NEUP Final Report: Analysis of Thermal Transients for a Sodium-CO₂ Heat Exchanger

Nuclear Science and Engineering Division

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ABSTRACT

The design of heat exchangers for use in a supercritical carbon dioxide (sCO₂) Brayton cycle power converter must provide for acceptable performance for duty cycle events encompassing anticipated transients and postulated accidents. Argonne National Laboratory participated in the NEUP project, “Thermal Hydraulic and Structural Testing and Modeling of Compact Diffusion-Bonded Heat Exchangers for Supercritical CO₂ Brayton Cycle” with the task of conducting a comprehensive analysis of thermal transients for sCO₂ cycle heat exchangers, with emphasis on the sodium-to-CO₂ heat addition heat exchanger. A range of transients, from normal operation to severe accidents, were simulated with the coupled PDC and SAS4A/SASSYS-1 system level dynamic analysis computer codes. For each transient, the calculated change in the heat exchanger wall temperature is determined as a measure of the thermal loading. In addition, an analysis to find an equivalent helium-CO₂ heat exchanger was carried out to facilitate testing with helium rather than sodium on the hot side.

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Nomenclature

AFR	=	Advanced Fast Reactor
AOO	=	Anticipated operational occurrences
BDBE	=	Beyond design basis events
DBA	=	Design basis accidents
DEG	=	Double-ended guillotine (break)
HTC	=	Heat transfer coefficient
HTR	=	High temperature recuperator
HX	=	Heat exchanger
IHTS	=	Intermediate heat transport system
IHX	=	Intermediate heat exchanger
LBB	=	Leak before break
LHA	=	Limiting hypothetical accidents
LOHA	=	Loss of heat addition
LOHR	=	Loss of heat removal
LT	=	Limiting transients
LTR	=	Low temperature recuperator
NO	=	Normal operation
NEUP	=	Nuclear Energy University Program
PCHE	=	Printed Circuit Heat Exchanger
PDC	=	Plant Dynamics Code
RHX	=	Reactor heat exchanger
sCO ₂	=	Supercritical carbon dioxide (Brayton cycle)
SFR	=	Sodium-cooled fast reactor
TIN	=	Turbine inlet (control)
TBP	=	Turbine bypass (control)
TM	=	Turbomachinery

1 INTRODUCTION

Supercritical carbon dioxide (sCO₂) Brayton power cycles and their technologies are being developed and demonstrated by the U.S. Department of Energy and U.S. industry for applications to fossil energy, solar thermal, and nuclear heat sources. In order to compete with the existing and other emerging energy conversion systems, sCO₂ cycles need to demonstrate clear advantages in both the cycle efficiency and the capital cost. One of the major contributors to the cycle's capital cost is the cost of the heat exchangers. For the commonly used indirect recompression sCO₂ cycle configuration, these heat exchangers include the source-to-CO₂ heat addition heat exchanger, high- and low-temperature recuperators, and cooler. In order to improve the economic performance of the cycle, innovative compact heat exchanger technologies are currently being investigated for sCO₂ cycles, such as the Printed Circuit Heat Exchanger (PCHE) developed by Heatric Division of Meggitt, UK [1]. The heat exchanger manufacturers develop their equipment to meet the design conditions, such as temperatures and pressures specific for each heat exchanger in a sCO₂ cycle.

However, the heat exchangers also need to survive a wide range of operating transients, preferably without a need for equipment replacement during the plant lifetime. Because the sCO₂ cycle is a relatively new concept, it has never been operated at a large commercial scale. Therefore, an experience database on how the heat exchangers perform when subjected to transients is nonexistent at the moment for sCO₂ cycle equipment. Therefore, the designer can only simulate the performance of the heat exchangers with structural analysis tools and testing in which heat exchanger test articles are deliberately subjected to transients. For both analysis and testing, the severity of the imposed loading must be specified.

To address these challenges, a Nuclear Energy University Program (NEUP) project, "Thermal Hydraulic and Structural Testing and Modeling of Compact Diffusion-Bonded Heat Exchangers for Supercritical CO₂ Brayton Cycles," was initiated by the U.S. Department of Energy. Argonne National Laboratory participated in this project, together with Georgia Institute of Technology, University of Wisconsin – Madison, and Sandia National Laboratories. Argonne's part of the workscope was to use Argonne's Plant Dynamics Code to carry out a comprehensive study of the set of transients that can be imposed on the sCO₂ cycle heat exchangers in a power plant and the resulting transient thermal loadings. The results of these simulations were then used in the structural analyses carried out by Georgia Tech and UW. Some of the transients were also planned to be reproduced in the experimental test loop being constructed at Georgia Tech.

The analysis presented in this report is carried out for the sCO₂ cycle designed as an energy converter for the AFR-100 nuclear power plant. The AFR-100 is a Sodium-Cooled Fast Reactor (SFR) that delivers 250 MW of thermal energy to the sCO₂ cycle. The calculated net electrical output from the plant is slightly higher than 100 MWe. Figure 1 shows the design conditions of the AFR-100 sCO₂ cycle, including temperatures, pressures, flow rates, and heat duties for the major cycle components.

Figure 1. AFR-100 sCO₂ Brayton Cycle Steady-State Conditions.

The analysis presented here is focused on the thermal transients for the sodium-CO₂ reactor heat exchanger (RHX in Figure 1). This heat exchanger is selected for several reasons. First, this is the heat exchanger for which the highest sCO₂ temperatures are achieved in the cycle. In addition, the CO₂ pressures are close to the maximum value of about 25 MPa, so that the combination of high temperatures and high pressures makes the heat exchanger design likely more challenging than for other heat exchangers in the cycle. The AFR-100 RHX is also a heat exchanger with very different fluids on its two sides: the cold side is supercritical, gas-like, CO₂, while the hot side is liquid metal (sodium) at about atmospheric pressure. As such, the transient behavior of the fluids on the two sides of this heat exchanger can be significantly different, presenting more issues for transient design and performance. Next, the RHX provides heat transfer between two major AFR-100 plant subsystems: the reactor side and the energy conversion side. Because of that, more transient initiators than for any other heat exchanger can be expected for the RHX, originating in the two plant subsystems. For example, the flow rates on the two sides of the RHX are controlled by the sodium pumps and the sCO₂ compressors and thus can be changed independently of each other; a

degree of freedom not easily available for the sCO₂ recuperators. Lastly, because the RHX is related to the nuclear side of the plant, it is possible that more strict reliability requirements would be applied to it. In the AFR-100 design, the intermediate sodium loop and the RHX do not carry a nuclear safety function due to enhanced safety features of that particular design, but it is not expected to be the case for all possible applications of sCO₂ cycles as the energy conversion approach for nuclear reactors.

Even though the analysis presented in this report is carried out for a specific sCO₂ cycle application involving a SFR, the results of this analysis would be similar for other types of heat addition heat exchangers. In particular, the results in this report would be directly applicable to Concentrating Solar Power (CSP) plants using sodium as the heat carrier fluid. Results would also be similar for CSP plants with liquid salt heat carrier fluid.

The RHX conditions at steady-state design operation are also shown in Figure 1. The sodium inlet and outlet temperatures are 528 °C and 373 °C, respectively, while the sodium pressure is close to atmospheric. On the CO₂ side, the inlet and outlet temperatures are 356 °C and 523 °C, respectively, with the pressure close to 25 MPa. The heat exchanger effectiveness is 97.5 %. The RHX is a modular Hybrid Heat Exchanger design proposed by Heatric for this type of applications. The sodium side is a Formed Plate design with rectilinear channels 6 mm wide by 4 mm deep, while the CO₂ side is a classical Printed Circuit design with semi-circular channels of 2 mm diameter. The AFR-100 RHX channel configuration and dimensions are shown in Figure 2. The entire heat exchanger for the two sodium loops consists of 92 blocks, each 0.6 m wide, 0.6 m high, and 1.5 m long. The total heat duty is 250 MW_{th}, corresponding to 2.72 MW_{th} heat duty per block.

Figure 2. AFR-100 RHX Channel Configuration and Dimensions.

Although the analysis presented in this report is focused on the thermal transients for the RHX, a vast database was also generated during the course of this work for the transient behavior of the other sCO₂ cycle heat exchangers. For example, the transient conditions during normal load following, as well as several mild and severe accidents - such as sudden loss of turbine load - are also calculated for the two recuperators and the cooler. Those results are not presented in this report, but are available from the authors upon request.

The results of the transient analysis presented below to a large degree are defined by the plant control strategy and how the control system reacts to various transient initiators. The AFR-100 control system was developed in previous ANL work on sCO₂ cycle analysis; the detailed description of the system as well as the results of the transient control simulation are provided in Reference [2]. The summary of the AFR-100 plant control system is shown in Figure 3 and Table 1. The system uses the combination of turbine bypass and inventory controls on the sCO₂ side, as well as the sodium flow rate and reactor power controls on the reactor side, to match the required grid demand and to maintain the compressor-inlet and reactor-side temperatures in transients. In addition, other control mechanisms are simulated, for example, to maintain compressor-inlet temperature, which is important for sCO₂ cycles operating close to the critical point.

Figure 3. AFR-100 Control System.

Table 1. AFR-100 Control Logic

	Mechanism	Controls	By changing
Reactor	Reactor power [1]	Core-outlet temperature	Control rod position
	Primary flow [4]	IHX-outlet temperature	Primary pump speed
	Intermediate flow [5]	RHX-outlet temperature	Intermediate pump speed
sCO ₂ Cycle	Turbine bypass [16]	Generator output	Turbine bypass flow
	Turbine throttle [15]	Turbine flow	Valve pressure drop
	Inventory [17]	CO ₂ flow rate	CO ₂ mass
	Compressor-inlet temperature	Compressor-inlet temperature	Cooler bypass flow [18] and air flow rate [14]

[X] indicates index in Figure 3

2 COMPUTATIONAL TOOLS

The analysis presented in this report has been carried out using the coupled PDC and SAS4A/SASSYS-1 codes.

The Argonne National Laboratory Plant Dynamics Code (PDC) [3] has been developed specifically for the analysis of sCO₂ power cycles. It is based on a highly accurate representation of sCO₂ properties and their effects on the cycle and components, both for design and performance. Specifically for the transient analysis presented in this report, the PDC features a multi-node compressible flow simulation of each heat exchanger with transient effects such as the thermal inertia of the wall mass, as well as a cycle-wide simulation such as turbomachinery off-design performance and the performance of the plant control system. These details allow the PDC to accurately simulate a wide range of thermal transients as well as interactions between individual components and the entire plant. For example, in the a small CO₂ pipe break in the vicinity of the RHX, the PDC would account not only for the local CO₂ flow rate increase due to changing pressure conditions, but also for the global CO₂ flow rate decrease due to reducing CO₂ pressures and densities as a result of the cycle inventory loss.

The SAS4A/SASSYS-1 code is Argonne's liquid metal reactor analysis code system [4], which is the leading capability for modeling liquid-metal reactors at the system level. The SAS4A/SASSYS-1 code couples reactor neutronic dynamics with thermal hydraulics calculations.

Coupling the PDC and SAS4A/SASSYS-1 codes allows investigation of the mutual transient performance of the reactor and power converter. For example, using the coupled codes enables one to analyze anticipated operational transient effects on the RHX ranging from reactor scram to turbine trip. More generally, the coupled codes facilitate analysis of the scenarios including accidents resulting from transient initiators originating on both the reactor and CO₂ sides of the plant, as well as the mutual influence of these events. The details of the PDC-SAS4A/SASSYS-1 coupling approach are provided in Reference [5].

3 ANALYZED TRANSIENTS

The goal of this work was to investigate what thermal transients the RHX can be subjected to during its lifetime in the plant. Among all possible transients, those that have a potential to impose the greatest changes in temperature on the RHX were selected for consideration. These transients affect either the inlet temperatures, flows, or both on each side of the heat exchanger. The transients were organized into the following four classes of events, depending on their likelihood and the severity of the thermal transients they can impose on the heat exchanger.

Normal Operation (NO) and Anticipated Operational Occurrences (AOO). These transients are expected to occur during the plant operation. The examples include normal startup, shutdown, and load following.

Design Basis Accidents (DBA). These transients are originated by some sort of an equipment failure or operator error. It is assumed that all plant control and protection systems and equipment are functioning as expected, including the mitigation action for the specific failure sequence. Because the plant protection systems operate as intended, these transients are also characterized as single-fault events. Examples in this class include inadvertent partial opening of a sCO₂ valve, small and intermediate (i.e., not catastrophic) CO₂ pipe breaks, sodium pump trip with normal coastdown and reactor scram, and loss of generator load.

Severe Beyond Design Basis Events (BDBE). This class of events assumes that in addition to the originating event, the plant protection system also fails to either recognize the event or properly respond to it. Because of this additional failure, these transients are characterized as double-fault events. Due to two simultaneous failures, these events would be very unlikely to occur, but have a potential to expose the heat exchanger to more severe conditions, possibly resulting in heat exchanger failure. The examples in this class include reactor trip while the CO₂ cycle keeps operating (and cooling down the RHX), turbine trip while the reactor fails to scram, and an uncontrolled increase in the reactor power. In addition, large CO₂ pipe breaks are also included in this class due to their low probability and significant impact on the CO₂ flow in the heat exchanger.

Limiting Hypothetical Accidents (LHA). The events in this class although theoretically possible are never expected to occur in the plant lifetime. The examples include sudden and complete removal of either sodium or CO₂ from the heat exchanger. Although there is no credible event to initiate such transients, they are still analyzed in this report to characterize a theoretical limit on all other transients not specifically investigated in this work. For example, sudden and complete loss of sodium presents the bounding case for all sodium pipe rupture accidents.

These four classes of events *roughly* correspond to the ASME Service Levels A through D. However, more information and/or analysis is needed to properly characterize the expected likelihood of each event and thus sort the transients into the ASME Service Levels. For example, reliability data on the CO₂ turbine bypass valve, at prototypical conditions and size, is required to relate the unintentional valve opening accident as either a Service Level B or Service Level C event. In this report, only the results of the thermal transients are presented, and the events are *not* characterized or analyzed according to the ASME Service Level classification. The report will not draw any conclusions whether the ASME Service Level criteria are satisfied and if the heat exchanger will be able to survive any of the analyzed events. Such an analysis will need to be carried out separately using structural analysis codes, based on the thermal transient results presented here.

Table 2 lists all transients considered in this work. The transients are classified into four categories described above. For each transient, a transient definition is provided, including the initiating event (highlighted by yellow cells) and the action (or failure) of each control system. For some transients, different variations were considered, such as different break sizes for CO₂ pipe break accidents. The last column in Table 2 specifies if the transient was simulated in this work. Some of the transients were not included in the actual analysis due to limitations on the workscope. For example, moderate load following with 2%/min rate was not simulated since a more aggressive 5%/min load following transient is analyzed, which results in larger thermal loading on the heat exchangers. Some of the transients are not analyzed directly, but are rather replaced by the limiting transients (LT). These Limiting Transients are listed in Table 3 and provide the upper bound for many transients in Table 2. For example, complete loss of CO₂ Limiting Transients bound all CO₂ pipe break accidents as well as RHX isolation valve malfunctions. Another reason to include the limiting transients in this analysis was that simulating of such transients may be more practical than the actual transients. For example, the normal heat transfer equations in the PDC are not developed for conditions of zero flow or zero mass on one side of a heat exchanger. At the same time, the corresponding Limiting Transient of, for example, complete loss of heat removal on the CO₂ side could easily be simulated by simply zeroing out the heat transfer from the HX wall to CO₂ in the transient.

Table 2. Classification and Definitions of RHX Transients

Class	Characteristic	Events	Control / Protection System (Gray – Different from NO, Yellow – Initiating Event)							Comments		Simulated ?
			Reactor scram	Primary Na pumps	Interm. Na Pumps	Grid connection	Turbine Trip	sCO ₂ Cycle Controls	Air Flow			
Normal Operation (NO)	Design conditions	Steady-state	No	Operational	Operational	Synch.	No	Active	Full			☒
Anticipated Operational Occurrences (AOO)	Normal Transients	Load Following - Aggressive	No	Operational	Operational	Synch.	No	Active	Full	To 50% and back to 100% at 5%/min rate		☒
		Load Following - Moderate	No	Operational	Operational	Synch.	No	Active	Full	To 50% and back to 100% at 2%/min rate		☐
		Startup/Shutdown	No	Active	Active	No	No	Active	Active	Not simulated. Can be as slow as needed to avoid thermal shock.		
Design-Basis Accidents (DBA)	Anticipated accidents; protection systems work as designed	Reactor scram	Yes	Trip with scram	Trip with scram	No	Trip with scram	Active	Active			☐
		Reactivity insertion	Yes	Trip with scram	Trip with scram	No	Trip with scram	Active	Active	Start inserting at 1c/s rate; scram at 115% power		☒
		Int. Na pump trip	Yes	Trip	Trip	No	Yes	Active	Active	Similar to Rx scram case, except for delays in control action.		☐
		Na pipe break – RHX inlet	Yes	Trip	Trip	No	Yes	Active	Active	Break sizes from small to LBB, delay in all control actions.		LT
		Na pipe break – RHX outlet	Yes	Trip	Trip	No	Yes	Active	Active	Break sizes from small to LBB, delay in all control actions.		LT
		CO ₂ pipe break – RHX inlet	Yes	Trip	Trip	No	Yes	Active	Active		Small break Intermediate break Large break DEG break	☐ ☐ ☐ LT
		CO ₂ pipe break – RHX outlet	Yes	Trip	Trip	No	Yes	Active	Active		Small break Intermediate break Large break DEG break	☒ ☒ ☐ LT
		Loss of grid load	Yes	Trip	Trip	No	Yes	Active	No?	Expect some turbine overspeed, Air fan power is included in net generator output in PDC – can be operated without offsite power		☒
		CO ₂ isolation valve closure	Yes	Trip	Trip	No	Yes	Active	Active	Simulate as TIN valve closure		LT
		TBP valve uncontrolled opening	No	Active	Active	Yes	No	Active	Active	Opening of TBP to 50% in 5 s		☒
Beyond Design Basis Events (BDBE)	Unlikely events with one or several failures of protection system. Conservative	Reactor scram with sodium pumps and sCO ₂ TM operating	Yes	Operational	Operational	Synch.	No	Active	Full	Cold front propagating through Rx and IHTS		☒
		Reactor scram with intermediate sodium pumps and sCO ₂ TM operating	Yes	Trip	Operational	Synch.	No	Active	Full	Similar to previous case		☒
		Reactor scram with sodium pumps tripped and sCO ₂ TM operating	Yes	Trip	Trip	Synch.	No	Active	Full			☒

Class	Characteristic	Events	Control / Protection System (Gray – Different from NO, Yellow – Initiating Event)						Comments		Simu lated ?	
			Reactor scram	Primary Na pumps	Interm. Na Pumps	Grid connection	Turbine Trip	sCO ₂ Cycle Controls				Air Flow
	assumptions (most thermal shock)	Reactivity insertion without scram	No	Operational	Operational	Synch.	No	Active	Full	20c over 20 s		☒
		Reactivity insertion with late scram	Yes	Operational	Operational	Synch.	No	Active	Full	Scram at highest core-outlet temperature		☒
		Int. Na pump trip with full CO ₂ flow	No	Operational	Trip	Synch.	No	Active	Full			☐
		Unprotected Na pipe break – RHX inlet	No	Operational	Operational	Synch.	No	Active	Full	Break sizes from small to DEG		LT
		Unprotected Na pipe break – RHX outlet	No	Operational	Operational	Synch.	No	Active	Full	Break sizes from small to DEG		LT
		Unprotected CO ₂ pipe break – RHX inlet	No	Operational	Operational	Synch.	No	Active	Full	No control action on reactor side to maintain Na temperatures	Small break	☒
											Intermediate break	☒
											Large break (1/2 ID, 34 cm)	☒
											DEG break	LT
		Unprotected CO ₂ pipe break – RHX outlet	No	Operational	Operational	Synch.	No	Active	Full	No control action on reactor side to maintain Na temperatures	Small break	☒
											Intermediate break	☒
Large break	☒											
DEG break	LT											
Unprotected CO ₂ isolation valve closure	No	Operational	Operational	Synch.	No	Active	Active	Close TIN valve		LT		
Unprotected TBP valve uncontrolled opening	No	Operational	Operational	Synch.	No	Active	Active	Fully open TBP valve		LT		
Unprotected loss of offsite power	No	Trip	Trip	No	Yes	Active	Active			☒		

LT – simulated with Limiting Transients (see Table 3 below)

Table 3. Limiting Transients

Class	Events	Limiting Transient	Control / Protection System (Gray – Different from NO, Blue – Not Applicable)							Comments	Simulated ?
			Reactor scram	Primary Na pumps	Interm. Na Pumps	Grid connection	Turbine Trip	sCO2 Cycle Controls	Air Flow		
Design-Basis Accidents (DBA)	Large Na pipe break – RHX inlet Large Na pipe break – RHX outlet Fast IHTS drain	Protected Loss of Heat Addition (PLOHA)	N/A	N/A	N/A	No	Yes	Active	Active	Modeled as sudden and complete loss of heat transfer between Na and HX wall	☐
	Large CO2 pipe break – RHX inlet Large CO2 pipe break – RHX outlet CO2 isolation valve closure TBP valve uncontrolled opening	Protected Loss of Heat Sink (PLOHS)	Yes	Trip with scram	Trip with scram	N/A	N/A	N/A	N/A	Modeled as sudden and complete loss of heat transfer between HX wall and CO2	☒
Beyond Design Basis Events (BDBE)	Unprotected large Na pipe break – RHX inlet Unprotected large Na pipe break – RHX outlet Unprotected fast IHTS drain	Unprotected Loss of Heat Addition (ULOHA)	N/A	N/A	N/A	Synch.	No	Active	Full	Modeled as sudden and complete loss of heat transfer between Na and HX wall	☒
	Unprotected large CO2 pipe break – RHX inlet Unprotected large CO2 pipe break – RHX outlet Unprotected CO2 isolation valve closure Unprotected TBP valve uncontrolled opening	Unprotected Loss of Heat Sink (ULOHS)	No	Operational	Operational	N/A	N/A	N/A	N/A	Modeled as sudden and complete loss of heat transfer between HX wall and CO2	☒

4 RESULTS OF ANALYSIS

In this section, the results of transient simulations with PDC of all transients described in the previous section are presented. For each transient, the PDC results are shown in two figures. The first figure will show general results, which include temperatures, pressures, and flow rates in the system, as well as control system action, as a function of time.

Since the main goal of this work was to investigate thermal transients for the RHX, the detailed results of the heat exchanger are presented in the second figure for each transient. This figure will demonstrate the RHX wall temperatures during each transient and how fast these temperatures change. This rate will be shown in the units of °C per second (°C/s).

The current PDC model for AFR-100 RHX defines five nodes along the heat exchanger length. Therefore, for each transient, a set of five wall temperature curves will be shown for the duration of the transient, along with the temperature change rates for each of these five nodes. An example of these results is shown in Figure 4. The wall temperature curves are plotted for each node, with the steady-state value (at t=0) defining where each node is located. In Figure 4 and other similar figures below, the black, blue, red, green, and purple curves correspond to Nodes one through five, respectively, from the hot end of the heat exchanger. The temperature change rate plots use the same color coding.

Figure 4. Example of Transient Results for RHX Wall Temperature Change.

4.1 Normal Operation

4.1.1 Load Following

For this work, a rather aggressive load following, from 100% to 50% load and back to 100% at 5%/min rate was postulated. The load was reduced from 100% to 50% during first 600 seconds (10 minutes), held at 50% level for 400 seconds, and then increased back from 50% to 100% between 1000 and 1600 seconds. The transient was completed with steady 100% load from 1600 to 2000 seconds. The AFR-100 plant control system was set to match the required grid demand [2]. During the inventory control action, between 90% and 50% loads, the CO₂ flow rate is reduced everywhere in the cycle, including that through the RHX, while the CO₂ RHX-inlet temperature increases by about 50 °C. The reactor control system maintains the hot-leg temperatures, so the sodium temperature at the RHX inlet does not change much, although the sodium flow rate reduces with load to maintain the heat transfer balance in the RHX. The general results of the load following simulation for AFR-100 are presented in Figure 5. All plant control system work as expected such that the actual generator output matches the specified target output all the times.

Figure 6 shows the results of the load following transient in terms of the RHX wall temperature change. The maximum temperature change rate of +0.27 °C/s was calculated during the load increase stage, although for the majority of the transient the rate stayed with ± 0.1 °C/s.

Figure 5. Transient Results for Load Following.

(figure continues on next page)

Figure 6. RHX Wall Temperature Change during Load Following.

4.1.2 Normal Startup and Shutdown

An analysis of normal startup and shutdown sequences was not included in this work because at least for the nuclear power plants, such as AFR-100, the rate of power change during startup and shutdown can be as slow as it is required to satisfy any thermal stress requirement on the reactor structures. This rate is usually of the order of few degrees *per minute*, which would be lower than the rates calculated for the load following in Figure 6.

4.2 Design-Basis Accidents

In DBA accidents, a single fault (equipment failure) is postulated. The plant control and protection systems work as expected, including the normal sCO₂ cycle controls and the reactor side coolant flow and power controls.

4.2.1 Small CO₂ Pipe Break

In the current AFR-100 design, the RHX is connected to the turbine by a single pipe 0.68 m in inner diameter. In the pipe break simulation, a small opening (break) in this pipe is postulated at the point where this pipe is connected to the RHX. The break size is equivalent to a circular hole of 1 cm in diameter and is simulated to occur at time=0. The PDC simulates the pipe break as a flow through a break contraction, from the pipe pressure to the atmospheric pressure outside the pipe. The PDC results for this accident are shown in Figure 7. The immediate effect of the pipe break is a reduction in pressure in the RHX-outlet pipe, leading to an increase in CO₂ flow rate through the heat exchanger. This results in overcooling of the RHX structure. However, the effect is offset by the reduction of the CO₂ inventory in the cycle, leading to a reduction in the flow rate everywhere in the cycle – similar to the inventory control action – including that in the RHX. No control action is initiated on the sCO₂ cycle since the plant output decreases below the requested 100% level. Figure 8 for the RHX results shows that the effect of this small pipe break on the RHX wall temperature is minor, with the maximum wall temperature change rate calculated to be -0.011 °C/s, which is about an order-of-magnitude lower than in the normal load following in Figure 6.

Figure 7. Results for Small CO₂ Pipe Break DBA.

(figure continues on next page)

Figure 8. RHX Results for Small Pipe Break.

4.2.2 *Intermediate CO₂ Pipe Break*

The intermediate CO₂ pipe break scenario is similar to the previous case, except the equivalent pipe break diameter is 5 cm. The general results for this transient are shown in Figure 9. Compared to previous figure, this larger break increases initial overcooling of the heat exchanger wall. But it also increases the sCO₂ cycle depressurization rate, resulting in faster decrease in the CO₂ flow rate in the cycle. Figure 9 also shows that some controls, such as for compressor inlet temperature, become unstable towards the end of the transient when CO₂ pressure and heat removal rate decreases significant. This happens because the controls were never optimized to work in this regime.

The results of this transient in terms of the RHX wall temperature change are shown in Figure 10. Due to the pipe break and increasing CO₂ flow rate, the immediate cool down rate is about -0.1 °C/s. However, for the majority of the transient, the RHX is being undercooled due to the decrease in the CO₂ flow rate from the inventory reduction effect on the entire cycle. The maximum wall temperature change rate is +0.14 °C/s.

Figure 9. Results for Intermediate CO₂ Pipe Break.

(figure continues on next page)

Figure 10. RHX Results for Intermediate CO₂ Pipe Break.

4.2.3 *Partial Opening of Turbine Bypass Valve*

In this accident, an unintended opening, either due to equipment failure or operator error, of the turbine bypass (TBP) valve is simulated. In the AFR-100 design, the turbine bypass line connects the two CO₂ streams at the HTR hot end. Therefore, opening the bypass valve sends part of the CO₂ flow around both the RHX and the turbine. In normal operation at full power, the TBP valve is fully closed. In this event, it is simulated to partially open to the 50% position in 5 seconds. The results for this transient are shown in Figure 11. The overall plant response is similar to the forced power reduction by TBP action. For the RHX temperatures, TBP valve opening means a significant reduction in the CO₂ flow rate through the RHX, leading to an increase in the wall temperatures. However, the effect is partially mitigated by the working reactor-side controls, which reduce the sodium flow through the RHX in an attempt to maintain the temperature of the reactor coolant.

The results of this transient are shown in Figure 12. Shortly after the valve failure, the heat exchanger temperature increases at a rate up to +0.81 °C/s. The reactor side control manages to stop the temperature increase in about 100 seconds.

Figure 11. Results for Partial TBP Valve Opening.

(figure continues on next page)

Figure 12. RHX Results for Partial TBP Valve Opening.

4.2.4 Reactor Power Increase with Scram

This transient simulates a fault in the reactor power control system. Due to either an equipment malfunction or an operator error, one or more control rods are being withdrawn from the core, increasing the core power. The PDC results of this simulation are shown in Figure 13. The reactor protection system responds by inserting the other control rods in the core when core power reaches the 115% level, at 8 seconds into the transient. This system also trips both the primary and intermediate sodium pumps at 10 seconds to avoid thermal shock on the reactor structures. The sCO₂ turbine is also tripped at 10 seconds into the transient by opening the turbine bypass valve at the maximum allowed rate (at 10%/s).

The results of the RHX wall temperatures for this transient are shown in Figure 14. Because it takes time for the hot temperature front to propagate from the core outlet to the RHX, the RHX does not “see” the effect of the reactor power increase. In fact, the heat exchanger temperatures only respond to the plant protection action, which trips the sodium pumps and the CO₂ turbine at 10 seconds. Due to the imposed limit on the TBP valve action in this simulation, the CO₂ flow decreases slower than the sodium flow, resulting in overcooling of the heat exchanger. The maximum calculated wall temperature change rate for this transient is -0.98 °C/s.

Note that the results in Figure 14 will also be representative of the plant response to an accidental reactor scram (without the initial power increase). The plant protection system response with regard to tripping the sodium pumps and the CO₂ turbine will be the same, except it will occur earlier in the transient, just after the postulated scram. Since the initial power increase is not showing in RHX in Figure 14, the results for a reactor scram event are expected to be similar, if not identical, to those presented in Figure 14.

In general, the results in Figure 14 will be representative for *any* event involving tripping of the intermediate sodium pumps, regardless of what happens elsewhere on the reactor side (as long as the CO₂ turbine is tripped at the same time). When the sodium pumps are tripped, the sodium flow rate will reduce significantly, such that the time scale to communicate any temperature changes in the reactor to the RHX would be much longer than 200 seconds analyzed in Figure 14.

Figure 13. Results for Reactor Power Increase with Scram.

(figure continues on next page)

Figure 14. RHX Results for Reactor Power Increase with Scram.

4.2.5 *Loss of Grid Load with Reactor and Turbine Trips*

In this transient, a sudden and instantaneous disconnection of the generator from the electrical grid is postulated. Figure 15 shows the results for this transient. Due to loss of the electrical load, the turbine will start to overspeed. To protect the plant equipment, a fast turbine overspeed protection system is initiated, simulated in the PDC by fast closing of the turbine throttle valve (see Figure 3) in 0.5 seconds. With this action, a turbine overspeed of 10% is calculated by the PDC. The plant control system will also scram the reactor and will trip the sodium pumps. However, the decrease in sodium flow rate will not be as fast as the decrease in the CO₂ flow rate caused by fast shut down of the turbine throttle valve.

The results of this transient on the RHX wall temperatures are shown in Figure 16. Due to fast decrease in the CO₂ flow rate, the wall temperatures increase initially, reaching the rate of +1.68 °C/s at the peak. The reactor protection system action eliminates the heatup in about 20 seconds for all the heat exchanger nodes, except the one at the cold end. The entire transient is completed in about 1 minute, when the wall temperatures are stabilized.

Figure 15. Results for Loss-of-Load Accident.

(figure continues on next page)

Figure 16. RHX Results for Loss-of-Load Accident.

4.3 Severe Beyond Design Basis Events

For this class of events, severe transients are analyzed. These transients usually include double-fault events, such as an initiating event or failure, *plus* the failure of the plant protection system either to recognize the event or to properly respond to it. Because of this double-fault assumption, these events have very low probability of occurring in the plant lifetime, but may have significant consequences for the plant components and structures, including RHX.

In addition, large CO₂ pipe breaks, although they are single-fault events, are included in this class due to low probability of such events.

4.3.1 Reactor Trip with sCO₂ Cycle Operating

In the previous section, the RHX thermal transient during the reactor scram was analyzed. In that simulation, a normal plant response to the event was simulated, including tripping of the CO₂ turbine. For a severe variation of this event analyzed in this section, it is assumed that the CO₂ turbine *is not* tripped in response to the reactor scram. Since the reactor scram also trips the primary and intermediate sodium pumps, not tripping the CO₂ turbine in this case introduces an imbalance between the flows on two sides of the heat exchanger. Figure 17 shows the results of the PDC simulation of this transient. The sodium flow quickly decreases, while close to full flow continues to exist on the CO₂ side, introducing a significant misbalance in the RHX heat transfer rates. Because of the sodium pump trips, the simulation is terminated shortly after 100 seconds, when intermediate sodium rate in RHX reduces to a value close to zero.

The results of this transient for the RHX, shown in Figure 18, demonstrate that there is a significant overcooling of the heat exchanger structure. The maximum cooling rate reaches -1.68 °C/s.

The results in Figure 18 are also representative for other accidents where the sodium flow is tripped, but CO₂ flow continues. The examples of such transient initiators on the sodium side include failure of the intermediate sodium pumps as well as operator error or plant control system failure resulting in sodium pump trips. Because the sodium flow rate reduces quickly – in about 100 seconds – whatever happens on the reactor side in such events has little, if any, effect on the RHX temperatures. In all these cases, the results shown in Figure 18 will be obtained, only if the CO₂ side control system also fails to respond properly to such events.

Figure 17. Results for Reactor Trip with sCO₂ Cycle Operating Accident.

(figure continues on next page)

Figure 18. RHX Results for Reactor Trip with sCO₂ Cycle Operating Accident.

4.3.2 Turbine Trip with Reactor Operating

An opposite example of the RHX flow imbalance is a situation when the CO₂ flow rate is reduced while the full sodium flow rate is maintained. An example of such an event is a postulated turbine trip, from an equipment failure or an operator error, while the reactor control and protection system also fails to recognize the event. The results of this transient are shown in Figure 19. Note that the initial results of this transient are similar to those for the loss-of-load event in Figure 15. At these early stages, the CO₂ flow rate decreases much faster than the change in sodium flow rate, even if the sodium pumps are tripped. However, if the sodium pumps are not tripped – like in Figure 19 – then the heatup continues even after the initial phase.

The results of this transient are shown in Figure 20. The RHX wall temperatures continue to heat up during the entire transient, reaching a rate of +1.78 °C/s at the maximum.

Figure 19. Results for Turbine Trip with Reactor Operating Accident.

(figure continues on next page)

Figure 20. RHX Results for Turbine Trip with Reactor Operating Accident.

4.3.3 Unprotected Reactor Overpower

A transient with reactor power increase is analyzed in the previous section (Figure 14). In that transient, though, the reactor protection system counteracts the transient initiator by scrambling the reactor. For the following double-fault event, it is postulated that *reactor scram does not occur* and the power continues to increase beyond the 115% trip level. The reactor protection system is a highly reliable nuclear safety grade system, such that a double failure of this system (one to withdraw a control rod and the other to fail to respond to increasing power) is an extremely unlikely event. The AFR-100 reactor has strong passive safety characteristics due to favorable reactivity feedbacks, such that it has been shown [6] that the reactor itself will survive such an extreme event. The goal of the current analysis was to see what this transient means for the RHX temperatures. The results of this transient in Figure 21 show significant increase of reactor power and heat addition in RHX beyond 115% level in previous simulation (in Figure 13). Eventually, though, negative reactivity feedbacks bring the entire plant to a new steady-state at about 110% level and elevated temperatures.

These results for the RHX wall are shown in Figure 22. There is a significant initial increase in the heat exchanger temperatures, both in the rate and magnitude. Note that because this event involves reactor power increase and heating up of the reactor structures, the time scale in Figure 22 is much longer than for all other severe accidents presented above. The maximum temperature increase rate is calculated at +1.87 °C/s, but it is maintained at or above 0.5 °C/s for about 240 seconds (four minutes), such that all the temperatures increase by at least 100 °C during the transient.

Figure 21. Results for Unprotected Overpower Accident.

(figure continues on next page)

Figure 22. RHX Results for Unprotected Overpower Accident.

4.3.4 *Reactor Overpower with Delayed Scram*

One more variation of the reactor overpower accident was analyzed in this work. In this case, the reactor protection system does scram the reactor, but the action is delayed for some reasons and it occurs at the worst possible moment when the core-outlet temperature reaches its maximum value. It is also assumed here that the sodium pumps are not tripped with the reactor scram, such that cold shock is initiated in the core and is propagated throughout the system. Figure 23 shows the PDC results for this transient. For the RHX temperatures, this accident sequence means a combination of a heatup transient, when the initial reactor power increase reaches this heat exchanger, followed by a rapid cool down transient from the reactor scram action.

The heat exchanger temperature results for this transient are shown in Figure 24. Similar to the previous case, during the power increase the temperatures rise with a rate up to $+1.87\text{ }^{\circ}\text{C/s}$. However, this temperature increase is quickly transformed to a cooldown phase after the reactor scram, with the wall temperature change rates reaching $-3.2\text{ }^{\circ}\text{C/s}$.

Figure 23. Results for Overpower with Delayed Scram Accident.

(figure continues on next page)

Figure 24. RHX Results for Overpower with Delayed Scram Accident.

4.3.5 Large CO₂ Pipe Break – RHX Outlet Pipe

In this transient, a large break of the CO₂ pipe at the RHX outlet is simulated. The pipe break equivalent diameter is 34 cm, which is one-half of the pipe inner diameter (compared to the 5 cm break analyzed in Section 4.2.2). The CO₂ sound speed at the RHX outlet location is about 500 m/s, so the critical flow rate through the 34 cm diameter hole is estimated¹ at 45 m³/s or 7,100 kg/s based on the bulk CO₂ density of 158 kg/m³. With that flow rate, the entire sCO₂ cycle inventory would be evacuated in less than 10 seconds. However, with this fast depressurization of the cycle, the PDC predicts reaching the choke limit in the main compressor in only 1.3 seconds.

Because the leak flow rate is about six times larger than the nominal CO₂ flow rate of 1,190 kg/s through that pipe (see Figure 1), the PDC calculates that the instantaneous CO₂ flow rate through the heat exchanger increases more than four times in about 0.2 s. Consequently, the instantaneous heat removal rate by CO₂ in the RHX increases to the 400% level, as shown in Figure 25. Due to rapid system depressurization, the simulation was terminated shortly after 1.3 seconds due to a compressor choking.

Figure 26 shows the results for RHX temperatures. An increase in heat removal results in HX wall cool down rates of -6.8 °C/s at the peak. However, these rates are maintained only for a fraction of a second and the entire transient lasts slightly over one second. As a result, the change in absolute values of the wall temperatures is barely noticeable in Figure 26.

¹ The PDC calculates the critical flow rate based on the local sound speed and density at the break, not the bulk properties in the pipe used in this estimate.

Figure 25. Results for Large CO₂ Pipe Break at RHX Outlet.

(figure continues on next page)

Figure 26. RHX Results for Large CO₂ Pipe Break at RHX Outlet.

4.3.6 Large CO₂ Pipe Break – RHX Inlet Pipe

Consequences of a similar large CO₂ pipe break were also analyzed for a break in the RHX-inlet pipe. In this case, the RHX inlet header loses pressure, such that the CO₂ flow reverses in the RHX. With this flow reversal, hotter CO₂ from the heat exchanger outlet is brought back to the cold end of the heat exchanger. This is in addition to the hot sodium flow in the same direction, which is now not being cooled as effectively by CO₂ when it reaches the HX cold end. The results for this transient are shown in Figure 27, which confirms that the heat removal rate in RHX by CO₂ reverses to a negative value immediately after the break. Similar to the previous case, PDC predicts compressor choke at 1 second, such that the entire transient terminates quickly without significant changes in the absolute values of the HX temperatures. Note that for the RHX-inlet break location, the CO₂ density at the pipe is higher such that the system is depressurizing faster than in the previous case and the transient terminates 0.3 second earlier. The wavy structure of the results in Figure 27 (and also in Figure 28 below) is due to propagation of the shock wave through the RHX and the entire sCO₂ cycle.

The RHX results for this transient are shown in Figure 28. Due to CO₂ flow reversal in the RHX, hot sodium heats up the heat exchanger at the maximum rate of +2.13 °C/s. The maximum temperature increase occurs at the cold end of the heat exchanger (green and purple lines in Figure 28).

Figure 27. Results for Large CO₂ Pipe Break at RHX Inlet.

(figure continues on next page)

Figure 28. RHX Results for Large CO₂ Pipe Break at RHX Inlet.

4.4 Hypothetical Limiting Accidents

In the previous section, low-probability severe accidents were analyzed. Those accidents likely present the most severe conditions a heat exchanger will be subjected to during its lifetime. Still, in order to see the worst-case scenarios, a series of hypothetical transients were also analyzed for the AFR-100 sodium-CO₂ heat exchanger. In these accidents, a mathematical limit of the heat addition or the heat removal from the heat exchanger is introduced by instantaneously removing fluid from one side of a heat exchanger.

For the PDC simulation, these limiting transients are simulated by turning off the heat transfer from the wall to either hot- or cold-side fluid. The fluid on the other side is assumed to continue to circulate at full flow and, basically, the nominal heat removal rate.

Even though there is no practical way to achieve such hypothetical conditions, analyzing these transients here provides the upper bound for other transients, which are difficult or impossible to simulate with system analysis tools, for example, due to zero or very small mass or flow rate, which will likely pose computational challenges.

4.4.1 Complete Loss of Heat Addition (LOHA)

In this hypothetical transient, the sodium is completely removed from the hot side, while the full flow rate remains on the cold side. The results of this simulation in Figure 29 show that the heat exchanger is being quickly cooled by CO₂. The maximum wall temperature change rate is -2.86 °C/s, with the cool-down rate greater than -1 °C/s sustained for about 4 minutes. Since there is no heat addition in this simulation, the RHX and all other sCO₂ cycle temperatures continue to decline. The PDC simulation terminates around 360 seconds due to approach to choke conditions in both compressors and in the turbine.

The loss-of-heat-addition accident provides an upper bound for all accidents that involve partial or complete loss of sodium from the RHX. The examples of such transients include a large sodium pipe break as well as rapid sodium draining from the system. The latter could either occur as a normal plant response to a sodium leak and fire or due to failure of the (redundant) sodium drain valve(s). Still, in all those accidents, results similar to those in Figure 29 will only be obtained if CO₂ continues to circulate through the RHX at full flow, which is improbable given the magnitude of the temperature changes in Figure 29.

Figure 29. RHX Results for Hypothetical LOHA Accident.

4.4.2 *Complete Loss of Heat Removal (LOHR)*

The loss of heat removal is an opposite of the loss of heat addition accident. In this case, a sudden and complete removal of CO₂ from the RHX is simulated, while full sodium flow is maintained. The results of this transient are shown in Figure 30. The heat exchanger wall heats up with initial maximum rate of +2.58 °C/s, which decreases with time. Note that the heat exchanger temperatures in this transient exceed the nominal sodium-inlet temperature (528 °C in Figure 1) due to heatup of the entire reactor system. The transient was run for 900 seconds (15 minutes) at which point the wall temperature change rate decreases to zero. (Previous safety analysis for AFR-100 reactor [6] showed that the reactor itself is able to survive loss-of-heat removal accidents even without activation of the reactor protection system.)

The hypothetical loss of heat removal accident serves as the limiting case for other transients where the CO₂ flow is partially or completely lost. The examples of such transients include complete closure of the turbine throttle valve, closure of RHX isolation valves (if those are included in the design), complete opening of the turbine bypass valve, or instantaneous loss of a CO₂ compressor due to, for example, turbomachinery shaft failure. Again, the results in Figure 30 will only be achieved if during these accidents the reactor protections system fails to trip the reactor and the sodium pumps.

Figure 30. RHX Results for Hypothetical LOHR Accident.

5 EQUIVALENT HELIUM-CO₂ HEAT EXCHANGER

The analysis presented so far in this report was focused on the sodium-CO₂ heat exchanger in the AFR-100 design. For practical reasons, a decision was made in the NEUP project to conduct the heat exchanger testing at Georgia Tech with helium and CO₂ rather than with sodium and CO₂. This chapter presents the results of an investigation into how to best represent sodium-CO₂ heat exchanger with helium on the hot side of the test heat exchanger.

Since the goal of the entire NUP project was to investigate and simulate the transient performance of a heat exchanger, and, specifically, wall temperature change rates, ideally, an equivalent He-CO₂ HX would provide the same wall temperature transient response as the Na-CO₂ HX. Practically, however, it's understood that due to unavoidable differences in fluid properties, such as heat capacities of liquid-metal sodium and gaseous helium, an exact match would be unlikely. Therefore, the goal of this analysis was set to find as close a match as possible between the He-CO₂ heat exchanger and a Na-CO₂ heat exchanger in terms of transient behavior. In this work, it was assumed that the heat exchanger design remains the same (as that shown in Figure 2) such that the results of the transient analysis with the PDC in the previous chapter would still be valid. Thus, the goal of this analysis was to find the conditions on the hot helium side which would provide an equivalent transient performance to the Na-CO₂ HX.

5.1 Steady-State Analysis

The analysis is carried out for the same heat exchanger design as the AFR-100 RHX (in Figure 1), for the same heat duty of 250 MW. Sodium at atmospheric pressure is replaced with helium at assumed 8 MPa pressure on the hot side. Figure 31 shows the overall heat transfer equation in the RHX. In that equation:

Q = heat transfer rate (250 MW),

S = total surface area,

HTC = overall heat transfer coefficient,

$\overline{T}_{hot}$ and $\overline{T}_{cold}$ = average temperatures on hot and cold side, respectively.

Figure 31. Heat Transfer Equation in RHX.

In the following analysis, Q and S are fixed due to fixed heat duty and the HX design and size. The cold side temperatures are also fixed, to a first approximation, from the cycle design (RHX-inlet temperature is the same as the HTR-outlet temperature). Since the properties and HTC on the helium side will be different from those for sodium, Figure 31 demonstrates that either overall the HTC, hot-side temperatures, or both, will be different in the helium-CO₂ HX compared to the AFR-100 RHX with sodium.

5.1.1 RHX Performance with Same Hot Side Conditions

As the basis for finding the equivalent He-CO₂ heat exchanger, first, calculations were carried out with the same inlet and outlet temperatures for helium as with sodium. Figure 32 shows the PDC steady-state results for sodium and helium RHXs with the same 528/373 °C inlet/outlet temperatures on the hot side. Due to differences in specific heats, the helium mass flow rate is about four times lower than that of sodium. Figure 32 also demonstrates that due to inferior heat transfer characteristics of helium compared to sodium, the overall performance of the helium RHX is worse, as CO₂ is heated to only 456 °C at the turbine inlet (compared to 521 °C with sodium). Also note from Figure 32 that lower turbine-inlet temperature means lower HTR-outlet and RHX-inlet temperatures with helium. The conclusion from Figure 32 is that in order to get similar performance at steady-state (even before any transient considerations), helium temperatures need to be increased compared to that of sodium.

Figure 32. RHX Steady-State Results with Same Hot Side Temperatures.

5.1.2 RHX Performance with Same Hot Inlet and Turbine-Inlet Temperatures

On the next step, an attempt was made to obtain the same heat exchanger performance, in terms of CO₂ outlet temperature, while maintaining the same hot side inlet temperature. To do that, the helium temperature at the RHX outlet had to be increased. Figure 33 shows the PDC steady-state results that indicate that in order to match the turbine-inlet temperature of 521 °C, the hot side RHX-outlet temperature needs to increase from 373 °C with sodium to 443 °C for helium.

Figure 33. Matching Turbine-Inlet Temperature with Fixed Hot Side Inlet.

The change in the hot-side outlet temperature, however, distorts the temperature profiles inside the heat exchanger. Figure 34 compares the temperature profiles along the heat exchanger length for Na-CO₂ and He-CO₂ heat exchangers for the conditions in Figure 33. Figure 35 plots the same results as in Figure 34, but directly compares the wall and CO₂ side temperature profiles between the two heat exchangers. Even though the CO₂-side inlet and outlet temperatures are close in two cases, the temperature profiles inside the heat exchanger are noticeably different. Specifically to the wall temperature, this difference is expected to result in different transient behavior of a heat exchanger, since the variation in the axial profiles is caused by a different distribution of heat transfer rate between the heat exchanger nodes (sections).

Figure 34. RHX Temperature Profiles for Matching Turbine-Inlet Temperature.

Figure 35. Change in Wall (top) and CO₂ (bottom) Temperature Profiles for Matching Turbine-Inlet Temperature.

5.1.3 RHX Performance with Same Hot Side Temperature Change

In the next variation, the CO₂ temperature at the RHX outlet was matched by increasing both inlet and outlet temperature on the helium side, while preserving the same temperature change (-155 °C) on the hot side, as for the reference design with sodium. The results in Figure 36 show that in order to achieve this goal, the hot-side temperatures with helium need to be 66 °C higher than with sodium.

Figure 36. Matching Turbine-Inlet Temperature with Fixed Hot Side ΔT .

The temperature profiles in RHX for this case are shown in Figure 37. This figure also clearly demonstrates that in order to achieve similar heat transfer performance with helium, the temperature difference between the helium and the wall needs to be significantly larger than that with sodium, due to much better heat transfer characteristics of sodium. Figure 38 shows that in this approach, the accurate matching of wall temperature profiles is still not achieved, although the profiles are matched somewhat better than in previous case in Figure 35.

Figure 37. RHX Temperature Profiles for Fixed Hot Side ΔT .

Figure 38. Change in Wall and CO₂ Temperature Profiles for Fixed Hot Side ΔT .

5.1.4 Matching Temperature Profiles

Previous results showed that accurate matching of the RHX wall temperature profiles could not be achieved with simple variations of hot-side conditions for the He-CO₂ HX. Therefore, more detailed calculations were carried out next, where both the inlet and outlet temperatures on the RHX hot side were varied independently of each other in order to: i) still match the turbine-inlet temperature, and ii) also match wall temperature profiles as close as possible.

Figure 40 shows the results of this study and demonstrate that both the wall and CO₂ temperatures can be matched with helium pretty closely for all internal nodes. Figure 39 demonstrates that in order to achieve such good agreement, *the helium RHX-inlet temperature needs to increase, compared to sodium, from 528 °C to 546 °C, while the RHX-outlet temperature needs to increase from 373 °C to 429 °C*. Figure 41 shows all temperature profiles for this case, and again confirms the requirement of a larger temperature difference between helium and the wall, compared to sodium.

Figure 39. Conditions to Match Temperature Profiles.

Figure 40. Matching Temperature Profiles.

Figure 41. RHX Temperature Profiles for Matched Case.

5.2 Transient Simulations

To check if the equivalent RHX performance at steady-state conditions also results in a similar transient response, the dynamic simulation of RHX transients with helium had to be performed. However, the same transients analyzed in previous chapter of this report could not be repeated with helium for the following reasons. The results in previous chapter were obtained with the coupled PDC and SAS4A/SASSYS-1 codes. The latter was used to calculate the transient response of the AFR-100 sodium-cooled reactor. Not only the same SAS4A/SASSYS-1 code could not be used for helium, but also there doesn't exist a helium-cooled reactor equivalent to the AFR-100. The only option that exists in the PDC and could be used for He-CO₂ HX transients is the user-specified helium conditions at the RHX inlet, including temperature, pressure, and flow rate, as a function of time. Since the dynamic model of a helium reactor is not available, the number of the transients that can be meaningfully simulated with helium for this work is severely limited. For example, normal operation transients, which would require knowledge of the plant control system, are excluded from the list. Also, only short-term transients can be simulated, where the helium conditions (e.g., temperature) at the RHX inlet are not significantly affected by the transient itself. For these reasons, only two transients were simulated with the He-CO₂ heat exchanger and are described below. Both transients begin from steady-state conditions for the “matching temperature profiles” case in Figure 39.

5.2.1 Reactor Coolant Pump Trip

This transient is initiated by trip of the reactor-side pump, such as an intermediate sodium pump or a helium circulator. For comparison purposes, a severe variation of this transient, where the CO₂ side controls do not react to the accident, is simulated. The results for this transient for the sodium case are presented in Section 4.3.1 Reactor Trip with sCO₂ Cycle Operating.

To obtain boundary conditions for the He-CO₂ HX, the SAS4A/SASSYS-1 results for normalized sodium flow rate in the RHX were fitted with a table function, as shown in Figure 42. Note that this flow reduction curve is obtained for a sodium pump and is not necessary representative of a coastdown of a helium pump. It is used here only to provide similar reduction in the hot side flow rate for the RHX transient.

The results for the sodium case also showed that the RHX-inlet temperature on the hot side does not change much in this transient, since with a tripped pump it takes a long time to communicate any change in the reactor temperatures to the RHX inlet. Therefore, for the helium case, the RHX-inlet temperature is assumed to remain at the steady-state level during the entire transient.

Figure 42. Hot Side Flow Rate Fit.

Figure 43 shows the comparison of the transient results for the RHX wall temperature for the Na-CO₂ and He-CO₂ heat exchangers. Figure 44 shows a similar comparison for the RHX wall temperature rate change. In both figures, the results for sodium and helium are close, even though the helium temperatures start at and remain higher than those in the sodium case. Figure 44 also shows that the maximum wall temperature rate changes are very similar, at -1.7 to -1.8 °C/s. These results confirm that the appropriate matching of temperature profiles at steady-state also results in a similar transient response of a heat exchanger.

To further see if matching temperature profiles was important for the transient response, another case with a He-CO₂ heat exchanger was simulated. In this case, the transient was initiated from steady-state conditions in Figure 34, where the RHX-inlet temperature was fixed at 528 °C. The results of this simulation in Figure 45 are compared with both the reference sodium case and the “matched profiles” helium case in the previous figure. Even though the results for all three cases are generally close, Figure 45 demonstrates that matching temperature profiles provides better agreement with the reference sodium case, both in terms of short-term response and the maximum wall temperature change rate. For the case of fixed inlet temperature, temperatures of some temperature nodes decrease noticeably faster at -2 °C/s rate.

Figure 43. RHX Wall Temperature Results for Reactor Pump Trip.

Figure 44. RHX Wall Temperature Rate Change Results for Reactor Pump Trip.

Figure 45. Effect of Matched Temperature Profiles.

5.2.2 CO₂ RHX-Inlet Pipe Break

The previous transient represented a cool-down transient where the RHX temperature decreased due to loss of heat addition. To compare the behavior of the He-CO₂ HX under different conditions, a CO₂ pipe break at the RHX inlet was selected as an example of a heatup transient. With a CO₂ pipe break at the RHX inlet, the CO₂ flow rate in the RHX is reduced, resulting in degraded heat removal by CO₂. It is assumed that the reactor protection system fails to respond to this event by still providing the full hot side fluid flow into the RHX. For this comparison, an intermediate break diameter of 10 cm is selected.

For simulation with helium, it is assumed that the helium RHX-inlet temperature will remain constant at the steady-state value of 546 °C. Simulation of a similar transient for sodium with SAS4A/SASSYS-1 showed that this is a good assumption for the initial stage of transient, which lasts for about one minute. After that time, degraded heat removal in the RHX starts to communicate back to the RHX inlet location and the sodium temperature at the inlet starts to rise.

Figure 46 shows the comparison of the RHX wall temperatures during the transients. Both sodium and helium cases exhibit similar trends in the wall temperatures for all nodes. Figure 47 shows the comparison of the RHX heatup rates. For the initial stage of the transient, for the first 60 seconds, the results are very similar between the sodium and helium HXs, with maximum wall temperature change rates around 0.4 °C/s in both cases. After 60 seconds, the sodium RHX shows higher rates, which is attributed to the change in the RHX-inlet temperature on the hot side, which was not included in the simulation with helium.

Figure 46. RHX Wall Temperature Results for CO₂ Pipe Break.

Figure 47. RHX Wall Temperature Rate Change Results for CO₂ Pipe Break.

Overall, the following conclusions can be made from the analysis described in this chapter:

- Equivalent heat exchanger performance *can be* achieved with helium,
- When done right, similarity can be obtained *both in steady-state and in transients*,
- Achieving this equivalency required *matching wall temperature axial profiles* at steady-state,
- Because of the difference in heat transfer characteristics, a helium heat exchanger needs to operate at *noticeably higher hot-side temperatures* to provide equivalent performance.

At the same time, the following observations are made during this work and need to be noted for designing an equivalent helium-CO₂ heat exchanger:

- The analysis presented in this report *assumed the same heat exchanger design and size*. Among other things, it assumed that the original Na-CO₂ HX designed for atmospheric sodium pressure will work for higher-pressure helium conditions,
- The equivalent performance required matching overall heat transfer on the hot side and thus is *design-specific*, meaning that the conditions obtained in this work for the helium side are not expected to hold for different HX design or size (although the general approach for matching HX performance should still be valid),
- The analysis presented here included only two transients. More comprehensive analysis of a wider range of transients would require developing *a helium reactor model* and coupling it with a sCO₂ Brayton cycle code,
- Specifics of reactor or experimental loop controls with helium will affect the transient results for the heat exchanger and need to be taken into account,
- Similarly, pump characteristics will also affect the transient results for the heat exchanger. To get similar performance in transients, operation of helium pumps need to match the transient response of sodium pumps as closely as possible.

6 SUMMARY

For the design of innovative heat exchangers for sCO₂ Brayton cycles, it is important to specify what transient conditions those heat exchangers will be subjected to during their lifetime. Since the sCO₂ cycle has never been built at a large scale for a commercial application, an experience base for heat exchanger thermal transients does not currently exist for this cycle.

Argonne has participated in a NEUP project, “Thermal Hydraulic and Structural Testing and Modeling of Compact Diffusion-Bonded Heat Exchangers for Supercritical CO₂ Brayton Cycles,” with the workscope to use Argonne’s Plant Dynamics Code to carry out a comprehensive study of the set of transients that can be imposed on the sCO₂ cycle heat exchangers in a power plant and the resulting transient thermal loadings. This report presented the results of analytical simulations of thermal transients for a sCO₂ cycle carried out using the coupled Plant Dynamics Code and SAS4A/SASSYS-1 code. The analysis was done for the AFR-100 SFR with the sCO₂ cycle energy conversion system producing about 100 MWe. The analysis was focused on thermal transients of the sodium-CO₂ reactor heat exchanger, although the results of other heat exchangers were also obtained during the course of this work.

A wide range of operating and accident conditions were investigated and analyzed. The considered transients were organized into four classes, depending on the likelihood of the event and its potential to impose limits on the RHX structure. These classes included normal operation, design-basis accidents, severe beyond design basis events, and hypothetical limiting accidents. The scope of the analyzed transients ranged from normal load following, small CO₂ pipe breaks and minor valve malfunction, to reactor scram and failure of the sodium pumps and reactor protection system, to large CO₂ pipe breaks, and to hypothetical loss of heat addition and heat removal in the RHX. For each transient, the change in the RHX wall temperature was calculated and presented. The main figure-of-merit in this analysis is the maximum rate of the HX wall temperature change expressed in °C/s units. These values are summarized in Table 4, presented at the end of this report, for each considered transient. As a general rule, the maximum rates of ± 0.2 °C/s, ± 1 °C/s, ± 2 °C/s, and ± 3 °C/s are calculated for normal operation, design-basis accidents, severe events, and hypothetical accidents, respectively.

Under the scope of the NEUP project, the results of this work will be used for structural analysis and design of heat exchangers that will be able to survive all possible transients during the plant lifetime.

In addition to the analysis of thermal transients for the sodium-CO₂ HX, the report also presented the work on finding an equivalent design of a helium-CO₂ RHX. This work was necessary because, for practical reasons, the experimental setup developed under the NEUP project uses helium rather than sodium for the hot-side fluid. The analysis involved both the steady-state and transient capabilities of the Plant Dynamics Code and found that an equivalent heat exchanger performance can be achieved with helium, both in steady-state and in transients. To achieve this result, the specific conditions on the helium side were found that provided matching wall temperature axial profiles at steady-state. It was also found that a helium heat exchanger needs to operate at noticeably higher hot-side temperatures to provide the equivalent performance.

At the same time, it is noted that the results of this particular analysis of an equivalent He-CO₂ HX are design-specific and should not be directly applied to any heat exchanger design. The design itself may need to be revised to account for the generally higher pressures of helium. If the design modifications are made, then more detailed transient simulations of the helium-CO₂ heat exchanger would be needed. That simulation, however, would require development of the helium loop model (either for a reactor or an experimental loop) and coupling that model to a sCO₂ cycle dynamics code. In addition, in order to provide an equivalent heat exchanger performance in transients, the boundary conditions on the hot side will need to be matched as well, which would require careful design of the control system and components, for example, to provide equivalent pump characteristics in transients.

Table 4. Summary of the AFR-100 RHX Thermal Transients

Class of events	Transient	Transient summary	Simulation duration, s	Max. wall temp. change rate, °C/s
Normal Operation	Load Following	From 100% load to 50% and back to 100% at 5%/min rate	2,000	+0.27 -0.21
Design-Basis Accidents	Small CO ₂ Pipe Break	1 cm break at RHX-outlet pipe	2,000	-0.011
	Intermediate CO ₂ Pipe Break	5 cm break at RHX-outlet pipe	700	-0.12 +0.14
	Partial Opening of Turbine Bypass Valve	TBP valve opening from fully closed to 50% in 5 seconds	200	+0.81
	Reactor Power Increase with Scram	Control rod withdrawal with reactor scram and sodium pumps trip at 115% power	220	-0.98
	Loss of Grid Load	Sudden disconnection of the generator from the electrical grid with turbine trip and reactor scram	65	+1.68
Severe Beyond Design Basis Events	Reactor Trip with SCO ₂ Cycle Operating	Reactor and sodium pumps trip, CO ₂ cycle continues to operate at full flow	100	-1.68
	Turbine Trip with Reactor Operating	Turbine tripped, reactor and sodium pumps operate at nominal level	95	+1.78
	Unprotected Reactor Overpower	Control rod withdrawal, reactor protection system fails to scram	2,000	+1.87
	Reactor Overpower with Delayed Scram	Control rod withdrawal, reactor protection system scrams the reactor at peak temperatures	700	+1.87 -3.20
	Large CO ₂ Pipe Break – Outlet Pipe	34 cm (1/2 pipe diameter) break at RHX-outlet pipe	1.4	-6.80
	Large CO ₂ Pipe Break – Inlet Pipe	34 cm (1/2 pipe diameter) break at RHX-outlet pipe	0.9	+2.13
Hypothetical Limiting Accidents	Complete Loss of Heat Addition	Sudden removal of sodium from the RHX hot side, CO ₂ continues to circulate at full flow	350	-2.86
	Complete Loss of Heat Removal	Sudden removal of CO ₂ from the RHX cold side, sodium continues to circulate at full flow	900	+2.58

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