h after SBO at 7 MPa. After this time, the thermal power removed by the sCO_2 loops prevails over the power generated in the reactor core, pressures in the main steam lines start to decrease and SDAs close. When the sCO_2 loop is switched off, pressure in the corresponding steam line increases. SDAs on loops 3 and 4 with switched-off sCO_2 loops open again within a time interval 19 h - 22 h.

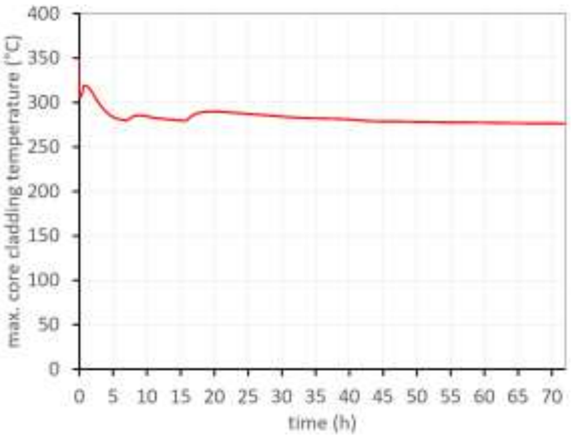


Figure 23: Maximum core cladding temperature

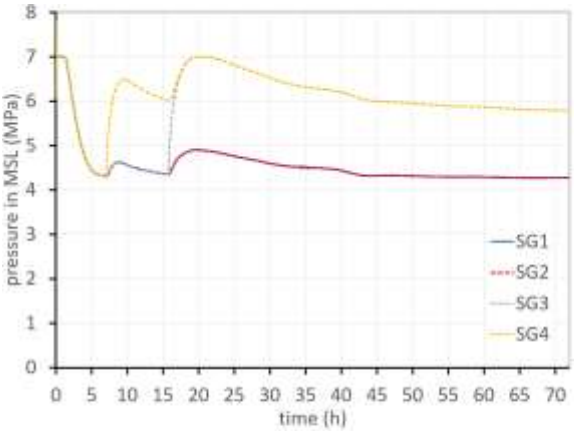


Figure 24: Pressures in the main steam lines

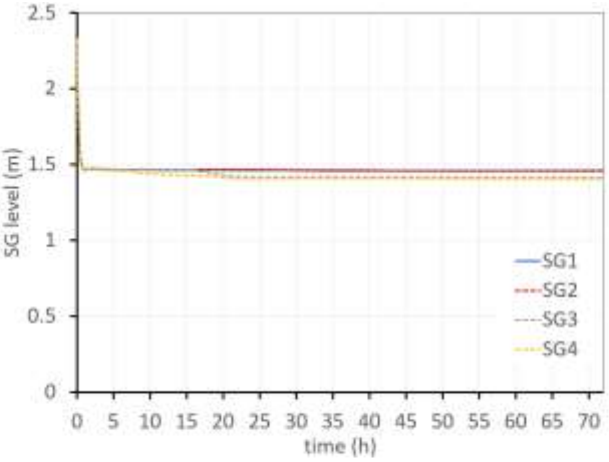


Figure 25: Water levels in the steam generators

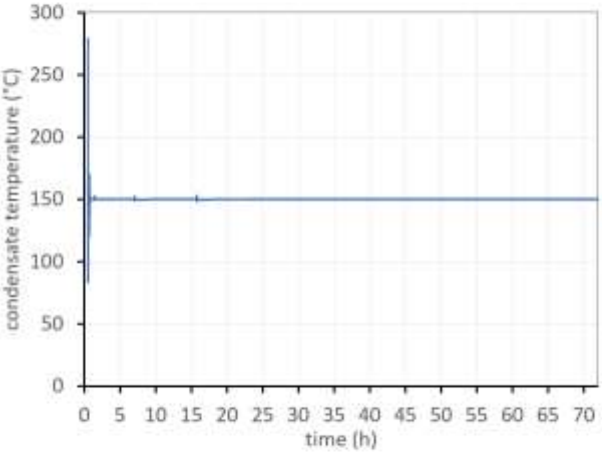


Figure 26: Water temperature at CHX No. 1 outlet

Figure 25 shows the water levels in the steam generators. Water levels in SGs decrease during the initial 1.5 h after the SBO due to opened SDAs. After the closure of all the SDAs, enough water is left in the steam generators for the operation of the sCO_2 system. Evaporation and reopening of SDAs on loops 3 and 4 with switched-off sCO_2 loops lead to a decrease of water levels in corresponding steam generators.

Water condensate temperature at the outlet of the CHX was again kept at a constant value of 150 °C (Figure 26) during the SBO.

At the end of this chapter sCO_2 loop controllers' settings are summarized as follows (Table 3):

Controller equation (PI):

$$dy = k \times \; error + \left(\frac{1}{\tau_i}\right) \times \; \int error \; \times dt$$

$error$ = set - measured

Table 3: Controller’s settings

Name	TAC speed controller	Unit	UHS fan speed controller	Unit
proportional constant k	-0.5	(rad/s)/°C	-0.01	(rad/s)/°C
integral constant τ_i	-20	°C*s/(rad/s)	-200	°C*sec/(rad/s)
Error	turbine inlet temperature	°C	compressor inlet temp	°C
Dy	TAC angular velocity	rad/s	fan angular velocity	rad/s

Name	loop filling controller	Unit	UHS bypass valve controller	Unit
proportional constant k	+20	(kg/s)/bar	+8e-5	(opening)/°C
integral constant τ_i	+0.1	bar*s/(kg/s)	+500	°C*s/opening
Error	compressor inlet pressure	bar	compressor inlet temp	°C
Dy	mass flow	kg/s	opening	1

TAC speed controller and UHS fan speed controller settings remain the same as for the +45 °C SBO simulation scenario. There are two new controllers added for the changing ambient air temperature scenario, namely the loop filling controller and the UHS bypass valve controller. There is also the sCO$_2$ loop on/off controller that is switching one loop after another always when the heat input per one loop decreases below 5.4 MW. Regarding the timing (that results from the simulation) of the loop switching, this is depicted in Figure 27 and is the same as for the +45 °C simulation scenario.

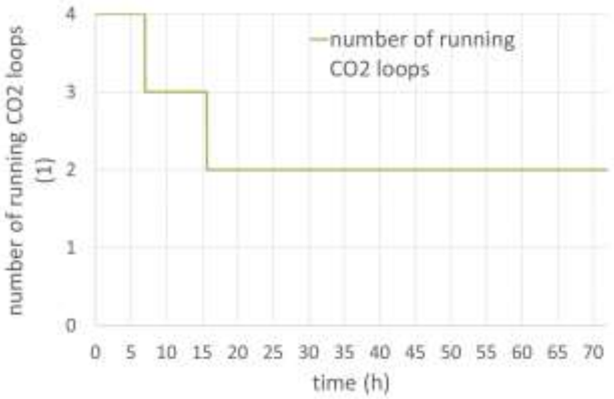


Figure 27: Number of running sCO$_2$ loops

4.4 Summary of the ATHLET/Dymola simulation for low ambient air temperature

Chapter 4.3 concentrates on the presentation of the coupled simulation results of the Dymola sCO_2 heat removal system model with the ATHLET VVER-1000 nuclear power plant block model for low ambient air temperatures. Two additional control loops were added to the previously analysed (D2.2) sCO_2 loop to handle this low ambient air temperatures scenario. The coupled simulation proves that this new sCO_2 loop layout can remove the reactor decay heat after the SBO occurs during the 72 hours so that the maximum core cladding temperature stays within the safe limits. The assumption is that the sCO_2 loop will contain an expansion tank and some other auxiliaries as described in the next chapter 5 that is dedicated to the description and simulation results presentation of the push-up starting procedure.

4.5 Summary of the Konvoi PWR simulations with ATHLET at an ambient temperature of -45 °C

In order to present an alternative approach to operate the cycle at lower ambient temperatures without inventory control and the UHS bypass, some further ATHLET simulations of the Konvoi PWR were carried out. So far, all ATHLET simulations of the Konvoi PWR in Deliverable 2.2 were conducted at an ambient temperature of 45 °C. However, the compressor inlet temperature may be kept constant at its design value of 55 °C at any ambient temperature by adapting the fan speed of the UHS, as already discussed in Deliverable 2.2. Additionally, less UHS modules might be used at low ambient temperatures to enable better control of the CO_2 cycle. To justify this assumption, the simulations of chapter 5.3.2 of Deliverable 2.2 were repeated at an ambient temperature of −45 °C. Only one quarter of the UHS modules were used including less sensitive controller gains for the air mass flow rate. The results exhibit the same qualitative behaviour compared to the previous results of Deliverable 2.2. In the following, the quantitative differences are discussed. Higher operating pressures in the CO_2 cycles can be observed, e.g. the compressor inlet pressure varies between 13 MPa and 16 MPa compared to 12 MPa and 13.5 MPa. The increased pressure is caused by the different temperature and density distribution along the length of the UHS together with the constant mass inventory. The higher compressor inlet pressure together with the same inlet temperature also results in a higher inlet density and a higher speed of sound. The different compressor inlet condition leads to a slightly higher cycle mass flow rate of 32 kg/s compared to 29.7 kg/s at the design point since the turbine inlet condition stays in a similar range compared to the previous simulation. Together with a slightly higher enthalpy difference over the CHX, the maximum thermal power of the CHX increases from 39 MW to 42.7 MW at an ambient temperature of −45 °C. The increased heat removal from the NPP leads to a slightly faster cooldown and the CO_2 cycles are switched off earlier, namely at 3.2 h, 7.1 h and 19.2 h compared to 3.8 h, 9.2 h, 25.8 h from the previous simulation. Moreover, the lower fan power consumption leads to a higher excess.

5 sCO_2 loop starting procedure: push-up start

In this chapter, the basic idea and layout of the sCO_2 loop push-up starting procedure shall be presented together with the Dymola simulation results for the case when the ambient air temperature is +45 °C. In the current case, the simulation is based on the manual control. To make the method general and convenient for automatic control, control criteria need to be worked out with special attention to low ambient air temperatures when two phase CO_2 conditions need to be handled. This is a task for the future work.

Another possibility is to use so called operational readiness state start that is based on keeping the sCO_2 loop in a “hot reserve” during the whole time of the NPP block operation. This method is not elaborated within the frame of the current deliverable.

5.1 Push-up start idea and layout

The idea of the push-up start is that in normal NPP operation the sCO_2 loop is filled with CO_2 slightly above the atmospheric pressure only to avoid air penetration to the loop. After the SBO occurs, CO_2 from the high-pressure external source is injected to the loop thus causing the turbomachinery to start rotating. In this way, it is not necessary to supply any power to the sCO_2 loop before the SBO. On the other hand, the sCO_2 loop push-up start is a rather complicated procedure. Special attention will have to be paid to the proper heating of all components after the SBO occurs. This task is not elaborated here but is a serious question from the operational point of view.

Current layout of the sCO_2 loop with the push-up start accessories is depicted in Figure 28, Figure 29 and is explained in Table 4.

Proposed sequence of the push-up start is as follows:

- Before the SBO, initial pressure of the CO_2 in the loop is 2 bara. This means that for any ambient air temperature the CO_2 in a loop is in a gaseous state.
- 30 minutes after the SBO (the time that operators perform other corrective actions), steam line from SG opens and water steam starts to flow into the starting CO_2 evaporator (position 13)
- Opening line “g” from the pressure source cause the CO_2 flows into the loop
- Opening steam line from steam generator to CHX
- The rotational speed of the TAC is increasing autonomously. No electricity input or output to the TAC shaft is needed. However, external electricity supply (battery) will have to be provided for the systems ensuring the sCO_2 loop control and measurement and for magnetic bearings at least.
- After the pressure difference between the source and loop pressure decrease to some limit the starting control valve opens (position “i”)
- After reaching required TAC speed, this speed is fixed by switching on the electricity generator with the help of frequency converter
- Loading the generator – UHS fans and electricity dissipation
- Reaching of nominal parameters
- Control of CO_2 pressure (CO_2 content in the loop) and of other parameters according to the course of the decay heat and ambient air temperature

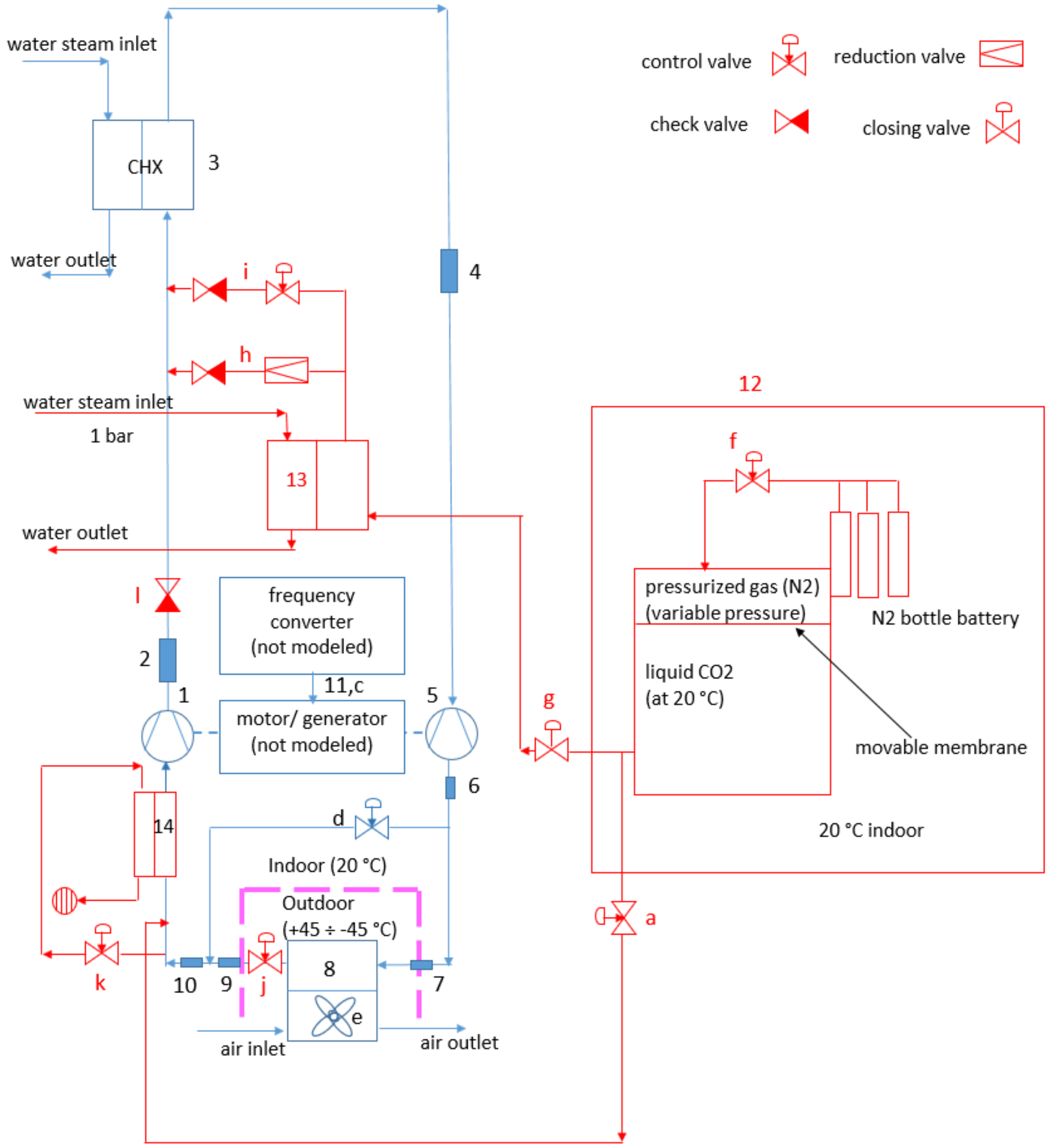


Figure 28: Push-up start accessories

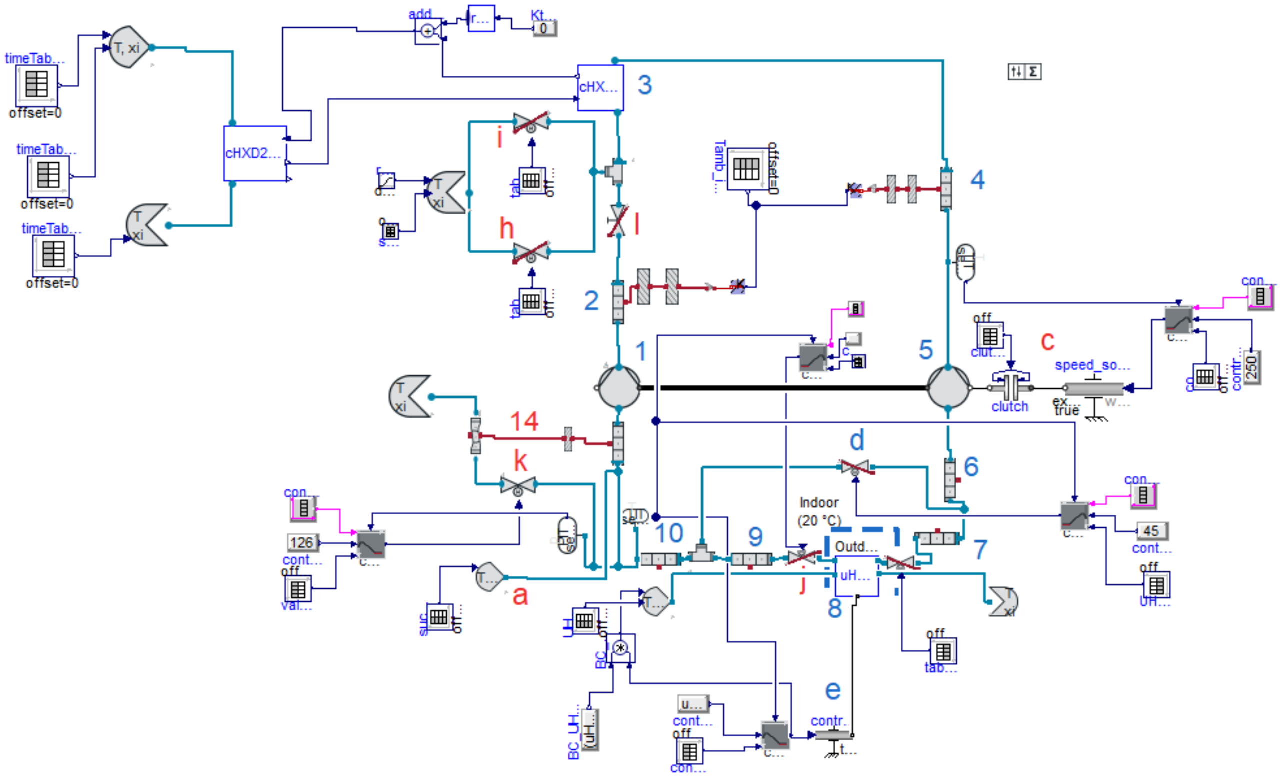


Figure 29: Dymola model with push-up start accessories

Table 4: sCO_2 loop components with push-up start accessories

Symbol	Component	Note
1	Turbocompressor	Placed in a shelter (20 °C)
2	Interconnecting piping	The compressor outlet (ground level) is connected to the CHX (33 m above the ground). Mostly in the building (20 °C)
3	CHX (CO_2 side)	CHX is an interface for coupling of ATHLET (water side) with Dymola (CO_2 side). The water side of the CHX is then connected with the steam generator of the VVER 1000 secondary loop. In the building (20 °C)
4	Interconnecting piping	Connects CHX with the turbine. Mostly in the building (20 °C)
5	Turbine	Placed in a shelter (20 °C)
6,7	Interconnecting piping	Modelled as if in the shelter (20 °C)
8	UHS	Outdoor
9,10	Interconnecting piping	Modelled as if in the shelter (20 °C)
11	Motor / generator with frequency converter	Serves for electricity production when power excess is available. This component has not been modelled yet and is replaced in Dymola model by speed source
12	CO_2 pressure source	Source consists of expansion tank with movable membrane, nitrogen bottle battery and accessories. High pressure nitrogen gas is injected above the membrane to keep CO_2 in a liquid state. Control valve “f” controls the pressure. This part is not modelled here, instead the boundary condition is placed in front of the valves “i” and “h” (Figure 29)
13	Starting CO_2 evaporator	In this heat exchanger, liquid CO2 is being evaporated to enter the loop in a gaseous state.
14	Starting CO_2 cooler	Decrease the CO2 temperature at compressor inlet. Low temperature CO_2 after the expansion through the control valve “k” is used. Later, when the “k” valve is closed and there is enough power excess to drive the UHS fans, this cooler is no longer operated
a	Filling	Serves for changing the sCO_2 loop filling during the heat removal campaign. Control variable is mass flow rate (PI controller). Controlled variable is the pressure at compressor suction (126 bara)
b	Divider	This component function is to switch off one sCO_2 loop when the heat to CO_2 medium falls below 5.4 MW within one CHX.
c	TAC speed control	Serves for changing the sCO_2 loop CO_2 mass flow rate. Control variable is speed of TAC (PI controller). Controlled variable is the temperature at the turbine inlet (250 °C). Component serves in place of the frequency converter and motor/generator (electrical part of the loop has not been modelled yet. In the future, simple electrical/mechanical coupling of chosen components shall be incorporated to the model. The mechanical clutch component in the Dymola model is used to couple the turbine shaft free end with the speed source (motor/generator).
d	UHS bypass valve	For low ambient air temperatures, this valve opens and bypasses the UHS so that the cold stream of CO_2 coming from UHS is mixed with the hot stream coming from the turbine outlet. Control variable is mass flow rate (PI controller). The controlled variable is compressor inlet temperature (+55 °C)
e	Fan speed control	Fan speed is a control variable (PI controller). The controlled variable is a compressor inlet temperature (+55 °C)

Table continuation

Symbol	Component	Note
f	Nitrogen control valve	Control nitrogen pressure above the movable membrane
g	Closing valve	Isolates starting line from the loop
h	Starting reduction valve	Opening this valve begins the sCO_2 loop start-up procedure. This valve is used to handle high pressure drops.
i	Starting control valve	Opens when the sCO_2 loop is partly filled
j	UHS outlet control valve	This valve serves during low ambient air temperatures start-ups.
k	Compressor inlet pressure control valve (for start only)	During start-up procedure controls the pressure at compressor inlet
l	Check valve at compressor outlet	Isolates high- and low-pressure part of the loop during the start up. When compressor overcome the starting pressure, this valve automatically opens

5.2 Simulation of the push-up start

In this chapter, boundary conditions and basic results of the push-up start simulation for the ambient air temperature +45 °C are depicted. It should be noted again that the current simulation is mainly based on manual tuning of the actuating signals. No checks were performed regarding the appropriate heating procedures.

5.2.1 Boundary conditions for the push-up start (T amb = +45 °C)

In the next figures “true” boundary conditions as well as actuating signals evolution are presented. Actuating signals setting was manually tuned to get “reasonable” system evolution (chapter 5.2.2). Basically, it was required that after fixing the TAC rotational speed (electric generator is switched on):

- only limited torque peak is allowed
- only positive power excess is allowed

In the current Dymola model the effect of the generator / frequency converter is modelled with the help of mechanical clutch and speed source (Figure 28 positions 11 and “c”; Figure 29 position “c”).

Figure 32 shows the evolution of the CHX steam inlet temperature and mass flow rate (time 0 seconds corresponds to the signal “start the sCO_2 loop”). The jump in the water temperature represents the moment when the valves on the CHX water side opens. The stepwise water mass flow rate increase represents an attempt to consider the heating phase of the CHX at the beginning and loading phase at the end. CHX water side outlet pressure was kept constant during this simulation.

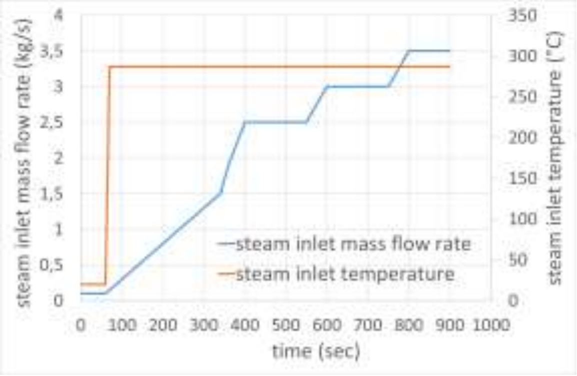


Figure 30: CHX water steam mass flow rate and inlet temperature

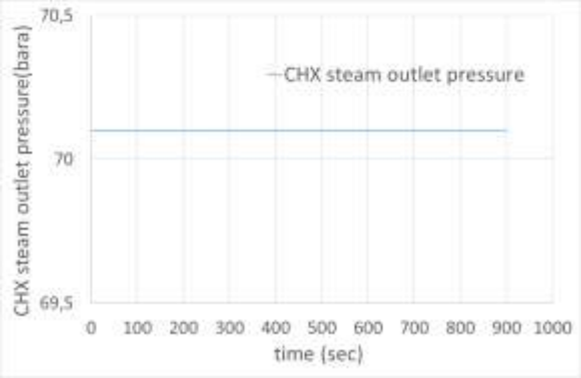


Figure 31: CHX water outlet pressure

The CO_2 source pressure starts at 90 bara (Figure 32, green curve). In the CO_2 expansion tank this pressure together with the ambient air temperature 20 °C ensures that CO_2 is being stored in a liquid state. At evaporator outlet, CO_2 temperature is 80 °C what ensures that after isenthalpic throttling to almost empty loop the CO_2 temperature will not fall much below zero degrees of Celsius (Figure 37).

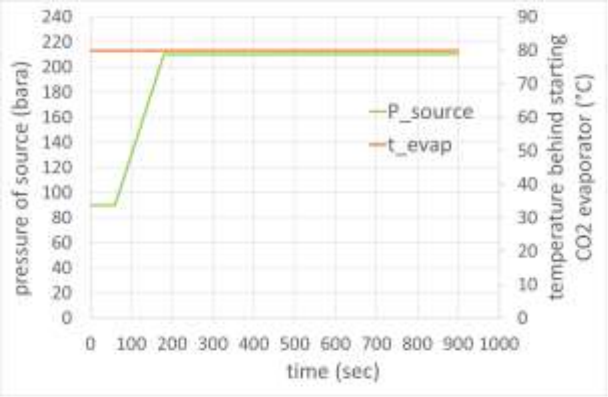


Figure 32: CO_2 source pressure and evaporator temperature

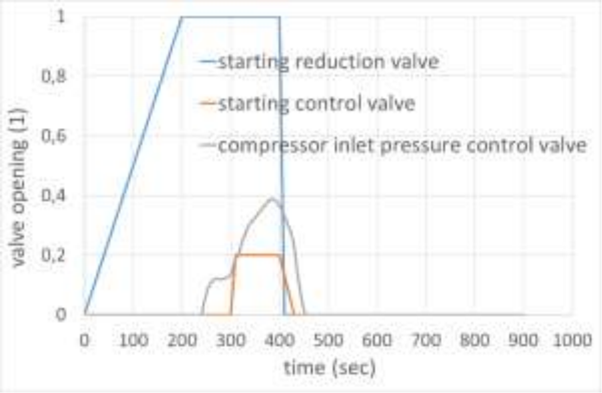
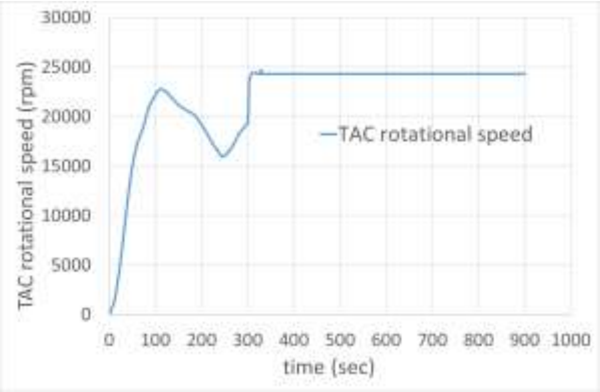


Figure 33: Valves opening

Starting reduction and control valves opening mainly determines the time evolution of the TAC speed of revolution (Figure 34). At time 330 seconds the generator fixed the TAC speed. UHS fan speed evolution is depicted in Figure 35.



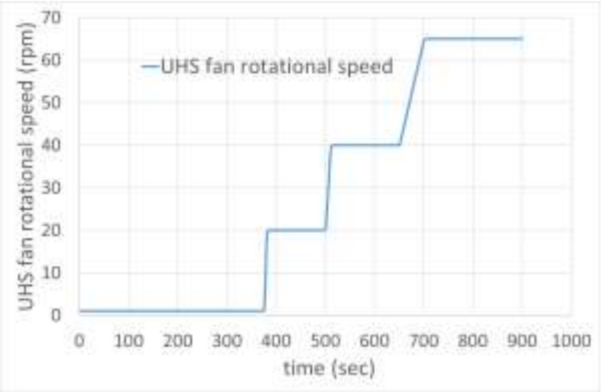


Figure 34: TAC rotational speed

Figure 35: UHS fan rotational speed

5.2.2 Results of the push-up start simulation (T amb = +45 °C)

Here, based on the previously mentioned settings, some basic results of the push-up start simulation are presented.

Figure 36 depicts information about the pressures at the different loop places. The green curve represents already known pressure of the CO_2 source; the orange curve represents the pressure behind the starting valves. This pressure is followed by the compressor outlet pressure (blue curve). Closer examination of the graphs reveals that from the time 80 seconds the check valve at compressor outlet (position "l" in Figure 28 or Figure 29) opens. This is visualized in Figure 38 (after about 80 seconds the CO_2 starts to flow through the check valve). The grey curve in Figure 36 represents the compressor inlet pressure evolution. Temperature behind the valves (Figure 37) reflects the real gas behaviour during isenthalpic expansion.

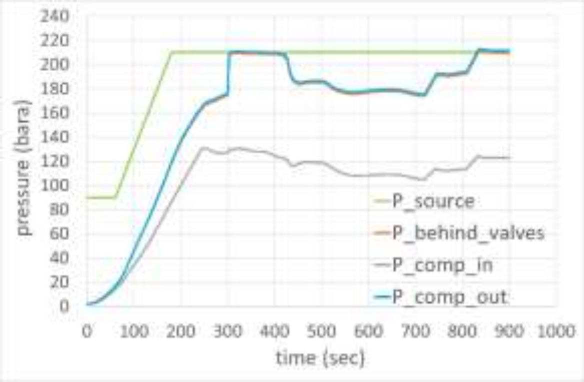


Figure 36: Pressure behind the starting valves

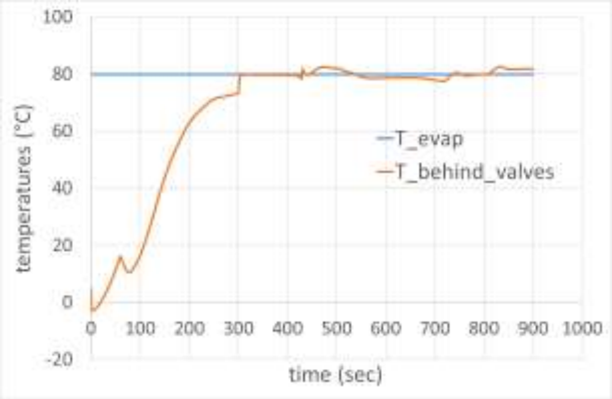


Figure 37: Temperature behind the starting valves

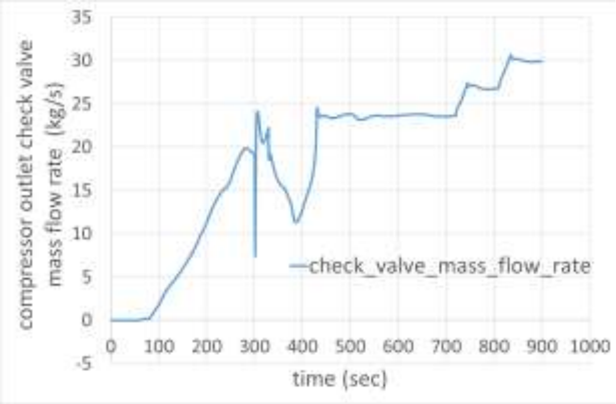


Figure 38: Compressor outlet check valve mass flow rate

There are four regions visible concerning the pressure behind the valves (Figure 36, orange or blue curve). First region corresponds to the smooth continuous pressure increase till 300 seconds. During this time span, only starting reduction valve is open. At time 300 seconds, the starting control valve opens what is accompanied by the pressure jump - the source and local loop pressure settled. The second region corresponds to the time span 300 - 428 seconds when the starting control valve is opened, and the compressor inlet pressure controller act to keep compressor inlet pressure near the set value of 126 bara (grey curve). During this time span, the TAC shaft speed is fixed at time 330 seconds (24 321 rpm). Then there is a third region (428 - 720 seconds) when the starting valves are already closed but - at the time interval beginning - the compressor inlet pressure control valve is still slightly opened for some short period what is accompanied by the pressure decrease. During the third phase, the loop is being continuously loaded by the increasing water steam mass flow rate what allows for the UHS fan speed to be increased as well. Consequently, the temperature at compressor inlet begins to approach the design value of 55 °C (Figure 39). The last, fourth region (720 - 900 seconds) corresponds to the loop CO_2 mass content increase so that the design pressure at compressor inlet is almost reached (in the current simulation this pressure ends at 123 bara). Also, the water steam mass flow rate is increased to a value of 3.5 kg/s. Then the CHX heat transfer is 8.1 MW.

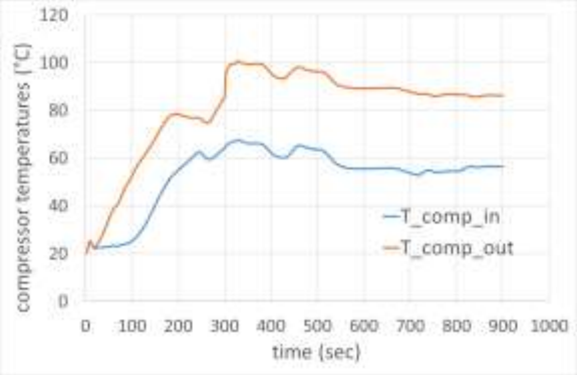


Figure 39: Compressor CO_2 inlet temperature

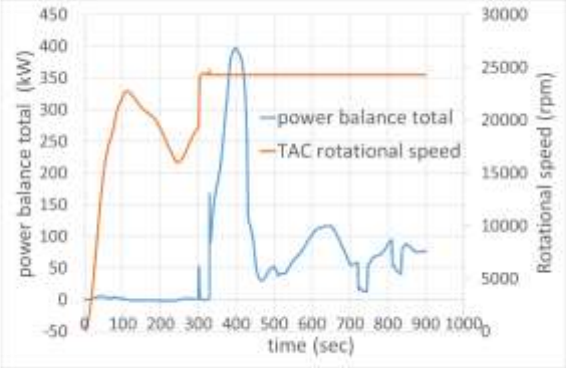


Figure 40: Power total balance (fans included)

As already mentioned, the basic requirement is that after switching on the generator (TAC speed is fixed), the system shows only power excess. This behaviour is visualized in Figure 40.Here, the power total balance equals to the turbine power output minus the sum of the compressor and UHS fans power input. This power excess should be high enough to cover energy consumption of the sCO_2 loop accessories and motor/generator windage losses (modelling of these effects shall be part of the future work).

The high power excess (the power "hill") in between 328 sec and 458 sec is mainly caused by the difference in the mass flow rates through the turbine and compressor as depicted in Figure 41. This difference in turbine and compressor mass flow rates is a result of the valve "k" control action (Figure 33). The function of valve "k" is to keep the compressor inlet pressure near 126 bara (see Figure 36).

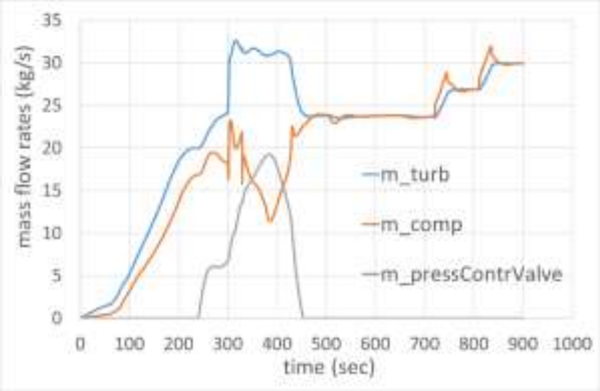


Figure 41: Mass flows

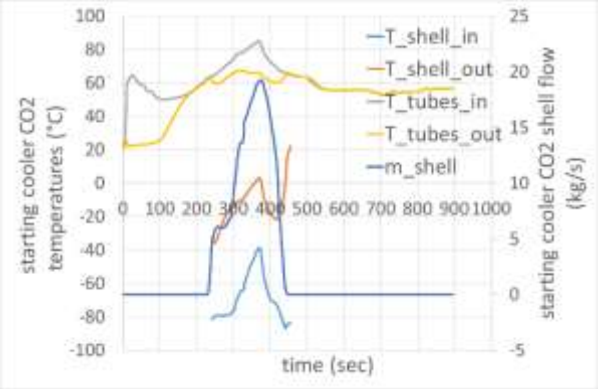


Figure 42: Starting cooler

In front of the compressor, starting CO_2 cooler has been added to support UHS cooling capacity when the UHS fans are switched off due to electric power unavailability. Cooling capacity of this starting cooler is available only when the compressor inlet pressure control valve operates (**Error! Reference source not found.**; 240 - 450 seconds; at the beginning the cooling capacity effect of the cooler walls on CO_2 temperature is visible – grey and yellow curves).

To conclude this chapter, some basic push-up start data were derived from the simulation results and are summarized in the following Table 5.

There is still a lot of work to be done with respect to the push-up start. To make the start automatic, some suitable control criteria need to be defined for wide range of ambient air temperatures when even two-phase CO_2 might be presented in the loop. Next, the appropriate loop tempering procedure based on component thermal requirements should be considered during the future analysis.

Table 5: Start-up basic data (T_amb = +45 °C)

Symbol	Component Parameter	Note
-	Starting time	Time duration 900 seconds till full load
12	CO_2 pressure source	CO_2: 5000 kg, 6 m^3; N_2: 600 kg, 2.5 m^3, bottle pressure 250 bar
-	CO2 exhaust to the atmosphere	2000 kg
14	Starting CO_2 cooler	Shell: D=0.5 m, L=10 m
13	CO2 evap. Steam consumption	300 kg

6 Conclusion

In the first part of this report (chapter 4), results of the ATHLET VVER-1000 and Dymola sCO_2 loop coupled simulation were presented for the changing ambient air conditions. The control strategy in Dymola model is based on changing the loop filling and UHS bypassing (Figure 8, Figure 11). An alternative approach without changing the loop filling and without UHS bypassing was presented by USTUTT in chapter 4.5. Presented results of these two approaches may serve as a basis for further discussions among the project partners concerning the control strategies.

In the second part of the report (chapter 5), the push-up starting procedure and simulation results are discussed. For now, only the results for +45 °C ambient air temperature were presented, leaving the more severe conditions (-45 °C ambient air temperature conditions) as a future work to be done. Based on the current simulation results, we may conclude that it is possible (at least theoretically) to start the sCO_2 loop this way. On the other hand, it should be noted that many aspects were not considered (system heating, automatization of the control strategy, etc.) and that the method may seem complicated compared to variant solution, namely the operational readiness state starting procedure (this method has not been analysed in the current report but was already analysed in D 2.2 with ATHLET in chapter 5.3.3). Regarding the push-up start, the current model shall be utilized also as an input for the subsequent WP6 activities (KSG-GfS Konvoi simulator and Dymola sCO_2 loop model coupling).

7 References

Hofer, M., Buck, M., Prusek, T., Sobecki, N., Hecker, F., Vyskocil, L., & ...Hacks, A. (2021). *sCO2-4-NPP_D2.2: Analysis of the performance of the sCO2-4-NPP system under accident scenarios.*